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# Possible Climatic Changes of Hydrological Regime of Valley Reservoirs

**M. G. Grechushnikova**

*Moscow State University, Vorob'evy gory, Moscow, 119899 Russia*

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**Abstract**—The paper presents the simulation outputs of changes of hydrological characteristics of reservoirs of different kind (changes in residence time and in water column stratification) in case of forecast warming according to the most adverse scenario for Moscow water supply, when annual flow and springflood flow depth decrease.

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## 1. INTRODUCTION

Analysis of hydrometeorological observational network data enabled to draw a conclusion on the effect of climate changes since the late 1970s on flow formation conditions and intra-annual flow redistribution. Certain physiographic conditions and regional peculiarities result in ambiguous response of river flow to the changes in climatic conditions. Surface air temperature increase of 1.5–2.5°C in January–February and of 2–3°C in March can be considered the cause of changes. As a result, soil freezability decreased and moisture migration and infiltration conditions changed within the aeration zone, thereby resulting in increasing groundwater feed [6]. Mathematical modeling method is used to study the features of climatic changes and their possible consequences. The forecasts are based on numerous climate model outputs. More than 20 atmosphere–ocean general circulation models (AOGCMs), developed at world-recognized research centers, participate in the Coupled Model Intercomparison Project Phase 3 (CMIP3). Model simulations were based on three 21st century climate scenarios.

The 21st century climate simulation outputs for IPSS A2 scenario (the "most severe" variant) were taken as initial data for studying possible river flow changes [4]. As a result, background estimates of flow characteristics variations were obtained for the second half of the 21st century and their geographical and water management generalization was carried out. These data formed the basis of the present paper. Its objective is mathematical modeling of possible changes in hydrological characteristics of Ivan'kovo and Mozhaisk reservoirs under conditions of changing climate by the 2050s. The GMV-MGU model (HMR-MSU, hydrological model of a reservoir, developed at the Department of Land Hydrology of Moscow State University) is used to simulate the intra-annual water temperature and electrical conductivity. The model enables to obtain differentiated estimates of reservoir water masses state, taking into account the peculiarities of their bed shape and the task of flow control for optimization of the regime of water yield to water supply systems, as well as of the quality of supplied water under changing weather conditions.

## 2. INITIAL DATA

Simulation outputs from the climate model of the Institute of Numerical Mathematics, Russian Academy of Sciences (INM RAS) for A2 scenario were used to specify the changing weather conditions. Author used available series of mean daily values of meteorological parameters for 1945–1975 for the grid point 56° N, 40° E nearest to reservoir basins. These values were averaged for 30 years. Forecast of changes in meteorological parameters, as compared with the data presented in [8] for the town of Mozhaisk, indicates that annual precipitation amount increased by 1.5 times, mean annual temperature values, by 1.9 times, and air humidity, by 1.3 times.

The GMV-MGU model has a one-day computational time step, that enables to estimate for all seasons the range of hydrological characteristics variability caused by the changes in synoptic conditions. Analysis of peculiarities of changes in climatic conditions in correspondence with the forecast is based on 30-year averaged values of meteorological parameters. In this case synoptic scales playing an important role for the

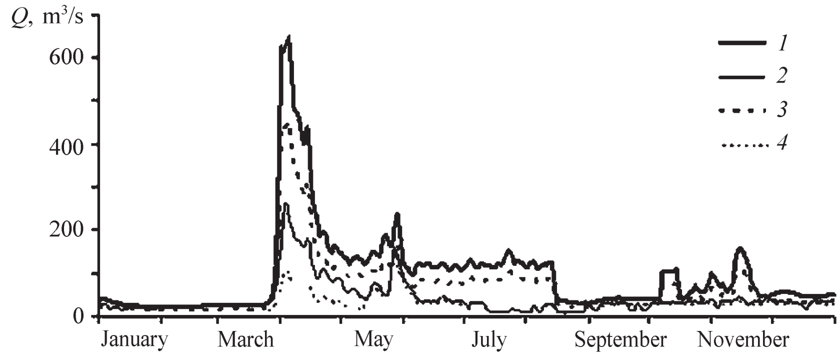


**Fig. 1.** (*1*, *2*) Actual (1973) and (*3*, *4*) projected by the 2050s (reduced by 30%) water discharge values of the main tributaries of the Ivan'kovo Reservoir. (*1*, *3*) The Volga River, (*2*, *4*) the Tvertsa River.

life of water objects and their hydrological structure formation are leveled as a result of averaging. Weather changes should be considered with regard to probable values of reservoir inflow. Therefore, initial data were prepared in the following way.

The year 1973 with low water content and the year 1984 with mean water content were taken as initial data for Ivan'kovo Reservoir. The results obtained by M.V. Sidorova [5] are used to forecast the probable water flow changes. According to the forecast of flow changes from AOGCM ensemble for the central part of East European Plain, a slight change in river flow and its substantial decrease south of the latitudes 54°–55° N can be expected. The trend towards flow decrease by the end of the 21st century will get more pronounced in the southern part of East European Plain, whereas the trend in its northern part will be weak or not pronounced at all. Thus, there will be no unidirectional annual flow depth changes in Ivan'kovo and Mozhaisk reservoir basins. According to the flow charts plotted by Sidorova (isolines of modulus coefficient), 90% confidence interval may be 0.7–1.3. A decrease in springflood flow depth is expected in the central part of East European Plain by the 2050s. Modulus coefficient of springflood flow depth will probably amount to 0.4–0.9 (upper and lower limits of 90% confidence interval). In case of decreasing springflood flow depth and constant annual flow, summer and fall flood flow will increase by 10–60%.

Modulus coefficients of 0.7 and 0.4 were taken for model simulations as the worst combination of annual and springflood flow decrease for water supply of the city of Moscow. Probable values of reservoir inflow discharges were calculated based on the chosen modulus coefficients and actual discharges in 1973 and 1984. Proceeding from the supposition that it will be necessary to maintain the present water level regime (maintaining normal maximum level in the spring and summer) for navigation needs and operation of the Moscow Canal pumping stations (minimal costs for water supply), there is a respective reduction in the water release to the tailwater pool. Since the Volga River flow is controlled by reservoirs, there was no separation of springflood period for this inflow and water discharge reduction corresponds to probable annual flow change (Fig. 1). The value and regime of water intake to the Moscow Canal remain the same, though the fact cannot be ruled out that water supply of the city of Moscow will increase by the 2050s.

Probable inflow regime should be related to synoptic cycles, i.e., flood formation should correspond to rain periods. Therefore, the following technique is used to specify probable changes in weather conditions for each computational year. Periods when reservoirs are ice-covered and ice-free are determined from observational data. Mean values of meteorological parameters for a certain year (for example, air temperature $T$ and averaged climatic model series $T^*$) are determined for these periods and transition coefficients $k$ are computed for correction of actual mean daily values: $T^*_i = kT_i$. Precipitation, wind velocity, air temperature and humidity, and atmospheric pressure series were obtained in the following way. The GMV-MGU model simulation outputs under given actual (1973) weather conditions were used as initial series to compute possible changes in coming long-wave atmospheric radiation. The results, total precipitation and mean values of other parameters, are reduced to characteristic forecast values computed using the INM RAS climate model.

To discuss simulated probable changes in the Ivan'kovo Reservoir hydrological regime, one needs the results of mean daily surface-layer water temperature verification computations. Surface water temperature is well simulated by the model: mean ice-free period error is –1.2°C and maximum error is less than –3.5°C (section 3, the first May ten-day period, when the most rapid water column heating-related changes occur); root-mean-square error is less than 1.7°C.

**Table 1.** Mean monthly and annual values of water exchange coefficient (year$^{-1}$) from the GMV-MGU model, Ivan'kovo Reservoir, (1) present-day water regime and (2) projected climate changes.

| Regime | January | February | March | April | May | June | July | August | September | October | November | December | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Low water content | | | | | | | |
| 1 | 0.36 | 0.34 | 1.67 | 1.86 | 1.02 | 0.56 | 0.41 | 0.32 | 0.27 | 0.34 | 0.47 | 0.29 | 7.24 |
| 2 | 0.31 | 0.30 | 1.21 | 1.15 | 0.77 | 0.46 | 0.34 | 0.27 | 0.23 | 0.28 | 0.37 | 0.23 | 5.42 |
| | | | | | | Mean water content | | | | | | | |
| 1 | 0.55 | 0.47 | 0.49 | 1.36 | 0.68 | 0.78 | 0.80 | 0.49 | 0.60 | 0.79 | 0.60 | 0.27 | 8.13 |
| 2 | 0.44 | 0.35 | 0.34 | 1.03 | 0.83 | 0.65 | 0.70 | 0.39 | 0.49 | 0.65 | 0.45 | 0.20 | 6.81 |

## 3. MID-21ST CENTURY RESERVOIR REGIME SIMULATION RESULTS IN CASE OF LOW AND MEAN WATER CONTENT

### *3.1. Ivan'kovo Reservoir*

Under projected climate changes, computed values of surface water temperature will increase by 3.3°C (upper reaches) to 5.1°C (near the dam) for May–October and of 2.1–3.4°C respectively for the year on average in case of low water content. Less considerable increase in case of mean water content will amount to 3.4°C (upper reaches) to 2.7°C (near the dam) for the year on average.

Changes in reservoir water residence time are expected. Mean value of reservoir water exchange coefficient $K_w$ for 1952–1980 is 8.3 year$^{-1}$ [7]. This value was 1.2 times lower in 1973 (low water content). Under projected inflow decrease, $K_w$ value will drop down to 5.42 year$^{-1}$ that is 1.5 times less than its present-day mean annual value. According to the data of Table 1, reservoir water residence time will decrease on average by 25% in case of low water content ("experimental" year) and by 19% in case of mean water content. Maximum residence time decrease occurs in spring (March and April) due to reducing springflood inflow volume, when there is a need to fill the reservoir in order to maintain the specified water stage.

One of the consequences of reservoir residence time decrease will be the surface and bottom layer temperature difference increase. According to research data, direct stratification is present in the reservoir till the late summer; it is caused by flowing of warm river water masses onto relatively cold springflood waters which displace winter water mass [2]. Cold bottom water mass release to the tailwater pool takes place up to the late summer; by that time quasi-horizontal zone of warm and cold water mixing goes down under conditions of multifactor water column mixing. In case of projected climatic changes, reduced release to the tailwater pool and more intensive surface layer heating, the difference between surface and bottom water temperature increases. Under conditions of actually observed changes, maximum surface and bottom temperature difference was registrated in May (up to 5.1°C), whereas this difference amounted to less than 1.5°C in August. Under conditions of probable climatic changes and residence time reduction, reservoir water stratification will be most clearly pronounced a month later, in June (the difference $T_s - T_b$ will amount to 6.2°C in low-water year and to 1.9°C in case of mean water content). In August there still will be considerable stratification in the reservoir (3.8°C and 2.1°C instead of actual 0.9°C and 1.3°C for low and mean water content, respectively).

Duration of freezeup period is expected to decrease. According to the modeling results, the ice-free period will begin two or three weeks earlier and freezeup, one or two weeks later in case of heating.

In case of projected climatic changes, the changes of thermal regime and its features are originally caused not only by residence time changes but also by the changes in thermal balance structure of the reservoir. There are no substantial changes in absolute values of turbulent thermal exchange, except for heat losses decrease due to this component in the upper reaches (for a low-water year, there is an increase in the near-dam section). Heat losses due to evaporation will increase by 1.3 times in the upper reaches and by 1.4 times, in the near-dam section on average for a low-water year. As compared to the values for the year 1973, heat losses due to effective radiation will be almost zero in the upper reaches and decrease by 2.4 times in the

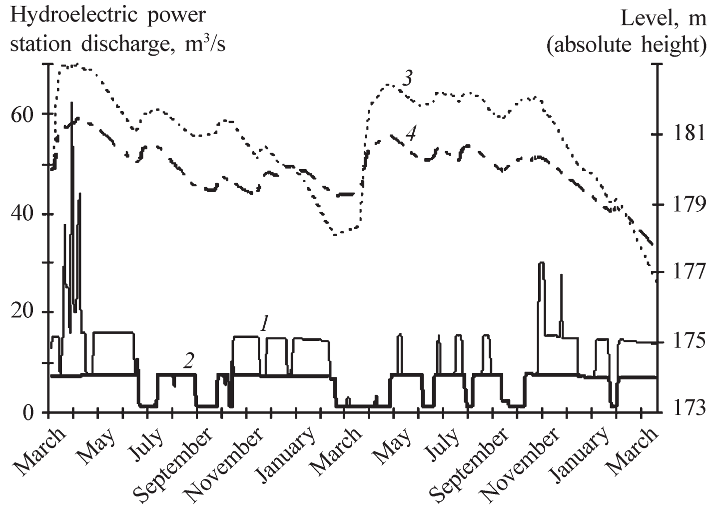


**Fig. 2.** Variations of (*1*) measured and (*2*) simulated values of water release to the tailwater pool of the Mozhaisk Dam and (*3*) observed (1983–1984/1985) and (*4*) simulated water stage variations for the years of mean water content.

near-dam section on average for a low-water year. Decrease in total heat losses over the period December through July, as well as their increase from July to November due to more intensive heating of the water column, will change substantially the intra-annual structure of the thermal balance.

As compared to the values for the year 1984, heat losses due to turbulent thermal exchange for the open water period will decrease by 20% in the upper reaches and by 30% in the near-dam section on average for a mean water content year. There will be a slight decrease in heat losses due to effective radiation for a year with mean water content. Evaporation will increase by 2.2 times in the upper reaches (maximum increase is expected in August, September, and October) and by 1.8 times, in the near-dam section. In case of projected climatic changes, there will be substantial decrease in the value of total heat losses for the summer months in the near-dam section and more intensive heat loss will take place in the fall, especially in the year with mean water content.

The computation results presented in this paper are one of scenarios under possible climatic changes, as well as in case of reduced inflow to the Ivan'kovo Reservoir and stable regime of water intake by the Moscow Canal. In case of increasing intake for sanitary water supply development of Moscow, water release to the tailwater pool should be reduced to maintain the normal maximum level, that will result in further reduction in residence time and intensification of the stratification. Of course, the interests of energy development, as well as the water balance of Uglich Reservoir, should be taken into account when choosing the strategy of dam management (these issues are beyond the frameworks of this study).

### *3.2. Mozhaisk Reservoir*

Similar approach was used to prepare the input data to compute the possible changes in Mozhaisk Reservoir hydrological conditions. The period March 1983 through March 1985, when hydrological surveys were carried out more frequently, was used for experimental calculations. The measurement results of this period were multiply used for calibration of new model blocks. The analysis shows that the model simulates well the actual variations of hydrological characteristics. One of the principal differences between Mozhaisk and Uglich dam operation is the drawdown of water storage accumulated during springflood period for water supply of the city of Moscow. It implies that during low flow period Mozhaisk reservoir water stage gradually decreases. Preliminary test computations showed that in case of maximum reduction in annual and springflood inflow in the 2050s, maintaining present discharge volumes, the reservoir drawdown to the dead storage level takes place by the midsummer, that makes further use of the reservoir for water supply impossible. The reservoir will still be functioning within the water supply system in case of simultaneous reduction of inflow and water release to the tailwater pool. Polyvariant calculation analysis showed that water release via a spillway should be abandoned and release volume decreased (using only one turbine) in order to avoid drawdown to the dead storage (Fig. 2). In such functioning mode, water stage fluctuation amplitude decreases from 6.5 m to 4.5 m. It may be possible for water stage of the reservoir to

**Table 2.** Mean monthly water stages and coefficients of water exchange for the years of mean water content: (1) actual data for 1983–1984/1985 and (2) in case of probable climatic changes.

| Period | Water stage, abs m | | $K_w$ | | Period | Water stage, abs m | | $K_w$ | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | | 1 | 2 | 1 | 2 |
| April 1983 | 182.32 | 180.95 | 0.41 | 0.15 | April 1984 | 178.49 | 179.33 | 0.33 | 0.15 |
| May 1983 | 182.81 | 181.34 | 0.15 | 0.11 | May 1984 | 182.47 | 180.92 | 0.10 | 0.09 |
| June 1983 | 182.11 | 180.83 | 0.17 | 0.12 | June 1984 | 182.13 | 180.49 | 0.09 | 0.09 |
| July 1983 | 181.04 | 180.23 | 0.11 | 0.12 | July 1984 | 182.13 | 180.42 | 0.17 | 0.15 |
| August 1983 | 181.63 | 180.59 | 0.10 | 0.11 | August 1984 | 182.13 | 180.39 | 0.14 | 0.12 |
| September 1983 | 181.06 | 179.77 | 0.07 | 0.08 | September 1984 | 182.05 | 180.26 | 0.12 | 0.10 |
| October 1983 | 180.79 | 179.37 | 0.13 | 0.13 | October 1984 | 181.96 | 180.15 | 0.11 | 0.10 |
| November 1983 | 181.00 | 179.57 | 0.20 | 0.13 | November 1984 | 182.21 | 180.31 | 0.20 | 0.10 |
| December 1983 | 180.26 | 179.49 | 0.23 | 0.18 | December 1984 | 181.03 | 179.87 | 0.15 | 0.10 |
| January 1984 | 180.10 | 179.99 | 0.18 | 0.12 | January 1985 | 180.05 | 179.27 | 0.14 | 0.10 |
| February 1984 | 179.43 | 179.81 | 0.14 | 0.08 | February 1985 | 179.17 | 178.81 | 0.14 | 0.08 |
| March 1984 | 178.33 | 179.22 | 0.04 | 0.04 | Average for 1984 | 181.04 | 180.10 | 1.78 | 1.26 |

reach the normal maximum level in the years of maximum water content. Due to forecasted inflow reduction, a problem of water supply to Moscow from the Moskva River reservoir system emerges (since there will be similar water regime changes in other reservoirs of the system); hydroelectric power production will reduce as well. However, one should bear in mind that some part of the flow are released through the spillway during springflood and flood periods, thus not contributing to the formation of water storage for water supply and hydroelectric power production. As is clear from Fig. 2, winter-period release reduction may get significant; otherwise, the reservoir water stage will not even reach 180 m (absolute elevation). The summertime drawdown is minimum, therefore, it will not undergo any changes.

During considered 50-year period, reservoir residence time reduction is possible, especially in the spring, that is related to the need in release reduction due to inflow decrease, and during the winter low flow period as well. During the summer and fall low flow period, there will be minimum change in residence time due to increase in flood flow. Reservoir residence time may decrease by 40% for the year on average (Table 2).

The changes in weather, inflow and residence time conditions will affect the characteristics of reservoir water properties. Average increase in surface water temperature for the period under consideration will amount to 4.1°C and that for the period May through October, to 5.9°C. The difference in surface water temperature in the upper reaches and near the dam during the period of heat accumulation in the water column will decrease by 1°C due to earlier ice melt, as well as to a smaller part of relatively warmer springflood waters at intensive heating of the water area. During the cooling period, the difference in surface water temperature in the upper reaches and near the dam will increase by 0.3°C (due to more rapid cooling of shallow water at relatively low water stage). There will be changes in water column stratification formation conditions, as well as in stratification intensity and duration. Due to large number of determining factors, it is difficult to draw unambiguous conclusions. Though main regularities may be derived: wind velocity increase in case of climatic changes results in the stratification period duration decrease, as well as in the decrease in the surface and bottom water temperature difference. The effect of this factor increases with decreasing water stage. Intensive spring heating in case of earlier ice disappearance dates causes earlier formation of thermal layers.

In case of decreasing residence time, stratification will be more pronounced in the reservoir during its origination and formation. However, in case of probable increase in wind velocity during summer rain period, as well as in case of smaller amount of water in the reservoir, the average decrease in surface and bottom water temperature difference may amount to 2.7°C for the reservoir. Numerical experiments demonstrated that mostly pronounced thermal stratification will be registered on average a month earlier (i.e., in May instead of June); mean near-dam surface and bottom water temperature difference for the period of stratification formation through its destruction (April–August) will increase from 6.8°C to 7.4°C.

There may be substantial changes in water mineralization distribution: the difference of its values in upper reaches and in the near-dam region may decrease on average by 60 mg/l due to decreasing spring snowmelt low-mineralization water inflow part. It will also cause the decrease in the surface and bottom water mineralization difference from –48 mg/l to –5 mg/l on average over the whole period, whereas average reservoir water mineralization will increase by 20 mg/l. In this paper, water mineralization is considered only as an example of one of numerous drinking and technological water characteristics in surface water sources of the city of Moscow. Thus, despite the decrease in residence time, the changes in qualitative water composition and water stage regime may lead to leveling of typical values of conservative hydrological characteristics of Mozhaisk Reservoir water masses.

There may be some environmental consequences of reservoir residence time changes. Predictors of biological processes development are thermal regime, biogenic matter supply both from the watershed and from bottom sediments, and weather type during the summer period (stormy weather frequency and intensity); therefore, the changes for the whole biocoenosis are difficult to predict. Hydrobiont development features may affect earlier fish puberty, changes in spawning dates and ovum incubation duration. Growing environment temperature affects plankton fertility and specific production. However, the effect of this factor on population density change is unambiguous [3]. Various phytoplankton species may begin to develop earlier due to their temperature optimum date shift. Their development intensity will be also determined by biogenic matter supply. In case of decrease in springflood inflow volume, phosphorus inflow decrease may be expected. Thermal regime change may affect the development of higher aquatic vegetation: temperature increase impedes intensive weed growing in the reservoir, limiting possible depth of plant penetrating (through reducing the illuminance) [1]. Note that under natural conditions water temperature does not reach experimentally determined threshold of 38–39°C (when the temperature exceeds this value, thermal damage of vegetation begins). Temperature increase up to 28–30°C stimulates the processes of growing and photosynthetic assimilation of $CO_2$; however, biomass accumulated by the vegetation is not large due to intensive night respiration.

## 4. CONCLUSIONS

Analysis of results of mathematical modeling of possible changes in hydrological regime of two reservoirs of different type within the system of water supply of the city of Moscow demonstrated that in case of predicted warming, annual flow decrease and its intra-annual distribution change, substantial changes in reservoir hydrological regime should be expected. Reservoir residence time reduction is possible (by 19–30%, depending on the water content of the year), as well as water temperature increase, ice melt and ice formation dates change, earlier formation of water masses stratification, and increasing hydrodynamical stability and water mineralization due to decreasing part of spring snowmelt waters and increasing phosphoric load during heavy summer floods. Such changes in hydrological regime may lead to intensification of production and destruction processes, more intensive blue-green algae blooming with oxygen oversaturation of the photic layer and increase in hypolimnion fish kill frequency and duration. Probable decrease in dynamical water resources requires timely preparation of water supply system, as well as complex changes in dam operation schedules.

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