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Modeling of spatial distribution of average long-term evaporation from the water surface in the central part of European Russia

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ABSTRACT

Relevance. Studying spatial distribution of evaporation from water surface is becoming an increasingly relevant area of research under the observed climatic changes. In this connection it is quite evident that for spatial generalizations one should use more precise methods taking into account all diversity of natural factors of the above process formation. **Methods.** To extend the database for the evaporation spatial generalization there was used the re-analysis technique based on the physical/mathematical model of vertical hydrothermal transfer in the aquatic environment. The model was calibrated on the data of observations of evaporation with GGI-3000 at 35 sites of the central part of European Russia. **Results.** We calculated long-term average values of water evaporation for the period of 2000–2020 using the data on average daily values of meteorological parameters on a spatial grid at the locations of 105 meteorological stations. Maps of evaporation distribution for the central part of European Russia were drawn. Results of spatial modeling were generalized and we obtained a number of regularities connecting the value of average long-term evaporation from water surface with air temperature and wind velocity of the warm season. We analyzed variability of transition coefficients from evaporation gauged with GGI-3000 to evaporation from small water bodies proving that they are subjected to climatic changes.

KEYWORDS: water surface, evaporation, mathematical modeling, reanalysis, spatial variability, mapping, meteorological factors impact

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INTRODUCTION

Accurate spatial estimates of evaporation from water surface are of great practical importance. Evaporation data have been mapped for quite a long time. Back in 1944, at the State Hydrological Institute, V. K. Davydov prepared a map “Evaporation from the water surface in the European part of the USSR” edited by B. D. Zaikov [1]. The most well-known and widely used is the map on the

average long-term value of evaporation from the water surface of a 20 m^2 evaporation pool given in the Guidelines for estimating evaporation from the surface of reservoirs[1]. Recently, A. N. Postnikov has prepared a map on the average long-term evaporation from the surface of natural reservoirs for an ice-free period in Russia [2]. It should be noted that all these maps were made on the basis of simplified calculation methods. The Guidelines use the evaporation formula of the State Hydrological Institute (SHI), A. N. Postnikov estimating evaporation based on the thermal balance method.

In foreign practice, when studying the spatial distribution of evaporation, the most popular are calculation methods based on the Penman approach and the Bowen ratio to determine the energy balance of water bodies [3, 4]. Several studies use regression models and artificial neural networks to estimate evaporation based on climate data [3]. The calculation methods listed above reflect only certain aspects of the multi-factorial evaporation process and are approximate in nature. In view of this, developing more accurate methods for spatial generalizations considering the full variety of natural factors in forming this process has become highly relevant.

The paper proposes the authors' methodology allowing for estimation of evaporation from water surface. Presented in detail in [5, 6], physically based mathematical model of runoff formation processes – the GGI-Gidrofizika Model (certificate of state registration No. 2025697103) describes almost all physical processes of evaporation formation over a long period of time; climate change occurred in recent decades taken into account.

In recent years, there has been growing the role of new sources of information about the current state of water bodies and trends in changes in their characteristics, both in space and in time. This is primarily due to the decreasing observation network and serious problems in gap filling when summarizing observations of many hydrological characteristics. This fully refers to observations of evaporation from the water surface. Due to these circumstances, reanalysis methods are becoming very popular. Based on meteorological observations scientists can restore information about evaporation in the absence thereof a measurement system for this component of the water and heat balance, mathematical models of different complexity being used. The GGI-Gidrofizika Model was used for this purpose for the first time.

The successful use of mathematical models is impossible without testing them based on observational data, i.e. solving problems related to the expansion of knowledge about spatial patterns of evaporation is complex, based both on the results of measurements on the observation network and on theoretical generalizations obtained with various computational methods. At the same time,

1 Guidelines for calculating evaporation from the surface of water bodies. L.: Hydrometeoizdat, 1969. 84 pp.

it is necessary to take into account the fact that in the case of evaporation from the water surface, using GGI-3000 evaporators is almost the only mass measurement method. The data obtained with this instrument cannot be directly used to estimate evaporation from real water bodies. Transition coefficients are used for these purposes. However, about fifty years ago, methods for their determination were developed based on the experimental information available [7]. Therefore, for the correct interpretation of the evaporation assessment results based on observations using GGI-3000 evaporators, it is important to refine transition coefficients taking into account the data obtained in the subsequent period.

The central part of European Russia, ranging from 45 to 61.5° N and 31.5–61°E, was chosen as the object of research. The choice of this territory is mainly due to the location of the Volga River basin, the most important waterworks and hydrological facility in Russia. The calculation of the average long-term values of evaporation from the water surface for the period of 2000–2020 was made. Generalizations for this period are not so numerous due to sharp reduction in the observational base.

RESEARCH METHODS

As long-term studies show, evaporation processes and their spatiotemporal dynamics are primarily due to meteorological conditions, the network of meteorological observations being much denser than the network of various evaporation components observations. Meteorological observations in the area under study were carried out at 104 weather stations, evaporation measurements being taken at only 35. This circumstance makes it possible to obtain additional spatial information about this hydrological feature using reanalysis methodology based on mathematical modeling of the above-mentioned processes from meteorological data.

The reanalysis method is a two-step process. At the first stage, called data assimilation, the mathematical model of the system under study is calibrated against all available observable information of the input and output parameters and characteristics of the model. As a rule, the range of such observations is small, which imposes some limitations on the accuracy of calibration. In our case, it is a set of meteorological and hydrological information at observation points. At the same time, it is necessary to achieve maximum convergence of estimated and test features.

Next, reanalysis is performed, i.e. using the calibrated model, evaporation values are calculated at the initial information nodes. Calculations can be made both on a regular and irregular spatial grid, e.g. on an uneven grid of weather stations, the density of which significantly exceeds the network of evaporation observations. A variant of reanalysis based on a regular spatial grid is widely

used. In this case, all the meteorological information necessary for modeling should be presented in mesh nodes, but, as a rule, it is lacking or it is also obtained on the basis of reanalysis of the results of meteorological observations. Questions about accuracy of such a double reanalysis arise. In which case is the accuracy of evaporation estimation at grid nodes higher – with model calculations based on reconstructed weather data or model data on evaporation at weather station locations obtained by spatial interpolation? This issue requires a special study.

Modeling plays a key role in reanalysis. The main equations for calculating evaporation from the water surface are the equations of thermal balance and turbulent diffusion supplemented with a system of differential equations describing the processes of heat and moisture transfer in the water column. A detailed description of all the equations of the mathematical model is given in [5, 6].

Simulation of vertical hydrothermal transfer is carried out on a 10 m deep water column. The estimate vertical pitch is 1 cm. Evaporation calculations for a long-term period are carried out in time increments of 1 hour. As the initial information for mathematical modeling, there are used daily values of meteorological data at the altitude of 2 m (air temperature, precipitation, wind speed, water vapor elasticity), as well as data on lower and upper cloudiness. The set of parameters for calculating the characteristics of solar radiation includes solar declination, latitude at the design point, total and lower cloudiness, and albedo of the water surface.

At the first step of reanalysis (data assimilation), the mathematical evaporation model used is calibrated against all available for the territory observations. In the case of reanalysis of evaporation from the water surface, there is a problem of choosing observation series most suitable for calibration of the model, both for the amount of evaporation and for related meteorological parameters. To achieve maximum accuracy in comparing measured and estimated values, the meteorological data obtained should be as close as possible to the sites where evaporation measurements are taken. In practice, there is a greater or lesser spatial gap between locations of these two observation types.

The second calibration problem is the choice of the type of instrumental observations of evaporation from the water surface – using a 20 m^2 evaporation pool or evaporator GGI-3000. The 20 m^2 evaporation pool is recognized by the World Meteorological Organization (WMO) as an international reference instrument characterizing evaporation from small lakes and reservoirs, which is practically free from measurement distortions caused by processes in the soils surrounding the evaporator. This fact, in its physical essence, brings together the processes of measurement in the pool and calculations based on the test spatial-one-dimensional model. However, despite the advantages of this measurement technique, it has a significant drawback that does not allow for a full use of

the 20 m^2 pool for calibration of the mathematical model. This disadvantage is due to a relatively small number of observation ranges in various natural areas, especially in recent years. Observations of evaporation from the water surface using a 20 m^2 evaporation pool are currently carried out at only four stations in European Russia.

Based on the above, in order to test and calibrate the mathematical model, we used observations on the GGI-3000 evaporator as the most numerous and closely related to meteorological observations. In European Russia, observations were carried out at 54 stations.

It should also be emphasized that the process of testing and calibrating the mathematical model was carried out on three levels. At the first and second, estimated and measured data of the annual and long-term evaporation were compared. The results of comparisons are described in detail in [6]. Correlation coefficients between estimated and measured evaporation values range from 0.7 to 0.9. Standard calculation errors are less than 10 per cent, i.e. convergence of the results is quite high. The dynamics of evaporation from the water surface is complex, and the mathematical model correctly describes it [6].

The third level of comparisons includes a comparison of average long-term evaporation values. For the central part of European Russia 35 observation points were selected. During the calibration process, optimal values of mathematical model parameters were obtained, the latter being unchanged in the entire computational domain. These parameters include, first of all, roughness of the underlying surface, albedo, radiation absorption coefficients, and heat transfer characteristics in the aquatic environment. As a result, when moving from one

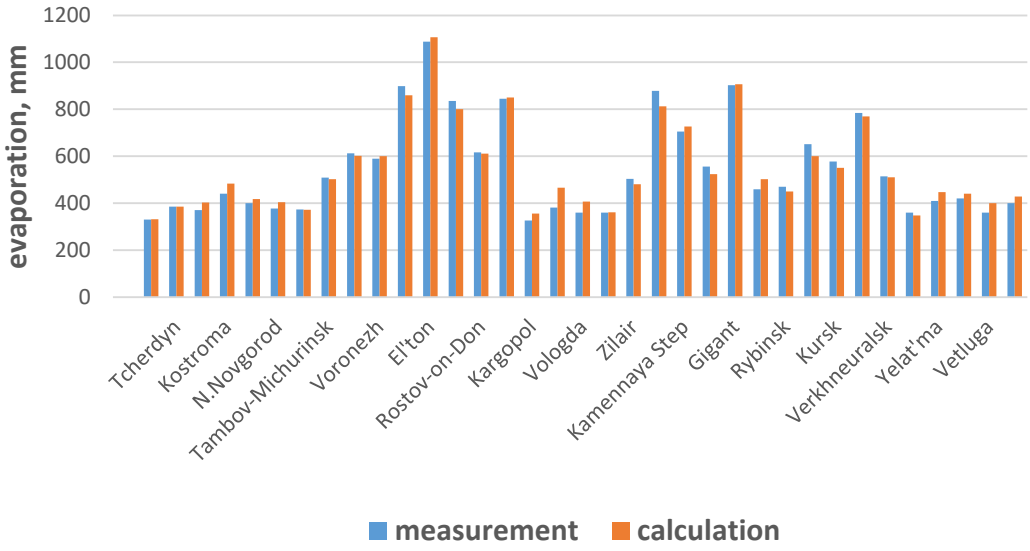


Fig. 1. Comparison of measured and estimated average long-term values of evaporation from water surface for the period of 2000–2020 at a number of stations of European Russia

point to another, only mean daily series of observations of meteorological data (air temperature, steam pressure, wind speed, as well as total and lower cloudiness) changed in the calculations. The value of the latitude of the area used to determine the radiation characteristics also changed.

Figure 1 shows a diagram demonstrating the final result of comparing calculated (E_c) and measured (E_m) average annual evaporation values after performing the calibration procedure. The equation of the relationship between calculated and measured values is as follows:

$$E_c = 0.999E_m, \qquad R^2 = 0.97. \tag{1}$$

The average standard calculation error is 6 per cent.

RESULTS OF MODELING

Despite some calculation errors, a fairly high degree of convergence of the model and measured average long-term evaporation values makes it possible to restore the values of this feature at the locations of meteorological measurements. Figure 2 shows a map of spatial distribution of the estimated average long-term evaporation values in the area under study. The map was drawn in the QGIS environment based on data from the evaporation calculation at the meteorological station sites.

An additional analysis of the simulation results showed that the amount of evaporation primarily depends on weather conditions and the latitude of the area. Spatial fields of evaporation and temperature are the most similar. Within the framework of observations, there were studied correlations between the calculated annual average values of evaporation (E_c) and the main meteorological variables for the warm period of the year, air temperature, water vapor pressure and wind speed, as well as total and lower cloudiness. Statistical analysis has shown that the closest relationship is observed between evaporation and the temperature of the warm period (T_{wp}), with a correlation coefficient of $R = 0.9$ (Fig. 3).

The equation of this relation (2) is exponential in nature, which is due to a similar type of dependence of the saturated vapor pressure of the evaporating water surface on its temperature:

$$E_c = 40.4 \exp(0.2T_{wp}). \tag{2}$$

When performing calculations on formula (2), the standard error was 15 per cent.

From the statistical analysis, it also follows that the correlation coefficient between the long-term average values E_c and wind velocity (v_{wp}) is 0.74, and

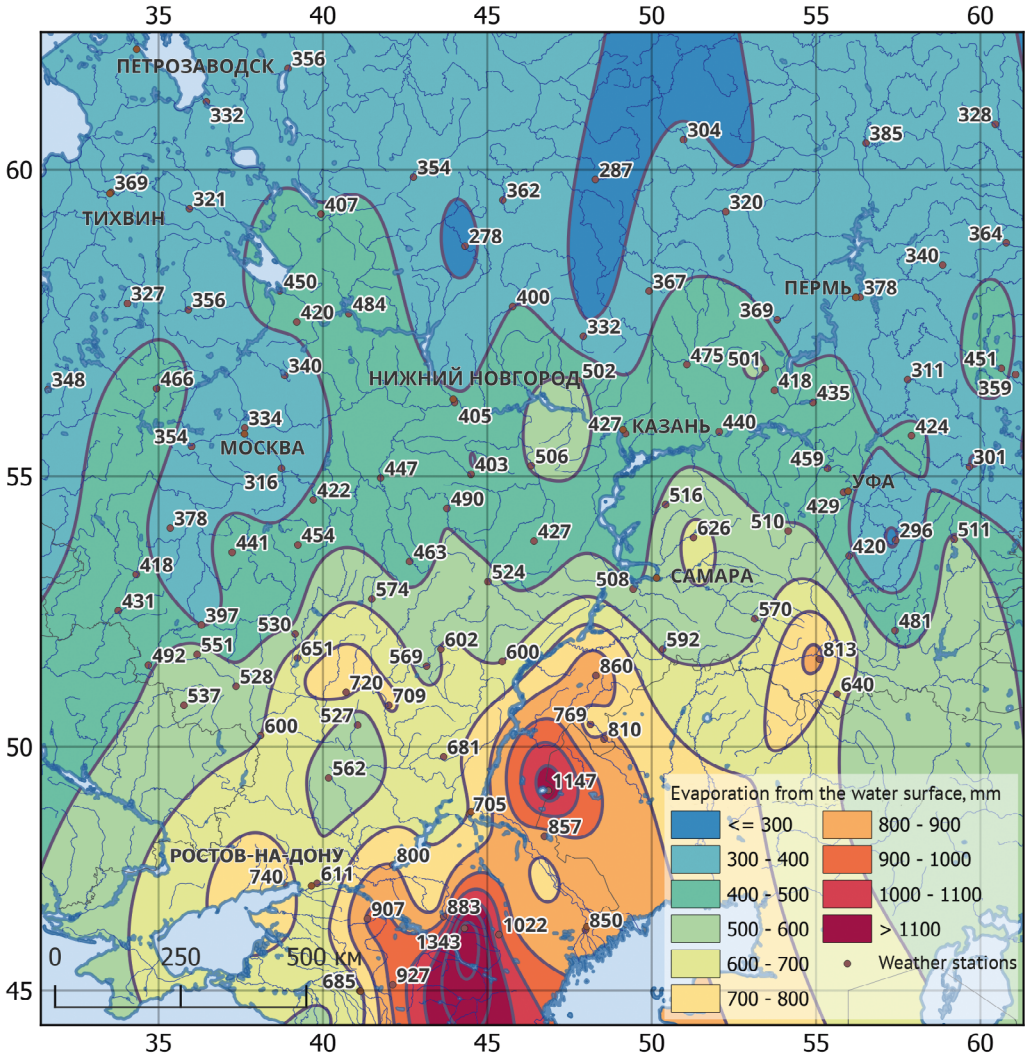


Fig. 2. Spatial distribution of estimated average long-term evaporation values for the period of 2000–2020

there is practically no such relationship between evaporation and vapor pressure in the atmosphere. There is also a fairly high inverse correlation between evaporation and indicators of total and lower cloudiness (R = 0.75 and 0.7). However, these characteristics are strongly inversely dependent on air temperature with a correlation coefficient greater than 0.8, so it is quite difficult to identify the individual influence of these factors.

However, as it follows from the results obtained, temperature is not the only factor in the formation of the spatial distribution of evaporation. Therefore using the method of multiple linear regression an equation was constructed for the relationship between average long-term values of evaporation, air temperature and

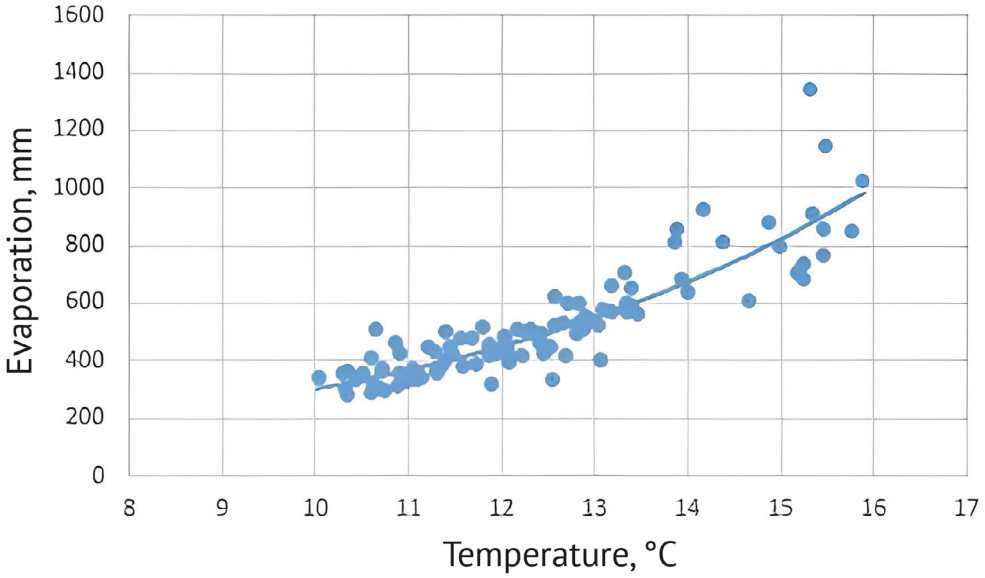


Fig. 3. Dependence between estimated average long-term values of evaporation from water surface and air temperature of a warm season

wind velocity in the warm period (v_{wp}), another of the most important variables used in evaporation calculations.

Taking into account the exponential nature of the E_c dependence on temperature, the logarithm of its value was used as a variable instead of evaporation in the regression analysis. In this case, the following calculation equation is obtained:

$$E_p = \exp(0.16T_{wp} + 0.22\, v_{wp} + 3.7). \quad (3)$$

The correlation coefficient of such a relationship is 0.97, the standard error being 8 per cent.

Using the average temperature and wind velocity of the warm period as weather data variables introduces some uncertainty into the method of calculating these characteristics. In the GGI-Gidrofizika Model, the warm period is defined as a period with no snow cover, and in the work of A. N. Postnikov [2], the warm period includes months with average temperatures above zero. To avoid difficulties in determining these characteristics, in our study we used average weather data for the five warmest months of the year, from May to September (T_{5m} and v_{5m}) as variables. The following coupled equations are obtained, which are similar to (2) and (3):

$$E_p = 61.3 \exp(0.12T_{5m}), \quad (4)$$

$$E_p = \exp(0.1T_{5m} + 0.22\, v_{5m} + 4). \quad (5)$$

The correlation coefficients of these relations are 0.93 and 0.99, respectively, the standard calculation error being 13 per cent and 7 per cent. Thus, using their average values for five months as weather data variables increases accuracy of calculations and simplifies preparation of initial information.

In addition to analyzing long-term characteristics of evaporation from the water surface, annual evaporation data and their relationship to the average air temperature and wind velocity in the warm period were also considered. In this case, the correlation coefficient is 0.76, the standard error of calculations based on the regression equation being 85 per cent, i.e. the use of such information in calculations is inappropriate.

However, using the multiple linear regression method to analyze the annual average data on evaporation, temperature, and wind velocity (T_{A5m} and v_{A5m}) for the five warmest months of the year can significantly improve the accuracy of the calculation. In this case, the equation similar to (5) is as follows:

$$E_c = \exp(0.07T_{A5m} + 0.22\, v_{A5m} + 4). \quad (6)$$

The correlation coefficient of this relation is 0.92, the standard calculation error being 12 per cent: the accuracy of calculations has increased significantly compared to using only one variable – temperature.

Climatic characteristics, such as solar radiation fluxes and air temperature, are known to have a strong latitudinal dependence and, accordingly, the amount of evaporation also depends on the values of the northern latitude of the area (φ). The correlation coefficient of the obtained relationship (7) is 0.85, the standard calculation error being 17 per cent:

$$E_c = 22974 \exp(-0.07\varphi). \quad (7)$$

Formulas (2) – (7) are not universal because they are obtained only for the territory studied in the framework of this work. Despite the fact that they reflect physical patterns of evaporation from the water surface under the influence of such basic meteorological parameters as air temperature and wind velocity, the formulas obtained are to some extent determined by spatial patterns of distribution of meteorological factors in European Russia, the mathematical model being calibrated only on experimental data obtained in this area.

The use of the above-mentioned calculation formulas to determine evaporation from the water surface makes it possible to apply a simplified reanalysis technique on a regular spatial grid. For this purpose, there should be relevant information in its nodes. To calculate evaporation for the period of 2000–2020, air temperature data were taken from the Global (land) archive of meteorologi-

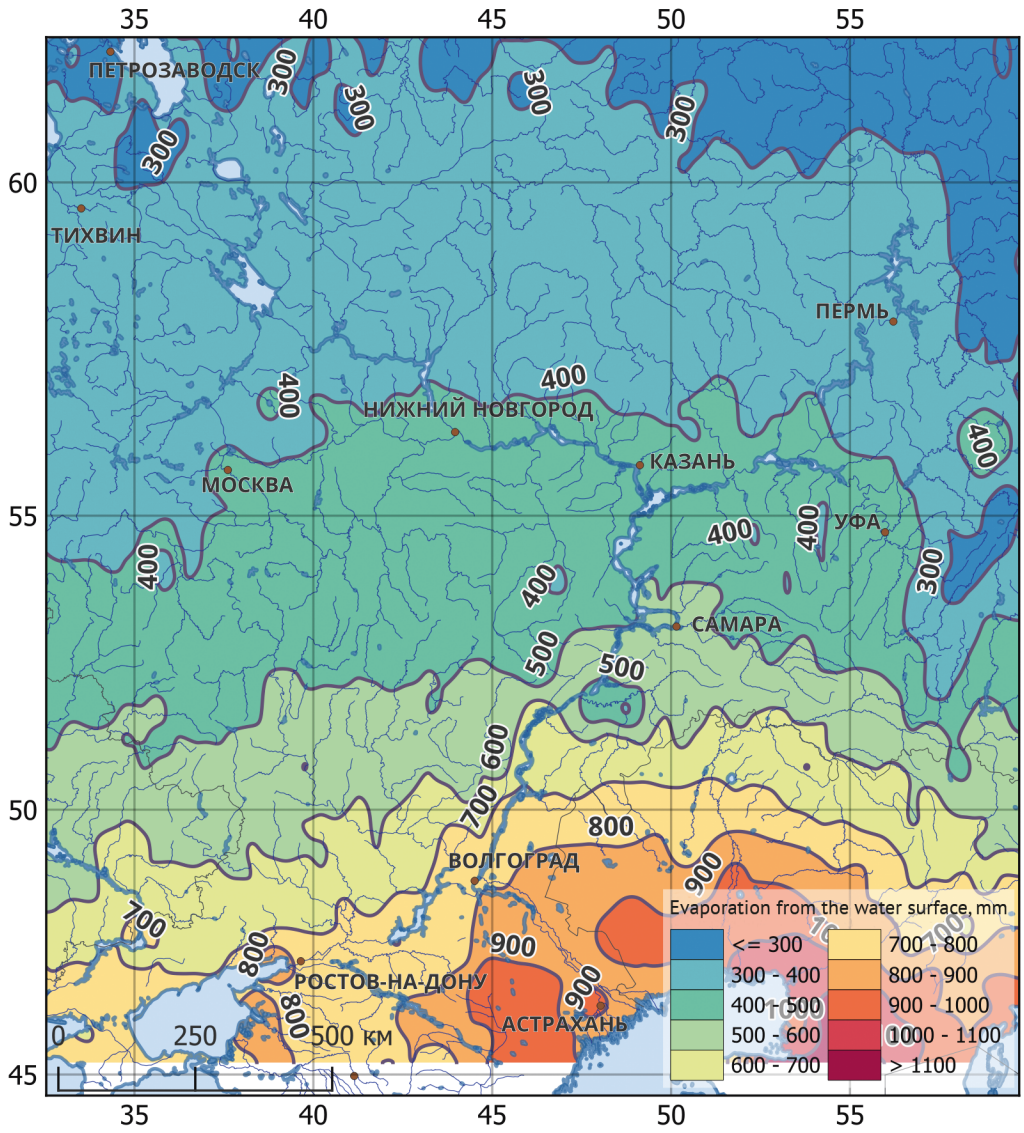


Fig. 4. Spatial distribution of estimated long-term values of evaporation from water surface

cal data by Willmott & Matsuura[2]. Monthly average air temperature values at weather stations were interpolated into a spatial grid of 0.5-degree latitude × 0.5-degree longitude. For reanalysis, there was used formula (4) relating the value of long-term average evaporation to the average air temperature for five warm months. Unfortunately, we do not have a database of grid values of wind velocity in European Russia, so it is not possible to use a more accurate formula (5) for reanalysis when calculating evaporation from the water surface.

2 http://climate.geog.udel.edu/~climate/html_pages/archive.html

Fig.4 shows a map of long-term average evaporation values obtained with a similar reanalysis technique on a regular spatial grid. When comparing the map in Fig. 4 with the one in Fig. 2 noticeable differences are revealed, which is due to both the lack of wind velocity in calculations and differences in reanalysis methods. In the first case (Fig. 2), evaporation calculations were performed based on the measurement of meteorological data at weather stations sites, and in the second (Fig. 4) – based on their preliminary reanalysis at the regular mesh nodes. Taking into account the non-linearity of relationship between evaporation and air temperature, methods for approximating this characteristic in areas not covered by observations can significantly affect the estimated evaporation value. In addition, comparisons of monthly average temperatures measured and obtained as a result of preliminary reanalysis have shown that noticeable differences between them sometimes reach 1degree C. Thus, the problem of choosing a reanalysis method is related to the accuracy of calculating spatial characteristics of evaporation and requires additional research.

The average value of evaporation from the water surface in the area under study ranging from 45 to 61.5° N and 31.5–61° E was calculated. According to the reanalysis on a regular grid (Fig. 4), this value is 524 mm per year, with a variation coefficient of 40 per cent. The mean of estimated values at the weather station sites is 514 mm per year, i.e. deviation is less than 2 per cent; the measured average evaporation at 35 observation points used in calibrating the mathematical model is 544 mm per year. This is only 4 per cent higher than the grid average. The data obtained indicate a fairly high degree of accuracy of the re-analysis procedure used to assess long-term average spatial characteristics of evaporation from the water surface.

Problems of using calculation results. Transition coefficients

The above model calculations of evaporation relate essentially to reanalysis of the results of observations on evaporator GGI-3000. The data obtained with ground-based evaporators cannot be directly used to describe evaporation from natural water bodies. From the very start of using the small-sized evaporator method, including GGI-3000, it became clear that due to the difference in the thermal conditions of the water environment in the evaporator and in larger reservoirs, certain distortions appeared in the measurable value. For an evaporation pool of 20 m^2, these distortions are minimal, so it is recognized as a reference instrument for measuring evaporation. Because of this there is a problem with transition from evaporation measured on the evaporator (in our case, calibrated on the evaporator data) to the one from the pool surface. For this purpose, the so-called transition coefficients are widely used. The basics of their calculation methods were developed by V. I. Kuznetsov [8, 9], supplemented by A. R. Kon-

stantinov [10], P. P. Kuzmin [7] and V. S. Golubev [11]. We should also mention the later work of V. S. Vuglinsky [12], where this technique was further developed.

In general, the formula of transition from evaporation on evaporator GGI-3000 ($E_{0.3}$) to evaporation on the surface of the pool (E_{20}) is as follows:

$$E_{20} = \alpha E_{0.3}. \quad (8)$$

It was noted in [7] that it is necessary to distinguish three types of transition coefficient α: actual (calculated for particular months), regional (averaged for all years of observations in this place) and global (averaged for all observation points regional coefficient).

For the purposes of this study, regional transition coefficients from some long-term mean data to others are of the greatest interest. In his work, V. I. Kuznetsov [8] presents a formula for transition of evaporation readings obtained on the GGI-3000Model to readings from the pool in the form of:

$$\alpha = rK_t, \quad (9)$$

where r is the instrumental coefficient of the evaporator;

K_t is a coefficient depending on thermal conditions of the water environment, considering the difference in the temperature of the water surface in the pool and the evaporator.

$$K_t = (e_{20} - e_2) / (e_{0.3} - e_2), \quad (10)$$

where e_{20}, $e_{0.3}$ is saturated water vapor elasticity calculated from the temperature of the water surface in the pool and the evaporator;

e_2 is water vapor elasticity at the height of 2 m.

V. I. Kuznetsov [8] believed that the instrumental coefficient of the evaporator depends on the turbulence effect of the collars, evaporation losses from the wetted walls and the advective lifting of steam from the evaporating surface. The average value of coefficient r for continental evaporators is determined equal to 0.75, but in each case there are deviations depending on meteorological conditions. According to P. P. Kuzmin, the approach of V. I. Kuznetsov is unnecessarily complicated and leads to noticeable calculation errors. Therefore, to calculate regional coefficients (α_{av}), P. P. Kuzmin [6] proposes formula (11) relying only on the average readings of evaporator GGI-3000 and believing that the transition coefficient is weakly dependent on weather conditions, the variability of which is already manifested in the formation of the monthly average evaporation value $E_{0.3av.}$:

$$\alpha_{av} = 0.98 - 0.0007E_{0.3av}. \quad (11)$$

According to P. P. Kuzmin, the correlation coefficient of this relationship is 0.79, the standard error being 6.5 per cent.

Formula (11) is important because it reflects the linear nature of the dependence on the average value of evaporation, which is measured in *mm/mon.*, i.e. it is suitable for any range of averaging over time.

Paper [10] presents a methodology for calculating transition coefficients based on their dependence on air temperature and humidity. There are also given nomograms there to determine average values of transition coefficients for the warm season on the data on the average annual temperature and elasticity of water vapor. The use of nomograms complicates the application of this technique in spatial generalizations.

V. S. Golubev [11], as well as P. P. Kuzmin, suggested using average evaporation rates for a particular month (mm per day) to calculate α:

$$\alpha_{av} = 1 - 0.063E_{0.3av}^{0.6}. \quad (12)$$

However, this equation is non-linear with respect to $E_{0.3av}$, so it is difficult to average the transition coefficient for long time intervals.

In his work [13] V. S. Golubev suggested his formula should be used for transition of seasonal values of evaporation from GGI-3000 to evaporation in the pool using additionally information on the latitude of the observation point (φ) in degrees and duration of the observation period (τ) in days:

$$E_{20} = 0.47E_{0.3} + 1.6\tau - 1.2\varphi + 54. \quad (13)$$

As the length of the observation period and the latitude are related to the evaporation value $E_{0.3}$, formula (13) reflects the dependence of transition coefficients on the value of evaporation from GGI-3000 only in a more complex form.

When analyzing the above, we conclude that for the task set in this paper, the methods for determining regional transition coefficients proposed by P. P. Kuzmin and V. S. Golubev can be used. Formula (11) was obtained based on the data from comparative evaporation measurements at 15 stations under the WMO program, including two domestic stations (Valdai and Dubovka). The work [7] was published in 1979, when problems of climate change and their impact on hydrological processes were not yet considered. An analysis of observations of evaporation from the water surface in 1960–1990 showed that despite warming of the climate, a negative trend of this characteristic was recorded almost everywhere in European Russia and in other countries of the world [14–16]. The effect is called the "evaporation paradox." A detailed study of the dynamics of meteorological data in the areas under study and mathematical modeling showed that the effect of increasing air temperature is largely compensated by a significant

decrease in wind velocity in a number of regions of Russia, Australia, China, and the United States [6, 17–21].

In order to determine the impact of climate change on the transition coefficient, the authors analyzed the joint long-term trends of evaporation measured using GGI-3000, the pool and coefficient α. For this purpose, we used all currently available observational data at the Salekhard, Valdai, Yershov, Tsimlyansk, Cherdyn, Nizhnedevitsk, Rybinsk and Vyazovye stations. The relative monthly values of evaporation and transition coefficients are calculated using the formula:

$$K_i = X_i / X_{av}, \quad (14)$$

where X_i is the value of the series under study in the i-year of observations;
X_{av} is the long-term average value for the entire observation period.

The performed comparisons have shown that the trends in the relative values of monthly evaporation and transition coefficients are in the antiphase (Fig. 5).

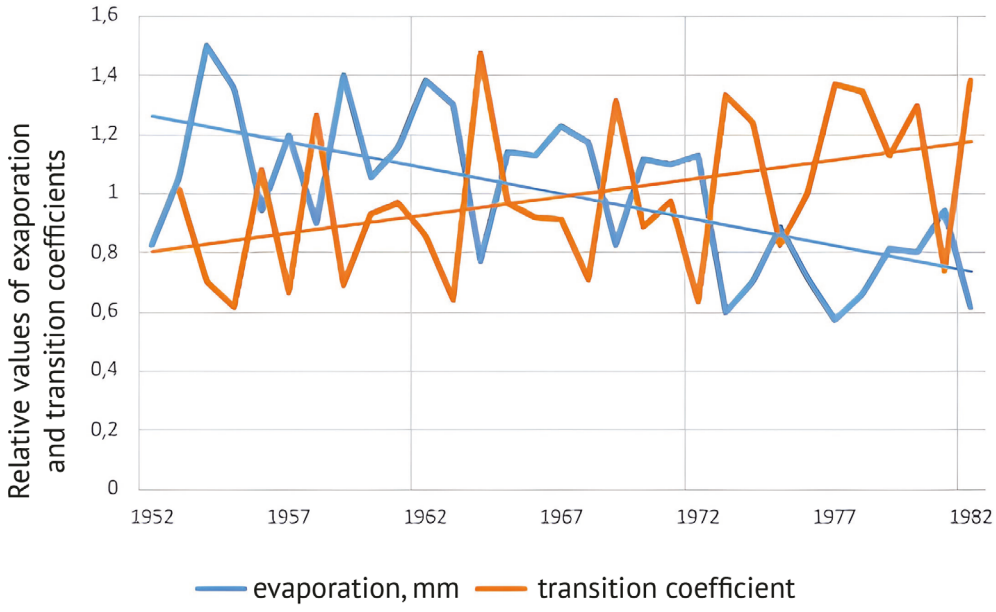


Fig. 5. Dynamics of relative values of monthly evaporation and transition coefficients for Tsimlyansk station (July)

These patterns were recorded at all stations under study from May to September, seasonal changes in evaporation and coefficient α being often out of phase. As Fig. 5 shows, when evaporation from the water surface was observed to be falling everywhere in the Volga basin, transition coefficients were increasing. This fact was often not taken into account in practical calculations. This

trend is most pronounced for Tsimlyansk. The correlation coefficient between monthly evaporation values and the transition coefficient for this station ranges from 0.75 to 0.8.

Table 1 shows the data for calculating transition coefficients for various observation periods, the values of coefficients of the first period (1950–1960) taken from the work of V. I. Kuznetsov [9]. In the subsequent period, up to 1990, there was a widespread increase in transition coefficients. After the 1990s, joint observations of evaporation from the pool and GGI-3000 were carried out only at three sites – Yershov, Nizhnedevitsk and Vyazovye; in Yershov, with an increase in evaporation there being a decrease in transition coefficients.

Table 1. Long-term average values of transitional coefficients for different observation periods

Station	Observation period	Month						
		May	June	July	August	September	October	Average
Tsimlyansk	1954–1967	0.87	0.76	0.75	0.75	0.84	0.97	0.81
	1968–1987	0.81	0.94	0.89	0.91	0.97	1.04	0.93
Yershov	1952–1967	0.79	0.74	0.75	0.76	0.77	0.79	0.77
	1968–1990	0.85	0.82	0.84	0.87	0.88	0.94	0.87
	1991–2020	0.77	0.79	0.8	0.78	0.84	0.88	0.81
Tcherdyn	1952–1967	0.83	0.87	0.86	0.9	0.88	–	0.87
	1968–1989	0.83	0.87	0.92	0.99	0.97	1.07	0.94
Valdai	1948–1968	0.96	0.97	0.95	0.95	0.95	0.94	0.95
	1969–1989	0.99	1.03	1.03	0.95	0.88	–	0,98
Rybinsk	1965–1968	0.93	0.92	0.96	0.91	1.1	1.19	1.00
	1969–1987	0.92	0.97	1.03	1.02	1.05	1.1	1.02
Nizhnedevitsk	1956–1967	0.83	0.96	0.95	0.93	0.95	0.96	0.93
	1968–1990	1.01	1.03	1.1	1.07	1.04	1.02	1.05
	1991–2012	1.01	1,02	1.04	1.1	1.07	1.1	1.06
Vyazovye	1952–1966	0.86	0.87	0.91	0.94	0.98	0.97	0.92
	1967–1990	0.95	1.00	1.04	1.04	1.01	1.01	1.01
	1991–2020	1.04	1.07	1.07	1.02	1.04	1.04	1.05
Salekhard	1961–1966	–	1.03	1.06	1.06	1.09	–	1.06
	1967–1987	–	1.2	1.06	1.03	1.11	–	1.11

A more detailed analysis of the results of observations at the sites of the Nizhnedevitskaya and Vyazovye hydroelectric power stations in recent decades shows that transition coefficients underwent significant fluctuations during this

period. Until 1973, the average value of the transition coefficient for the Vyazovye station was 0.9; in the period of 1973–2003. α = 1.1. At the same time, the coefficient of variation of this characteristic increased from 0.2 to 0.4. However, a significant increase in evaporation in June observed from 2000 to 2015 led to a clear drop in the transition coefficient during the same period. Significant fluctuations in coefficient α were also observed at the Nizhnedevitskaya station. In 2006–2007, it became less than the one in the period of 1956–1967 followed by a sharp rise to values more than 1 again.

Another important aspect arising from the analysis of the information obtained should also be considered. In [9], generalizations did not use the data for the Nizhnedevitskaya and Rybinsk stations when coefficient α exceeded 1: they were classified as "doubtful" during the observation period of 1950–1960. When analyzing the information received in subsequent years, as shown above, more than half of monthly data on the transition coefficient at the Nizhnedevitskaya, Rybinsk and Vyazovye stations, can be attributed to such "doubtful" information. As Table 1 shows, for these stations, even the average annual values exceed 1, i.e. evaporation from the pool is greater than from GGI-3000. The main causes of this phenomenon may be climatic changes, factors of relative location of these devices on the ground and features of their installation in the soil, measurement errors, as well as equipment malfunction.

According to formula (9), the transition coefficient is the product of instrumental coefficient r with values less than 1 according to V. I. Kuznetsov [8, 9], and coefficient K_t, which depends on the monthly average temperature difference between the water surface in the evaporator ($t_{0.3}$) and the pool (t_{20}). According to observations, the temperature in the pool is higher than in the evaporator due to the lower impact of the thermal regime of the surrounding soil. Therefore, coefficient K_t is more than 1. V. I. Kuznetsov found [9] that the relationship between monthly average temperature of water in the pool and the evaporator is linear and it is expressed by the equation:

$$t_{20} = \gamma t_{0.3} + \lambda . \qquad (15)$$

For continental evaporation plants, λ is equal to one, γ varying within 0.94–1. The values of this characteristic are mapped.

Using the method of V. I. Kuznetsov, the authors of the paper constructed the dependence of t_{20} on $t_{0.3}$ for the Nizhnedevitskaya station for the period of 1998–2012. The dependence parameters (15) happened to have values λ = 1.1 and γ = 1.01, i.e. beyond the values indicated in [9]. Based on the data on α and K_t obtained by the authors of the paper and using formula (9), instrumental coefficients of evaporator r were calculated. For the most part they exceeded 1. The latter also differs from the results of [9]. When analyzing the instrumental

component, meteorological information about wind speed, steam pressure and temperature at the location of the evaporator and the pool was used. The coefficients obtained were always less than 1. It is possible that the specifics of the relative location of the pool and the evaporator may change the air steam in such a way that the instrumental coefficient will exceed 1. Too many joint evaporation measurements lead to similar results. Otherwise, such results are measurement errors or methodological errors in observations.

At present, it can only be stated that methodological foundations for transition from evaporation from an evaporator to a pool, developed more than 50 years ago, require adjustments taking into account climatic changes. At the same time, evaluation of reliability of experimental information needs a thorough revision of the results of observations for the same period. It is advisable to conduct additional, more detailed studies of this aspect of the problem of transition from evaporation from GGI-3000 to a pool of 20 m^2 and further to larger reservoirs. So far, observations from the GGI-3000 evaporator remain almost the only source of information about the actual evaporation from reservoirs.

Having considered complex aspects of transferring data from evaporators to small reservoirs, the analogue of which is a 20 m^2 pool, the authors came

Table 2. Long-term average values of evaporation ($E_{0.3av}$) and (GGI-3000), transition coefficient (α_{av}) and squared coefficient of correlation between them for annual values

Station	Month								
	May			June			July		
	$E_{0.3av}$	α_{av}	R^2	$E_{0.3av}$	α_{av}	R^2	$E_{0.3av}$	α_{av}	R^2
Tsimlyansk	135	0.81	0.6	175	0.88	0.6	207	0.8	0.66
Yershov	147	0.8	0.2	191	0.79	0.2	208	0.8	0.44
Tcherdyn	96	0.84	0.2	107	0.85	0.2	105	0.9	0.4
Valdai	73	0.97	0.2	88	1	0.1	90	1	0.17
Rybinsk	98	0.94	0	122	0.97	0	108	1	0
Nizhnedevitsk	95	0.99	0.14	113	1.01	0.14	116	1.05	0.53
Vyazovye	106	0.97	0.35	117	1	0.39	117	1.03	0.31
Salekhard	–	–	–	83	1.15	0.31	93	1.4	0.42
Tsimlyansk	192	0.9	0.62	125	0.91	0.57	62	1	0.44
Yershov	182	0.8	0.44	122	0.83	0.42	60	0.88	0.17
Tcherdyn	78	1	0.35	39	0.94	0.02	25	1.03	0.27
Valdai	77	0.9	0.14	44	0.9	0.16	–	–	–
Rybinsk	108	1	0.08	69	1.06	0.13	39	1.1	0
Nizhnedevitsk	106	1.06	0.48	71	1.05	0.38	37	1.05	0.23
Vyazovye	102	1.01	0.23	65	1	0.24	37	1.03	0.3
Salekhard	56	1.06	0.35	27	1.09	0.54	–	–	–

to the conclusion that it is reasonable to use the approach of P. P. Kuzmin [7] and his formula (11). First, as mentioned above, it has a linear dependence of transition coefficients on evaporation, which makes it possible to use it for any long-term time intervals. Secondly, in a way, this formula tracks the effect of climatic changes in evaporation on coefficient α. According to it, with a decrease in evaporation, an increase in transition coefficients is observed, and vice versa. However, this formula obtained before 1979 was based on observations of those years, so it needs to be verified taking into account subsequent information. In the course of the study, the authors calculated long-term monthly average values of evaporation and transition coefficients for the entire observation period for eight stations. The total observation periods are given in Table 1. Table 2 shows long-term monthly average values of evaporation (GGI-3000), the transition coefficient and the correlation coefficient between them.

As follows from Table 2. for most stations the degree of relations between these characteristics is quite low. Based on the calculation results according to the method of P. P. Kuzmin a similar relationship was constructed (11), its coefficients differ from those obtained in [7]. Moreover, the correlation coefficient of the new relationship (R = 0.62) is lower than that of (11) (R = 0.79). However, if we exclude the data from the Nizhnedevitskaya, Rybinsk and Vyazovye stations from the analysis, the parameters of the new relationship will be almost the same as those in P. P. Kuzmin's formula, i.e. the information obtained at these stations does not fit into the previously developed schemes of V. I. Kuznetsov and P. P. Kuzmin. Apparently, these schemes need to be adjusted.

In our work, we relied on the information about seasonal evaporation values. Therefore, a correlation was constructed between the seasonal evaporation values from the pool (E^s_{20}) and from GGI-3000 ($E^s_{0.3}$) for all years of observations at eight stations (Fig. 6). This dependence is well described by the equation:

$$E^s_{20} = E^s_{0,3}(1.15 - 0.0004E^s_{0.3}). \quad (16)$$

The correlation coefficient of this relationship is 0.9, i.e. it is quite high. the standard calculation error being also high (13 per cent). When calculating with P. P. Kuzmin's formula (15), the error is two times less. However, it is based on the data obtained only before 1972, and, as mentioned above, only two observation points are located on the territory of Russia.

The part of formula (16) in brackets shows how to calculate seasonal evaporation values α^s. It has the same form as (11), but with different coefficients:

$$\alpha^s = 1.15 - 0.0004E^s_{0.3}. \quad (17)$$

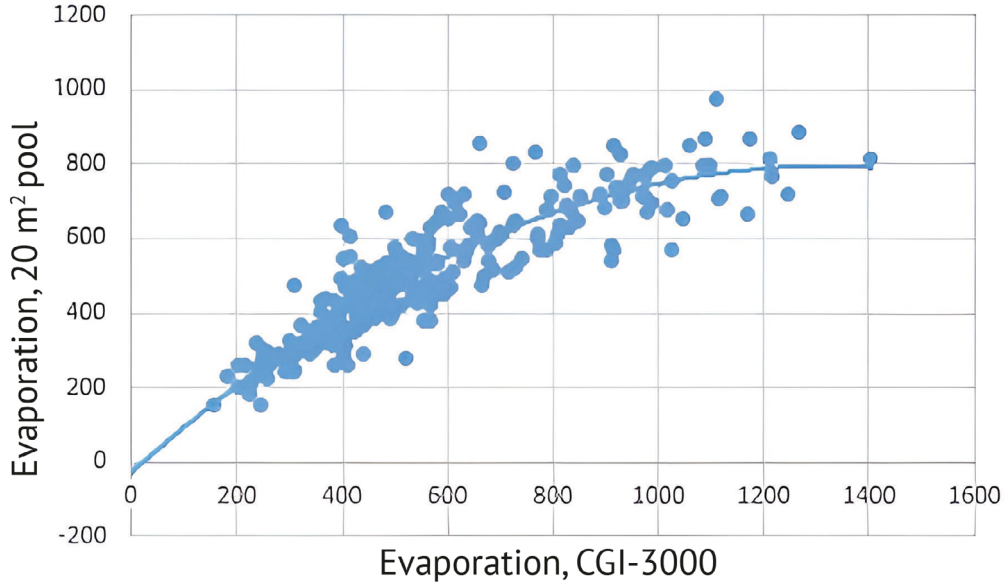


Fig. 6. Dependence between seasonal values of evaporation from the pool and from GGI -3000

This is due to the fact that in order to calculate transition coefficients according to formula (11), information on long-term monthly averages is needed, and according to formula (17), – on seasonal values.

Using V. S. Golubev's formula (13), there were also calculated seasonal values of evaporation from the pool for all years of observations at all stations [22]. The correlation coefficient with the observed data was 0.88, i.e. slightly lower than according to formula (16). The standard calculation error is 17 per cent, which is higher than in calculations according to (16), V. S. Golubev's formula is inferior in accuracy to the equation obtained by the authors. Average values of seasonal transition coefficients for the eight above-mentioned observation points were also compared, the transition coefficient for V. S. Golubev's method being calculated by dividing the evaporation from the pool obtained by formula (13) by the amount of evaporation from GGI-3000. Table 3 shows the results of comparing seasonal average values of transition coefficients obtained on the basis of the observation results using the method of V. S. Golubev and formula (17). In the vast majority of cases, calculation results according to formula (17) were closer to the experimental data.

The correlation coefficient between the measured and calculated data for the authors' formula is 0.85, for V. S. Golubev's equation – 0.7. This can be explained by the fact that formula (13) was constructed more than 40 years ago and it does not take into account new observational data. However, it is quite difficult to modernize it. In [13], where it is given, here is no information about observation points and data series on the basis of which the formula was derived.

Table 3. Long-term average values of coefficients of transition α from evaporation gauged at GGI-3000 to evaporation from a 20 m² pool and standard errors of their definition δ obtained according V. S. Golubev's calculation method [13] and according formula (17)

Observation point	Observation data	Calculation on V. S. Golubev's method		According to formula (17)	
	α	α	δ per cent	α	δ per cent
Tsimlynsk	0.82	0.77	15	0.81	13
Yersov	0.79	0.75	12	0.79	10
Tcherdyn	0.96	1.15	21	0.99	15
Valdai	0.94	1.09	19	1.00	10
Rybinsk	0.99	0.93	9	0.95	7
Nizhnedevitsk	0.99	0.96	15	0.95	15
Vyazovye	1.02	0.95	19	0.95	19
Salekhard	1.03	1.40	34	1.05	15
Average	**0.94**	**1**	**18**	**0.94**	**13**

Nothing is said about the method of obtaining it, therefore, it is recommended to use formula (17) in calculations.

Average values of transition coefficients for all test stations, which are global for the area under study, coincide for the observation data and calculations according to formula (17) and are equal to 0.94. Due to proximity of the global coefficients to 1, one can conclude that in modern conditions, the average value of evaporation from small reservoirs in the area under study is close to that measured with GGI-3000 evaporators.

We can compare the data from our reanalysis (Fig. 2, Fig. 4) with the mapping results provided in Guidelines for calculating evaporation from the surface of water bodies[1]. Comparative analysis shows that long-term average evaporation for the period of 2000–2020 is about the same or slightly lower than in the 1960s. This circumstance is explained by the fact that in the 1970s and the 1980s, a rather noticeable drop in evaporation from the water surface was recorded in European Russia. [6, 14, 16, 17]. In the 1990s, the decline in evaporation mostly stopped, its growth recorded at some evaporation sites. However, despite the increase in evaporation in recent decades. the average evaporation rate for the period of 2000–2020 did not reach the values used to draw a map in the late 1960s.

CONCLUSION

As part of the work done, to expand databases and spatial generalizations about evaporation from the water surface, there was implemented reanalysis on GGI-Gidrofizika, a physically based mathematical model, for the first time.

Based on the data about daily average values of air temperature, wind speed, water vapor pressure, lower and total cloudiness on the spatial grid at the sites of 105 meteorological stations in European Russia, long-term average values of evaporation from the water surface for the period of 2000–2020 were calculated. The model was previously calibrated based on observations of evaporation from the water surface at 35 sites and corresponding maps were built for this area of Russia.

The results of spatial modeling have been generalized. A number of new patterns connecting long-term average evaporation from the water surface with long-term average values of air temperature and wind speed for the period of 2000–2020 have been obtained. Correlation coefficients of particular relations are 0.99, the standard calculation error being 7 per cent. The formula obtained by the authors for calculating evaporation from air temperature data was used in the reanalysis of evaporation values on the 0.5 degree latitude × 0.5 degree longitude regular spatial grid.

When reanalyzed on the regular grid, the average amount of evaporation from water surface for the period of 2000–2020 in the area under study was 524 mm per year. according to the calculation data at the nodes of location of weather stations – 514 mm per year, and the average measured evaporation at 35 observation points used in the calibration of the mathematical model – 544 mm per year.

The mathematical model of evaporation from the water surface was calibrated based on observation data from the GGI-3000 evaporator. The study shows for the first time that coefficients of transition of the observation results obtained with the evaporation method to evaporation from small and medium-sized reservoirs are subject to climatic changes that have occurred over the past decades. At the same time, an increase in evaporation leads to a decrease in transition coefficients, and vice versa. For the first time, the basic calculation formulas for determining transition coefficients that were obtained more than 50 years ago and are still in use have been adjusted. Statistical analysis of the observational data showed that for the area under study the average value of the transition coefficient from evaporation measured with GGI-3000 evaporators to evaporation from a 20 m^2 pool is 0.94.

The results of long-term average evaporation values for the period of 2000–2020 obtained during the study are compared with the mapping data presented in the Guidelines for calculating evaporation from the surface of reservoirs for the 1960s. Comparisons have shown that evaporation rates in the 2000s often do not exceed those observed in the 1960s. This is explained by the fact that in European Russia in the period of 1970–1980 there was a significant decrease in evaporation compared to the 1960s, and its subsequent increase in the 2000s could not compensate for this decrease on average.

CONFLICT OF INTERESTS
The authors declare no relevant conflict of interests.

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