RESEARCH PAPER

IMPACT OF MOZHAYSK DAM ON THE MOSCOW RIVER SEDIMENT TRANSPORT

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ABSTRACT. Sediments are an essential part of the aquatic environment that define its transformation and development. The construction of dams results in severe changes in sediment fluxes. This study aims to assess how the sediment load of the upper Moskva River is affected by the Mozhaysk Dam flow regulation and to estimate its dynamics over the years of the reservoir's existence. Our analysis of the 1968, 2012 and 2016 detailed field data shows a 20-40% decrease in the proportion of the spring flood in the annual sediment load into the reservoir, which is caused by changes in the streamflow regime of the inflowing rivers. The peak suspended sediment concentrations have decreased 5- to 10-fold, likely due to a significant decline in the watershed's cultivated land area, which caused a decrease in the erosion rate. In the Moskva River below the dam, the seasonal dynamics of the suspended sediment concentration no longer corresponds to the natural regime. The annual suspended load of the Moskva River below the Mozhaysk Reservoir decreased up to 9-fold. The sediment retention in the reservoir has dropped from 90% to 70-85% and is to some extent restored by an outflow of the particulate organic matter produced in the reservoir. We also described the relationships between water turbidity and suspended sediment concentration of the reservoir's tributaries, which allow for the first time to estimate the sediment load with higher accuracy than was previously possible.

KEY WORDS: Mozhaysk Dam, sediment load, suspended sediment concentration, reservoir

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INTRODUCTION

Sediment is an essential part of a river ecosystem that defines its transformation and development (Vanmaercke et al. 2011; Wang et al. 2016). The erosion rate may vary under the influence of a great range of watershed processes, including climate change and various human activities (Syvitski et al. 2005). Soil erosion determines the chemical composition of the river water and its nutrient supply. Solid particles also act as a means of pollution transport due to their high sorption capacity for heavy metals and organic contaminants, such as pesticides, insecticides, etc.

At the same time, erosion, sediment transport, and deposition in the river system control the patterns of the spatial distribution of the riparian biomes. The macrophyte growth increases the self-purification capacity of a river and its resilience to human pressure; floodplain sediments act as a spawning and nursery zone for freshwater fish. Many aquatic organisms are sensitive to water turbidity and bedload properties (Shields 2009). This dictates the need to study the sediment flow in rivers as a necessary step towards understanding and predicting the dynamics of freshwater ecosystems, and preserving the habitat for indigenous species.

The construction of dams results in severe changes in both water and sediment fluxes (Kondolf et al. 2014; Kovacs et al. 2012; Snoussi et al. 2002; Yang et al. 2006). The disruption of the ecological integrity of a river leads to an increase in bank erosion rates at the downstream reaches (Grimshaw and Lewin 1980; Wright and Schoellhamer 2004), causing degradation and loss of river-floodplain habitats (Ligon et al. 1995). The peak sediment load in dammed rivers is separated in time from the maximum water flow (Dang et al. 2010; Topping et al. 2000). Moreover, the balance between inorganic and organic sediment is disrupted. The predominately mineral particles from the river are deposited in the bottom sediments, and increased biological production rates cause the suspended load of the reservoir outflow to be largely composed of the organic matter of the aquatic organisms.

Reservoirs interrupt the transit of suspended sediment with river runoff, trapping up to 50-90% and more of the incoming sediment flux and altering the distribution between particles of different sizes (Hojan and Rurek 2017; Berkovich 2012; Le et al. 2020; Piqué et al. 2017; Suif et al. 2017; Van Binh et al. 2020). This effect is particularly evident in cascades of reservoirs and in large reservoirs located in mouth zones of rivers, where the sediment retention rate may reach 100% (Guo et al. 2020; Huang et al. 2018; Ibàhez et al. 1996), although in the case of rivers with large sediment loads cascade reservoirs have lesser retention potential (Wu et al. 2018). In arid and semiarid regions of many countries (Mexico, Spain, Italy, Iran, and China), check dams are constructed as an effective measure for reducing the sediment load, allowing to intercept from 7% to 100% (50-90% on average) of the river sediment (Díaz-Gutiérrez et al. 2019; Tang et al. 2020).

The study of the long-term variability of the river sediment budget under the influence of flow regulation is not only relevant from the ecosystem dynamics point of view; it also has implications in reservoir design and management (Nagle et al. 1999; Zhao et al. 2017). Reservoir siltation reduces the water storage capacity and limits the operation performance of the dam (Anselmetti et al. 2007; Nagle et al. 1999; Palmeiri et al. 2001). In reservoirs with high siltation rates, especially in arid regions with highly cultivated watersheds, flushing is used to control rapid sediment deposition. Although flushing is highly efficient for restoring the water storage capacity, it causes significant deformation of the bottom sediment in both the reservoir and its downstream reaches (Maneux et al. 2001).

High interannual variation of the suspended load causes instability in the assessments of the reservoir siltation rates (Krasa et al. 2009; López et al. 2016). It is, therefore, necessary to overview long-term dynamics of the suspended sediment flux in the river system and its deposition in the reservoir to develop an efficient watershed management strategy (Jansson and Erlingsson 2000). In mountain watersheds, climatic changes become the primary driver for the changes in the suspended sediment load (Anselmetti et al. 2007; Chalov 2017; Valero-Garcés et al. 1999). In lowland reservoir watersheds, soil erosion rates are mostly controlled by agricultural development; its dynamics over the years can lead to a manifold increase or decrease in the reservoir siltation rates (Gellis et al. 2006; Thothong et al. 2011).

Over the last 35 years, social and economic factors have led to many changes in the land-use management of the watersheds in Russia (Kurganova et al. 2014; Oltchev et al. 2002; Walker et al. 2011). The major changes include the decrease of the cultivated land area and land afforestation, which led to a reduced soil erosion rate (Ivanov 2018; Sieber et al. 2013). The decline in the suspended sediment load is further enhanced by the climatic and hydrological changes, the key ones being the changing patterns of the spring flood and the increasing role of rain floods in the water budget. All this results in a significant shift in the sediment budget of reservoirs and alters the effect of dams on sediment transport.

For the Russian reservoirs, an accurate evaluation of the long-term sediment load dynamics is often hampered by the lack or insufficiency of monitoring data in the reservoir watersheds, and especially in their downstream reaches. An adequate assessment of the annual sediment load is also dependent on frequent measurements of the suspended sediment concentration (SSC) during peak discharge, rising and falling limbs of each flood, especially during the spring flood, which carries up to 75% of the total sediment load (The Mozhaysk… 1979; Sokolov 2015), as the SSC value may increase or decrease by several times in a very short time during high-flow periods.

For smaller reservoirs, determining the long-term variation of the sediment load is most crucial. All of the drinking water reservoirs in the Moscow Region have a low water storage capacity but play an essential role in supplying the drinking water for the 17-million population of Moscow city. One of the major parts of this water supply system is the Moskva River watershed, which in 2018 contributed to 78% of the total drinking water for the city; its water runoff, dissolved and particulate load is significantly affected by the Mozhaysk Dam on the Moskva River (Moscow City…).

The first detailed observations of the suspended sediment load that illustrate the Mozhaysk Reservoir's impact on the suspended sediment transport in the Moskva River were carried out in 1968 (Vinogradova 1970; The Mozhaysk… 1979), but until recently, no new studies have been conducted. In 2012 and 2016, we carried out two field programs with a similar level of detail. The objectives of this study are: a) to assess how the sediment load of the upper Moskva River is affected by the flow regulation by the Mozhaysk Dam and b) to estimate its dynamics over the years of the dam operating.

MATERIALS AND METHODS

Site description

The Mozhaysk Reservoir (55°35' N, 35°50' E) is located in the western part of the Moscow Region (Fig. 1). It was created in 1960 and serves as a part of the Moscow city water supply system. The reservoir has a drainage area of 1,360 km^2, covering a total surface area of 30.7 km^2 and has a storage capacity of 235 million m^3 at a normal pool level. Three rivers – The Moskva, Lusyanka, and Koloch (catchment areas F = 755 km^2, 170 km^2, and 279 km^2 respectively) – cover 91% of the reservoir's watershed; their combined flow accounts for 83% of the total water inflow to the reservoir (The Mozhaysk… 1979).

There are two discharge gauging stations operated by the Russian Federal Service for Hydrometeorology and Environment Monitoring (Roshydromet): Barsuki on the Moskva River and Cherniki on the Lusyanka River; both can be considered outlet stations as they are situated closely upstream from the backwater zones that form where the rivers reach the reservoir.

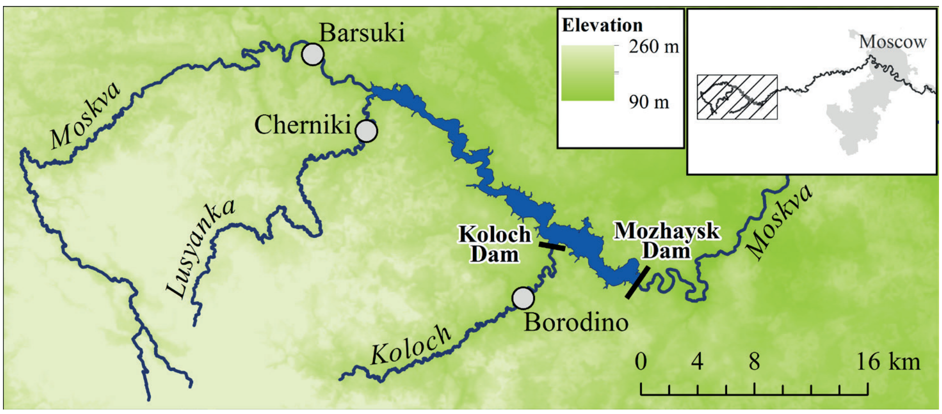

Fig. 1. The Mozhaysk Reservoir and its main tributaries

The Koloch River inflow is controlled by a pumping station that regulates the water flow between the Mozhaysk Reservoir and the smaller Koloch Reservoir.

Data collection

In an average-flow water year, 1968 (total inflow ΣIN = 245 million m^3), suspended sediment concentration was determined in 220 samples taken from the reservoir tributaries and the Moskva River below the dam (40-63 samples from each of the 4 designated stations). During the spring flood, samples were taken once every 1-2 days, in summer and autumn – about once a week, and in winter – once every 10 days (Vinogradova 1970).

In a high-water year, 2012 (ΣIN = 360 million m^3) we carried out a similar, though less detailed study (Sokolov 2015), with a total of 182 samples taken on the rivers (34-38 samples from each of the 5 stations). The samples were taken once every 2-4 days during the spring flood, once every 1-2 weeks in summer and fall, and once every 2-3 weeks in winter.

In another average-water year between March 2016 and March 2017 (ΣIN = 287 million m^3), we conducted another, more comprehensive study of the suspended load transport in the Mozhaysk Reservoir system (Sokolov et al. 2018). A total of 224 samples were taken from the rivers (56 samples at each of the 4 stations): once every 1-2 days during the spring flood and separate rain floods, and once every 10 days the rest of the year.

In 1968, observations on the Moskva River were carried out 1-2 km downstream from the Barsuki station (and 7-8 km downstream during winter due to a reduced extent of backwater zone). In 2012 and 2016, the observations made on the Moskva River were made directly at the gauging station.

Sampling of the Lusyanka River was carried out 1.5 km upstream from the Cherniki station in all 3 years.

In 1968, water samples from the Koloch Reservoir were taken directly from the pipe during periods of active pumping (Vinogradova 1970). In 2012, samples were taken near the dam, and at a free-flow part of the Koloch river at Borodino (9-10 km upstream from the Koloch dam, 3-4 km upstream from the backwater zone, F = 266 km^2, or 95% of the total watershed area). In 2016, samples were only taken at Borodino.

Sampling on the Moskva River below the reservoir was carried out 0.5 km downstream from the dam from a spillway during all three research years.

Measurement and analysis methods

The conventional method for estimating the concentration of suspended solids in water is gravimetric analysis, which is based on the determination of the total mass of the sediment and the subsequent calculation of its mass concentration SSC, mg/l. In 1968, membrane filters with a pore diameter of 0.90 µm were used to separate the sediment (Vinogradova 1970), and in 2016 0.45 µm membrane filters were used (Sokolov et al. 2018).

Since the gravimetric method is time-consuming, indirect methods for defining suspended sediment concentration are widely used; the most popular one being the optic measurement of water turbidity T, NTU (nephelometric turbidity units), which can indicate the presence of suspended solids, microorganisms, etc. In 2012 and 2016, we used a HACH 2100P portable turbidimeter to measure water turbidity with ±2% precision.

Water runoff data is also crucial for suspended sediment load estimation. Complete data series on the water discharges from the Mozhaysk Dam and the Koloch pumping station are present in the Mozhaysk Reservoir hydrological reports. Daily water discharges from Roshydromet gauging stations at Moskva and Lusyanka were published in official hydrological bulletins until the 1990s. After that, only water level data is available. Water discharges (Q) can be calculated from water levels (H) using a $Q = f(H)$ rating curve. However, this relationship needs to be regularly updated, whereas the most recent official rating curves for the Moskva and Lusyanka were published in 1996. These calculations also include sets of adjustment coefficients k_Q, which help to account for ice and vegetation at different times of the year. These coefficients can also vary greatly over time, and demand detailed observations of the channel state, which is unavailable for these rivers.

Because of these difficulties, we used data on the daily net inflow into the Mozhaysk Reservoir, also published in hydrological reports, to recreate daily discharges of the Moskva and Lusyanka Rivers. The percentage of each river in the total inflow was proportional to the shares of their watershed areas in the reservoir's total drainage area.

To assess the impact of the Mozhaysk Reservoir on the sediment transport in the Moskva River, we estimated the annual sediment load of the three of the reservoir's main tributaries and compared it to the sediment load of the Moskva River below the dam. The annual sediment load (ASL, t/year) was calculated as a sum of daily sediment loads (DSL, t/day). Daily sediment loads were estimated by multiplying the daily water discharge volumes by the suspended sediment concentrations:

$$ASL = \Sigma DSL = \Sigma(Q \times 86{,}400 \times SSC \times 10^{-6}) \quad (1)$$

where Q is the mean daily water discharge (m^3/s), 86,400 is the number of seconds in a day.

Regular field observations and increased frequency of sampling during the spring flood allowed us to use linear interpolation between the data points to get reliable daily values of suspended sediment concentration.

Given that in 2016 we only collected data on the suspended flow of the free-flow part of the Koloch River, but a significant part of the sediment is retained in the Koloch Reservoir and does not reach the Mozhaysk Reservoir, to estimate the sediment load from the Koloch watershed we used the retention rate of the Koloch Reservoir, which we calculated based on the data of 2012 when suspended sediment concentration was determined both at the Borodino station and at the Koloch Dam.

RESULTS AND DISCUSSION

Sediment load calculations

To assess the sediment load, it is necessary to convert turbidity units *(T, NTU)* into *SSC, mg/l*. This conversion is often hampered by the fact that the empirical dependences $SSC = f(T)$ usually vary across different regions (Belozerova and Chalov, 2013). For the water of the Mozhaysk Reservoir itself we have used before (Sokolov et al. 2011) the equation:

$$SSC = T \quad (2)$$

This equation (r = 0.97 on sample size n = 219) closely matches the one that is recommended for small and medium rivers of the European part of Russia (Belozerova and Chalov, 2013), so we have also used it in an attempt to quantify the sediment load into the reservoir in 2012 (Sokolov 2015). However, despite the high statistical significance of both links, it is obvious that their applicability to specific rivers requires additional justification.

Regular coupled measurements of the suspended sediment concentration and water turbidity in 2016 allowed us to obtain the hitherto first-ever *SSC = f(T)* relationships (Sokolov et al. 2018) for the tributaries of the Mozhaysk Reservoir (Fig. 2):

$$\begin{cases} \text{SSC (the Moskva, Barsuki)} = 1.1T + 1.6 \\ \text{SSC (the Moskva, below the dam)} = 0.8T + 1.4 \\ \text{SSC (the Lusyanka)} = 1.7T - 4.3 \\ \text{SSC (the Koloch)} = 1.6T - 0.7 \end{cases} \quad (3)$$

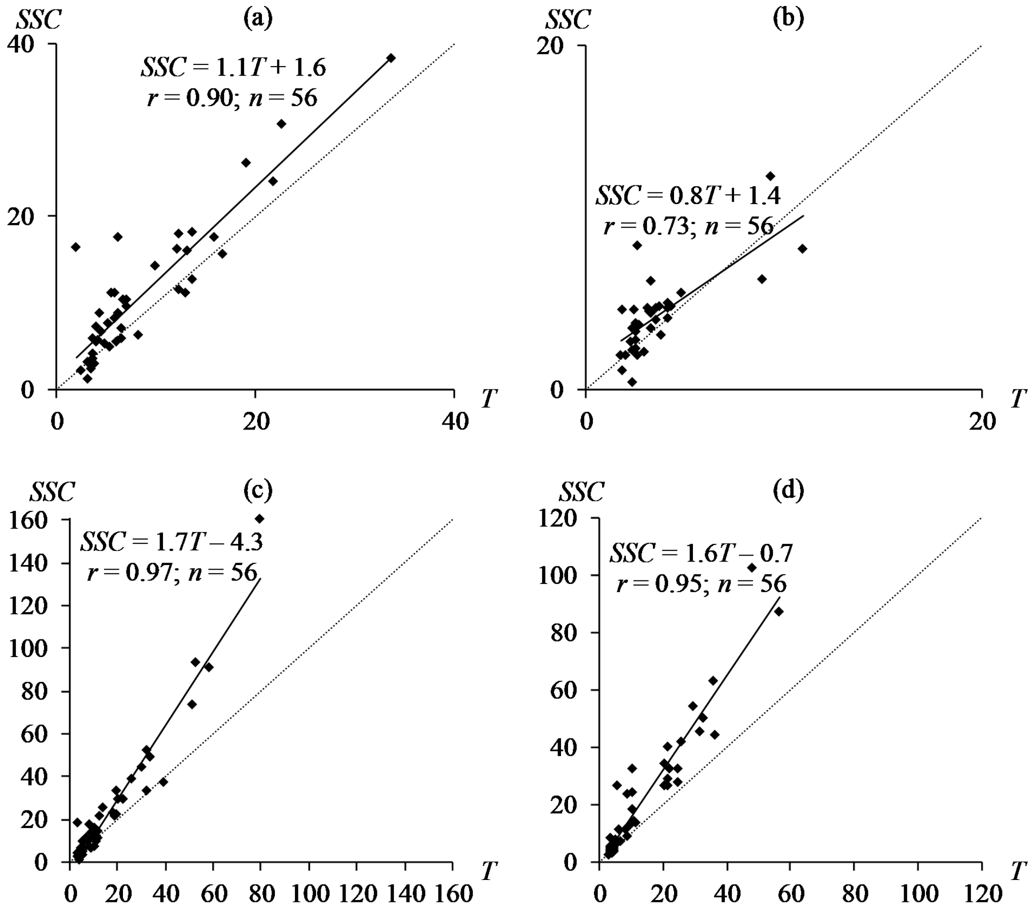

Fig. 2. Relationships (Eq. 3) between suspended sediment concentration *(SSC, mg/l)* and water turbidity (*T*, NTU) in the Moskva River upstream (a) and downstream (b) from the Mozhaysk Reservoir, and in the Lusyanka (c) and Koloch (d) based on 2016-2017 data. The dotted line represents the *SSC* = *T* (Eq. 2) relation for the Mozhaysk Reservoir water

According to (Belozerova and Chalov 2013), river-specific values of regression coefficients in the *SSC = kT + b* equation depend on geographical patterns of the water and sediment runoff, the extent of anthropogenic impact on the watershed, hydrological seasons, the sediment's genesis and composition, its natural variability and the streamflow parameters. For instance, the value of the k constant varies quite widely (0.65-4.85) and is proportional to the mean diameter of the suspended particles. The Lusyanka (*k* = 1.7) and Koloch (*k* = 1.6) have steeper stream profiles and higher banks, and on average have a bigger sediment particle size compared to the Moskva River at Barsuki (*k* = 1.1), and even more so compared to the Moskva river below the dam (*k* = 0.8), which receives the finer fraction of sediment from the reservoir.

Table 1 contains our estimates of the annual sediment load of the main tributaries of the Mozhaysk Reservoir and the Moskva River downstream from the reservoir in 1968, 2012, and 2016. Several assessments were made for

Table 1. Estimated suspended sediment inflow, outflow and retention in the Mozhaysk Reservoir in 1968, 2012 and 2016

ar	Method for SSC assessment	Annual sediment load, tons				Total income ASL⁺, tons	Annual sediment load from the dam ASL⁻, tons	Sediment retention $1-\frac{ASL^-}{ASL^+}$
		Moskva	Lusyanka	Koloch	Other inflows			
1968	gravimetric	11.510	4.540	1.750	4.450	22.250	2.250	90%
2012	Eq. 2	3.204	1.443	1.043	1.324	7.014	1.426	80%
	Eq. 3	3.847	2.277	1.691	2.089	9.904	1.600	84%
2016	gravimetric	1.870	840	561	771	4.042	1.160	71%
	Eq. 2	1.440	590	353	541	2.924	970	67%
	Eq. 3	1.860	880	534	808	4.081	1.140	72%

each river using different methods of defining the sediment concentration: using measured suspended sediment concentrations and based on the older (Eq. 2) or updated (Eq. 3) relationships between the sediment concentration and water turbidity. The sediment influx via other streams and non-streamflow runoff in 1968 was set using the data of (Vinogradova 1970), and in 2012 and 2016 was calculated by extrapolating the specific sediment yield of the Lusyanka watershed to ungauged areas.

The results presented in Table 1 suggest high convergence of the annual sediment loads in 2016 calculated using the measured suspended sediment concentrations, (which should be considered the most reliable method), with those derived from turbidity values and converted using the Eq. 3 (the error does not exceed ±5% for each river and 1% for total annual influx into the reservoir). The application of the older relationship (Eq. 2), which was based on the Mozhaysk Reservoir data, results in a significant underestimation of the annual sediment load of all of the rivers (22-34% for the tributaries and 15% for the Moskva River downstream from the reservoir).

Comparison of the $SSC = kT + b$ formulae that we suggested for the Mozhaysk Reservoir itself (Eq. 2) and its tributaries (Eq. 3) and the data presented in Table 1 allow concluding that the choice of a particular calculation method significantly affects the estimates of the suspended load. Regularly updated and catchment-specific SSC-turbidity relationships allow for more accurate assessments (as shown by the high convergence of ASL values calculated from direct SSC measurements and recent relationships in 2016).

Hydrological regime

The spring flood hydrographs and dam operation regimes varied greatly between the years covered by this research (Fig. 3). In 2012, the spring flood was the latest, the shortest, and had the highest peak discharge. In 2016, it started the earliest, had a low peak discharge with two separate peaks, and lasted the longest.

In 1968, the water discharge below the Mozhaysk Dam during the rising of the spring flood did not exceed the environmental flow (1.5 m³/s) and increased up to 50 m³/s after the peak. In the spring of 2012, the discharge was over 9-12 m³/s and reached 124 m³/s at maximum flow. During the entire reservoir filling in 2016, the discharge below the dam did not exceed 1.5 m³/s.

Suspended sediment dynamics

In the winter of 1968, the suspended sediment concentration in the rivers ranged from 1 to 9 mg/l, reaching 12-16 mg/l during thaws (Fig. 3). During spring, the concentration rose from 9 mg/l to 100 mg/l and more in the Moskva River, and from 7 to over 300 mg/l in the Lusyanka. During the peak flow, maximum suspended sediment concentration reached 500 mg/l in the Moskva, over 300 mg/l in the Lusyanka, and 90 mg/l in the water pumped from the Koloch River. After the peak of the spring flood, the concentrations dropped sharply to 6-10 mg/l, increasing to 30-40 mg/l during rainy periods. During the summer and fall, low flows the sediment concentration

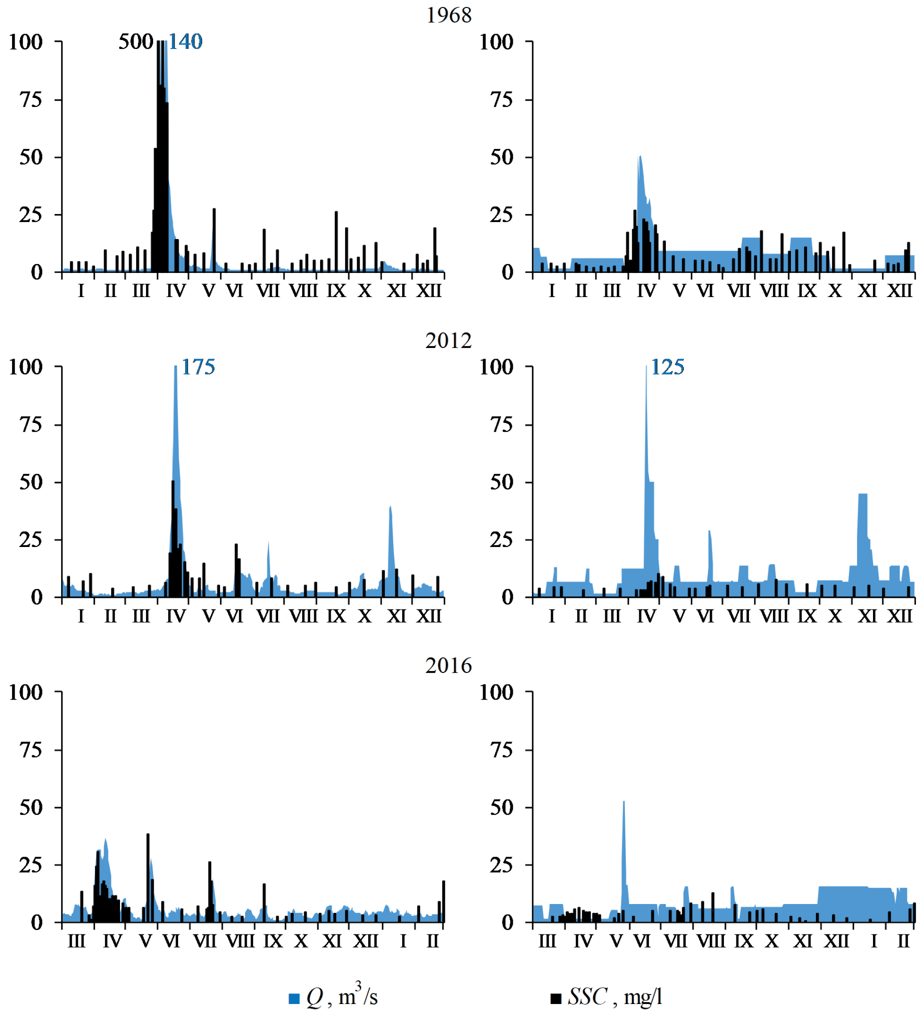

Fig. 3. Water discharge *Q*, m³/s and suspended sediment concentration *SSC*, mg/l in the Moskva River upstream (left) and downstream (right) from the Mozhaysk Reservoir in 1968, 2012 and 2016 (*SSC* values for 2012 were calculated from measured *NTU* using Eq. 2, in 1968 and 2016 – directly measured; interpolated daily values are not shown)

varied greatly from 2-9 mg/l to 10-25 mg/l during rainwater inflow (Vinogradova 1970).

In the Moskva River below the dam, the suspended sediment concentration ranged from 1.4 to 3.8 mg/l during the ice-covered period of 1968. When the spring flood began, the concentration rose quickly to 20 mg/l. During the summer and fall of 1968, the sediment concentration varied from 1.4 to 16.8 mg/l with maximum values achieved during phytoplankton blooms and in periods of strong wind mixing (Vinogradova 1970).

In winter of 2012, the turbidity of the Mozhaysk Reservoir's tributaries ranged from 2 to 9 NTU (which corresponds to SSC values of 3-12 mg/l when using Eq. 3) and reached 7-13 NTU (9-18 mg/l) during thaws. During the spring, flood turbidity increased to 33-45 NTU (38-50 mg/l) in Moskva River and Koloch Reservoir and to 70-80 NTU (110-130 mg/l) in Lusyanka and Koloch Rivers. Similar to 1968, by the end of the spring flood, the turbidity in the rivers fell sharply to 6-13 NTU (8-18 mg/l). During summer and fall, the sediment load into the reservoir with river flow steadily declined, reaching minimum values in August-September at 2-4 NTU (2-6 mg/l). During rain floods, the turbidity reached 30-50 NTU (35-80 mg/l) in summer and 9-26 NTU (12-41 mg/l) in autumn.

In the winter of 2012, the water turbidity downstream from the dam ranged from 2.3 to 5.6 NTU (3.2-5.9 mg/l with Eq. 3). The lowest value (1.7-2.2 NTU, or 2.8-3.2 mg/l) was observed at the beginning of the reservoir's fill during the spring flood. The turbidity increased as the reservoir filled up, but less significantly than in 1968 – up to 9-11 NTU (9-10 mg/l). During summer and fall water turbidity below the reservoir varied from 3 to 8 NTU (4-8 mg/l).

In the winter of 2016, suspended sediment concentration in the reservoir's tributaries was 2-9 mg/l, and water turbidity ranged from 3 to 5 NTU. Because of a low double-peaked spring flood (Fig. 3), during the spring, the suspended sediment concentration in the Moskva River upstream from the reservoir did not exceed 31 mg/l, and turbidity – 23 NTU. In the Lusyanka and Koloch, however, during the rise of the spring flood these values reached 100-160 mg/l and 60-80 NTU. During low-flow periods of the summer and fall, the suspended sediment concentration ranged between 2-9 mg/l. During the summer rain floods, the sediment concentration reached 20-40 mg/l (20-30 NTU) in the Moskva River, 70-90 mg/l (50-60 NTU) in the Lusyanka and 30-45 mg/l (20-30 NTU) in the Koloch. During the fall rain floods, the suspended sediment concentration increased up to 15-20 mg/l in the Lusyanka and Koloch and did not change in the Moskva River.

In 2016, the suspended sediment concentration downstream from the reservoir stayed within 1-6 mg/l (2-7 NTU) throughout the year, except for August, when it reached 8-12 mg/l (7-11 NTU) during a phytoplankton bloom in the reservoir.

The highest suspended sediment concentration and total suspended load are observed during the spring flood. As stated in (Vinogradova 1970; The Mozhaysk… 1979), in 1968 over 90% of the annual suspended sediment load passed in April and May. Our data of 2012 (Sokolov 2015) show the share of the spring flood in the annual sediment load to be around 75%, in 2016 – less than 50%. This decline in the spring sediment load over the decades is caused by the modern changes in the streamflow regime – decreasing spring flow and the increasing importance of the summer and fall rain floods and winter thaws (Kireeva et al. 2019).

Downstream from the Mozhaysk Dam, the seasonal variability of the sediment concentration is reduced compared to that of the reservoir's tributaries (the coefficient of variation C_V is reduced by half – from 0.8–1.2 to 0.4–0.6).

Long-term sediment load dynamics

Even considering high possible errors (up to 100-150%) in our estimates of the suspended load caused by short observation periods (Vanmaercke et al. 2012), it is hard to ignore the manifold decrease in the suspended sediment concentration and the annual suspended load of the Mozhaysk Reservoir tributaries that occurred over the past half-century.

Peak suspended sediment concentration of the spring flood in the Moskva, and Lusyanka has decreased by almost 10 times – from 300-500 mg/l to 45-80 mg/l (see Fig. 3). Annual values decreased by 3-7 times: in the Moskva River – from 70 mg/l in the average-water 1968 to 18 mg/l in the high-water 2012 and to 10 mg/l in the average-water 2016; in Lusyanka – from 130 mg/l to 48 and 21 mg/l, respectively. Such significant changes cannot be dismissed as a calculation inaccuracy, especially since the results of 1968 were more likely to be underestimated and not overestimated, due to the use of filters with pore diameter twice bigger than that of the filters used in 2012. The changes in the sediment load of the Koloch River can only be roughly estimated, as the data of the three study years are not completely compatible. Our estimates do not suggest any significant changes in the suspended sediment outflow from the Koloch Dam. This is likely caused by the sediment retention by the small Koloch Reservoir, which, much like the Mozhaysk Reservoir itself, accumulates some part of the Koloch River sediment load and lessens its seasonal variation.

Below the Mozhaysk Dam, the suspended sediment concentration has been reduced approximately by half between 1968 and 2012-2016 (see Fig. 3). The peak suspended sediment concentration, for one, dropped from 20 to 11 mg/l.

The annual sediment load has changed correspondingly (see Table 1). According to (Vinogradova 1970; The Mozhaysk… 1979), the total sediment load of the three major tributaries (the Moskva, Lusyanka, and Koloch) varied over the first 10 years of the reservoir's operation from 8,100 tons in the low-flow 1964 to 68,000 tons in the high-flow 1962. The annual sediment inflow into the reservoir decreased by almost 9 times between the two of high-water years – 1962 and 2012, and by over 5 times between two average-water years – 1968 and 2016.

The total sediment outflow from the reservoir in the 1960s has varied from 1,150 tons in 1964 to 10,000 tons in 1962 (Vinogradova 1970; The Mozhaysk… 1979). Thus, the suspended load of the Moskva River downstream from the dam has decreased by 6 times for high-water years and halved for the average-water years.

We attribute these trends to an effect of the land-use changes that occurred on the reservoir's watershed: after the 1980s–90s, there was a significant decline in agricultural activities and a noted decrease in cultivated land area (Koronkevich and Melnik 2015).

In 1968, the annual sediment outflow from the Mozhaysk dam was equivalent to 20% of the annual suspended load of the Moskva River, 13% of the combined sediment load of the Moskva, Lusyanka, and Koloch, and to 10% of the total sediment load from the reservoir's watershed. In 2012, the annual suspended load of the Moskva River below the dam amounted to 42% of the suspended load of the Moskva River at Barsuki, 20% of the total sediment load of the three major tributaries, and 16% of the total sediment inflow to the reservoir. In 2016, these percentages were 62%, 35% and 29%, respectively.

It can be concluded that the manifold decrease of the suspended loading of the Mozhaysk Reservoir is paralleled by a decline of its sediment retention capacity, which was reduced from 90% in 1968 to 84% in 2012, and to 71% in 2016 (see Table 1).

CONCLUSIONS

In this study, we have assessed the effect of the Mozhaysk Dam on the suspended sediment transport in the Moskva River and addressed the dynamics of its sediment load over the past 50 years.

The major part of the annual suspended load into the Mozhaysk Reservoir is received during the spring flood, but its share decreased from 90% to 50-75% over the past half-century, likely due to the transformation of the river flow regime confirmed by various authors. Downstream from the dam, the seasonal dynamics of the suspended sediment content is less pronounced, and its variability is reduced by half compared to the reservoir's tributaries.

Peak suspended sediment concentrations, and annual sediment inflow into the reservoir have decreased 5- to 10-fold over the 50 years, sediment concentration and suspended load of the Moskva in downstream reaches decreased by 2-6 times. It is most likely caused by the significant decline in the cultivated land area on the watershed.

Although the larger part of the sediment inflow is accumulated in the reservoir, its sediment retention capacity over the half-century has dropped from 90% to 70-85%. Such trap efficiencies are common for most lowland reservoirs (Berkovich 2012; Le et al. 2020; Piqué et al. 2017; Suif et al. 2017; Van Binh et al. 2020). We attribute this to the progressing siltation of the reservoir, combined with an increased production of autochtonous particulate organic matter and its subsequent outflow from the reservoir due to its continuous eutrophication (Datsenko et al. 2017), which creates additional biogenic sediment flux.

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