Water management load on water resources of the Volga reservoirs

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Abstract. Monitoring and assessment of anthropogenic load on water bodies is a permanent task of environmental protection. A complex parameter of water management load is suggested. It is calculated using the official water management statistics, and represented as a ratio of the utilization factor of river water runoff to the contribution of effluent treated to standard quality to the total amount that was required to be treated. Changes in the water runoff, water withdrawal and wastewater discharge in the sites of the Volga hydroelectric power stations by the periods from 1993 to 2018 were analysed. It is shown that the Ivankovo, Cheboksary and Gorky reservoirs experience maximum load on water resources. The first is due to the low river discharge and a high share of the withdrawal into the Moscow canal. Both others are due to poor wastewater treatment.

1. Introduction

The anthropogenic load on water resources in general consists of numerous factors. In recent years, it has become a widely accepted approach to conduct a comprehensive assessment taking into account as many factors as possible, for example, up to 15 indicators of natural conditions and economic use of the catchment area [1, 2]. At the same time, such a large catchment area as the Volga River has can be divided into administrative divisions [3]. The evaluation algorithms themselves are very diverse. Sources of pollutants can be divided into those that have a direct and indirect impact [4]. Incoming pollutants can be normalized to water runoff and background concentrations, taking into account seasonal variability of runoff, concentrations of pollutants in wastewater, and variability of diffuse pollution [5]. In such cases, the assessment process is complicated by the task of collecting and summarizing primary information.

The assessment of the water management load, which mainly includes the withdrawal of water from water bodies for municipal water use and the return of used water back to water bodies, is a much narrower task. At all stages of water use, quantitative accounting and quality control of waste water should be carried out. This information is included in the state statistical yearbooks [6]. According to the data provided, since the beginning of the 1990s, there has been a significant reduction in water withdrawals and wastewater discharges. In this connection, the discharge of pollutants has also decreased. Such situation was observed on all major rivers, including the Volga [7, 8, 9]. At the same time, interannual fluctuations of the same indicators of water consumption and pollutant input for most river catchments show a well-pronounced synchronicity, which in itself seems strange. [8]. Besides, the reduction of the polluted wastewater, in theory, should be partially offset by an increase in the treated sewerage, which, as a rule, is not observed. Both of these circumstances and the lack of an adequately...
expressed water quality improvement, cause some distrust in official data, especially in data on the polluted wastewater and pollutants discharged with it. In this regard, it remains relevant to search for indicators that allow assessing the water management load in the most appropriate ways, while maintaining its simplicity through the use of official statistics.

As a rule, any synchronicity in the treated wastewater fluctuations in different catchments is not observed. On average, in Russian rivers, their volume is 10–11% of the total amount of water to be treated. This suggests that this indicator can more realistically characterize the efficiency of treatment facilities and assess the load due to the inflow of contaminated wastewater.

In this paper, a complex parameter of water management load on water resources is suggested and applied. It is represented as a ratio of the utilization factor of river water runoff to the contribution of effluent treated to standard quality to the total amount that was required to be treated. The complex parameter arbitrarily consists of two parts: one characterizes the water withdrawal load, the second – the load from wastewater due to poor wastewater treatment facilities performance. The paper presents the results of assessment of the anthropogenic load on the Volga reservoirs water resources made with the help of the proposed complex parameter. Its use makes the assessment simple and universal, while the unified approach makes the comparison of reservoirs by load more objective than that by primary data on wastewater.

It is considered that water management directly affects water resources, as is usually accepted in environmental assessments [9].

2. Materials and methods

To analyse the spatial-temporal variability of water management load used the statistical data of Yearbooks and Reviews issued by the State Hydrological Institute and Research and Production Center “Priroda” [10, 11, etc.]. They give the annual values of water withdrawals and wastewater discharges at the dam sites of hydroelectric facilities in an integral format, that is, in total for the entire catchment area. The following indicators were used: water withdrawal from surface water bodies, discharge of different wastewater categories into surface water bodies, river flow at the sites of the Volga dams. The complex parameter is calculated by the formula (1):

\[ K = \frac{V_1}{V_2} = \frac{V_1}{V_3 \times V_4}, \]  

where \( V_1 \) – water withdrawal, \( V_2 \) – flow at the dam site, \( V_3 \) – effluent treated to standard quality, \( V_4 \) – volume of wastewater to be treated.

Further, after a slight correction, the results obtained were recalculated into indicators for individual sections within the boundaries of local lateral catchments of reservoirs using the formula (2):

\[ K_i = \frac{(V_{4i} - V_{4i-1}) \times (V_{1i} - V_{1i-1})}{(V_{3i} - V_{3i-1}) \times (V_{2i} - V_{2i-1})}, \]  

where \( i \) is the ordinal number of a reservoir or river section, i.e. its dam or hydrometric section, and \( i-1 \) is the ordinal number of the dam of upstream reservoir or hydrometric section. The existing disadvantage of the proposed parameter is the lack of certainty, if the treatment facilities do not carry out wastewater treatment to the standard quality at all. In this case, their volume can be artificially assigned within the accuracy of the estimate (for example, 0.0001 km\(^3\)/year).

The series of annual characteristics (1993–2018) for water flow at the dams of reservoirs and lower sections of the river, for water withdrawal from surface water bodies by local catchments and by the entire catchment, for polluted and standard-treated wastewater, as well as for complex parameters are formed. The average long-term values are calculated for three characteristic periods: 1993–2000, 2001–2009 and 2012–2018, and the values of water withdrawal load and polluted wastewater load are given. The spatial variability of the water management load is analysed by the local catchments, and is
compared to the version of the integrated assessment. The load on the catchment area of the Ivankovo Reservoir is calculated relative to the initial value at the Rzhev site, since it is the closest to the reservoir for which data are available in the yearbooks.

3. Results and discussion
During the period being studied, the Volga annual water flow in the main-stream station near the Verkhnye Lebyazhye village has decreased by 3.5%, in 2011 its value became lower than the long-term average, while maintaining a pronounced downward trend [7]. Discussing the average values by the periods at this station, the reduction for the 2012–2018 period was 9.2 % compared to the 1993–2000 period (table 1). Upstream, the reduction in the average long-term runoff is less (on the river section between the Cheboksary hydroelectric power station (HPS) and the Volgograd HPS – across the 3.0–6.8% range). The flow has decreased by 3.5 % in the uppermost section near Rzhev, and in the last three reservoirs of the Upper Volga the average annual water flow has increased by 6.3–9.7%. The given values of water runoff changes show possible fluctuations in the water management load due to this factor.

Table 1. Average annual values of water withdrawal load and polluted wastewater load (the ratio of water management indicators to water runoff) by local catchments of reservoirs.

| Site                  | River flow, km³/year | Water withdrawal load, % | Polluted wastewater load, % |
|-----------------------|----------------------|--------------------------|-----------------------------|
|                       | 1993–2000 | 2001–2009 | 2012–2018 | 1993–2000 | 2001–2009 | 2012–2018 | 1993–2000 | 2001–2009 | 2012–2018 |
| Ivankovo HPS          | 7.40       | 8.70     | 8.12     | 87.7b     | 41.5      | 41.7      | 1.88       | 0.96      | 1.20      |
|                       | (0.73)     | (0.72)   | (1.29)   | (15.2)    | (4.24)    | (11.18)   | (0.37)     | (0.09)    | (0.28)    |
| Uglich HPS            | 11.1       | 12.0     | 11.8     | 0.56      | 3.46      | 9.69      | 0.84       | 0.60      | 0.51      |
|                       | (0.80)     | (0.91)   | (1.78)   | (0.07)    | (0.29)    | (3.11)    | (0.13)     | (0.05)    | (0.08)    |
| Rybinsk HPS           | 30.8       | 31.4     | 33.1     | 2.04      | 2.04      | 1.19      | 0.53       | 0.36      | 0.20      |
|                       | (2.45)     | (2.56)   | (3.75)   | (0.18)    | (0.19)    | (0.19)    | (0.04)     | (0.05)    | (0.02)    |
| Gorky HPS             | 51.1       | 49.9     | 51.8     | 4.19      | 4.11      | 4.42      | 0.89       | 0.74      | 0.49      |
|                       | (3.41)     | (3.10)   | (4.86)   | (0.31)    | (0.26)    | (0.47)    | (0.06)     | (0.07)    | (0.05)    |
| Cheboksary HPS        | 113        | 112      | 107      | 5.03      | 4.05      | 3.53      | 4.31       | 3.59      | 2.93      |
|                       | (7.00)     | (4.19)   | (7.44)   | (0.34)    | (0.21)    | (0.30)    | (0.29)     | (0.20)    | (0.19)    |
| Zhiguli HPS           | 259        | 252      | 247      | 2.27      | 2.16      | 1.60      | 0.94       | 0.75      | 0.65      |
|                       | (12.1)     | (6.34)   | (9.52)   | (0.11)    | (0.04)    | (0.10)    | (0.04)     | (0.02)    | (0.05)    |
| Saratov HPS           | 264        | 254      | 256      | 0.56      | 0.44      | 0.32      | 0.25       | 0.19      | 0.14      |
|                       | (12.3)     | (6.32)   | (9.47)   | (0.03)    | (0.02)    | (0.02)    | (0.01)     | (0.00)    | (0.00)    |
| Volgograd HPS         | 266        | 258      | 248      | 0.71      | 0.39      | 0.05      | 0.14       | 0.10      | 0.00      |
|                       | (11.9)     | (6.76)   | (8.82)   | (0.04)    | (0.05)    | (0.00)    | (0.02)     | (0.01)    | (0.00)    |
| Verkhnye Lebyazhye    | 261        | 249      | 237      | 0.33      | 0.26      | 0.53      | 0.07       | 0.06      | 0.05      |
| village               | (11.8)     | (6.81)   | (9.41)   | (0.02)    | (0.01)    | (0.03)    | (0.00)     | (0.00)    | (0.01)    |
| The Volga mouth       | 261        | 249      | 237      | 0.40      | 0.23      | 0.16      | 0.03       | 0.03      | 0.01      |
|                       | (11.8)     | (6.81)   | (9.41)   | (0.06)    | (0.00)    | (0.01)    | (0.00)     | (0.00)    | (0.00)    |

*a In parentheses – the error of the average value.
*b The load will be 63 % not taking into account the 1996 extremely low-water year.

3.1. Water withdrawal load
The load on water resources from water withdrawals gradually has been decreasing over time within more than a half local catchment of reservoirs. When using integral indicators, this decrease was previously noted for all sites of the Volga and for most other large rivers [7, 8]. The load increase on the Volgograd HPS – Verkhnye Lebyazhye section is due to a water runoff reduction, and the fluctuation in the volume of runoff withdrawal for irrigation determines the unevenness of the load fluctuation (table 1).
Until recent years, the water resources of the Ivankovo and Uglich reservoirs were under the influence of a strong variability in water flow caused by fluctuations in humidity and by a significant water transfer into the Moscow Canal. In the extremely low-water years, the annual water withdrawal from the Ivankovo Reservoir may exceed the annual discharge through the dam (for example, in 1996 and 2015). The role of this factor is manifested by the presence of a negative correlation between the flow and the total water withdrawal ($r^2 = -0.61; p=0.05$), where $r^2$ and $p$, respectively, are the correlation coefficient and its statistical significance) and the volume of water transfer to the Moscow River via the canal ($r^2 = -0.67; p=0.05$). During the last period (2012–2018), when withdrawal for the water transfer almost stopped, the load on the Uglich Reservoir water resources is directly related to the water withdrawal from the Ivankovo Reservoir ($r^2 = 0.76; p=0.05$). It should be noted that very often this factor was not taken into account. It is believed that the creation of the canal has not led to significant environmental costs [9].

3.2. The polluted wastewater load

According to annual statistics, the discharge of polluted wastewater is decreasing in the most rivers [7, 8]. This is also evident from the data on the local catchments of reservoirs (table 1). The maximum load is observed in the Cheboksary Reservoir. The second largest load is in the Ivankovo Reservoir, followed by the Kuibyshev and Gorky reservoirs. The reason for a small increase in the polluted wastewater load on the water resources of the Ivankovo Reservoir in the last period has to do with nothing but a water flow decrease.

3.3. Standard-treated wastewater and its share in the volume of wastewater to be treated

The largest absolute volume of the standard-treated wastewater comes from the catchment area of the Kuibyshev Reservoir (table 2). Until recently, the catchment area of the Cheboksary Reservoir by the standard-treated wastewater was in the second place. Lately, the volume of treatment here has sharply decreased and turned out to be at the level of that of the Saratov reservoir catchment area, where it also has decreased. Only on the catchments of the Rybinsk and Gorky reservoirs there is a tendency to increase in the volume of treated wastewater, which can be attributed to the treatment facilities work improvement. The section of the river between the Volgograd reservoir and the vil. Verkhneye Lebyazhye receives a relatively large amount of treated wastewater, despite the fact that the catchment area here is disproportionately smaller than that of the Kuibyshev reservoir, into which the Kama River flows, and the Cheboksary reservoir with the Oka tributary. At this section, 45% of all wastewater to be treated is currently being treated. This is the maximum volume for the selected local catchments of the Volga (table 2). The worst-performing treatment facilities are in the catchments of the Cheboksary and especially Gorky reservoirs (approximately 2–6%), where even a weak positive trend is absent A significant increase in the share of treated wastewater is observed on the catchments of the Volgograd and Rybinsk Reservoirs, where it has become 40 and 34%, respectively.

3.4. Complex parameter of water management load

The average long-term value of the complex parameter varied differently over time and over the territory of the Volga basin. The maximum value was observed in 1993–2000 at the Gorky reservoir (more than two thousand units). Since then, the load has decreased many times and in the 2012–2018 period became about 70 units (table 2), so as in the Uglich Reservoir, where on the contrary the water management load since 1993 has grown significantly. The main reason of such situation in the both reservoirs is the fluctuation in the efficiency of wastewater treatment.

The Ivankovo and Cheboksary reservoirs experience the top water management load on water resources. The load in the first one “reacts” to the water flow, which is relatively small (1.7–13.3 km$^2$/year) and varies significantly. In the second one it is due to a very low share of treated wastewater in the total wastewater to be treated (3.5–8.7 %). This may affect the quality of the river water. In fact, in general terms, the deterioration of water quality from class 3a (according to the integrated indicators of water quality) in the Ivankovo Reservoir to class 4a in the reservoirs of the middle Volga river,
accompanied by sharp fluctuations in the extreme values of individual ingredients, was noted earlier [12].

**Table 2.** Standard-treated wastewater, it share in the total wastewater to be treated and the complex parameter of water management load for local catchments of reservoirs (the average annual values for the periods)

| Site             | Standard-treated wastewater, km³/year | Standard-treated wastewater share in the total wastewater to be treated, % | Complex parameter |
|------------------|---------------------------------------|--------------------------------------------------------------------------|-------------------|
|                  | 1993–2000   | 2001–2009 | 2012–2018 | 1993–2000   | 2001–2009 | 2012–2018 | 1993–2000   | 2001–2009 | 2012–2018 |
| Ivankovo HPS     | 0.032       | 0.027    | 0.020    | 24.17       | 26.88    | 23.48     | 370        | 156       | 177       |
|                  | (0.000)     | (0.002)  | (0.000)  | (0.41)      | (1.09)   | (0.60)    | (65.6)     | (15.6)    | (49.6)    |
| Uglich HPS       | 0.019       | 0.009    | 0.009    | 20.21       | 11.60    | 15.36     | 2.78       | 42.6      | 68.8      |
|                  | (0.000)     | (0.001)  | (0.001)  | (0.44)      | (1.65)   | (2.13)    | (0.38)     | (8.51)    | (23.4)    |
| Rybinsk HPS      | 0.002       | 0.030    | 0.030    | 1.132       | 24.65    | 33.82     | 203        | 53.4      | 3.54      |
|                  | (0.000)     | (0.004)  | (0.001)  | (0.116)     | (4.32)   | (6.61)    | (26.4)     | (24.0)    | (0.59)    |
| Gorky HPS        | 0.001       | 0.005    | 0.016    | 0.318       | 1.369    | 6.371     | 2256       | 351       | 71.3      |
|                  | (0.000)     | (0.000)  | (0.000)  | (0.077)     | (0.147)  | (0.244)   | (481)      | (43.9)    | (8.47)    |
| Cheboksary HPS   | 0.221       | 0.257    | 0.075    | 4.533       | 6.229    | 2.428     | 113        | 67        | 155       |
|                  | (0.015)     | (0.006)  | (0.005)  | (0.220)     | (0.247)  | (0.154)   | (8.67)     | (5.56)    | (19.6)    |
| Zhiguly HPS      | 0.368       | 0.309    | 0.209    | 13.48       | 14.11    | 12.10     | 17.2       | 15.8      | 16.5      |
|                  | (0.011)     | (0.015)  | (0.024)  | (0.44)      | (0.58)   | (1.70)    | (1.29)     | (0.86)    | (2.77)    |
| Saratov HPS      | 0.129       | 0.132    | 0.074    | 16.93       | 22.07    | 16.72     | 3.35       | 1.99      | 3.61      |
|                  | (0.001)     | (0.002)  | (0.014)  | (0.28)      | (0.12)   | (2.98)    | (0.22)     | (0.08)    | (1.09)    |
| Volgograd HPSb   | 0.016       | 0.018    | 0.001    | 1.386       | 9.039    | 39.76     | 51.2       | 1.11      | 0.14      |
|                  | (0.010)     | (0.009)  | (0.000)  | (0.858)     | (4.687)  | (5.12)    | (0.02)     |           |           |
| Verkhne Lebyazhye village | 0    | 0        | 0.112    | 45.18       | -        | -         | -          | 1.42      |           |
|                  | (0.000)     | (0.015)  | (0.000)  | (0.858)     | (4.687)  | (5.12)    | (0.02)     |           |           |
| The Volga mouth 2016 | 0    | 0        | 0.001    | 5.556       | -        | -         | -          | 3.26      |           |

a. In parentheses – the error of the average value.
b. For the 1993–2000 and 2001–2009 periods the indicators are most likely to be underestimated, since the official statistics on standard-treated wastewater for 1993 and from 1995 to 2007 gives zeros, for 1994 and 2009, respectively, 0.126 and 0.137 km³/year. The complex parameter was calculated from the average annual values of the initial characteristics, so the error of the average value is not specified.

The favourable dynamics of the water management load is observed in the Rybinsk Reservoir – a decrease over the entire analysed period from 200 to 4 units. Approximately at this level, the load on the water flow in the lower reaches of the Volga. It is the lowest in comparison with many local catchments located upstream.

The information on water use in the statistical yearbooks of the State Hydrological Institute [10] for the last quarter of the century most often is provided for main-stream stations. Quantitative characteristics relate to the entire catchment area, they are, in a way, an integral characteristic of the anthropogenic load on the entire river [7]. A comparison of the distribution of complex indicators for the 2012–2018 period, calculated in two ways, that is, separately for local catchments and additionally as an integral characteristic, shows that their variability has significant similarities. This is indicated by the 0.89 correlation coefficient between the parameters at p=0.001. However, the curves on the figure 1 differ from each other on most sections of the river.

There is a complete quantitative match of local and integral load for the Ivankovo Reservoir because the local catchment coincides with the integral one. The closest load values are for the Gorky reservoir: 71 for the local catchment, and 74 for the entire catchment. For the Cheboksary reservoir the corresponding indicators increase to 154 and 214. For other sites, the differences are even greater, with
the maximum discrepancy occurring at the Volgograd reservoir (0.14 and 0.78). Thus, it is obvious that
the integrated indicators of water management characteristics for main-stream stations, which are given
in the yearbooks, are far from objective estimates both for the entire river catchment of a river, and for
the local catchment of its estuarine section. The difference is most pronounced in cases where the load
decreases downstream of the river.

![Graph showing variability of water management load parameters along the Volga River](image)

**Figure 1.** Variability of water management load parameters along the Volga River in reservoirs and
lower sections of the river: 1 – for local catchments; 2 – integral value for the entire catchment area
above the control point.

4. Conclusion

A relatively simple parameter for assessing the water management load on water body water resources
is proposed. It is presented as the ratio of the water runoff utilization factor to the share of treated
wastewater in the total wastewater amount requiring treatment. The analysis of the water management
load on water resources of the Volga reservoirs and its delta section using this complex parameter
showed that the Ivankovo Reservoir is experiencing the greatest load mainly due to the water transfer
into the Moscow canal, as well as Cheboksary and Gorky reservoirs due to a small share of treated
wastewater (within 6%). A decrease in the load is observed in the Rybinsk and Gorky reservoirs, and an
increase in the Uglich Reservoir. In the Lower Volga the load from the local catchments is minimal.

With the evidence at hand, the proposed load calculation algorithm allows for its continuous
monitoring not only with annual discreteness, but also much more often.

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