

Article

Assessment of Siltation Processes of the Koronowski Reservoir in the Northern Polish Lowland Based on Bathymetry and Empirical Formulas

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Abstract: Artificial reservoirs have an important role in water management of river systems in terms of flood control, water supply and sediment budgeting. Therefore, it is important to maximize the time of their effective functioning. Sediment budgeting mainly depends on sediment transport dynamics. This article illustrates the impact of the Koronowski Reservoir on suspended sediments transported by the Brda River. The river system and the reservoir represent a typical lowland river environment. Our research is based on hydrological and sedimentological investigations on the reservoir and the river system. Field measurements were used to create the respective hydrological and sediment budgets. Moreover, we carried out bathymetric measurements to generate present day bathymetry and to calculate the reservoir's capacity. We assessed the silting of the reservoir following the approaches proposed by Goncarov and Stonawski. We show that the size and dynamics of suspended sediments are mainly determined by the hydrological conditions. Moreover, we illustrate that the suspended sediment measurements made with the filtration method correlate with the nephelometric results. Generally, we show that the Koronowski Reservoir is mainly filled up by suspended sediments. We further illustrate that the level of siltation estimated with the empirical formulas deviates significantly from calculations made by bathymetric measurements.

Keywords: sediment transport; suspended sediments; reservoir silting; artificial reservoirs; Koronowski Reservoir; lowland rivers

1. Introduction

The creation of artificial reservoirs not only results in water retention by inhibiting water outflows, but also has serious implications on qualitative and quantitative changes in the circulation of matter and energy in the whole river system. One of the processes disturbed by human interference is sediment transport. Rivers play a significant role in the global hydrological cycle, providing about 20 billion t year⁻¹ of sediments to the world's oceans. Moreover, the hydrological cycle also reflects climate change occurring as a result of human activity [1]. Therefore, artificial reservoirs are filled with sediments and thus can no longer fulfill the main functions they were created for, for example, hydropower generation, water retention, flood control, recreational purposes, etc. Dams accumulate transported sediments, which results in a decrease of their operating capacity and water storage [2]. The impact of reservoirs on the dynamics of sediment transport are quite significant, as documented in various studies in the last decades, for example, Van Rijn [3], Kondolf [4], Łajczak [5], Vörösmarty et al. [6], Shotbolt et al. [7], Babiński [8], Gierszewski [9], Hu et al. [10], Magnuszewski et al. [11] and Habel et al. [12]. However, these studies mainly focused on bed load

sediment transport or erosion processes further downstream of a reservoir. Instead, the dynamics of suspended sediment transport were not tackled. Studies conducted on the Koronowski Reservoir, which has been functioning for over 50 years, offer insights into sediment dynamics on the long term. Due to the location of the reservoir in the Polish lowland area, the sediment budget is dominated by suspended sediments. In artificial reservoirs, generally 100% of the bed load material is deposited, as shown by research conducted in the Brda River catchment [13] and the Vistula River basin [8]. The Polish Energy Strategy [14] is aiming at receiving 20% of the energy from renewable sources by 2020. This will most likely force the necessity to increase hydropower generation along Polish rivers. The impact of artificial reservoirs functioning, that is, changes in total supply of sediment, can affect the river network down to the estuary areas [6], which results in transformations of the delta areas and related deposits [15,16]. This study will support future planning and investments. Moreover, this study will contribute to the sustainable development strategy, namely, leaving the natural environment for future generations at the present-day status. Consequently, the main objective of this study is to assess the influence of artificial reservoirs located in Polish lowland areas on suspended sediment dynamics. We established the suspended sediment balance for the Koronowski Reservoir for 2015, taking into account available archive material and monitoring data, dating back to the construction of the dam in 1961. Potential sources of sediment delivery were identified using a soil erosion modeling approach based on the Universal Soil Loss Equation (USLE) [17]. In this paper we compare different methods to calculate reservoir siltation, looking at two traditional empirical formulas and modern bathymetric measurements. Moreover, we used two different methods to establish sediment concentrations.

2. Materials and Methods

2.1. Study Area

The study area is located in Northern Poland. It is drained by the Brda River which is a left tributary of the Vistula River. We focus our research on the Koronowski Reservoir, sited on the lower Brda River 20 km north of Bydgoszcz (Figure 1).

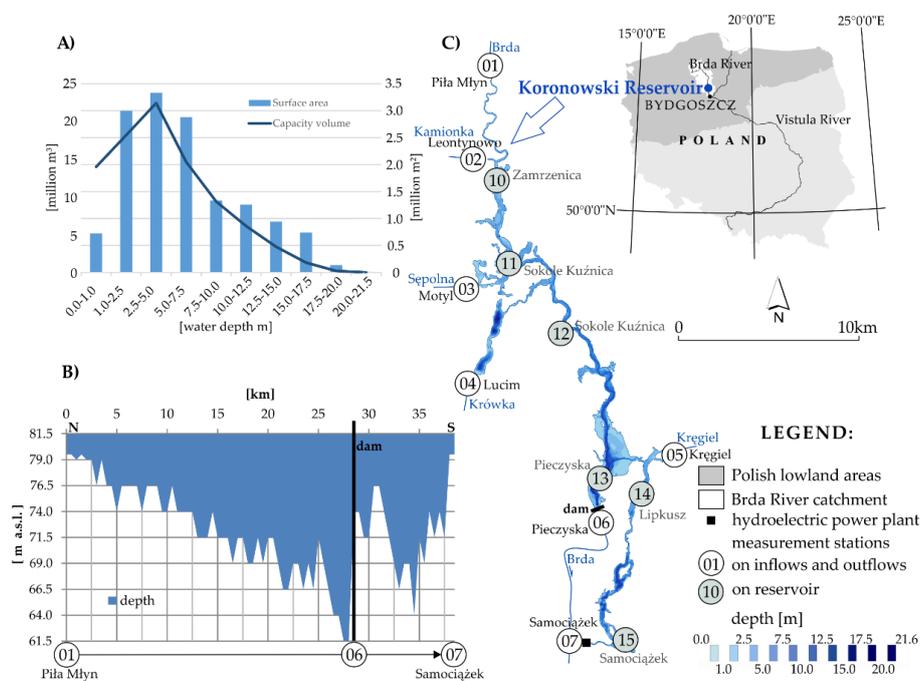


Figure 1. Location of measurement stations of suspended sediments of the Koronowski Reservoir catchment in the Polish lowlands [18,19]; 01–15 measurement stations (in grey on reservoir; in white on inflows and outflows), along with morphometric data: (A) Comparing surface area and capacity volume with depth; (B) longitudinal profile; and (C) bathymetry of the Koronowski Reservoir.

The first plans to use the water resources of the Brda River for hydroelectric purposes around the town of Koronowo came up in the early twentieth century [20]. However, it was only in the 1960s that a project under the direction of Józef Dębowski [21] was conducted to study the impacts of a reservoir on sediment dynamics. The Koronowski Reservoir itself was created in 1961. The dam, situated close to the village of Pieczyska (Figure 1), is damming water to a height of 15 m. An additional 10 m of hydraulic gradient was obtained by locating the hydroelectric power station further downstream. The water was directed through a gallery at the bottom of the lakes Lipkusz and Białe to the city of Samociażek (lateral canal), where the hydroelectric power station is located. The total capacity of the two installed turbines is 26 MW, which allows an average annual production of electricity of 40.841 GWh. The Koronowski Reservoir has a normal water level height of 81.5 m a.s.l. and a capacity volume of 81.0 million m³. However, about 73% of the volume consists of so-called “dead” (not used) storage, which significantly affects the water circulation system [22]. According to the physical and geographical description of Kondracki [19] the reservoir is a part of the South-Pomeranian Lake District. The Koronowski Reservoir is located in the lower part of the Brda Valley, which is formed of glacial outwash sands. The sander formation is flanked in the east by the Świecie Upland and in the west by the Krajna Lake District area, mainly consisting of clay rich postglacial formations. The catchment area of the Koronowski Reservoir amounts to 4299 km², with 65% of it belonging to the upper Brda River, which is its main tributary. Other tributaries draining the remaining 35% of the total catchment area provide considerably smaller amounts of water [23]. The average discharge of the Brda River flowing into the Koronowski Reservoir amounts to 23.7 m³ s⁻¹ in the period 1962–2015 [24]. We present detailed hydrological data for all small inflows of the Koronowski Reservoir only for 2015 (only existing data). Detailed hydrological characteristics of the Brda River catchment (reservoir inflows) are presented in Table 1.

Table 1. Discharge of the main Koronowski Reservoir tributaries (1962–2015) ([24] and own research [25]).

Discharge m ³ s ⁻¹	River				
	Brda River Piła Młyn 01	Kamionka Leontynowo 02	Sęplona Motyl 03	Krówka Lucim 04	Kręgiel Kręgiel 05
Min	4.6	0.6	0.2	0.0	0.0
Max	84.4	4.4	3.0	2.5	0.4
Av.	23.7	2.3	0.9	0.5	0.1

The Brda River is one of the Polish rivers with the most balanced ratio of flow irregularity (λ), given as the ratio between maximum and average discharge. The value of λ for the period 1974–1983 is 1.54 [26]. This has a decisive impact on the balance of suspended sediments of the Koronowski Reservoir. Moreover, the fact that 3.41% of the upper Brda River basin is a lake [23] is profoundly influencing the sediment balance and dynamics of the reservoir. The land cover of the Koronowski Reservoir catchment area is dominated by forests and agricultural land, covering 46.1% and 48.0% of the surface, respectively [27]. Land use has changed over recent decades, with a systematic reduction of forest areas and an increase of arable land and urban areas. This is a result of strong anthropogenic pressures, especially on the lower part of the Brda River catchment area. Land use and land cover significantly influence sediment delivery to the catchment [28]. As shown by Ciupa [29], intensively urbanized areas have a significant impact on the dynamics and quantity of fluvial transport. Nevertheless, sediment concentration is usually higher in agriculture areas, such as large parts of the Brda basin. However, artificial reservoirs reduce downstream sediment concentration significantly. The Koronowski Reservoir is the first and uppermost of three artificial reservoirs (Koronowski, Tryszczyn and Smukała), forming the Lower Brda River Dams system.

2.2. Hydrological Data

Discharges of the Brda River are measured at Samociażek Hydropower Plant, Piła Młyn (Figure 1C, location 01) and Samociażek (Figure 1C, location 07). Daily discharge data are calculated using local

rating curves available from 1962 to 2015 [24]. Gauging station measurements are complemented by field measurements (Figure 1C, stations 02–06) using the method described by Paślowski [30]. On the main tributaries of the Koronowski Reservoir, monthly observations of the flow rate were carried out using an acoustic current meter (OTT GmbH C20).

2.3. Suspended Sediment Data

Sampling of suspended sediments (total suspension in mg L^{-1} , and turbidity in Formazin Nephelometric Unit—FNU) took place at the main tributary inflows (Figure 1C, locations 01–05) and at the outflow (Figure 1C, locations 06–07) of the Koronowski Reservoir. Moreover, six locations (Figure 1C, locations 10–15) were measured within the reservoir in order to identify the internal dynamics of sediment transport. Measurements were taken on a monthly basis using a slowly filling bathometer, which is comparable to commonly used methods [31,32]. The concentration of suspended sediments in each sample was determined by two methods: (i) through a traditional filtration using paper filters with a porosity of $0.45 \mu\text{m}$ and a subsequent drying procedure (in mg L^{-1}) as well as (ii), by means of a nephelometric turbidimeter method (Hach Lange 2100QIS) (in FNU). Turbidimeters are widely used to monitor suspended sediments [33].

The capacity to retain suspended sediments is given by the balance of the material delivered to, and flushed off the reservoir (β):

$$\beta = \frac{R_Z}{\Sigma R} \quad (1)$$

where R_Z is the amount of suspended sediments retained in reservoir (t) and ΣR is the amount of suspended sediments delivered into reservoir (t).

We calculated the silting progress of the Koronowski Reservoir using two empirical methods. On the one hand, we applied the Goncarov's method, which is generally used [34–39] and suitable for our study area [40,41]:

$$Z_t = V_p \left[1 - \left(1 - \frac{R_1}{V_p} \right)^t \right] \quad (2)$$

where Z_t is the volume of sediments (in m^3) after “ t ” years, V_p is the initial volume of the reservoir (m^3), R_1 is the volume of sediments after the first year of functioning (m^3), t is the years of functioning.

We estimated the volume of accumulated sediments after the first year of exploitation using the following formula:

$$R_1 = \frac{\beta R_u}{\rho_0} \quad (3)$$

where R_u represents average annual weight of sediments delivered to the reservoir (t), β is the reservoir's ability to retain suspended sediments, ρ_0 is bulk density of sediments— $2.7 \text{ (t m}^{-3}\text{)}$ [35].

The second method to calculate the silting progress of the Koronowski Reservoir is based on the Stonawski formula [42], which was developed using five large reservoirs in Poland [43]:

$$Z_R = 0.01 V_p \times \exp \left(0.12 - 0.17 \frac{V_p}{SSQ} \right) \quad (4)$$

where Z_R is the volume of sediments (million $\text{m}^3 \text{ year}^{-1}$), V_p is the initial volume of the reservoir (million m^3) and SSQ is the average discharge flowing into the Koronowski Reservoir ($\text{m}^3 \text{ s}^{-1}$).

2.4. Bathymetric Measurements

In order to determine the volume changes of the Koronowski Reservoir during 54 years of functioning, we performed depth measurements with a single beam sonar (LOWRANCE HDS-5 Gen2) and a GPS positioning device (16-channels). The dual-band sonar frequency (50/200 kHz) allowed us to adjust the appropriate signal beam to a specific depth and type of bottom substrate. In total, we conducted 340 sounding sections. Due to the large area of the reservoir (14.4 km^2),

measurements were carried out in cross-sections at approximately 100–150 m intervals. The total length of the Koronowski Reservoir's soundings was about 254 km. We used the open source Geographic Information System software QGIS (version 2.16.3) to interpolate the bathymetry and the capacity volume of the reservoir. The final bathymetry was interpolated using a thin plate spline method implemented in QGIS.

2.5. Soil Erosion and Sediment Delivery

In order to get information about the sediments washed into the reservoir we applied the USLE soil erosion model, [17] given as

$$A = R \times K \times LS \times C \times P \quad (5)$$

where A is soil loss per unit area ($\text{t km}^{-2} \text{ year}^{-1}$), R is rainfall and runoff factor, K is the soil erodibility factor, LS is the slope-length factor, C is the cover and management factor and P is the support practice factor.

The model was applied in the Brda River catchment, showing the spatial distribution of soil erosion and sediment production at 20 m resolution. Input data are based on the work of the Institute of Meteorology and Water Management (R factor) [44], the Soil map of Poland (K factor) [45], a Digital Elevation Model of the Brda River catchment (LS factor) [46], and Corine Land Cover (C and P factors) [27]. Sediment delivery was derived using archive data of the National Environmental Monitoring Programme [47] and own research (2015) [25].

3. Results

3.1. Discharge

The average discharge of the Brda River (01) flowing into the Koronowski Reservoir in the hydrological year 2015 was $15.2 \text{ m}^3 \text{ s}^{-1}$ (Figure 2). The highest flows occurred in February ($21.7 \text{ m}^3 \text{ s}^{-1}$), followed by one of the most extreme dry periods in the history of observation, which also had an impact on the suspended sediment budget. The lowest recorded flow rate (month VII–IX) oscillated around $10.0 \text{ m}^3 \text{ s}^{-1}$, which is close to the lowest recorded discharge value of $9.79 \text{ m}^3 \text{ s}^{-1}$ at the Tuchola gauge [48]. Low flow rates are also registered for the other tributaries of the Koronowski Reservoir. Moreover, the amount of water discharged from the reservoir to the Koronowo hydroelectric power plant decreased and thus, hydroelectric energy production was also reduced.

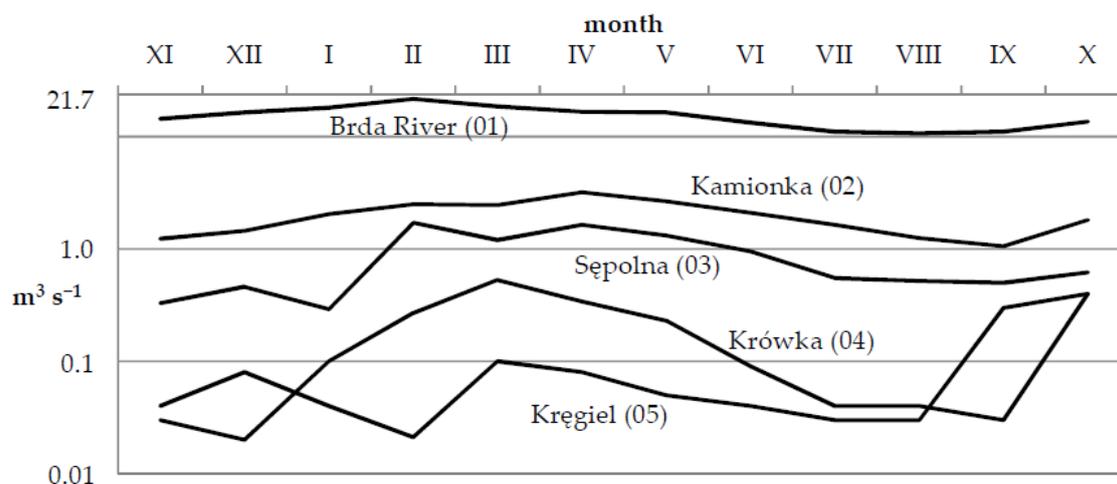


Figure 2. Discharges of main inflows to the Koronowski Reservoir in the hydrological year 2015 ([24] and own research [25]).

Water flowing into the reservoir comes from tributaries of different size. The Brda River delivered 477.9 million m³ of water to the Koronowski Reservoir in the analyzed hydrological year. The inflow of the Kamionka River (Figure 1C, location 02) contributed 62.7 million m³, Sępolna River (Figure 1C, location 03) 27.1 million m³, Krówka River (Figure 1C, location 04) 5.7 million m³ and Kregiel (Figure 1C, location 05) 3.2 million m³. Dividing the total volume of water flowing into the Koronowski Reservoir by its current capacity (76 million m³), we calculated the potential time of water exchange amounting to 7 days. The total discharge from the Koronowski Reservoir (Figure 1C, location 07) was 514.8 million m³ in 2015.

3.2. Sediment Distribution

The concentration of total suspended material in the main tributary to the Koronowski Reservoir (Figure 1C, station 01) oscillated between 2.0 mg L⁻¹ and 7.2 mg L⁻¹, with an average of 3.8 mg L⁻¹ in 2015 (Table 2). The concentration of total suspended material for the same inflow oscillated between 1.8 mg L⁻¹ and 46.0 mg L⁻¹ (VI. 1987), with an average of 5.8 mg L⁻¹ in the period from 1980 to 2013 [47]. The values of total suspended material on the outflow of the reservoir (Figure 1C, station 07) in 2015 oscillated at quite low levels (1.8–4.0 mg L⁻¹), averaging 2.6 mg L⁻¹. The concentration of total suspended material in the same outflow oscillated between 1.0 mg L⁻¹ and 23.0 mg L⁻¹ (VIII. 1988) with an average of 4.2 mg L⁻¹ in the period from 1980 to 2013 [47]. Other monitored tributaries might have higher concentrations of suspended sediments. However, these values represent characteristic suspended sediment concentrations of the Polish lowland areas [49].

In 2015, the turbidity of the Brda River at the inflow to the Koronowski Reservoir ranged from 1.29 FNU to 5.32 FNU, averaging 2.95 FNU. Similar values were measured at the outflow of the reservoir. The average turbidity of the other tributaries shows values twice as high (Table 2).

Table 2. Characteristic values of total suspended material (mg L⁻¹) and turbidity (FNU) for inflows and the outflow of Koronowski Reservoir in the hydrological year 2015.

Value	Stations					
	Brda River Piła Młyn 01	Kamionka Leontynowo 02	Sęplona Motyl 03	Krówka Lucim 04	Kregiel Kregiel 05	Brda River Samociążek 07
Min	2.0/1.29	2.4/3.04	4.0/3.64	1.8/1.36	2.0/2.46	1.8/1.34
Max	7.2/5.32	10.0/7.47	22.0/15.50	12.0/14.70	10.4/9.96	4.0/4.51
Av.	3.8/2.95	5.3/5.05	8.0/6.95	6.0/5.55	5.3/4.70	2.6/2.27

The delivery of sediments of the Brda River to the Koronowski Reservoir in the hydrological year 2015 fluctuated between 81 t (August) and 383 t (April) (Figure 3). The total load supplied from the upper basin of the Brda River amounted to 2439 t. In comparison, the average total load supplied to the Koronowski Reservoir in the period 1980 to 2015 amounted to 6110 t year⁻¹ [47]. Hence, due to the very dry conditions in 2015, the values of suspended load are less than half than the mean values in the period 1980 to 2015. However, the seasonal dynamics are preserved in the time series, which shows high concentrations in spring (April) and relatively low values in summer (August). Differences are illustrated in Figure 3 for the average values between 1980–2015, especially in December and January, which are much higher than in the dry year of 2015, with very low precipitation in the corresponding months. The supply of sediments from other tributaries of the reservoir oscillated throughout the year, ranging from 0.1 t (Krówka River) to 75.3 t (Sępolna River), amounting to a total of 631.6 t. In the analyzed period, the outflow of sediments from the Koronowski Reservoir ranged between 83.6 t and 240.0 t and totaled to 1742.9 t. In almost all months (except August) there is a prevailing accumulation of suspended sediments in Koronowski Reservoir (Figure 3). Only in August there is a slightly negative balance, meaning that there are more outflowing suspended sediments than inflowing. The negative balance is very small and might be related to resuspension of sediments or biologic activity. As Figure 3 illustrates, there is a general accumulation in all other months. The period characterized by a maximum supply of sediments (II–VI) was accompanied by the largest accumulation of sediments in the reservoir.

Given the volume of the flow rate, the main portion of suspended sediment load flowing to the Koronowski Reservoir is delivered by the Brda River. The other tributaries supplied about a quarter of the sediment load. The contribution of the small tributaries of the Koronowski Reservoir (excluding Brda River) to the total balance of suspended sediments should be emphasized. The relatively high sediment supply rates are conditioned by the morphometric features of these tributary catchments (e.g., soil erodibility, not many lakes).

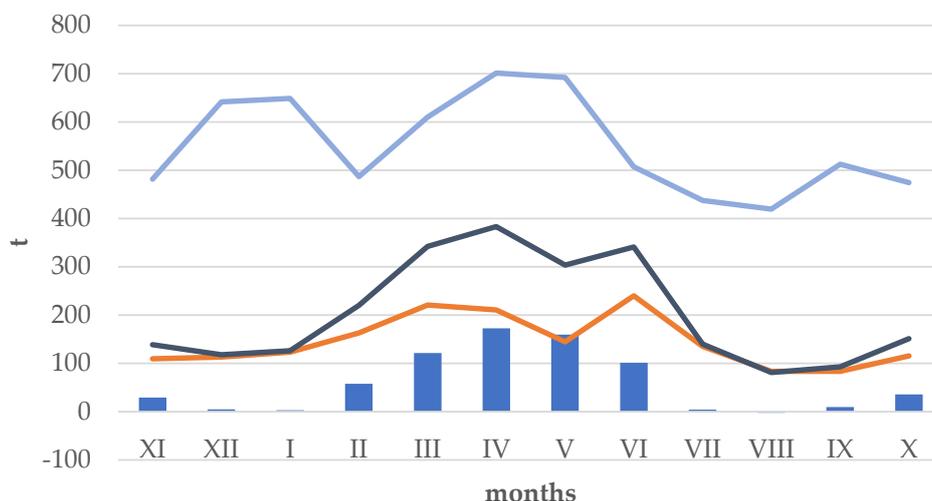


Figure 3. Total suspended sediment budget of Koronowski Reservoir during the hydrological year 2015. Explanations: inflowing suspended sediments (dark blue—2015; light blue—average 1980–2015 [47]); outflowing suspended sediments (orange) and suspended sediment balance (light blue columns).

3.3. Capacity of Koronowski Reservoir

The most precise method to determine the loss of reservoir capacity due to silting is a comparison of bathymetric volumes over time. Geodetic measurements, made for the technical project of the reservoir for the hydroelectric power plant Koronowo [22], assumed that the initial capacity in 1961 at normal water level (81.5 m a.s.l.) amounted to 81.0 million m³. The bathymetric map, made in 1988 [18], indicates that the volume had already decreased to a level of 77.5 million m³ (loss of 4.3%). Bathymetric measurements, made by the authors in 2015, allowed us to calculate the current water retention volume of the Koronowski Reservoir. Referring the results to the same water level at the dam as in the earlier measurements, we calculated a current retention capacity of 76.0 million m³. Compared with the bathymetric map made in 1988 [18], the volume decreased an additional 1.9%, yielding a capacity loss of 5.0 million m³ (6.2% in 54 years) in respect to the initial capacity of the Koronowski Reservoir.

4. Discussion

The sediment concentration in the discharge of the main tributaries of the Koronowski Reservoir is relatively low. This is mainly due to the typical hydrological and morphological characteristics of lowland river basins. Aligned supply of water, reduced by a significant component of underground outflow and a large retention capacity of the upper part of the catchment [50], results in a low intensity of erosion processes. Furthermore, anthropogenic impacts and effects such as point source pollutions are relatively small in the Brda River basin [26]. The annual distribution of sediment supply to the Koronowski Reservoir corresponds to the regime of the Brda River, where the highest flows (spring season) represent the largest delivery of material. This is a typical situation for Polish lowland areas, also found in other studies by Zwoliński [51] on the Pilica River or Jaworska [52] on the Wieprz River. Higher values of suspended load and turbidity of the Koronowski Reservoir tributaries and respective lower concentrations in its outflow, enable the calculation of the sediment load balance (Figure 3),

indicating an accumulation of sediments within the reservoir. Sediment accumulation and hence trapping of the supplied suspended sediments washed into the Koronowski Reservoir, proves that the reservoir is filling up and thus, fulfilling one of its major functions. Following Hartung's criterion [53], reservoirs that show a reduction in capacity by 80% lose their functionality. Globally, according to the assessment of the International Commission on Large Dams (ICOLD), operational artificial reservoirs are losing annually about 1400 million m³ of their capacity [54]. In most river systems around the world decreasing sediment loads are actually observed, mainly because of trapping by upstream dams [55]. On the basis of depth soundings and analysis of archival bathymetric maps, it was shown that the volume of the Koronowski Reservoir was reduced in 54 years by only 6.2%. The areas of the Koronowski Reservoir in which accumulation of sediments normally occurs were included in the assessment, such as: (i) the backwater zone, where runoff and energy and hence transport capacity is dropping; (ii) the dam zone, which is the main accumulation area; and (iii) the zones of bays and estuary of inflows that have a limnetic character. The average value of sediment concentration (mg L⁻¹) along the longitudinal profile of the Koronowski Reservoir shows a general downward trend of sediment concentration towards the hydroelectric power plant at Samociążek (Table 3). This pattern is disturbed at two locations (11 and 13), which are characterized by limnetic conditions. The increase in sediment concentration may result from the resuspension of sediments as a result of wave activity. Higher values in these zones may be due to a high biological production in isolated bays, especially during the summer. This might be the reason for the negative balance of suspended sediments in the Koronowski Reservoir (Figure 1C, location 13) in August 2015, where a higher outflow than inflow of suspended sediments was registered.

Table 3. Average values of total suspended material (mg L⁻¹) along the longitudinal profile of Koronowski Reservoir in the hydrological year 2015.

Value	Stations					
	Zamrzenica 10	Sokole Kuźnica 11	Sokole Kuźnica 12	Pieczyska 13	Lipkusz 14	Samociążek 15
Av.	2.50	2.72	2.10	2.33	2.10	2.21

The extent of mechanical denudation in the catchment area depends on land use, soils, geomorphology, management methods, climate and hydrological parameters [56]. The total supply of soil material by water erosion estimated with the USLE model [17] for the total catchment area of the Brda River amounts to 36.4 t km⁻² year⁻¹ [57]. Figure 4A illustrates the spatial differences of the delivery ratio in lowland Brda River and in turn, the source areas of suspended sediment supply within the catchment. Moreover, it is also shown that suspended sediment transport is significant in the sediment budget of the Brda River basin. Catchments characterized by a potential higher supply of sediment are located in the upper part of Brda River. However, due to the significant amount of lake surfaces and artificial reservoirs, those are not reflected in the total sediment balance. The analysis of the suspended sediments data of the Koronowski Reservoir, collected by field measurements and retrieved from the archive of the National Environmental Monitoring Programme [47], indicate fluctuations in the annual supply, varying between 26607 t (1980 year) and 1593 t (2000) (Figure 4B). The denudation rate, calculated based on actual measurements of suspended sediments for the years 1987–1999, amounted to 1.66 t km⁻² year⁻¹. In 2015, this value is lower, at about 0.87 t km⁻² year⁻¹. Moreover, the data reveal a characteristic feature related to the reduction of supply volumes in the 1990s, which are due to the decrease of point source pollutions [58,59] (Figure 4B). During this period, many water management and environmental programs were started in Poland, limiting the supply of pollutants, including suspended sediments. Hence, they contribute to the improvement of water quality [26]. Finally, most of the suspended material delivered from the catchment area accumulates in artificial reservoirs. In the analyzed period, only a few years show a negative sediment budget. The year 2015 was characterized by positive values of the retention potential with $\beta = 28.5\%$. However, based on the analysis of this parameter, the degree of capacity loss of the Koronowski Reservoir

cannot be unambiguously defined. Hence, we utilized empirical equations taking into account silting dynamics. Following Goncarov's method [34], reservoir retention capacity β was assumed to be 37%. This value of β results from the actual measurements of suspended sediments in the framework of the National Environmental Monitoring (1987–1999) [47]. Generally, data used to calculate the value of β for a longer period better reflect silting dynamics. Silting of the reservoir basin amounts to 18.9 million m^3 , which corresponds to a 23.3% reduction of volume in 54 years. Calculations of the capacity loss of the Koronowski Reservoir using the second method, the Stonawski formula [42], indicate a decrease of its volume in the analyzed period by approximately 33%. The discrepancies in the results of the capacity loss of the Koronowski Reservoir by the aforementioned methods are primarily due to the incomplete set of monitoring data taken into account in the budgeting of suspended sediments, especially in the initial phase of dam operation, when the circulation of material was most intense. However, the results allow us to compare the silting rate of the reservoir calculated using empirical methods (Goncarov, Stonawski) with the measured bathymetric volumes over time.

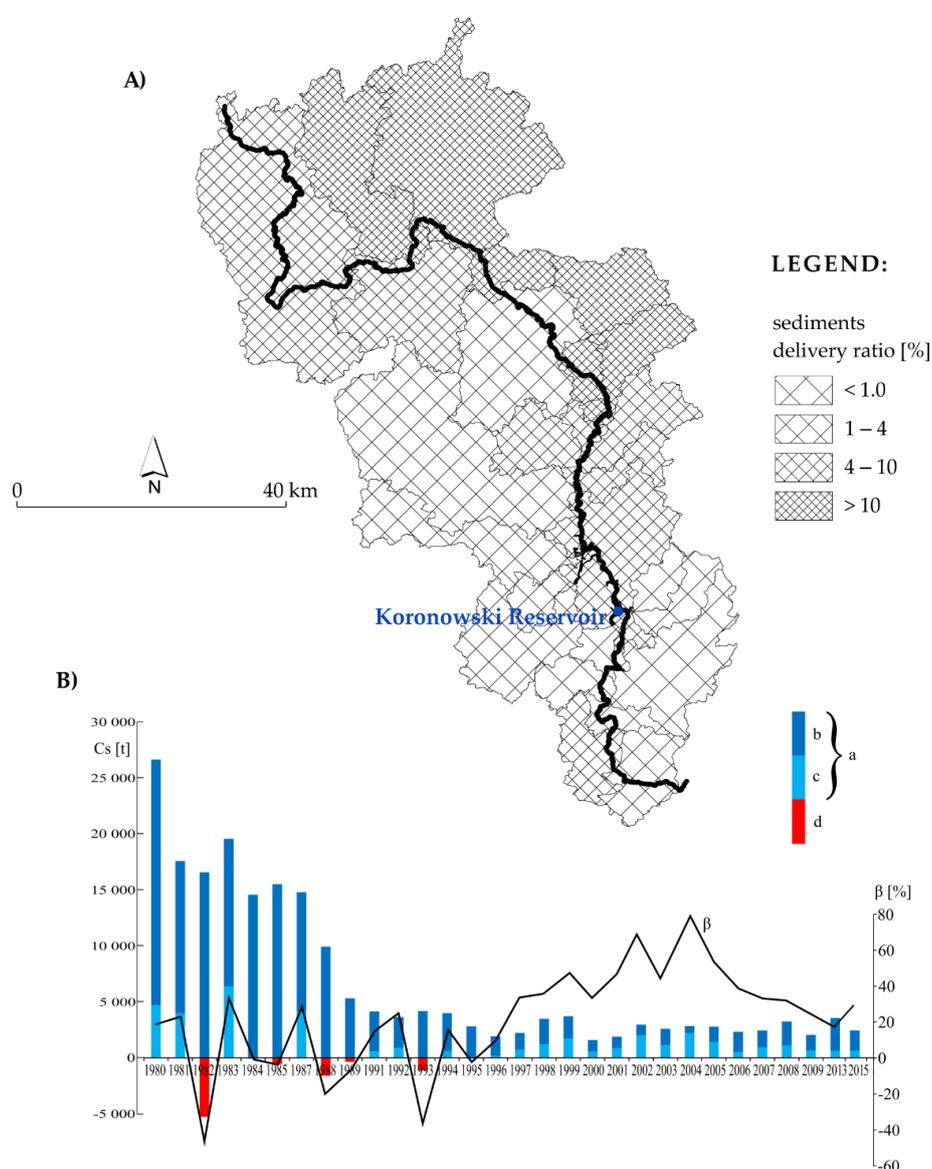


Figure 4. (A) Sediment delivery ratio calculated with the Universal Soil Loss Equation (USLE) [17]; (B) sediment budget (Cs) and the ability to retain suspended sediments (β) for the Koronowski Reservoir in the years 1980–2015 ([24,46] and own research [25]). Explanations: a—supply, b—accumulation, c—outflow, d—erosion.

Our results for the continuity of suspended sediments on the rivers with artificial reservoirs are confirmed by various authors. Research by Babiński [8] and Babiński and Habel [60] found that the Włocławek Reservoir, which is the biggest in the Polish lowlands, reduced suspended sediments of the Vistula River by 42%. Similar dynamics of suspended sediment transport were found in research on the Sulejów Reservoir (Pilica River), showing a 45% reduction of sediments [61,62], and on the Danube River in Serbia, where the sediment accumulation is estimated at 66% [63].

One of the objectives of the project was to compare benchmarks of sediment concentrations by two methods: (i) traditional (in mg L^{-1}) and (ii) nephelometric (in FNU). The coefficient of determination of the monthly series range from 0.822 to 0.964, showing a strong positive correlation. Similar results are reported in research by Lewis [64], IAEA report [65], Felix et al. [66] and Haimann et al. [67]. Only one measurement period (March 2015), showed no correlation (0.656). The results confirm the usefulness of the nephelometric method in determining the quantity of suspended sediment, which is characterized by a greater ease in obtaining qualitative data. This fact has also been confirmed by studies on the degree of mechanical denudation in other catchment areas, for example, by Szewrański et al. [68].

5. Conclusions

We carried out a detailed study of the suspended sediment dynamics in the Koronowski Reservoir system. The results obtained show that the average annual values of suspended sediments (total suspension in mg L^{-1} ; turbidity in FNU) in the tributaries are higher than in the outflow of the reservoir, indicating sedimentation processes. This emphasizes the accumulation character of the Koronowski Reservoir, especially for the dynamics of suspended sediments. The Brda River is the main source of suspended sediments transported into the Koronowski Reservoir, which in turn is conditioned by the hydrological characteristics and especially by the size of its tributaries. The suspended sediment budgets for the hydrological year 2015, and for most of the years in the period 1980 to 2013, indicate that the Koronowski Reservoir is filling with sediments. Bathymetric soundings, conducted by the authors, showed a volume loss of water retention in the Koronowski Reservoir of 6.2% over 54 years, with respect to the initial capacity. The degree of siltation, calculated based on Goncarov's formula, showed a much higher loss of 23.3%. Calculations of the capacity loss of the Koronowski Reservoir using the Stonawski formula showed an even higher decrease of its volume (33%). These differences are mainly due to the different input factors used in the empirical formulas. However, the results obtained by depth soundings are more reliable. This study confirms that due to the location of the reservoir in the Polish lowland area, the sediment budget is generally dominated by suspended sediments. Moreover, the project result will support future planning and investments, fulfilling one of the basic requirements of the sustainable development strategy, namely, leaving the natural environment for future generations at the present-day status.

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