Climate change impact on the inflow to the reservoirs of the Moscow water supply system

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Abstract. The dynamics of long-term fluctuations in the inflow to the reservoirs of the Moscow water supply system for different time intervals is analysed. The article deals with part of the Moscow drinking water supply system, namely Moskvoretskaya Water System and Vazuza Hydrotechnical System (MVHS). A significant change in the parameters of the inflow distribution is shown. It is concluded that it is necessary to clarify the rules for the operation of reservoirs system under conditions of hydrological regime changes.

Introduction
The operation of drinking water supply facilities, such as reservoir systems, is closely dependent on the hydrological regime of the rivers that feed these systems. Issues of the impact of climate change on water resources and, consequently, on the functioning of reservoirs have been intensively studied and discussed in the last decades. Water management faces serious challenges due to growing uncertainties caused by climate change, among others. Potential changes in precipitation over the coming decades may have important implications for reservoir planning and management. On the one hand, there is a mismatch between water demand and water supply capabilities, and on the other hand, existing water resource management strategies are called into question [1-3]. The task of assessing the risk of the functioning of reservoirs in new hydrological conditions and problem of adaptation of reservoir operation rules to climate change are in high demand in scientific research [4-13].

The design characteristics of the systems for water management throughout the world were carried out at the time when hydrology stationarity hypothesis was adopted as a cornerstone one. But the current climatic trends in the European part of Russia in general and in the Volga River basin in particular are manifested in the considerable changes in thermal and moistening regimes [14]. Climate change resulted in significant water regime transformation of many rivers over the world and, as well over European Russia [15]. These alterations undoubtedly affect the efficiency of operation of water reservoirs in this territory, including the reservoirs of the Moscow city water supply system.

The average annual inflow to the reservoirs of the Moskvoretskaya Water System and Vazuza Hydrotechnical System (MVHS) is the subject of this article. The objective of this article is to assess changes in the inflow to reservoirs of the MVHS because of the climate impact. In this study the average annual inflow to the reservoirs of the MVHS was analysed, and the change in the regime of inflow to the reservoirs over water management time intervals (months and decades) was considered.
Study area
The study area of this paper is the part of the Volga basin, related to the catchment basins of reservoirs included in the Moscow city water supply system. At present time the basis of Moscow's water supply is mainly water resources of Volga and Moscow rivers (taking into account the transfer of the Msta River runoff to the Volga). The water supply for the Moscow region is provided by three interconnected hydraulic systems located on the Volga and Moscow Rivers and their tributaries. These are Moskvoretskaya water system, Volzhskaya water system and Vazuza hydrotechnical system. The Vazuza hydrotechnical system is designed to transfer runoff from the Vazuza River basin to the Moscow River basin.

Catchments of the Moskvoretskaya water system and Vazuza hydrotechnical system (MVHS) are of interest for this article. This area is located in the western part of the Volga Basin and covers basins of Moscow and Vazuza rivers with these tributaries. Moscow River is the left tributary of the Oka River which in its turn is a tributary of the Volga. The Vazuza reservoir is located on the Vazuza River, the right tributary of the Volga. Total catchment area of MVHS is about 14500 km².

Runoff of the Moscow River and its tributaries are regulated by the reservoirs of the Moskvoretskaya water system – Istra reservoir on the Istra River, Mozhaisk reservoir on the Moscow River, Ruza one on the Ruza River and Ozerna one on the Ozerna River. From these reservoirs water comes by the Moscow River to the water intake of Rublyovo water treatment plant from where drinking water is supplied to Moscow city. Vazuza and Yauza reservoirs carry out long-term regulation of the Vazuza River flow, a tributary of the Volga. They operate in the mode of compensated regulation of the lateral inflow to the Moscow River from the area between the dams of Istra, Mozhaisk, Ruza and Ozerna reservoirs on the one hand, and the Rublyovo water treatment plant, on the other hand.

Data and methods
The long-term series of inflow to reservoirs of MVHS for the period 1914-2018 were used in this study. These are data of the runoff from six catchments areas – the basins of the Istra, Mozhaisk, Ruza, Ozerna, Vazuza reservoirs and an unregulated part of the Moscow River catchment between these reservoirs and Rublyovo dam. Since the Yauza Reservoir does not have a significant effect on the functioning of the MVHS, a detailed analysis of inflow to it is not given in the work.

The graphical presentation and statistical analysis of time series of the inflow to reservoir provide a methodological basis for this study. To demonstrate inflow changes, two type of graphs – chronological plot and curve of cumulative departure from the mean in dimensionless and normalized form (CDFM curve) were drawn. CDFM curve was used to detect the change point in the nonstationary long-term time series. For hydrological and water management calculations the time series were divided into two stationary parts at this change point which represents point of transition from one stationary state to another. Statistical analysis was used for these parts separately and the resulting distribution parameters were used for simulation modeling. This approach makes it possible to take into account the maximum of available information on the flow regimes peculiarities for each period.

Results and discussion
The pattern of long-term variations in the inflow to all reservoirs of the MVHS was studied for different time periods (years, months and 10-day periods).

It was found that changes in the mean annual inflow occurred in the period from 1975 to 1978 (figure 1). The increase in mean annual inflow was revealed after 1978. Thus, the hypothesis of stationarity cannot be considered true for the time series of mean annual inflow with the exception of inflow to Ruza Reservoir.

Analysis of the inflow to the Vazuza Reservoir by months showed that the hypothesis of stationarity also does not hold for most of the studied averaged monthly series of inflow. Seasonal distribution of the inflow to the Vazuza Reservoir has the same tendency as defined in [13] for the
inflow to reservoirs of the Moskvoretskaya water system (MWS). The increase is observed in the inflow during the winter and summer low water period, and during the flood period runoff values are reduced over several decades (figure 2). The most significant changes are observed during the winter low water season. The same regularity was revealed for long-term time series of water discharges for the periods of water scarcity. In the context of this study the term water scarcity means the lack water for the water demand in this area due to natural peculiarities of the hydrological regime.

In such cases the hypothesis of non-stationarity is accepted [16, 17]. For all non-stationary series of inflows to the MVHS, a single change date to a new stationary state 1978 is adopted.

For further analysis we have examined non-stationary time series of the average annual and monthly runoff from the considered six catchment areas of the MVHS. The parameters of the probability distribution (mean, variation and dispersion or standard deviation) were obtained both for the entire observation period and for two stationary parts of the time series before and since 1979.

**Figure 1.** Changes in the average annual inflow to the catchment areas of the MVHS: a) time series and trends (dotted line), b) CDFM curves.
Figure 2. Changes in the average monthly inflow to the Vazuza reservoir: a) chronological plots and trends (dotted line), b) CDFM curves.

For the average monthly runoff, parameters mean and variance have changed significantly over the past 40 years. The highest changes are observed during the winter low water period (in January and February) when the mean has roughly doubled, and the variance is even greater with a slight increase in $C_v$. The largest increase in dispersion of average monthly inflow time series occurred in the inflow to the Vazuza and Mozhaisk reservoirs in January (3.5 and 4.4 times, respectively). In April, the average values of inflow are slightly reduced during current period due to the climate-driven shift in the data of the spring flood beginning from April to earlier dates in the second half of March. Alterations in the average annual inflow to the reservoirs of the MVHS are not as significant as in the average monthly one due to contrary changes in low water runoff and in runoff of spring flood, and percentage values are in the range from 15 to 20% of the average annual inflow in the reference period. Table 1 shows examples of the changes of the parameters of the distribution for the most representative months relatively to reference period.

Table 1. Changes in runoff distribution parameters expressed as shares of their values in the reference period.

| Catchment area       | Mean (Jan.) | Mean (Feb.) | Mean (Apr.) | Mean (Jan.) | Mean (Feb.) | Mean (Apr.) | Mean (Jan.) | Mean (Feb.) | Mean (Apr.) |
|----------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Vazuza Reservoir     | 2.6         | 2.1         | 0.7         | 3.5         | 2.8         | 1.1         | 1.4         | 1.3         | 1.5         |
| Mozhaisk Reservoir   | 2.8         | 2.6         | 0.8         | 4.4         | 5.3         | 1.0         | 1.5         | 2.0         | 1.3         |
| Ruza Reservoir       | 2.1         | 2.1         | 0.6         | 2.3         | 3.9         | 0.9         | 1.1         | 1.8         | 1.5         |
| Ozerna Reservoir     | 2.2         | 2.2         | 0.8         | 2.3         | 3.0         | 0.8         | 1.1         | 1.4         | 1.0         |
| Istra Reservoir      | 2.0         | 1.9         | 0.8         | 1.8         | 2.6         | 0.8         | 0.9         | 1.4         | 1.1         |
| Unregulated part     | 1.5         | 1.5         | 0.5         | 2.2         | 2.8         | 0.6         | 1.5         | 1.8         | 1.2         |

For reliable operating water management, it is important to know the percentage of time that inflow to reservoir exceeds a certain discharge value. For any given discharge value, it can be determined by generating the exceedance distribution function (EDF). The EDF given by as $F_X(x) = P(X > x) =$
$1 - F_X(x)$, where $F_X(x) = P(X \leq x)$ is cumulative distribution function, $P$ – probability, $X$ – random variable.

To illustrate clearly how inflow to reservoirs of MVHS changed over time flow duration curves were generated for two different time periods before and since 1979. Annual inflow to all reservoirs in the current period since 1979 compared with reference period before 1979 exhibited quite a bit of variability in the entire range of probability. Here is an example EDFs of the average annual inflow to Vazuz and Mozhaisk reservoirs for two stationary parts of time series (figure 3).

**Figure 3.** Exceedance distribution functions of average annual inflow to Vazuz (a) and Mozhaisk (b) reservoirs for two time periods: 1 – before 1979, 2 – since 1979.

EDF of the average monthly inflow to Vazuz reservoir for two time periods demonstrate that the mid-range inflow has not changed much, but high flow discharge values (exceeded less than 50% of the time) changed significantly in the autumn low water period and in March. In April the picture changes to the opposite – low flow discharge values decreased. A similar pattern is observed for changes in the inflow over water management intervals. This needs to be taken into account in reservoir operating rules for MVHS. For reservoirs of long-term regulation such changes in the inflow regime are an important reason for analyzing the effectiveness of flow regulation in order to review the strategy for using the useful capacity of reservoirs under climate changes impact in the region.

**Conclusion**

As shown by the estimates, the regime of the average annual inflow to all reservoirs of MVHS in the period since 1979 has changed and water runoff increased compared to the runoff in reference period before 1979. At the same time the intra-annual distribution of the inflow to the reservoirs is characterized by an increase in water inflow in summer and winter low-water periods and by a decrease one during spring flood. The inflows to the Vazuz Reservoir and to the Moskvoretetskaya water system fluctuate synchronously, and this property creates additional difficulties in compensatory regulation of the flow of the MVHS in low-water periods.

Due to climate change, the time series of the inflow to reservoirs of the MVHS lost their stationarity (or, in other word, time homogeneity) as well as series of river flow in this area. The focus of this study was on understanding the inflow regimes changes at the catchment area MVHS. Related issue is how to optimize regulation of reservoirs in the new conditions because the uninterrupted supply of water to the Moscow region is the top priority in the work of regional water management.
Future studies should focus on developing new approach to assess the indicators of the reliability and sustainability of the operation of reservoirs taking into account revealed climate changes in runoff. These indicators in Russia are probability of exceeding in percentage the predefined number of years (or water management time intervals) where the failures occurred, and the distribution of deficits of the volume of storage capacity of reservoirs while maintaining a guaranteed release. Assessment of these indicators under climate change conditions needs to be investigated in the future research.

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