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Modeling the Genetic Components of River Runoff for the Mozhaisk Reservoir Watershed

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Abstract—The physically-based ECOMAG model of river runoff formation has been adapted to simulate the processes in the Mozhaisk Reservoir watershed. The main goal of the study was to correctly simulate the genetic components of the runoff considering the hydrochemical methods of identifying the water masses in calibrating the model parameters. To break down the runoff hydrograph by genetic components, a technique was applied, based on the chemical–statistical analysis of the composition of the water mass mixture. The many years' runoff hydrographs from 3 gauging stations and hydrochemical data from which the genetic components of the river runoff have been determined were used to calibrate model parameters. A satisfactory agreement has been obtained between the runoff hydrographs from gauge stations and the hydrographs simulated by the model and obtained by analyzing hydrochemical data of the genetic components of the river water. The regularities of the annual distribution of the genetic runoff components have been analyzed and the genetic types of waters prevailing in different phases of water regime have been demonstrated. The proposed method of determining model parameters by hydrometric and hydrogeochemical data allows simulation of the behavior of the water sources and description of the spatial-temporal genetic structure of the river runoff.

Keywords: simulation, river runoff formation, hydrograph, hydrogeochemical data, genetic components

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INTRODUCTION

Spatially distributed physically-based models of river runoff formation are being applied in the solution of a wide range of applied and scientific hydrological and hydrochemical problems. Physically-based mathematical models contain a large number of physically well-interpreted parameters, depending on the landscape, the types of soils, vegetation, and land use. The initial values of the parameters are adjusted in the process of calibration, so that the modeling results could reproduce the observation results as close as possible (for example, river runoff hydrographs). Unfortunately, physically-based models, just as the models of other types, are also vulnerable to the known disadvantage of calibration, the problem of equifinality, which consists in proximity of the simulation results to different values of the sets of model parameters [2, 3].

Equifinality to a large extent is caused by the shortage of data needed for calibration, related to certain processes of the hydrological cycle. Some of the parameters in the submodels of the subsurface and groundwater flow are difficult to estimate under natural conditions and are usually calibrated based on runoff observation data. The runoff at the outlet point of the catchment, reflecting the integral response of the complex system of the river watershed to external impacts, is related to all the particular processes taking place in the catchment and hence, to the set of model parameters. Purely mathematically, it is possible to select a large number of the sets of calibration parameters, reproducing the hydrograph at the watershed outlet with approximately equal accuracy. In other words, in attempting to find parameters based on a limited set of observation data, there may be several solutions of inverse modeling when the trial and error method is used [12].

Equifinality is one of the main disadvantages of parameter calibration of spatially distributed hydrological models. Imagine two different sets of parameters, providing approximately equal accuracy of runoff modeling. In fact, these are models of two different river watersheds with close integral response to external impacts. Given different sets of parameters, the hydrograph at the outlet of the catchment may be formed by different combinations of the simulated genetic components of the river runoff: for example, in one case, the subsurface runoff may prevail in the total hydrograph, while in another set of data, the same hydrograph may be formed by a combination of the surface and groundwater components. The behavior of the simulated genetic components of the river runoff will be totally different in these two cases, while the integral response of the catchment is approximately the same. Although modeling of the integrated response of the catchment is important for many hydrological problems (the hydrograph at the outlet of the catchment), in hydrochemical studies of river water quality formation, correct modeling of the genetic components of the river runoff plays the major role [20].

In hydrology, different methods of graphic division of runoff hydrographs into genetic components are known (the method of B.I. Kudelin, B.V. Polyakov, M.I. Lvovich, O.V. Popov et al.). Most of these methods consist in the qualitative division of water. A more objective representation of identifying the genetic components of the river runoff is achieved by applying the hydrochemical methods of identifying water masses. The goal of this study was to develop and adjust the physically-based ECOMAG model of river runoff formation for the watershed of the Mozhaisk Reservoir and to simulate the genetic components of the runoff using the hydrochemical methods of identifying water masses in calibrating the model parameters.

DETERMINING THE GENETIC STRUCTURE OF THE RIVER RUNOFF BASED ON HYDROCHEMICAL METHODS

There are two main approaches to division of a river runoff hydrograph into genetic types of waters on the basis of hydrochemical studies. One of them is based on the application of natural chemical tracers to identify water masses of different origin, while the other method is based on the use of chemical-statistical analysis of the composition of a mixture of water masses by chemical elements. Both methods use the analysis of equations of the balance of water and chemical elements (tracers) based on a formula of mixing water masses.

In the first method, natural chemical tracers are used according to the EMMA (End-Member Mixing Analysis) model. The main condition in choosing the tracers for the model is their being conservative, i.e., each tracer element should not interact with other elements. In addition, tracer concentrations in the origin and in the river water should be well distinguishable. The potential tracers are diverse and depend much on the specific conditions of the catchment. They may include macro-components (HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, etc.), microelements (Sr, Rb), and stable radio-isotopes of oxygen and other elements. The model core is the statistical method of the principal components, which, when a large amount of various data is analyzed, essentially reduces the dimensionality of the system under study, allows identification of the latent structure of data and separates the essential part of data from noise [4, 10].

Studies based on the EMMA-model are well-known in the hydrological community. For example, in [13, 23], this method was used for small alpine catchments to study the genetic categories of the sources of river waters, as well as for forecasting and regulating water supply. Three sources were investigated and evaluated: snow, rainfall, and groundwater supply. The model with four tracers has shown that the snowmelt water type constitutes approximately half of the entire river runoff and is the dominant source of the water. In Russia, such methodology has been applied in experimental studies conducted in small watersheds. In [11], using the tracer mixing model, the annual regime of three sources of the Laninsky creek (the watershed of Lake Baikal), were obtained, with rainfall waters, the share of which was insignificant, waters of the underground soil horizon, tending to prevail in the low-water period, and the so-called aufeis waters, playing an essential role in forming spring floods. In [8, 9], the shares of three sources of the river runoff in small alpine catchments of Central Sikhote-Alin' were determined. The authors came to a conclusion that the number of stable genetic components could vary from year to year depending on the water content of a catchment.

Another approach to determining the genetic components of the river runoff with a hydrochemical method is the method proposed by P.P. Voronkov [24], developing a graphic method of division of a river hydrograph based on the observation data over intra-annual changes of different chemical parameters. According to this method waters are classified by genetic categories, each of which is determined by the chemical composition and the properties of soils, through which water flows in the river channel network. In particular, the following categories are identified:

(1) Slope-surface waters, formed on catchment slope surfaces, given a complete water saturation of the surface layer of soil;

(2) Surface soil waters, formed in the surface layer of the soil cover and serving as sources of a micro-stream network;

(3) Ground soil waters, formed in waterlogged soil layers simultaneously with surface soil waters and forming temporary aquifers. Reaching these layers, water changes the direction of its flow in accordance with the hydraulic slope and, in case of drainage of the layer by the erosion gully, comes into the river;

(4) Groundwaters, coming from the existing aquifers, lying on the first from the Earth's surface solid aquiclude.

In accordance with this classification, sometimes slope waters are also distinguished, formed by mixing of slope-surface waters and surface soil types of waters and found in small rivers.

The main hypothesis of P.P. Voronkov consists in the possibility of developing quantitative methods of investigating the genetic structure of the local runoff on the basis of the hydrochemical difference between waters of the above categories. The differences are caused by the variety of the processes affecting the chemical composition of the waters as they flow towards a river. The surface horizons become enriched with mineral and organic components formed in the soil as a result of the vital activity of plants and animals. Waters contained in the soil horizon differ by their large concentrations due to the influence of the vital activity of the soil microflora. Groundwaters are characterized by increased salt content and electric conductivity due to the long-term contact with carbonates and other well-known soluble minerals. Thus, at any time moment, river water consists of a mixture of waters of different genetic origin with characteristic chemical compositions: the slope type of the surface water *(SfW)*, the soil water (*SW*) type, and the groundwater (*GW*) type. Quantitative estimation of each genetic component depends on the chemical parameters in different regions; the climatic, landscape, and morphological conditions of a territory; as well as on the specific features of the hydrological, hydrochemical, and hydrobiological regimes of water pools and watercourses.

The proportions for each genetic type of waters may be calculated by the mixing formulas of three water masses:

$$\begin{cases} Q_1 + Q_2 + Q_3 = Q_t \\ C_1^1 Q_1 + C_2^1 Q_2 + C_3^1 Q_3 = C_t^1 Q_t \\ C_1^2 Q_1 + C_2^2 Q_2 + C_3^2 Q_3 = C_t^2 Q_t \end{cases}, \quad (1)$$

where Q is the discharge of water (Q_t is the discharge in a river), C is concentration of tracers, the superscript is the tracer number, the subscript is the number of the source. To solve the system of equations, it is necessary to know the concentrations in a water sample containing independent chemical elements, as well as water mass indices, i.e., pairs of the values of these characteristics in each original mass of water (source) of a particular genetic type of water, not mixed with the other two types. To obtain indices of a homogeneous water mass, it is necessary to carry out detailed hydrochemical surveys at a catchment, taking samples of surface and soil water and groundwater, which is a cumbersome task. Therefore, in [5] an approach to dividing a hydrograph into genetic components was proposed by using the chemical-statistical method for calculating the genetic composition of a mixture of water masses. The uncertainty in choosing the indices of the types of waters is reduced by plotting a pair of mixing triangles by hydrochemical characteristics, similarly to the thermohaline analysis method, widely applied to analysis of seawater [15] in ocean studies. Should a pair of hydrochemical characteristics be correctly determined in a water sample, the points in both diagrams reflecting it will be in identical positions. Variances in the positions of these points are caused by an error in calculating the genetic composition of river water. Indices of the types of water taken for calculating the genetic composition of river water with minimal variances may be considered statistically significant values of the respective characteristics of the water composition of these types in their ‘pure’ form for the river catchment under study [5]. This hydrochemical method of dividing by the types of river water was used in this work to calibrate the parameters of the physically-based mathematical ECOMAG model and to simulate the genetic components of the river runoff.

STUDY OBJECT

The object of the study was the watershed of the Mozhaisk Reservoir, situated in the western Moscow region. The area of the watershed at the gauging station of the Mozhaisk Hydropower Plant is 1360 km^2, the main tributaries are the Moskva, Lusyanka, and Koloch Rivers (Fig. 1). The watershed is situated in the central part of the Great Russian Plain within the Smolensk–Moscow Elevation, with the absolute heights varying in the range of 153–312 m, flat landscape with alternating low plains and elevations, well-defined river valleys, flat-bottom valleys and ravines, and mostly boggy depressions. In the entire territory, sod-podzol soils prevail, having different mechanical compositions: heavy loams, medium loams, light loams, and sandy loams. The climate is temperate continental with clearly definite seasons: moderately hot and moist summers and moderately cold winters with stable snow cover. The mean annual air temperature is 5.0°C. The mean annual precipitation is 650–750 mm.

ECOMAG MODEL

The physically-based mathematical ECOMAG model (ECOlogical Model for Applied Geophysics) of river runoff formation describes the main processes of the land hydrological cycles in river watersheds with mixed rainfall and snow origin of water: the formation of snow cover and snow melting, infiltration of water into soil and its evaporation, thermal and moisture soil regime with the processes of soil freezing and thawing, the formation of the surface, subsurface, groundwater and river runoffs [17, 21]. In the model representation of a river watershed, its surface is divided by an irregular grid into separate calculation elements (elementary catchments) considering the details of the landscape and the structure of the river network. The hydrological processes in each elementary catchment are simulated at four levels: the surface layer of soil (horizon A), the deeper layer underlying it (horizon B), the storage of groundwater, and the storage in the zone of surface runoff formation. In the cold season, the storage of snow cover is added.

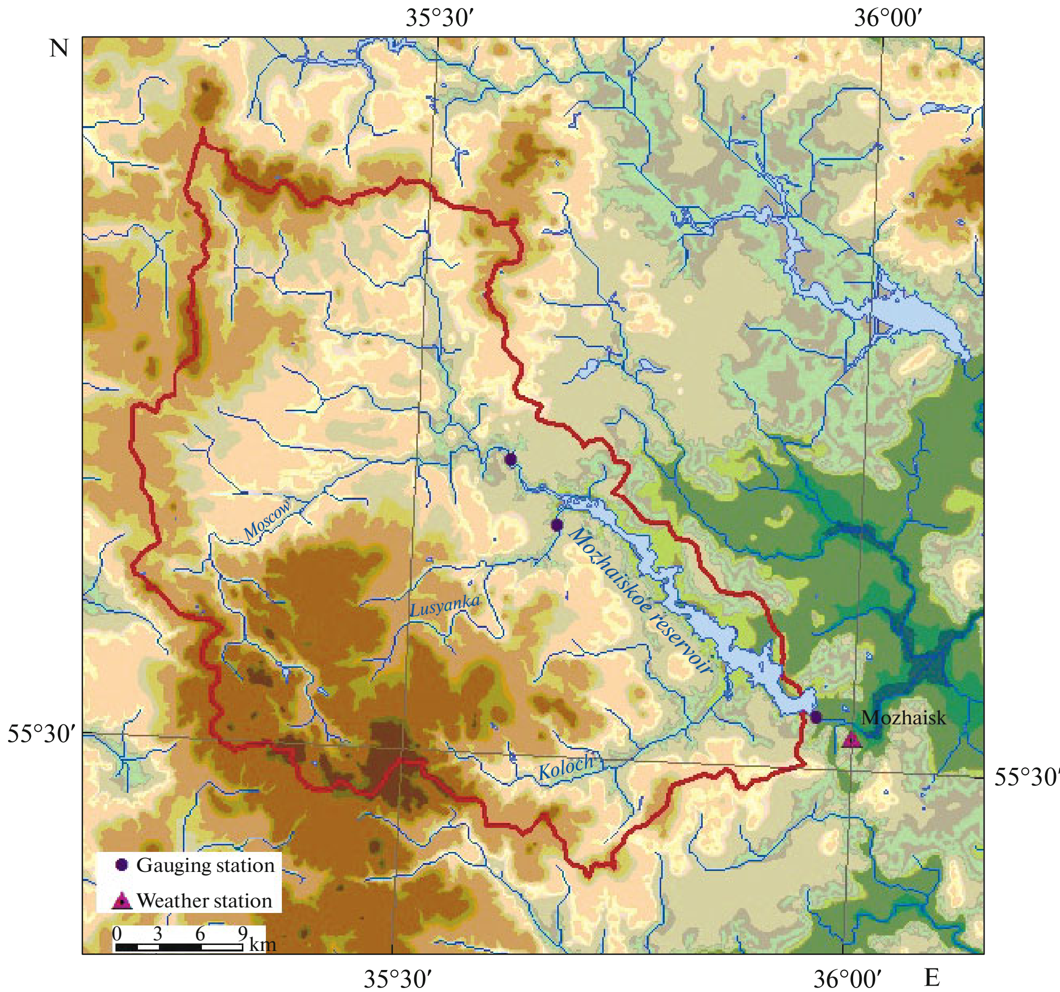

Fig. 1. The watershed of the Mozhaisk Reservoir.

The model has been tested on many river watersheds, in different geographical zones, and at different spatial scales and has proven to be effective both for calculating river runoff hydrographs with daily resolution and in modeling the behavior of hydrological fields (moisture content of soil, snow water equivalent, and runoff) in large river watersheds [18, 19]. The model has been widely used to solve applied problems and, in research, to assess the impact of anthropogenic activity and climate change on water resources [6, 7].

SOURCE DATA

Mapping Information

For the model schematization of the watershed area and the river network in the watershed of the Mozhaisk Reservoir, a digital elevation model was used, with the resolution of 100 × 100 m, obtained on the basis of topographic maps, the scale 1 : 50000 [1]. Using the Ecomag Extension module, 95 model elementary catchments were identified, their mean area being about 14.3 km^2; the simulated river network includes, in addition to the main river, 19 first-order tributaries, 23 second-order tributaries, and 5 third-order tributaries.

The model parameters were set considering the soil and landscape maps at the scales of 1 : 500000 and 1 : 200000, respectively [1]. In the watershed of the Mozhaisk Reservoir, three types of soils were identified (podzol, sod–middle podzolic, and sod–highly podzolic) and three types of landscapes (arable land, broad-leaved forest, and dark coniferous forest). In the territory under study, sod–middle podzolic soil and broad-leaved forests prevail.

Hydrometeorological Information

To set the boundary conditions of the model, long-term series of daily precipitations, mean daily air temperatures and air humidity values were used, specified according to the observation data from 10 meteorological stations located in the immediate proximity from the object under study. Interpolation of the meteorological characteristics for each elementary catchment was performed in the model based on the data from 5 nearest meteorological stations using weight coefficients.

To calibrate the parameters and to validate the model, observation data were used relating to daily discharges at the gauging stations of Barsuki (Moskva River) and Cherniki (Lusyanka River) and the inflow of water to the Mozhaisk Reservoir (Gidrouzel settlement). As the Koloch River is regulated, the data from the Koloch gauging station were not used in the calculations. The observation period at the gauging stations and at the Mozhaisk Reservoir was 28 years, lasting from 1982 to 2009.

Hydrochemical Information

Hydrochemical data obtained from the water the Barsuki water gauging station (the Moskva River) were used in the calculations. Six independent parameters were chosen for the analysis of the water chemistry: specific electric conductivity (μS/cm), characterizing the water mineralization; the concentrations of Na^+ and K^+ ions (mg/L) and total phosphorus (mg/L); the values of permanganate chemical oxygen demand (PCOD) and dichromate chemical oxygen demand (DCOD) of water (mg O/L) [5]. Increased values of the first two characteristics suggest the prevalence of the ground types of waters in the river water, while increased values of the remaining four characteristics indicate the prevalence of the soil and slope types of waters. The data relating to the chemical characteristics in question were collected in the period from July 1983 to March 2007. Of special interest is the detailed survey carried out according to the so-called ‘balance program’ at the testing site of the Moscow State University Krasnovidovo, during which, in the period from November 15, 1983 to December 12, 1984, 109 samples of water were taken from the Barsuki water gauging station (the Moskva River), with daily periodicity in the spring flood period and 1–2 times a week in other seasons.

After the analysis and schematization of all the obtained data, 12 possible combinations of pairs of mixing diagrams were developed (ϰ, DCOD and Na, PCOD; ϰ, DCOD and Na, K; ϰ, DCOD and Na, P; ϰ, PCOD and Na, DCOD; ϰ, PCOD and Na, K; ϰ, PCOD and Na, P; ϰ, K and Na, DCOD; ϰ, K and Na, PCOD; ϰ, K and Na, P; ϰ, P and Na, DCOD; ϰ, P and Na, PCOD; ϰ, P and Na, K). Both characteristics of groundwaters are used in all combinations, and four parameters of the surface soil runoff are used in six combinations. An example of mixing diagrams (triangles) for a combination of electric conductivity series and DCOD, Na and PCOD is shown in Fig. 2. Based on the diagrams and using the formulas of mixing three water masses, comparative analysis of obtained percentage proportions was made for each genetic type of waters.

THE METHODOLOGY OF PARAMETER CALIBRATION

The parameters of the ECOMAG model were calibrated against the daily hydrographs of the river runoff at three water gauging stations for the period of 1982–1992 and validated against data of 1993–2009. In addition, data were used in calibration relating to the proportions of the genetic types of waters derived from the analysis of hydrochemical observations at the gauging station Moskva-River–Barsuki [5].

To reduce the errors resulting from modeling varying data, it is recommended to carry out multi-purpose calibration of parameters (see, for example, [14]). The strategy consists in using the mean performance criterion by combining several criteria into one, for example, calibrating parameters by river runoff hydrographs at several gauging stations simultaneously. Or, in other variants, when absolutely different data are used (for example, hydrometrical and hydrochemical data), calibration is done by searching for a compromise solution providing maximum efficiency of calculations for each performance criterion.

As a target function in calibrating runoff parameters, the Nash–Sutcliffe model efficiency coefficient (NS), widespread in hydrological calculations (NS), is used [22]:

$$\mathrm{NS} = \frac{F_0^2 - F^2}{F_0^2}, \tag{2}$$

where $F_0^2 = \sum_i (Q_i - Q_{\mathrm{av}})^2$, $F^2 = \sum_i (Q_{i,p} - Q_i)^2$, $Q_{i,p}$ is the discharge in the ith day calculated by the model, Q_i is the actual discharge, Q_{av} is the average actual discharge for the period of calculation. The closer NS to the unity, the higher the accuracy of modeling, i.e., the less are the mean and mean-square errors of calculating the runoff hydrograph. The values NS < 0.35 indicate that the model is ineffective, while at NS > 0.75 the agreement of hydrographs may be considered good [16]. Criterion (2) indicates the agreement between calculated and measured hydrographs for one point of river network monitoring, for example, at the outlet station of a watershed. To ensure simultaneous assessment of the model efficiency in several monitoring points, an average criterion is used as (2), in which $F_0^2 = \sum_k \sum_i (Q_{i,k} - Q_{\mathrm{av}})^2$, $F^2 = \sum_k \sum_i (Q_{i,k,p} - Q_{i,k})^2$, $Q_{i,k,p}$ is the simulated discharge in the ith day at the kth point of comparison, $Q_{i,k}$ is the actual discharge on the ith day in the kth station of comparison, $Q_{\mathrm{av}} = \frac{1}{MN} \sum_k \sum_i Q_{i,k}$ is the aver-

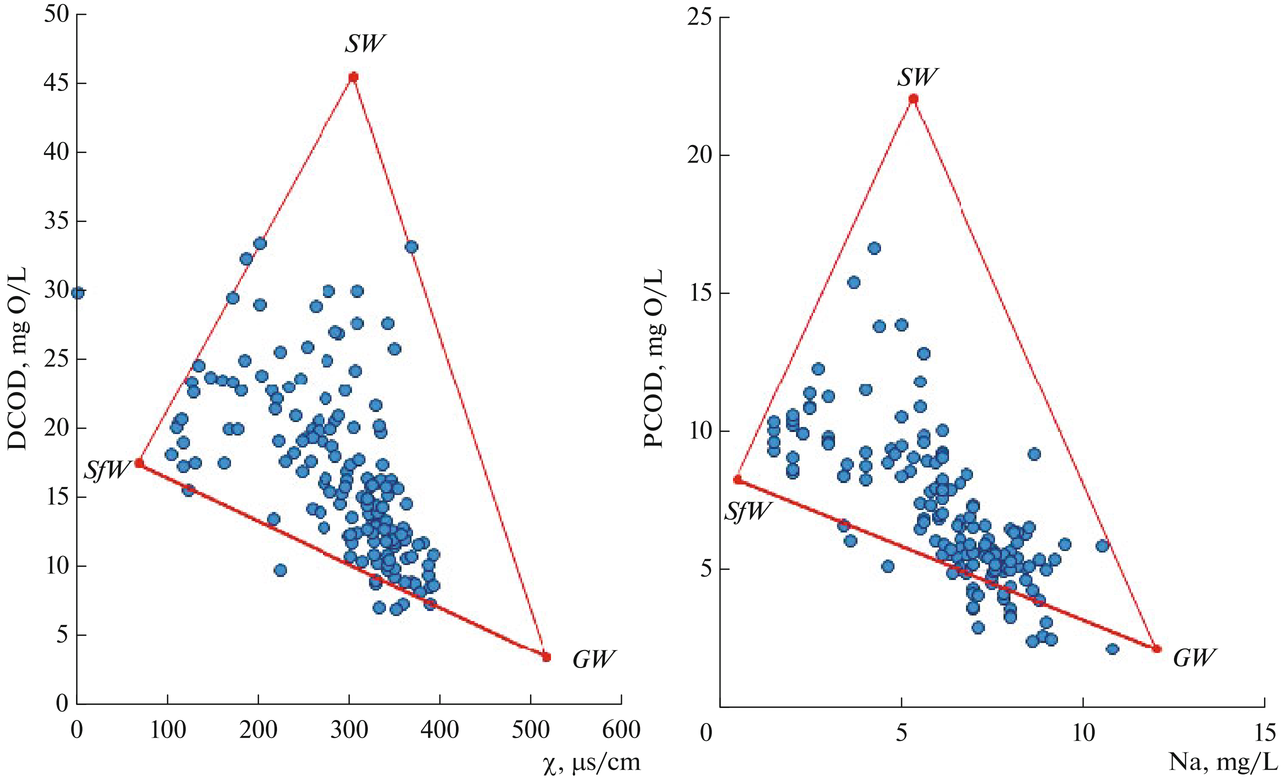

Fig. 2. Diagrams of mixing types of waters at the Barsuki water gauging station (the Moskva River) for the period of 1983–2007.

age over all comparison points M of the value of the actual discharge in the period of calculation for N days. In this case, weighing of the criterion (indicated as NS_{total}) is carried out by assigning greater weights to hydrometric gauge stations with greater discharges.

Before discussing the calibration by hydrochemical data, it is reasonable to dwell upon agreement between the structure of identified genetical runoff components in the ECOMAG model and in the classification proposed by P.P. Voronkov [24]. In the latter case, slope surface and soil surface waters form a slope type of water, as opposed to the model, where waters formed in the zone of slope surface runoff (Horton's overland flow) are considered separately, and soil surface and soil–ground waters, according to P.P. Voronkov, in the model are combined into a soil type of waters. Therefore, calibration of the parameters in the ECOMAG model for genetic types of waters was carried out based on the proportions of the groundwater component in the river waters and on the sum of soil and slope waters. As a target function, the same Nash–Sutcliffe model efficiency coefficient was adopted as (2), where in this case $Q_{i,p}$ is the percentage of the groundwater component in river waters on the ith day calculated by the ECOMAG model, Q_i is the percentage of the groundwater component in river waters on the basis of the analysis of hydrochemical data, Q_{mn} is the average percentage of the groundwater component in river waters based on the analysis of hydrochemical data for the period of calculation.

In addition to the above described methods of assessing the model's performance, the BIAS criterion was used, characterizing the relative error of calculating the mean long-term volumes of runoff (or the mean long-term percentage of the groundwater component in river waters). The relative systematic calculation error (%) is estimated as:

$$\mathrm{BIAS} = \frac{\overline{Q_i} - \overline{Q_s}}{\overline{Q_i}} \times 100\%, \qquad (3)$$

where Q_i and Q_s are the actual and calculated values, respectively; $\overline{Q}$ is the average actual quantity for the period of calculation. Depending on the value of the BIAS criterion, the modeling results in calculating runoff hydrographs may be considered good at |BIAS| < 10%, satisfactory at 10% < |BIAS| < 15% and unsatisfactory at |BIAS| >15% [Moriasi et al., 2015]. For hydrochemical data, the agreement estimations are less stringent.

SIMULATION RESULTS

River Runoff

Table 1 shows estimates of the results of runoff simulation for three gauging stations for the periods of calibration, model validation, and for the entire period of calculation according to the Nash–Sutcliffe model efficiency and BIAS. The values of the criteria for all periods did not differ much, indicating the stability of the model parameters.

The estimates of hydrograph agreement may be considered satisfactory ($0.54 < NS < 0.69$, BIAS < 13.6%), for both the calibration and validation series, as well as for the entire period of calculation. However, if we examine the values of the Nash–Sutcliffe model efficiency criterion for different years, we can see significant variance in values, for example, for the "good" year of 1992, they are in the range from 0.91 to 0.96 for three gauging stations, and for the "bad" year of 1987, the values are low ($0.32 < NS < 0.39$). Such differences in the estimates of hydrograph agreement may be due both to the errors in measuring water discharges and setting meteorological impacts and to the inadequacy of some model modules. The determination coefficient of the relation between the calculated and measured monthly volumes of water inflow to the Mozhaisk Reservoir was 0.85 for the period of calibration and 0.86 for the period of validation. Shown in Fig. 3 are the simulated and measured daily hydrographs of water inflow to the Mozhaisk Reservoir for the entire calculation period.

Genetic Components

The value of the Nash–Sutcliffe model efficiency criterion indicating the ratio between the simulated groundwater component in river waters and the values obtained from the analysis of hydrochemical data at the gauging station Moskva River–Barsuki for the period of calculation is 0.54, indicating a satisfactory accuracy of the modeling results. To determine the degree of data variance with respect to their mean value, a standard deviation of a sample was evaluated. For the proportions of the groundwater component determined by hydrochemical data, the standard deviation for the entire calculation period was 19.3% of the river runoff and 23.3% for the simulated values, suggesting a broad range of data variance. The value of the BIAS criterion for the relative error in the calculation of the mean annual percentage of the groundwater component in the river waters was 14%. The determination coefficient of the relation between the calculated values and those determined by hydrochemical data of the groundwater component was 0.52.

The results of simulating river runoff hydrographs and its genetic components can be analyzed in more detail by the example of the year of 1984, when more frequent hydrochemical observations were made, which can be used to trace down the intra-annual behavior of the groundwater component and the sum of the surface and soil slope types of waters. Figure 4 compares the simulated and measured total inflow of water from the watershed into the Mozhaisk Reservoir and the behavior of the genetic runoff components at the gauging station at the inflow of the Moskva River (Barsuki) in the Mozhaisk Reservoir, calculated by the model and derived from hydrochemical data.

As follows from Fig. 4a, in general, the ECOMAG model of runoff formation adequately describes different phases of the water regime (the winter and summer low-water periods, the spring high-water period, the summer and autumn floods) in the intra-annual course of the total inflow of water to the reservoir ($NS = 0.73$). The only deviation is a slight reduction of the calculated peak of the spring high-water period relative to its measured value.

Now the results of simulating the intra-annual behavior of the genetic runoff components (Fig. 4b) can be analyzed against the hydrographs of the total runoff (Fig. 4a). In the winter low-water season (January–March), the groundwater component of the river water dominates, its share being about 70% of the total runoff. In the spring high-water season (April), the share of the groundwater component decreases nearly to zero and, accordingly, the shares of the soil and surface components of the river runoff increase. In the periods of high-water recession (May) and the short summer low-water season (June), the share of the groundwater component rises again to 80–90%. In the summer–autumn flood season (July–November), the share of the soil water in the river runoff sharply increases. Under intense rainfall, short-term rises of the surface component of the runoff can be seen. By the beginning of the winter low-water season, the share of the groundwater component of the runoff again increases to 70%.

The results of simulating the groundwater component of the river runoff show acceptable agreement with those derived from hydrochemical data in terms of intra-annual behavior of these values. The highest values of the groundwater component are observed in the summer low-water season (July), when they amount to about 40–50%. In the other seasons, the differences are mostly within 10–20%, which, considering the rather low accuracy of determining the types of waters using the chemical–statistical method, may be considered quite an acceptable result.

The analysis of the results of simulating the genetic components of the river runoff for the entire calculation period of 1982–2009 allowed certain regularities to be revealed in the annual breakdown of the genetic structure of the river runoff in the watershed of the Mozhaisk Reservoir.

In the winter low-water season (December–March), stable prevalence of the groundwater type is observed in most years. The highest values of the groundwater component were observed in 1984,

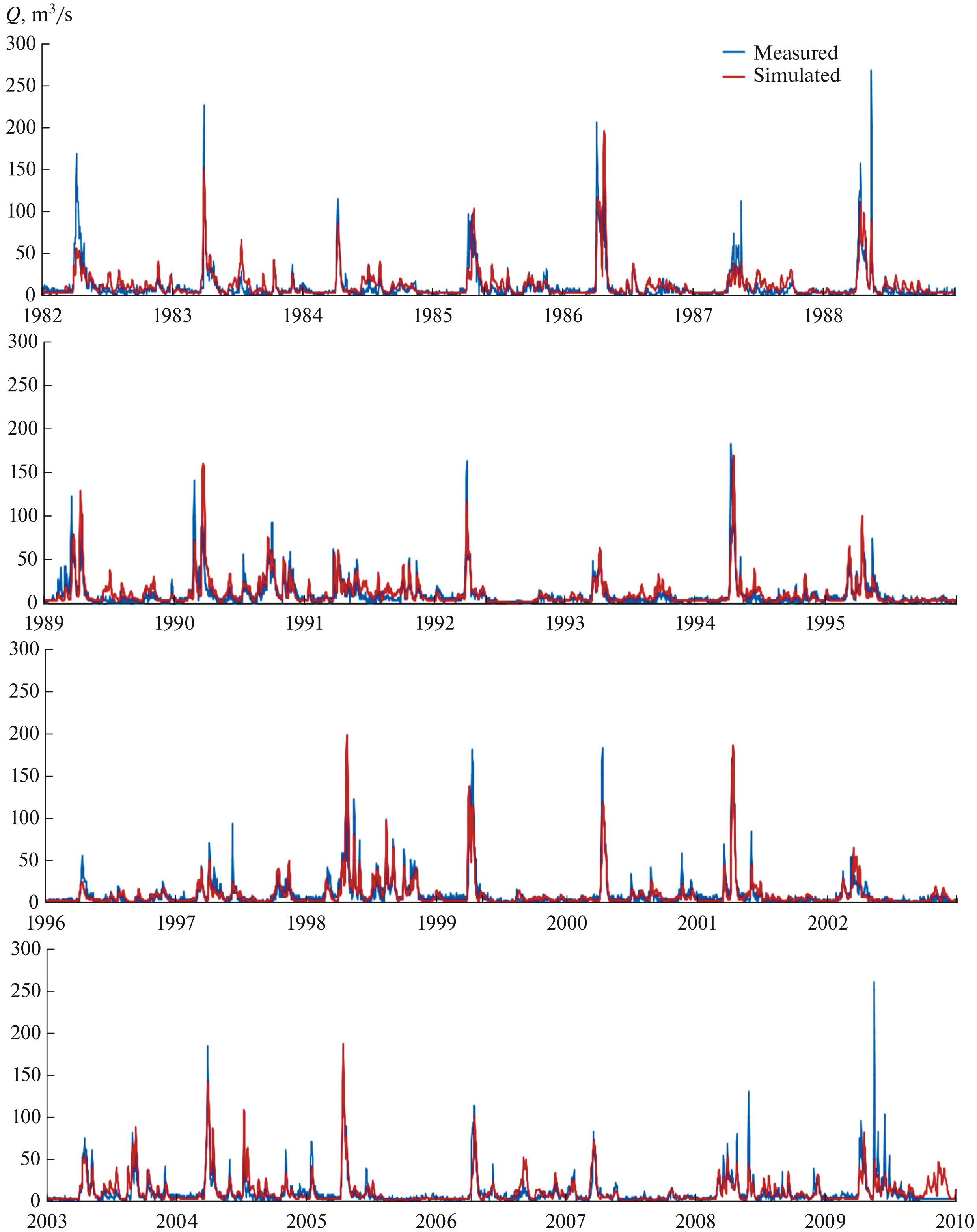

Fig. 3. Measured (blue) and simulated (red) hydrographs of inflow into the Mozhaisk Reservoir.

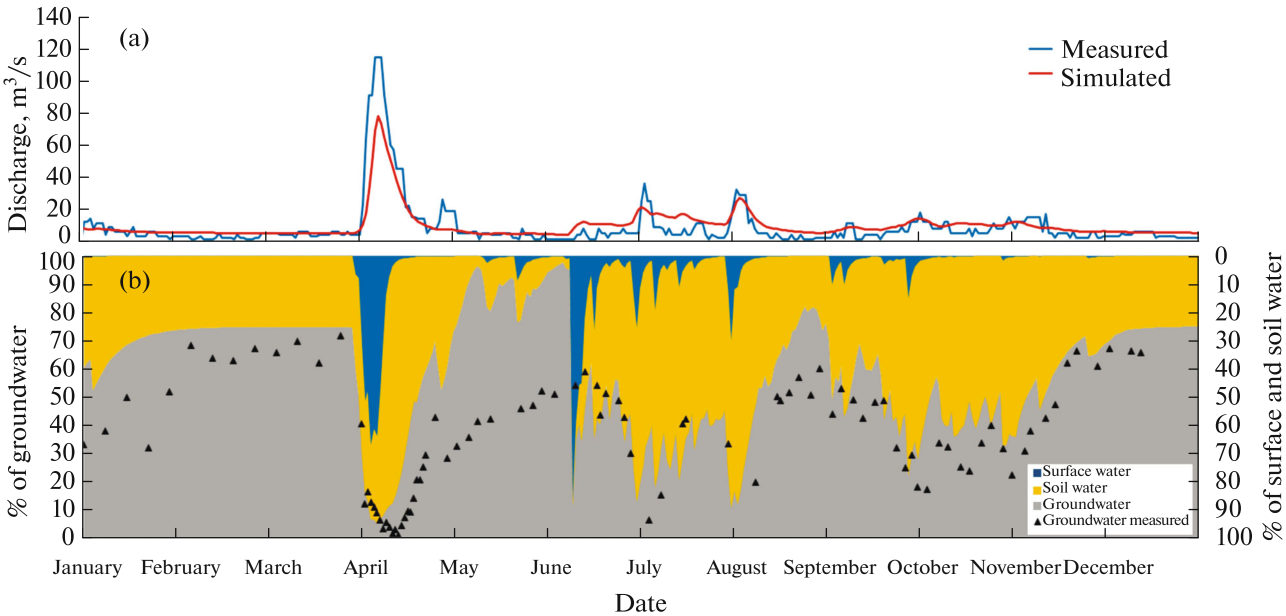

Fig. 4. (a) Hydrographs of the inflow into the Mozhaisk Reservoir and (b) the dynamics of the genetic components of the runoff (color—simulation-based, triangles—based on hydrochemical observations) at the Moskva River—Barsuki gauging station.

1986–1988, 1994, 1996–1998, 2001, 2003, and 2006, when the share of the groundwater type reached 70% and more. In 1989–1993, 1995, 1999–2002, 2004–2005, and 2007, short spans are observed in the winter low-water season (several days) with the soil type of waters prevailing, its proportion generally reaching 50–70% and rising to 90% in some years (1991, 2005, 2007). Such sharp increase in the genetic soil type of waters is related to winter thaws and to floods caused by them. In these periods, short-term peaks of the slope surface component are formed.

In the spring flood season (April–May), the share of the groundwater component of the river runoff decreases and at times achieves 2%, although in the quick freeze periods it may reach 70% (1994). In this phase of the water regime, the dominating type is the soil water, the proportion of which varies in the range from 40 to 90% of the total runoff. In the flood period, a sharp rise (up to 30–70%) of the slope surface component of the river runoff is observed. Mostly, these are short periods up to 10 days long. An exception to this rule was the year of 2007, when the percentage of the slope runoff in the flood period never exceeded 3%.

In the summer low-water season (June–August), the groundwater type is the prevalent genetic type of water, according to the simulation. The duration of the prevalence period (>70%) of the groundwater component in the river runoff may reach 145 days (1992). During summer floods, both the soil type and the surface type begin to prevail. For example, in 1986, a sharp short-term (two days long) increase in the proportion of the slope surface component up to 90% was recorded. In 2004, the soil water type was prevalent, accounting for 70–80% and lasting for 14 days. The differences in the genetic components of the water sources are mostly related to the current hydrometeorological situation and the previously accumulated moisture content in the watershed.

In the autumn season (September–November), it is difficult to identify the prevailing genetic type of the water source, as all the above-mentioned types of water alternate in their prevalence. The groundwater component varies from 10 to 70%, mainly in combination with the soil type of water. During the autumn floods, the soil type of water prevails, reaching 89% of the total river runoff (1990). The increased content of the soil water component may be observed from several days to two or three weeks. The slope surface component of the river runoff may be practically absent. In some years, the proportion of the slope surface component may rise to 18–20% (2001, 2005), rarer, in flood periods, to 70% (1995).

CONCLUSIONS

Based on the ECOMAG model complex, a physically-based model of runoff formation has been developed for the watershed of the Mozhaisk Reservoir. To reduce the degree of uncertainty and equifinality in choosing the model parameters for their calibration, daily river runoff hydrographs were used from three gauging stations along with data relating to genetic components of the river runoff, obtained using a chemical-statistical method for determining the types of river waters on the basis of hydrochemical measure-

Table 1. The values of the Nash–Sutcliffe model efficiency criterion for the periods of calibration, model validation, and for the entire calculation period

Gauging station	Catchment area, km^2	Simulation period								
		1982–1992			1993–2009			1982–2009		
		NS	NS_{total}	BIAS	NS	NS_{total}	BIAS	NS	NS_{total}	BIAS
Moskva River – Barsuki	750	0.60	0.62	–0.7	0.62	0.69	–13.6	0.62	0.67	–8.6
Lusyanka River – Cherniki	170	0.54		4.5	0.61		–7.0	0.58		–2.5
Tributary to Mozhaisk Reservoir	1360	0.60		10.0	0.68		–0.2	0.65		4.0

ments for a long-term period. Satisfactory agreement has been obtained between simulated and measured runoff hydrographs at the gauging stations for the periods of calibration and validation and for the entire 28-year calculation period (1982–2009). The values of statistical criteria of agreement between genetic components of the river runoff simulated and determined by hydrochemical data also indicate satisfactory accuracy of the simulation. The analysis of the results of simulating the behavior of the genetic components against the intra-annual course of runoff for 1984 has been performed, with more frequent hydrochemical observations. Satisfactory agreement has been obtained for the intra-annual behavior of the groundwater component of the river runoff, simulated by the model and determined by hydrochemical measurements. The major differences, reaching 40–50%, were observed in July, in the summer low-water season. In other seasons, the differences were 10–20%. The simulation results for the entire 28-year calculation period were analyzed to determine the intra-annual distribution of genetic components of the river runoff with prevailing genetic types of waters in different phases of the water regime. Thus, the method proposed for determining model parameters by hydrometric and hydrochemical data enables the calculation of river runoff hydrographs at different gauging stations of the river network, the qualitative estimation of the behavior of the river sources, and the description of the spatial–temporal genetic structure of the river runoff.

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