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The impact of climate change on the hydrological and water management situation in the Lower Don

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Abstract: In recent years, the attention of many researchers has been drawn to the problems of climate change and the associated variability of water resources. Understanding the relationship between climate change and the water content of a particular basin helps to plan the use of water resources more rationally. One of the methods for studying possible climate changes and their consequences is the analysis of river runoff in order to identify long-term patterns and trends caused by these changes. The presented study analyses long-term series of observed flow from tributaries to the Tsimlyansk reservoir, determines the year when a possible change occurred, substantiates this event using statistical methods, determines quantitative indicators of the changes that occurred and how they affected the water management situation in the Lower Don basin. The series of annual and seasonal inflows were studied - high water, summer-autumn and winter low water. Climate change can significantly affect the water management situation in the river basin. In accordance with Russian regulatory documents in the field of water relations, the parameters of hydraulic structures during design, reconstruction and operation significantly depend on the reliability of water use in the basin. The tool for assessing the reliability of water use is water management calculations, which are performed based on long-term hydrological series of inflow and determine the degree of possible satisfaction of water users' requirements. The possibility of ensuring uninterrupted functioning of the following main water users of the Tsimlyansk Reservoir was considered: transport, agriculture, fish farming, sanitation and ecology. The article presents studies of the water resources system of the Lower Don basin, namely: based on a statistical analysis of the observed hydrological series of inflow for 1881-2025, the parameters of the reliability curves are shown, based on the difference integral curves, the "breaking point" (1970) of the probable change in runoff was found, optimization calculations of water resources for two hydrological series were carried out: 1881-1969 and 1970-2025, an alternative solution was found in favor of the fishing industry, the results were analyzed. The methodology used in the research allows for the search for compromise solutions in favour of various water users and is based on the use of multi-criteria optimisation methods and compromise theory. The study yielded new knowledge about the hydrological and water management situation in the Lower Don basin in connection with climate change.

Table 1 Reliability normative levels for various sectors of the economy

N	Sectors of the economy	Years of the normative reliability level by inflow
1	Fisheries	75%
2	Agriculture (irrigation)	75%
3	Sanitary release and Public utilities	95%-99%
4	River transport	85%-95%
5	Winter energy (capacity, MW)	90-95%
6	Dam parameters (headwater level) depending on the class (1-st - 4-th)	0,1%, 1%, 3%,5%
7	Flooding in the upstream and downstream of reservoirs*	0,01%-5%
8	Limits and quotas for water intake and wastewater discharge	25%, 50%, 75%, 95%

*The annual inflow of 5% of the provision is the upper limit for the permissible flooding of the floodplain

Keywords: *Water resource calculation, Hydrology, Inflow time series, release rules, optimization methods*

1. INTRODUCTION

In recent years, the problems of climate change and the associated variability of water resources have attracted the attention of many researchers. Understanding the relationship between climate change and the water content of a particular basin helps to plan the use of water resources more rationally. One of the methods of studying possible climate changes and related consequences is the analysis of river runoff in order to detect long-term patterns and trends caused by these changes. It is assumed that the trends in runoff changes identified as a result of the analysis can be somehow related to climate changes in the corresponding region. It was decided to analyse the long-term series of observed inflows, to determine the year when a possible change occurred, substantiate this event with statistical methods, to determine the quantitative indicators of the changes that have occurred and how they affected the water management situation in the river basin. Such an approach to research is given in (Loucks 2002; Eum et al. 2010; Yujie Zeng et al. 2021).

There are quite a lot of works devoted to the study of these problems in the basins of various rivers, in which a noticeable change in water content and its intra-annual redistribution have been observed in recent decades (Ismajylova et al. 2022; Popova et al. 2019; Ismaiylov et al. 2019). It was found (Ismajylova et al. 2022; Popova et al. 2019) that long-term fluctuations in the Volga runoff contain two periods, which differ significantly in long-term average values. This difference is mainly due to changes in low-water runoff. The article by Ismaiylov et al. (2019) also revealed the intra-annual redistribution of the river runoff of the Upper Don. It is noted that this is typical for modern climatic conditions, which are expressed by an increase in both the average annual air temperature and the air temperature of the cold period of the year, as well as an increase in the number of winter thaws. In addition, the authors of this article conducted their own studies on inflow changes in the Lower Don basin (Bolgov et al. 2024). An important conclusion for hydrological applications is that the stochastic model of the temporal variability of the studied runoff characteristic is no longer stationary and must be more complicated. To obtain statistically significant conclusions about the location of these points on the time axis, approaches based on the Fisher and Student homogeneity criteria, as well as on the analysis of difference integral curves (DIC) (СП 33-101-2003; Bolgov et al. 2023), can be applied. The calculations use the water management year, from March of the current year to February of the next year. Statistical analysis of long-term hydrological series of inflow to the Tsimlyansk reservoir was performed for four seasons: annual, high water (March-May), summer-autumn low water (May-November), winter low water (December-February). The parameters of the Tsimlyansk Reservoir (Figure 1) are taken from the “Rules for the use of water resources of the Tsimlyansk Reservoir” (The rules 2016).

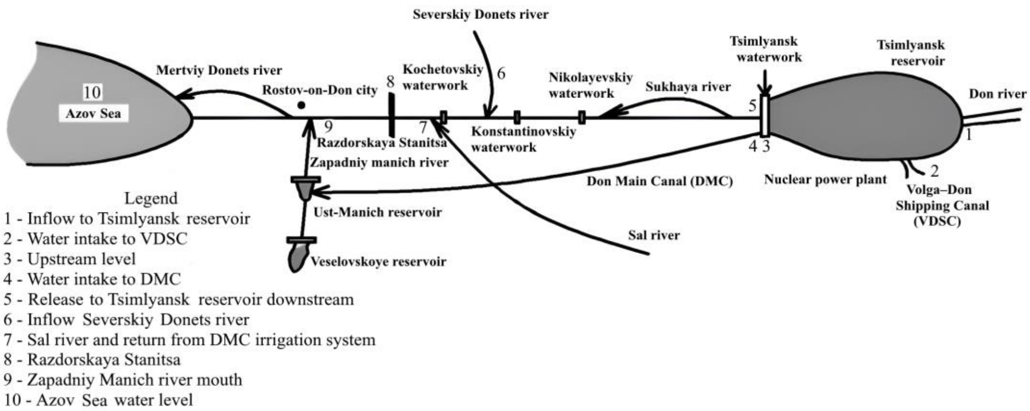

Figure 1 Overview of the Tsimlyansk Reservoir

Climate change can significantly affect the water management situation in the river basin. In accordance with Russian regulatory documents in the field of water relations, the parameters of hydraulic structures (HS) during design, reconstruction and operation are calculated depending on the water content of the river basin and the reliability of water use. The tool for assessing the reliability of water use is the Water Resources Calculations (WRC), which are carried out based on long-term hydrological series of inflows and determine the degree of possible satisfaction of water users' requirements. Reliability of water supply is understood as the probability of providing consumers with water throughout the entire calculation period. The reliability of water use is calculated by the formula m/(n + 1) where m is the number of years without violating the water user requirements, n is the number of years in the long-term series of inflow.

WRC are carried out in the design and reconstruction of hydraulic structures, preparation of the Schemes (SKIOVO) for the integrated use and protection of water bodies and in the development of the Rules (PIVR) for the use of reservoir water resources (Guidelines for the development of rules 2011). WRC determines the ratio of available water resources and estimated water consumption. When developing SKIOVO and PIVR for water users of various the economy sectors, the following standard reliability for ensuring normal water consumption by the number years without violation should be met: sanitary releases - 97-99%; water supply - 95-97%; hydropower - 85-95%; navigation - 85-90%; irrigation and agriculture - 75-90%; fisheries - 75-90%. The calculation of the parameters of hydraulic structures is carried out on the basis of the year of the corresponding water reliability. Table 1 Reliability normative levels for various sectors of the economy shows the standard reliability levels that are used to justify the characteristics of the hydraulic structures.

This article considers the possibility of ensuring the uninterrupted functioning of the following main water users of the Tsimlyansk Reservoir: transport, agriculture and fisheries, industry, ecology, and household services. The WRC was carried out using optimisation methods for both inflow series 1881-1969, 1970-2025. The management of the Tsimlyansk Reservoir was carried out on the basis of finding optimal releases to the downstream and water supply to the Don Main Canal (a similar approach is outlined in Buber et al. (2023). A 144-year series of inflows to the Tsimlyansk Reservoir with an annual division into 18 intervals was used to determine reliability. The following tasks were solved: the water management situation in the Lower Don basin was determined; the hydrological "breaking point" was determined; a statistical analysis of the change in inflow for two series was carried out; an optimization WRC was carried out for two series and the results were analyzed, the reliability of water supply to users of the Lower Don was determined.

2. MATERIALS AND METHODS

2.1. Initial data of observed inflow and processing methods

The series of annual and seasonal inflow were studied - high water (HW), summer-autumn low water (SLW), winter low water (WLW). The graphs of inflow data and trend lines are shown in Figure 2.

The annual and flood inflow trends for the period under consideration are descending. At the same time, both low-water trends are increasing, which may indicate a gradual redistribution of inflow from flood to low-water in favour of the latter. The annual inflow trend is decreasing. The method of difference integral curves (DIC) was used to identify patterns of fluctuations in inflow. Figure 3 shows the difference integral curves of annual and seasonal inflows (Belolubtsev et al. 2021).

The constructed curves enable the distinction of three substantial characteristic periods within the hydrological series, on average, across the entire time interval spanning from 1881 to 2025: 1881-1930, there is a positive trend during the high-water period and a negative trend during the low-water periods (this is a high-water period, annual trend is positive, mean annual inflow 23,3 km^3); 1931-1969, the flood trend is almost horizontal and the low-water trends are negative (this is a mid-water period, annual trend is slightly negative, 19,5 km^3); 1970-2025, the high-water trend is negative, while the low-water trends are positive (this is a low-water, 16,9 km^3).

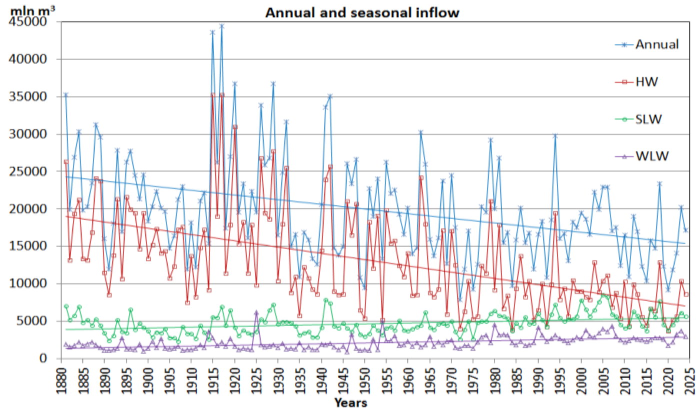

Figure 2 Annual and seasonal inflows to the Tsimlyansk reservoir

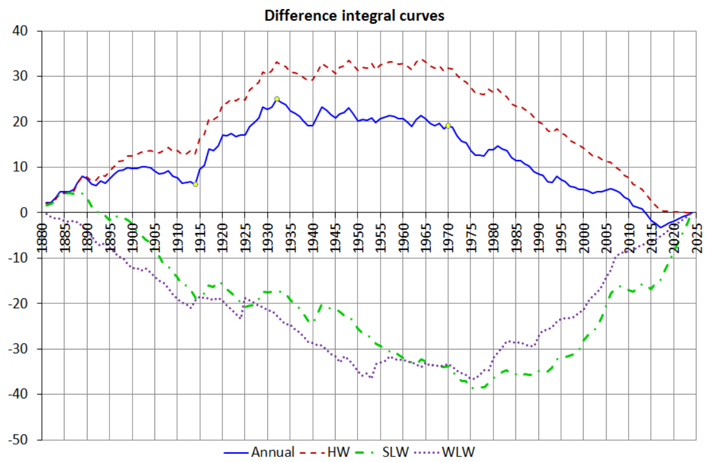

Figure 3 Difference integral curves of annual and seasonal inflows

2.2. Water resource calculation for a given inflow series by the optimisation method

Since the first and second series were combined in the last century to perform water resource calculation (WRC), two series were considered for the analysis of the water situation using optimisation methods: 1881-1969 and 1970-2025. Based on the constructed mathematical model of WRC for eighteen intervals (during flood March-May, by decades, and during the rest of the period, by months), the reliability of water users for two series of inflow was calculated. The mathematical model is based on water balance equations: the volume of water in the Tsimlyansk reservoir (TSR) at the end of the calculation interval is equal to the volume of water at the beginning of the interval plus the volume of inflow minus the non-returnable withdrawal from the water area minus the water supply to the Volga-Don Shipping Canal minus the water supply to the Don Main Canal (DMC) minus the release to the downstream (DS) of the Tsimlyansk waterworks (Figure 1) (The rules of the Tsimlyansk reservoir 2016). The variables to be optimised are the releases from TSR and the water supply to the DMC for all intervals and all years in the calculation hydrological series. The sum with weighting coefficients of the squares of the deviations of the variables from the threshold requirements of water users was used as the Objective Function (OF). This approach allows us to exclude sharp transitions and remain in the class of continuous piecewise differentiable functions. The weighting coefficients determine the importance of each water user in the water management system. The values taken as weighting factors for each group of equal water users are significantly (several times) different from each other, which ensures the principle during optimisation: first, a solution is sought for the group with the highest priority, then the remaining resources are used to satisfy the requirements of water users with lower priority, etc. Table 2 shows the requirements of the main water users of the TSR water management system:

Table 2 Water user requirements of the TSR water management system

N	Water users' requirements	Threshold Tr	Reliability %	Penalties µj
1.	The level should be between the dead and normal operating levels, m	[31, 36]	100	1000
2.	Normal transport release, m^3/s	410	85	10
3.	Reduced transport release, m3/s	340	98	20
4.	Normal sanitary release into the DS of the TSR, m^3/s	230	97	4
5.	Reduced sanitary release into the DS of the TSR, m^3/s	150	99	20
6.	Normal water intake volume in DMC, million cubic metres	1389	75	2
7.	Reduced water intake volume in DMC, million cubic metres	1048	90	4
8.	Normal Fishery release into the DS of the TSR, cubic kilometres	11,5	75	2
9.	Reduced fishery release into the DS of the TSR, cubic kilometres.	10,4	80	4
10.	Minimum fishery release into the DS of the TSR, cubic kilometres.	8,95	90	10

The hierarchy of priorities of water user requirements in modern conditions is as follows: (1) The TSR level (criterion 1); (2) Reduced transport and sanitary releases (criteria 3, 5); (3) Normal transport and sanitary releases, reduced volume of water intake in the DMC, minimum fishery release (criteria 2, 4, 7, 10); (4) Normal volume of water intake in the DMC, Reduced fishery release (criteria 6, 9); (5) Normal Fishery release (criterion 6).

The following computational scheme was used to perform the optimal water resource calculations:

Indices: t – year in the hydrological series of inflow to the Tsimlyansk reservoir, $t \in [1,T]$; m – interval number in the year, $m \in [1,M]$; j – criterion number, j=[1-10]

Constants: P_{mt} – Inflow to the Tsimlyansk reservoir; B_{mt} – non-returnable water withdrawal from the Tsimlyansk reservoir for all needs of various sectors of the economy; I_{mt} – evaporation losses per unit area (1000 sq.km) of the Tsimlyansk reservoir, taking into account precipitation; S_{mt} – water intake for sluicing in the Volga-Don shipping canal; D_{mt} – the required volume of water for agriculture in the Lower Don and the Manychi desalination, which must be supplied via the Don Main Canal (DMC).

Independent variables: X_{mt} – releases into the downstream (DS) of the Tsimlyansk waterworks to ensure fisheries, sanitation and water transport in million cubic meters or m^3/c; K_t – coefficient of reduction (cutting) of water supply to the DMC due to a possible shortage of water resources.

Functions and dependent variables: H_{mt} – level of the upper stream (US) of the Tsimlyansk reservoir (TSR), m; W_{mt} – volume of the TSR, million cubic meters; $H_{mt} = f_v(W_{mt})$ – bathymetric function defining the US level for the volume of the TSR; $F_{mt} = f_s(W_{mt})$ – bathymetric function defining the surface area for the volume of the TSR; $IS_{mt} = I_{mt} * F_{mt}$ – total evaporation losses from the TSR water area; $DS_{mt} = D_{mt} * K_t$ – volume of water supplied to the DMC taking into account the cut.

Penalty coefficients: $\boldsymbol{\mu}_j$ – penalty coefficients defining the hierarchy of priorities of water user requirements;

Balance equations: $W_{m+1t} = W_{mt} + P_{mt} - S_{mt} - B_{mt} - IS_{mt} - DS_{mt} - X_{mt}$; (1)

For each requirement of water users, an additive component of the objective function is formed, represented by the square of the deviation of the criterion value from the threshold value in case of its violation. The value of the criterion C^j_{mt}, for all m, t is, in general, determined by the formula:

C^j_{mt}= if $(X^j_{mt} > Tr_j)$ then $(X^j_{mt} - Tr^j_m)^2$ else 0; (2)

where X^j_{mt} is the requirement calculated from independent variables X_{mt} and K_t; Tr_j is the threshold value. The objective function is presented in the following form:

$OF = \Sigma_{j=[1\text{-}10]} \boldsymbol{\mu}_j * \Sigma_{m=[1\text{-}M]} \Sigma_{t=[1\text{-}T]} C^j_m$ (3)

Thus, the mathematical task of the WRC optimisation is formulated as follows: Determine the positive values of the independent variables X_{mt} and K_t that minimise the objective function (3): under constraints (1), and given $\boldsymbol{\mu}_j$, determining the hierarchy of priorities of water users' requirements.

The optimisation approach used in the WRC consists of finding the "best" releases from the TSR and the coefficient of water supply cuts to the DMC, ensuring maximum satisfaction of the hierarchically ordered requirements of water users. Optimisation calculations were carried out for two inflow series - 1881-1969 and 1970-2025.

3. RESULTS AND DISCUSSION

3.1. Analysis of the inflow time series reliability to the Tsimlyansk reservoir

To assess the changes that have occurred, all the studied series of seasonal inflow were divided into two parts in accordance with the selected point of change of state (1970). For the entire series and for each of its parts, empirical indicators of different reliability for inflow were calculated, close to 5%, 10%, 25%, 50%, 75% and 95%. The empirical reliability of exceeding Pm,% of hydrological characteristics is determined by the formula: Pm,% = 100*m/(n + 1), where m is the ordinal number of members of the hydrological characteristic series, arranged in descending order; n — total number of series members (СП 33-101-2003). Figure 4 shows a comparison of the empirical reliability calculations results for two series 1881-1969 and 1969-2025.

The data in Figure 4 show a significant decrease in the annual inflow and inflow during High Water, while the inflow increased during the summer-autumn low water period and increased significantly during the winter low water period. In the year of 5% reliability, the annual inflow in recent years has decreased by 24% compared to previous years, and the flood by 33%, while the summer-autumn and winter low water periods have increased by 12% and 38%, respectively. A significant reduction in the inflow per year of 5% reliability also has a positive effect - it is possible to significantly reduce the costs of building and reconstructing flood control hydraulic structures (HS) of the 4th class. Since in Russia the 4th class HS are the majority (more than 40 thousand), this will have a significant economic effect.

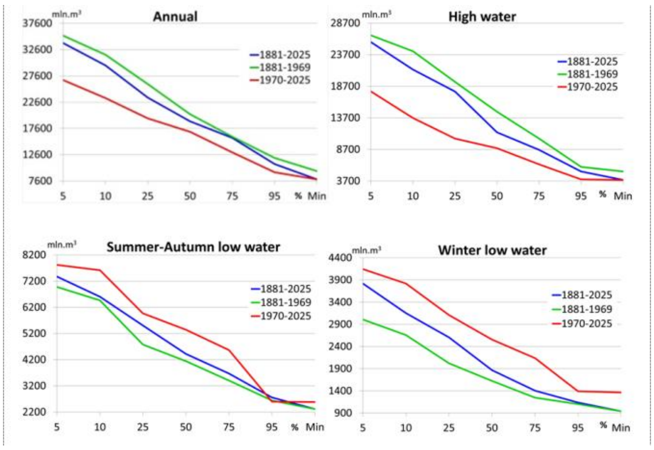

Figure 4 Comparison of inflow volumes for different empirical reliabilities of the series 1881-1969 and 1970-2025

The annual inflow has significantly decreased, by 25%, for both the years of 10% and 25% reliability. At the same time, the High Water inflow has almost halved, and the inflow in the summer-autumn and winter low waters, on the contrary, has increased by half. For the years of 75% and 95% reliability, the minimum annual inflow also decreased by about 20% due to a decrease in the High Water by 40%. At the same time, in the year of 75% reliability, the inflow increased in the summer-autumn low water period by 30%, and in the winter by

70%. Although the inflow increased during the growing season, water withdrawal for agriculture (irrigation) on the Lower Don decreased, since water is withdrawn from the TSR, the inflow to which decreased by 20%.

Almost all sectors of the Lower Don economy that consume water from the Tsimlyansk Reservoir suffered significantly. Naturally, Limits and quotas for water intake and wastewater discharge decreased. As a positive effect, it is necessary to note a significant decrease in the risks of harmful impact of waters. The last catastrophic flood was observed in 1994, which was considered a year of 10% reliability. The decrease in annual and flood runoff is associated with the intensive construction and an increase in overall water use.

The reasons for the increase in water content in rivers during the low-water period may be the increase in groundwater levels recorded at observation wells (Bolgov et al. 2024), which could have arisen due to the inflow from other basins, as well as due to the increasingly frequent thaws.

3.2. Analysis of the optimisation of water resources

To determine the impact of climate change on the water management situation in the Tsimlyansk reservoir basin, an optimisation of water resource calculations was performed for the inflow series 1881-1969 and 1970-2025. Optimisation was carried out in Microsoft Excel software using the generalised reduced gradient (GRG) method built into the Solver add-in. The reliability of ten water user requirements, obtained as a result of optimisation WRC, is presented in Figure 5.

Analysis of the optimisation results showed that the water user requirements for the hydrological series of 1881-1969 are not violated for the levels, reduced transport, reduced sanitary and reduced release into the DMC. There are minor violations for normal transport and normal intake into the DMC. There are significant violations according to normal sanitary and critical violations for the fishery.

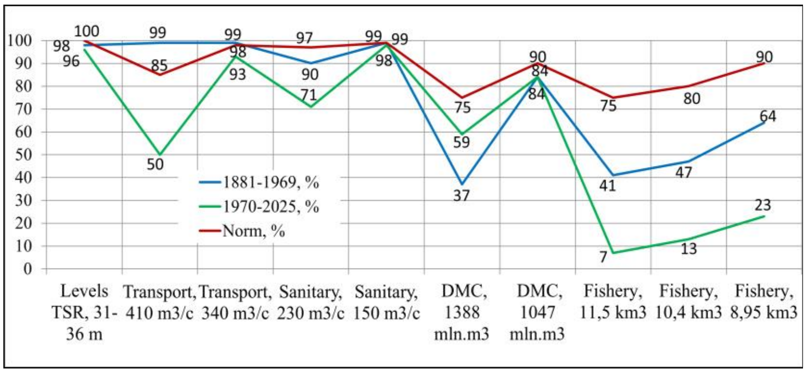

Figure 5 Reliability of water user requirements for the inflow series of 1881-1969 and 1970-2025

The requirements of water users obtained during the optimisation of the series 1970-2025 are violated by almost all criteria, except for the permissible levels, reduced sanitary and release into the DMC. Significant violations are observed for criteria - normal transport, normal sanitary and normal intake into the DMC. Agriculture has experienced an acute shortage of water resources in recent years. Fish criteria are practically not met due to a significant decrease in inflow during High water (Figure 4). Due to the changed hydrological situation, normal fishery releases were carried out only in three years: 1981, 1979 and 1994.

The presented comparative calculations showed that the observed climate changes have significantly worsened the ecological situation in the Lower Don basin for fauna and flora, especially the fishery industry and water transport have suffered.

The climate change that has occurred has significantly worsened the water management and environmental situation in the Lower Don basin. To clarify the conflict of interest between the fishery release rate and other water user requirements for the 1970-2025 series (an element of multi-criteria analysis), an optimisation water resource calculation was performed with penalty coefficients in favour of fisheries and ecology

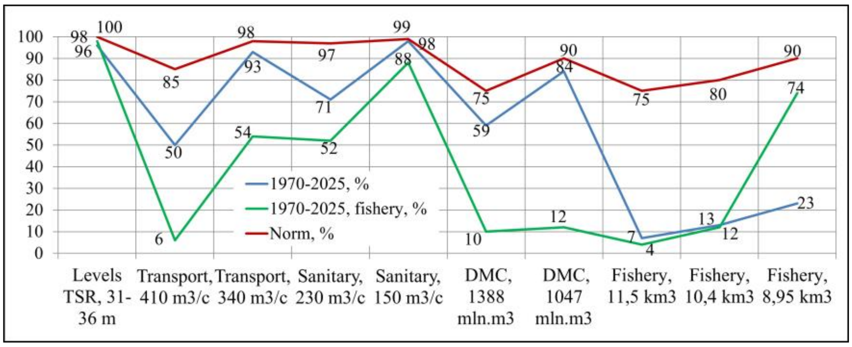

Figure 6 Reliability of water user requirements for the 1970-2025 series in comparison with the option in favour of fisheries and ecology

(penalty for fisheries were 10, 20 and 50, respectively). The calculation results are presented in Figure 6. Thus, attempts to bring the requirements of fisheries and ecology to the standard significantly worsen the indicators of all other water users, especially water transport, which is unacceptable for the normal functioning of the Lower Don water management system.

4. CONCLUSIONS

The main conclusion for this paper are as follows: Due to significant changes in the inflow, it is necessary to significantly revise the characteristics of almost all hydraulic structures being built, reconstructed and operated on the Don; In the period 1970-2025, significant changes in the hydrological regime occurred; A significant decrease in the annual and High Water inflow and an increase in the inflow in the summer-autumn and winter low water periods were revealed, here was a significant redistribution of flow in favor of low water; When designing new and reconstructing existing hydraulic structures, it is necessary to take into account the changed hydrological regime; Since the water inflow during the flood has significantly decreased for the years of 5%, 10% and 25% reliability, it is possible to adjust the flood control measures towards a decrease; For updating the Rules for the Tsimlyansk Reservoir, it is recommended to take into account the hydrology of only the last years.

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