REVIEW

SIMULATION OF THE WATER REGIME OF TWO LARGE EUROPEAN RUSSIA RIVERS UNDER THE CONDITIONS OF MODERN CLIMATE IN THE TERM LAND SURFACE MODEL

Medvedev A.I.[1,2], Stepanenko V.M.[1,2,3,4], Ryazanova A.A.[2,5]
[1]Lomonosov Moscow State University Research Computing Centre (119234, Moscow, GSP-1, Leninskie Gory, 1, p. 4)
[2]Institute of Geography of the Russian Academy of Sciences (119017, Moscow, Staromonetniy lane, 29)
[3]Faculty of Geography, Lomonosov Moscow State University (119234, Moscow, GSP-1, Leninskie Gory, 1, p. 1).
[4]Moscow Centre for Fundamental and Applied Mathematics (119234, Moscow, GSP-1, Leninskie Gory, Leninskie Gory, 1, p. 1).
[5]Institute for Monitoring of Climatic and Ecological Systems SB RAS (634055, Tomsk, 10/3 Akademichesky Ave., Tomsk, Russia)
*Corresponding author: a.medvedev@rcc.msu.ru
Received: September 2nd 2025 / Accepted: February 24th 2026 / Published: June 30th 2026
https://doi.org/10.24057/2071-9388-2026-4234

ABSTRACT. The paper is devoted to the application of the TerM land surface model to reproduce the water regime of typical watersheds of the European part of Russia (Vychegda River, Oka River) under the conditions of modern climate. The work evaluates the quality of the TerM model with respect to the main components of the water regime in regional climatic conditions: long-time runoff mean, mean snow water equivalent at the beginning of melting, volume and dates of spring floods in the studied catchments. The quality of the model is assessed by comparing the results of numerical experiments with observational data. To obtain optimal results, a number of model improvements are proposed, in particular: accounting for artificial irrigation of cultivated plants in the process of transpiration, calibration of the infiltration capacity parameter of watershed soils, roughness Manning coefficient for river bed and coefficient of river network tortuosity. The TerM model with the proposed modifications successfully reproduces main characteristics of the water regime in the studied catchments.

KEYWORDS: land surface models, river water regime under modern climate conditions, model calibration.

CITATION: Medvedev A., Stepanenko V., Ryazanova A. (2026). Simulation of the water regime of two large European Russia rivers under the conditions of modern climate in the TerM land surface model. Geography, Environment, Sustainability. 216-223
https://doi.org/10.24057/2071-9388-2026-4234

ACKNOWLEDGEMENTS: The studies were supported by grant of the Ministry of Science and Higher Education of Russian Federation (agreement № 075-15-2024-554 of 24.04.2024).

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

The TerM land surface model [34] is a numerical process-based model of the dynamics of thermodynamic, hydrological and biogeochemical processes in the active layer of the Earth's land. The model equations describe the dynamics of soil heat content, moisture, water vapour and ice, carbon dioxide and methane, carbon stocks and fluxes. The TerM model originate from the land surface block of the INMCM Earth System Model [38], implemented as an independent software code for simulations with prescribed atmospheric forcing. Within the TerM model, the initial code of the INMCM model was supplemented with a number of modifications, mainly related to the clarification of hydrological and carbon cycle processes, particularly for geographical conditions of Russia. The TerM model is used to develop and test promising physical parameterizations for the INMCM model and has been used for research of current state and anticipated response of ecosystems to future climate change in Russia.

In the original INMCM model, as in Earth System models in general, the hydrological simulations focus on reproducing the long-time runoff mean from the largest river catchments, which is necessary to describe the influence of hydrology on the thermohaline circulation in the ocean. At the same time, detailed representation of the intra-annual distribution of runoff and hydrographs on individual rivers is not usually considered a priority. However, the necessity for detailed reproduction of river runoff in Earth System models is gradually increasing with the increasing complexity of ocean models [15], the sophistication of carbon cycle parameterizations [21, 27], and improvements in atmospheric models to reproduce anomalous synoptic situations [19]. Also, the detailed representation of river runoff in Earth System models would facilitate hydrological predictions under different scenarios of anthropogenic impact or climate change for both well-studied and unexplored catchments, while the performance of statistical hydrological models in the same tasks is prone to overfitting the observational data [4]. At the side of hydrological modelling, a trend in the same direction, expressed in increasing of model robustness due to using of land-surface modelling approaches, can be noted (e.g., physically-based ECOMAG model [11]).

As part of the development of the hydrological compartment of the TerM model, a number of advancements were performed to the original INMCM model. A one-dimensional model of the river flow was incorporated in the TerM model to represent the water mass transport through the river network and river thermodynamics [35]. The model input data on the geographical distribution of land surface properties were updated [28, 29], in particular, those used for simulations of Russian territory. Substantial efforts were devoted to improving the TerM model's capability to reproduce the features of the water regime of rivers in the northern part of the East European Plain (Northern Dvina and Pechora river basins): the model's ability to simulate the key elements of the land hydrological cycle was studied and improved in terms of evaporation and transpiration [22], snow water equivalent [23], infiltration processes in frozen soil, and spring flood runoff formation [24].

In this paper we apply the TerM model to reproduce the water regime of rivers located at the northern and central parts of the European territory of Russia. The Vychegda and Oka rivers were selected as the study catchments. These catchments represent typical conditions of the water regime for the northern and central parts of the East European Plain, and successful reproduction of their runoff in the TerM model will indicate the acceptable quality of the model for a large part of the Russian territory. The novelty of this study lies in its application of TerM for regions with drier climate and under intense anthropogenic impact compared to those previously studied. In addition, so far the TerM model output has not been analyzed in terms of runoff hydrographs of rivers of comparable catchment area (the model was used only for the largest river basins or small elementary catchments [22, 24]). In the future, the TerM model can be applied to carry out simulations with these catchments under past and future climatic conditions and to assess the impact of climate change on river flow.

The purpose of this work is to analyze and improve the reproduction of the mean annual runoff hydrograph in the TerM model for the Vychegda and Oka rivers. For this purpose, we consider the quality of simulation of the main characteristics of the catchment water balance: multiyear-average runoff mean, snow water equivalent (SWE) at the beginning of melting, volume and dates of spring flood runoff. The quality of modelling is assessed on the basis of the results of numerical experiments with the model with prescribed atmospheric forcing. Based on the results of comparison of simulation results with observational data, a quantitative quality assessment is performed for the model, improvements in parameterizations of physical processes, and changes of calibration parameters are proposed.

MATERIALS AND METHODS

The main structural component of the TerM model is a solver for a system of one-dimensional equations of heat and moisture transport in a vertical soil column, which is applied in the cell centers of a regular latitude-longitude grid, with standard resolution 0.5°×0.5°. The depth of the soil column is assumed to be 10 m, and the equations are discretized at 24 vertical levels. At the upper boundary of the column (ground surface), the heat and water balance is evaluated taking into account the mosaic coverage of the cell by different types of surface (11 types of natural vegetation from SiB classification [7], 2 types of agricultural land, altogether grouped as a single vegetation tile, open soil tile, snow cover tile, intercepted moisture tile and open water tile represented by LAKE model [33]); zero-flux condition for diffusive transport of heat and liquid water are used as lower boundary conditions. The snow cover and a layer of intercepted moisture can be formed on the surface of the cell. Also in the cell, in case of water bodies, there can be an additional column representing the water body, in which the equations of heat, momentum and mass transfer in the aquatic environment are solved. Between the land cells, the water mass transport through the river network is performed using a diffusion wave type river network model [35]. The input data of the model include external parameter datasets (see below) provided by TerMPS package [29], which are used to specify the differential equations' coefficients, as well as atmospheric surface layer variables including temperature, specific humidity, surface air pressure, wind speed, precipitation rate, incoming shortwave and longwave radiation fluxes involved to specify the top boundary conditions.

In the heat balance of the land surface, the TerM model takes into account the shortwave (radiation balance of soil and snow under the vegetation canopy are set according to the vegetation radiation transfer model [6, 32]) and longwave radiation fluxes, the turbulent fluxes of heat and moisture (to evaluate the turbulent exchange coefficients, dimensionless Monin-Obukhov similarity theory (MOST) stability functions are used, while the dynamic and thermal roughness parameterizations specific to different types of surface are taken into account [36]; the model of stomatal conductivity [31] is used to represent transpiration – see below), heat effects of snow melting and freezing, and heat flux into the underlying soil. The water balance at the surface takes into account the snow melting rate and intercepted moisture throughfall, as well as infiltration into the soil and the formation of slope runoff when the maximum infiltration rate is exceeded and when water enters moisture-saturated soil areas [8]. In the snow cover, a system of equations for vertical heat and melt water transport and snow density dynamics is solved; these equations are discretized at 4 vertical levels [23]. In the soil column, heat and moisture transport under the action of diffusion and capillary forces is described; phase transitions of water, water withdrawal during transpiration, and formation of subsurface runoff are taken into account [8]. An additional component of subsurface runoff to rivers is also the percolation flux through the lower boundary of the soil column. A number of the model parameters can be calibrated to achieve a better fit to the observed data.

In the context of this article, it is necessary to focus in more detail on transpiration and runoff parameterizations. Transpiration of vegetation cover, including cultivated vegetation, is calculated in the TerM model according to the concept of resistances as:

$$E = \rho \frac{\Delta q}{r_a + r_{s,total}} \quad (1)$$

where E - transpiration rate *[kg/(m²xs)]*, Δq - difference of specific air humidity at the height of the atmospheric surface layer and inside the vegetation cover *[g/g]*, ρ - air density *[kg/m³]*, r_a and $r_{s,total}$ - aerodynamic and stomatal resistances of water vapour transport in the surface layer of the atmosphere *[s/m]*. The value of aerodynamic resistance characterises the efficiency of water vapour transport by turbulent vortices, while the stomatal resistance is linked to the degree of openness of plant leaves stomata, which determines the efficiency of water vapour diffusion from plant tissues into the atmosphere. The stomatal resistance of the vegetation cover rs,total is evaluated by integrating the expression for the stomatal resistance of a single leaf rs over the thickness of the vegetation cover, taking into account the photosynthetically active radiation attenuation [31]. The expression for an individual leaf is written within the multiplicative model expressing the concept of limiting factors [18]:

$$\frac{1}{r_s} = \frac{1}{r,min} \times f_P(P) \times f_T(T) \times f_d(d) \times f_W(W) \quad (2)$$

where $r_{s,min}$ is the minimum stomatal resistance given by the constant, individual for each plant functional type *[c/m]; $f_R(R)$, $f_T(T)$, $f_d(d)$, $f_W(W)$* are functions of photosynthetically active radiation *P*, temperature *T*, air moisture deficit *d* and soil moisture *W*, respectively. These functions take values from 0 to 1 and characterise the degree of opening of stomata on plant leaves depending on environmental factors. The function $f_W(W)$ for soil moisture has the following form:

$$f_W(W) = \frac{W - W_{wilt,end}}{W_{wilt,start} - W_{wilt,end}}, \quad 0 \leqslant f_W(W) \leqslant 1 \quad (3)$$

where *W* - integral moisture in the root-inhabited soil layer *[m]; $W_{wilt,start}$, $W_{wilt,end}$* - integral moisture at the beginning of wilting process and intensive wilting respectively in the root-inhabited soil layer [m] (the integral weights the soil moisture with the density of the root system). When calculating the parameters $W_{wilt,start}$ and $W_{wilt,end}$ the values of the soil water potential of the beginning of wilting and intensive wilting are used, which are considered constants individual for plant functional types of vegetation; for 2 types of agricultural land (arable land and tree plantations) the moisture potential of the beginning of wilting is set to -10000 cm and -19000 cm, the moisture potential of intensive wilting is -20000 cm and -25000 cm, respectively. Under moisture deficit conditions, the function $f_W(W)$ is the main limiting factor for plant transpiration. At this paper, in order to describe the effect of artificial irrigation of cultivated land in the TerM model for the corresponding vegetation types, it was supposed

$$f_W(W) = 1 \quad (4)$$

One of the components of total river runoff (surface infiltration-excess runoff), considered in this paper, is calculated as [25]:

$$R_{s,inf} = B - B_{cap} \times (1 - exp(-B/Bcap)), \quad B_{cap} = \gamma_{max} I_{z=0} \times k \quad (5)$$

where $R_{s,inf}$ - surface slope runoff due to infiltration excess *[m/s]*, B - water flux to the soil surface (consisting from liquid precipitation and melt snow water rate) *[m/s]*, B_{cap}- maximum infiltration rate into the soil *[m/s]* which depends on the soil type, γ_{max}- maximum hydraulic conductivity in the soil column *[m/s]* in the depth range *z*є*[0; h_{soil}]*, where *z=0* - soil surface, *z=h_{soil}* - lower boundary of the soil column; *k* - dimensionless calibration factor. The transfer of runoff through the river network is described by the diffusion wave model of riverflow dynamics [35]. In this model, the following equation is implemented to calculate the flow velocity in the cross section of the channel:

$$U = U_o \times \left(1 - \frac{1}{2s}\frac{\partial h}{\partial x}\right), \quad U_0 = \frac{1}{n} R^{2/3} s^{1/2} \quad (6)$$

where *U* is the flow velocity in the channel *[m/s]*, *R* is the hydraulic radius *[m]*, h is the river depth *[m]*, *s* is the tangent of the slope angle of the channel thalweg, n is the Manning roughness coefficient *[sxm$^{-1/3}$]*, *x* is the horizontal coordinate directed along the channel thalweg. The equation is solved using a finite-difference scheme along the *x-axis*; at the same time, the mesh spacing between nodes is corrected for the tortuosity of the channel network:

$$\Delta x = m \times \Delta x' \quad (7)$$

where *Δx* is the value of grid spacing along the channel thalweg *[m], Δx'* is the value of grid spacing assuming straight channels connecting neighboring cells *[m]* [35], m is the tortuosity coefficient.

TerM uses external databases to specify maps of a number of model parameters: the map of terrestrial ecosystems of Russia by ICR RAS [39] for land cover types, GLCC database [20] for the same but outside Russia; GLDBv2 database [2] for depths and areas of water bodies; database [5] for hydrophysical properties of soils, digital model ETOPO1 [1] for surface elevation, DDM30 [30] for river flow directions, MODIS data [10] for leaf index of vegetation. The TerMPS package of unified algorithms [29] is used for aggregation of the data from original resolution of above listed databases onto the model grid.

It is known that the main factors affecting the perennial runoff rate are precipitation and evapotranspiration from the catchment surface. The magnitude of spring flood runoff, which is the most characteristic feature of the water regime of the studied rivers, is formed duew to the magnitude of SWE at the beginning of melting, the amount of precipitation during the flood period and the magnitude of infiltration losses at the catchment [37]. Errors in precipitation, which is an input parameter for the TerM model, can be considered negligible if a representative source of precipitation data is selected. Thus, in order to verify the main factors of river runoff formation at the catchment, it is necessary to analyze the mean annual runoff (to assess the quality of modeled evapotranspiration), the SWE at the beginning of melting (as the main factor of spring flood runoff formation) and the analysis of annual runoff hydrographs (to assess the quality of flood runoff simulation). This analysis was carried out by comparing river runoff and SWE provided by the TerM model with observational data.

The Vychegda River catchment is located in the middle taiga zone, the precipitation-evaporation ratio is about 1.5, the landscapes are represented mainly by dark coniferous, light coniferous, small-leaved and mixed forests; anthropogenic impact on the catchment area is minimal. The Oka River catchment is located in the zone of broadleaved forests, the precipitation-evaporation ratio is about 1.0, natural landscapes are represented by mixed and broadleaved forests; in contrast to Vychegda, a significant share of the area is occupied by agriculture lands and meadow vegetation. The natural landscapes of the Oka River catchment have been significantly altered by anthropogenic factors. Both catchments are characterised by predominantly snow feeding of runoff with pronounced spring flooding and stable winter low-water periods; the Oka River is characterised by a greater contribution from ground feeding and sometimes interruption of low-water periods by flooding due to thaws. The runoff of both rivers is insignificantly regulated [9, 39]. For the water discharge, we selected observations at the closing river gauges of the studied basins: Koryazhma station (32 km from the mouth of Vychegda, upstream runoff area 119 thousand km^2) and Gorbatov station (78 km from the mouth of Oka, upstream area 244 thousand km^2). The period 2008-2020 was chosen for model-observations comparison; TerM model runs were performed for the period 2000-2020 (with spinup period of 8 years, primarily to bring the soil moisture to equilibrium with long-term atmospheric conditions) with a time step of 1 hour and a spatial resolution of 0.5º×0.5º (82 cells for Vychegda basin and 134 cells for Oka basin). The ERA5 reanalysis data [14] (spatial resolution 0.5º×0.5º, time resolution 1 hour) were used as atmospheric forcing except precipitation, and the GPCP 3.2 data [16] (spatial resolution 0.5º×0.5º, time resolution 1 day) were used as input data on atmospheric precipitation; daily mean intensity was used at each time step of the model within a day. The error in atmospheric forcing data in the study area was considered negligible [12, 26].

To assess the quality of SWE simulation, the TerM model output was compared with data from route snow measurement surveys counducted at meteorological stations within and in the immediate vicinity of the study catchments (4 stations for the Vychegda River and 9 stations for the Oka River). Observational data represent measurements of SWE each 5-10 days; data from routes in non-forested landscapes were selected for analysis. Observational data were linearly interpolated over time to obtain averaged seasonal dynamics. The period 2000-2020 was chosen for model validation; TerM model simulations were performed in a single-column mode for the same period with a time step of 3 hours at weather station points. In these numerical experiments, instantaneous 3-hourly observational data at meteorological stations were used as input data; the ERA5 reanalysis [14] was used for the magnitudes of incoming shortwave and longwave radiation fluxes, as well as to fill the gaps in station data for other variables.

RESULTS AND DISCUSSION

Table 1 compares the results of the TerM model simulation of the long-term runoff mean in the Vychegda and Oka basins with the observed data. The observed model deviation in the mean value is acceptable compared to the annual precipitation (overestimation by 7-8% in both catchments). However, compared to the value of the runoff rate, the error is more significant (overestimation by 17.8% for the Vychegda River and 34.8% for the Oka River). The overestimation of the runoff norm in the model indicates an underestimation of the summer evapotranspiration norm from the catchment (precipitation from GPCP are close to observational data [16], winter evapotransiration reproduced with high accuracy as shown below for SWE). At the same time, the relative error for the Oka River is almost twice as large as for the Vychegda River. We hypothesised that the larger error for the Oka River was due to an overestimation of the effect of wilting vegetation during drought periods in cultivated agricultural areas, which are widespread in the catchment of the river. In most agricultural areas, artificial irrigation of crops and maintenance of their optimal moisture regime are carried out on a permanent or one-time basis during periods of drought. This anthropogenic factor is not taken into account in the TerM model, which may result in an overestimation of evapotranspiration. A modification of wilting multiplier (3) for parameterization of transpiration was proposed for the TerM model in the form of parametrization (4). Although this parameterization is very simplified (possibly overestimating the effect of irrigation), it can nevertheless be considered that it reflects the physical consequences of irrigation and can be used as one of the options for parameterizing anthropogenic effects in the TerM.

The results of TerM model for Oka river with this modification are presented in Table 1 - the proposed parameterization reduced the relative error to a level comparable to the Vychegda River. The obtained overestimation of the mean annual runoff by 13.3% for the Oka River and by 17.8% for the Vychegda River can be considered acceptable. The observed error may be related to the magnitude of stomatal resistance parameters for different vegetation types, LAI data, etc.

Table 2 presents the metrics of the TerM model error in the magnitude of maximum SWE (SWE by the beginning of melting) according to route measurements within the studied catchments. The values obtained indicate a significant scatter in the observed error both between different stations (relative error of mean ranging from -29.4% to +38.4%) and for each individual station beween different years (correlation coefficient values for the time series from 0.35 to 0.87). However, the error metrics for the values averaged over a set of meteorological stations show acceptable values (overestimation by 4.4% for the Vychegda River, by 7.3% for the Oka River). A significant part of the model error and low values of error metrics at individual stations may be related to local factors (wind redistribution, blizzards, etc) in the snow measurement data that influenced the dynamics of snow accumulation in a particular year for a particular location [23]. This variability can be eliminated by averaging. We assume that the error over the catchment surface as a whole will be close to the error obtained over the set of stations.

Figure 1 compares the SWE averaged over all meteorological stations within the study catchments and all winters in the period 2000-2020 provided by the TerM

Table 1. Average runoff depth for 2008-2020 for the Vychegda and Oka rivers. Vychegda and Oka rivers according to observations and the TerM model output

	Vychegda	Oka	
		model, basic version	model, modified version
Precipitation, mm	764.0	702.7	
Runoff depth (observations), mm	345.1	151.3	
Runoff depth (model), mm	406.4	203.8	171.5
Absolute error, mm (±interannual standard deviation of error, mm)	+61.26 (±3.88)	+52.59 (±1.54)	+20.24 (±1.15)
Error relative to precipitation amount	+8.0%	+7.5%	+2.8%
Error relative to runoff depth	+17.8%	+34.8%	+13.3%

model and observations. In the averaging procedure, instead of the mean the median was calculated, due to the significant heterogeneity of samples during the periods of snow accumulation and snowmelt. The model correctly reproduces basic features of snow accumulation dynamics, such as the timing of snow cover emergence, the timing of the beginning of melting, the intensity of melting and the timing of snow cover melting. It should be noted that this was estimated only for snow cover at field landscapes, while part of the error of the model in spring flood runoff may be associated with errors of the snow dynamics at the forest, associated with the errors in taking into account the processes of radiation and turbulent transfer at the canopy.

Table 3 presents a comparison of the average spring flood depth (the spring flood depth is computed from the average hydrograph as an integral for part of curve which exceeding of the baseflow line) for the Vychegda River and the Oka River according to the TerM model and observations. Fig. 2 shows the corresponding mean runoff hydrographs. The results indicate an underestimation of the flood runoff volume and earlier timing of spring flood in the non-calibrated version of the TerM model. The observed error can be controlled by the values of the calibrated model parameters: the infiltration capacity parameter of the upper soil layer in the catchment, the roughness parameter in the river channels, and the tortuosity coefficient of the river network.

The calibration factor k for the infiltration capacity parameter of the topsoil is included in the equation for calculating the surface component of catchment runoff (5) [25], which is formed when the rate of water flux to the soil surface exceeds the maximum rate of infiltration through

Table 2. Average maximum snow water equivalent (SWE) at meteorological stations within the catchments of the Vychegda and Oka rivers for 2000-2020 based on observations and TerM model

Station	Average maximum SWE (observations), mm	Average maximum SWE (model), mm	Absolute error, mm (±interannual standard deviation of error, mm)	Relative error, %	Correlation coefficient for the time series
Vychegda River					
Veliky Ustyug	180.0	177.7	+6.79	+4.0%	0.35
Oparino	190.2	196.2	+5.99	+3.1%	0.57
Sura	135.1	159.0	+23.88	+17.7%	0.83
Ust-Tsilma	188.2	182.2	-5.96	-3.2%	0.64
for the set of stations	171.1	178.8	+7.7 (±37.0)	+4.4%	0.62
Oka River					
Bryansk	92.7	117.9	+25.18	+27.2%	0.80
Yelatma	101.6	135.1	+33.56	+33.0%	0.77
Kostroma	122.1	92.0	-30.10	-24.7%	0.69
Lukoyanov	103.2	112.3	+9.15	+8.9%	0.75
Mozhaisk	81.7	113.1	+31.38	+38.4%	0.81
Pavelets	105.7	74.7	-31.05	-29.4%	0.66
Penza	100.4	100.6	+0.13	+0.1%	0.87
Ponyri	92.2	92.5	+0.36	+0.4%	0.76
Sukhinichi	77.0	103.6	+26.6	+34.6%	0.87
for the set of stations	97.4	104.6	+7.1 (±37.7)	+7.3%	0.65

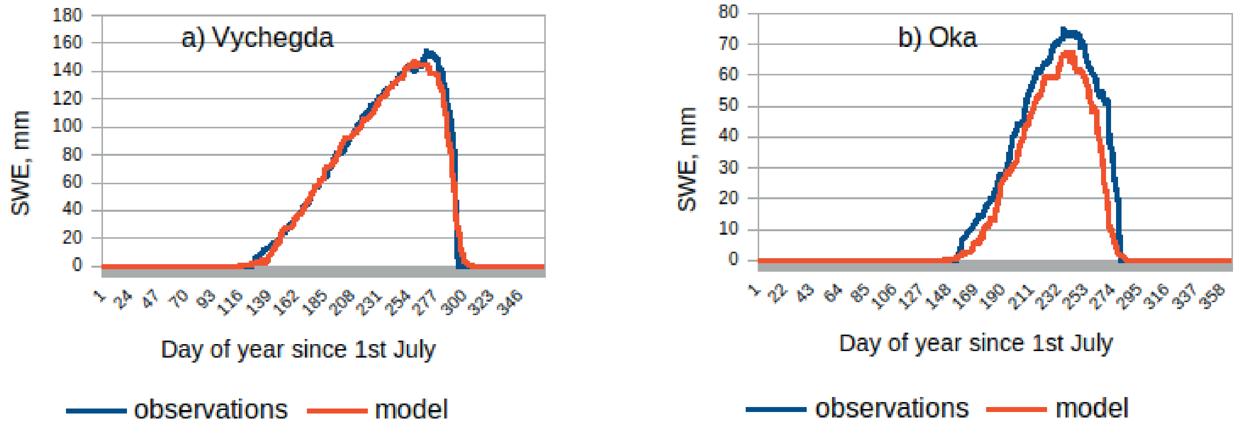

Fig. 1. Average seasonal course of snow accumulation at meteorological stations within the catchments of a) Vychegda River and b) Oka River for 2000-2020, based on observations and TerM model

Table 3. Spring flood runoff depth extracted from the mean hydrograph for the Vychegda and Oka rivers, 2008-2020, based on observations and TerM results

	Vychegda River		Oka River	
	model non-calibrated	model, calibrated	model, non-calibrated	model, calibrated
Spring flood runoff depth (observations), mm	229.2		74.2	
Spring flood runoff depth (model), mm	107.79	259.5	57.5	85.0
Absolute error, mm (±interannual standard deviation of error, mm)	−121.41 (±34.71)	+30.30 (±16.90)	−16.69 (±24.23)	+10.82 (±20.03)
Error relative to long-term runoff mean, %	−35.2%	+8.8%	−12.4%	+8.0%

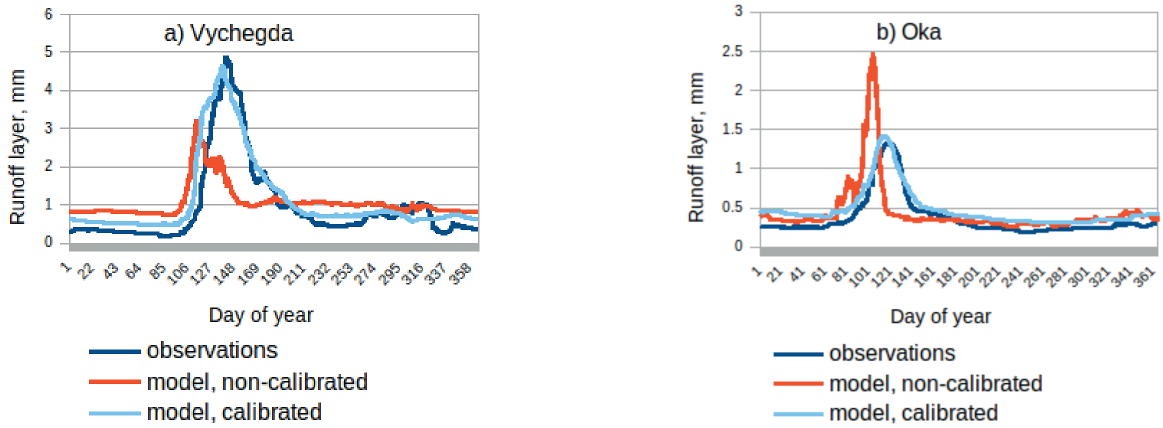

Fig. 2. Average annual hydrograph of the Vychegda and Oka rivers runoff depth for 2008-2020 according to observations and TerM model

the topsoil (soil infiltration capacity) and is the main mechanism of spring flood runoff formation when soils on watershed are frozen. This equation is written under the assumption of a subgrid distribution of infiltration capacity within a latitude-longitude model grid cell according to an exponential distribution law with mathematical expectation B_{cap}. From a physical point of view, the value of B_{cap} should be related to the value of γ_{max}, representing the maximum hydraulic conductivity of the topsoil averaged over the cell. In the TerM model, the value of γ_{max} is obtained by averaging the original fine-scale input data on soil properties [5]. However, the γ_{max} values thus obtained often cannot provide the actual observed flood runoff volume according to equation (5), which is due to the large spatial variability of soil hydraulic conductivity in the catchment within several orders of magnitude, which is reflected in the input data with high uncertainty. A common approach in hydrological modelling practice is to calibrate the parameter B_{cap} for each individual catchment under study [25]. A similar approach has been implemented in the TerM model; in this case, the calibration factor k in formula (5) is set to a single value for all cells located within the study catchment. By default, k is assumed 1. Once the calibration factor decreases, an increase in flood discharge can be expected and *vice versa*; the range of possible values of k spans from 0.01 to 100 [28].

The channel roughness parameter (Manning's coefficient) and tortuosity coefficient of the river network are used in the diffusion wave model of riverflow dynamics (6-7) [35]. By default in the TerM model, the values of river model parameters are set the same constants for all rivers: the Manning coefficient n is $0.035\ s{\cdot}m^{-1/3}$ and the tortuosity coefficient m is 1.4. In reality, the values of these parameters vary considerably. The value of the Manning coefficient depends on the state of the watercourse bottom surface and varies from about 0.025 (for smooth channels with free flow) to 0.2 (for overgrown forested floodplains) [3]. During flooding and overflow periods, the flow enters the vegetated floodplain, which results in an increase ofn the roughness coefficient; accounting for this process in the model can lead to slowing down the flow and shifting the timing of floods to later dates. The possible range of tortuosity coefficient values can be from 1 to 3 or more; for the Oka River, the maximum values are of the order of 2.6 (in some sections) [17]. Greater tortuosity and, accordingly, greater channel length entails in a later onset of flooding, under other conditions fixed. Thus, the refinement of the Manning coefficient and tortuosity coefficient parameters for the studied catchments can improve the TerM model performance in the timing of floods so that their values are considered as calibration settings and determined to achieve an optimal fit of the model to the observed river discharge. Nevertheless, it should be taken into account that assessing these parameters on a global scale may be difficult.

To assess the magnitude of the calibration parameter values in the TerM model for the Vychegda and Oka catchments, a series of sensitivity numerical experiments were carried out with values of the k, m and n of different orders. The calibration was done using the enumeration method and the objective function was the Nash-Sutcliffe coefficient for the daily runoff series. As a first approximation, the value of the roughness coefficient was set constant throughout the year; one can expect less influence of this coefficient change on runoff during low water periods compared to spring floods. The parameter values that allowed to demonstrate the lowest level of errors in the volume and timing of spring floods were as follows: $k = 0.1$ for the Vychegda River, for Oka $k = 2.0$, for both rivers $n = 0.050\ s{\cdot}m^{-1/3}$, for both rivers $m = 2.5$. Comparison of the results of the calibrated TerM model with the observed data is presented in Table 3 and Fig. 2. The calibrated model shows much lower errors in spring flood volume and timing. Fig. 3 shows the series of daily

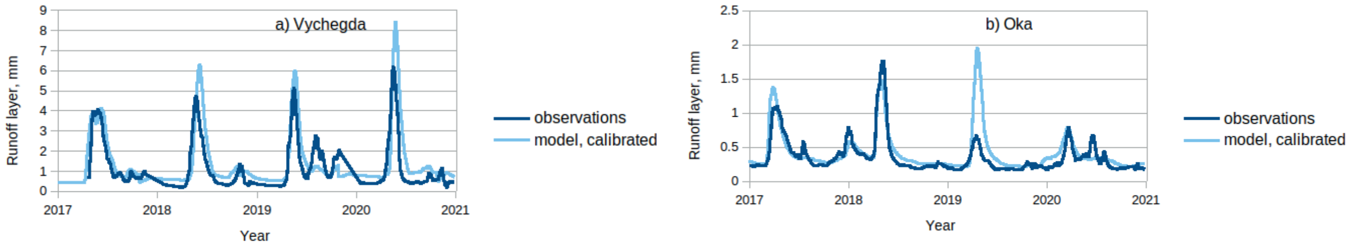

Fig. 3. Dynamics of daily runoff depth of the Vychegda River and Oka River for 2017-2020 according to observations and results of TerM model

values of the runoff depth for the studied catchments for a part of the analyzed time period. The model demonstrates realistic hydrograph pattern; the value of the Nash-Sutcliffe coefficient for Vychegda river is 0.67, while for the Oka river 0.62. The model overestimates the low-water discharge compared to the observed data which may be a consequence of errors in the reproduction of evaporation and errors in the calibration of spring flood runoff, and also does not well reproduce some flood events which may be related to the parametrization of groundwater and rain floods.

The values obtained are within physically reasonable ranges reported in literature. The value of the calibration coefficient for the infiltration capacity parameter obtained for the Vychegda River coincided with the optimal values of the order of magnitude obtained for the Northern Dvina River [24], for which the Vychegda River is a sub-basin. The Manning coefficient values obtained correspond to flow on a floodplain covered with cultivated crops or predominantly shrub vegetation [3]. The obtained coefficient of tortuosity values are close to the maximum values observed in these river sections along their entire length [17]. It is likely that the coefficient of tortuosity value obtained during the calibration process is slightly higher than the actual one, and the shift of optimal *m* from realistic value served to eliminate the errors of other model parameters as well as misrepresentation of physical processes.

CONCLUSIONS

As a result of a series of computational experiments, the TerM land surface model was shown to be of acceptable quality in reproducing the water regime of the Vychegda and Oka rivers under conditions of modern climate (2008-2020), in particular, such characteristics as the long-term runoff mean (error with respect to the long-term precipitation mean +8.0% and +2.8%, respectively, and with respect to long-term runoff mean provided by river gauges +17.8% and +13.3%, respectively), snow water equivalent at the beginning of melting (error +7.7% and +7.1%, respectively), spring flood runoff volume (error +8.8% and +8.0%, respectively), dates of spring flood and annual hydrograph behavior in general (Nash-Sutcliffe coefficient 0.67 and 0.62, respectively). The obtained quality metrics may be insufficient in comparison with specialized hydrological models, but are quite high in comparison with other land surface models [13]. In the process of model calibration, values of calibrated model parameters, in particular, the coefficient for soil infiltration capacity parameter, Manning's roughness coefficient and river network tortuosity coefficient were obtained for the studied catchments; the obtained parameter values fell within the physically reasonable ranges reported in literature. Also, a modification of vegetation wilting parameterization was proposed for the model, which allows taking into account the effect of artificial irrigation of cultivated lands and allowed improving the results of annual discharge reproduction for the Oka River. Based on the results obtained, it can be concluded that the TerM model can be successfully applied to perform hydrological simulations in geographical conditions typical for a large part of Russia.

Further work will be continued in the direction of carrying out numerical studies with the TerM model for the Vychegda and Oka rivers under climatic conditions of the past and future and to assess the impact of climate change on the water regime of the European part of Russia.

REFERENCES

Amante, C., & Eakins, B. W. (2009). ETOPO1 arc-minute global relief model: procedures, data sources and analysis.

Choulga, M., Kourzeneva, E., Zakharova, E., & Doganovsky, A. (2014). Estimation of the mean depth of boreal lakes for use in numerical weather prediction and climate modelling. Tellus A: Dynamic Meteorology and Oceanography, 66(1), 21295.

Chow V. T. (1969). Open-channel hydraulics. (In Russian).

Clark, M. P. et al. (2015). Improving the representation of hydrologic processes in Earth System Models. Water Resources Research, 51(8), 5929-5956.

Dai, Y. et al. (2019). A global high-resolution data set of soil hydraulic and thermal properties for land surface modeling. Journal of Advances in Modeling Earth Systems, 11(9), 2996-3023.

Dickinson, R. E. (1983). Land surface processes and climate—Surface albedos and energy balance. Advances in geophysics, 25, 305-353.

Dorman, J. L., & Sellers, P. J. (1989). A global climatology of albedo, roughness length and stomatal resistance for atmospheric general circulation models as represented by the simple biosphere model (SiB). Journal of Applied Meteorology and Climatology, 28(9), 833-855.

Dümenil, L., & Todini, E. (1992). A rainfall–runoff scheme for use in the Hamburg climate model. Advances in theoretical hydrology, 129-157.

Frolova, N. L. et al., Agafonova, S. A., Nesterenko, D. P., & Povalishnikova, Ye. S. (2013). Natural regulation of river flow in the Volga basin under changing climate conditions. Water management in Russia: problems, technologies, management, (6), 32-49. (In Russian)

Fu, G., & Wu, J. S. (2017). Validation of MODIS collection 6 FPAR/LAI in the alpine grassland of the Northern Tibetan Plateau. Remote Sensing Letters, 8(9), 831-838.

Gelfan, A., Motovilov, Y., Krylenko, I., Moreido, V., & Zakharova, E. (2015). Testing the robustness of the physically-based ECOMAG model with respect to changing conditions. Hydrological Sciences Journal, 60(7-8), 1266-1285.

Grigoriev, V., Frolova, N., Kireeva, M., & Stepanenko, V. (2020). Estimation of the accuracy of ERA5 reanalysis data. Proceedings of the IX International Scientific and Practical Conference «Marine Research and Education (MARESEDU-2020)», (2), 47-50.

Guo, H., Zhan, C., Ning, L., Li, Z., & Hu, S. (2022). Evaluation and comparison of CMIP6 and CMIP5 model performance in simulating the runoff. Theoretical and Applied Climatology, 149(3), 1451-1470.

Hersbach, H. et al. (2020). The ERA5 global reanalysis. Quarterly journal of the royal meteorological society, 146(730), 1999-2049.

Huang, B., & Mehta, V. M. (2010). Influences of freshwater from major rivers on global ocean circulation and temperatures in the MIT ocean general circulation model. Advances in Atmospheric Sciences, 27(3), 455-468.

Huffman, G. J., Adler, R. F., Behrangi, A., Bolvin, D. T., Nelkin, E. J., Gu, G., & Ehsani, M. R. (2023). The new version 3.2 Global Precipitation Climatology Project (GPCP) monthly and daily precipitation products. Journal of Climate, 36(21), 7635-7655.

Isaev D. I., Denschikova M. I., Vanchenko S. I. (2023). Assessment of the development of the Oka River bends based on the floodplain relief pattern. The historical approach in geography and geoecology, 100-104. (in Russian)

Jarvis, P. (1976). The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philosophical Transactions of the Royal Society of London. B, Biological Sciences, 273(927), 593-610.

Kislov, A. V., Varentsov, M. I., & Tarasova, L. L. (2015). The role of spring soil moisture in the formation of large-scale droughts in the East European Plain in 2002 and 2010. Proceedings of the Russian Academy of Sciences. Atmospheric and Oceanic Physics, 51(4), 464-464. (in Russian)

Loveland, T. R., Reed, B. C., Brown, J. F., Ohlen, D. O., Zhu, Z., Yang, L. W. M. J., & Merchant, J. W. (2000). Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. International journal of remote sensing, 21(6-7), 1303-1330.

Malakhova, V. V., & Golubeva, E. N. (2012). The role of the Siberian rivers in increase of the dissolved methane concentration in the East Siberian shelf.

Medvedev, A. I., Stepanenko, V. M., & Bogomolov, V. Y. (2024). Influence of External Parameters on Evapotranspiration in the INM RAS–MSU Land Surface Model. Russian Meteorology and Hydrology, 49(5), 420-429.

Medvedev, A. I., Stepanenko, V. M., Gelfan, A. N., & Bogomolov, V. Y. (2025) Simulation of snow water content at the northern part of the East European Plain at the TerM land surface model. Water Resources. (in print)

Medvedev, A. I., Stepanenko, V. M., Gelfan, A. N., & Bogomolov, V. Y. (2025) Simulation of spring floods on the rivers of the northern part of the East European Plain at the TerM land surface model. Proceedings of the Russian Academy of Sciences. Atmospheric and Oceanic Physics. (in print)

Motovilov, Yu. G., & Gelfan, A. N. (2018) Models of runoff formation in river basin hydrology problems. (in Russian)

Nogueira, M. (2020). Inter-comparison of ERA-5, ERA-interim and GPCP rainfall over the last 40 years: Process-based analysis of systematic and random differences. Journal of Hydrology, 583, 124632.

Raymond, P. A., et al. (2013). Global carbon dioxide emissions from inland waters. Nature, 503(7476), 355-359.

Ryazanova, A. A., Bogomolov, V. Y., & Medvedev, A. I. (2023). The Applicability of Various Pedotransfer Functions to the Description of Soils. Water Resources, 50(5), 732-747.

Ryazanova, A. A., Bogomolov, V. Y. E., Stepanenko, V. M., Varentsov, M. I., & Medvedev, A. I. (2024). TerMPS: software for preparing land surface parameter data used in land surface models and Earth system models. Numerical methods and programming, 25(5), 11-29.

Schewe, J., & Schmied, H. M. (2022). DDM30 river routing network for ISIMIP3.

Sellers, P. J., Mintz, Y. C. S. Y., Sud, Y. E. A., & Dalcher, A. (1986). A simple biosphere model (SiB) for use within general circulation models. Journal of Atmospheric Sciences, 43(6), 505-531.

Stepanenko, V., Pavinskiy, S., & Dyukarev, Ye. (2025). Comparison of two schemes of radiation transfer within the vegetation canopy based on measurements at the Mukhrino Carbon Polygon. Environmental Dynamics and Global Climate Change, 16(2), 58-68.

Stepanenko, V., Mammarella, I., Ojala, A., Miettinen, H., Lykosov, V., & Vesala, T. (2016). LAKE 2.0: a model for temperature, methane, carbon dioxide and oxygen dynamics in lakes. Geoscientific Model Development, 9(5), 1977-2006.

Stepanenko, V. M., Medvedev, A. I., Yu. Bogomolov, V., Shangareeva, S. K., Ryazanova, A. A., Faykin, G. M., ... & Chernenkov, A. Y. (2024). Land surface scheme TerM: the model formulation, code architecture and applications. Russian Journal of Numerical Analysis and Mathematical Modelling, 39(6), 363-377.

Stepanenko, V. M. (2022). River routing in the INM RAS-MSU land surface model: Numerical scheme and parallel implementation on hybrid supercomputers. Supercomputing Frontiers and Innovations, 9(1), 32-48.

Suiazova, V. I., Debolskiy, A. V., Mortikov, E. V., Shestakova, A. A., Gladskikh, D. S., & Chechin, D. G. (2025). Influence of Thermal Roughness Parameterizations on Simulations of Turbulent Fluxes by the Atmospheric Surface Layer Model. Izvestiya, Atmospheric and Oceanic Physics, 61(5), 531-541.

Varentsova, N. A., Kireeva, M. B., Kharlamov, M. A., Varentsov, M. I., Frolova, N. L., & Povalishnikova, Ye. S. (2022). Formation of spring runoff in rivers of the European part of Russia: main factors and methods of their consideration. I. Review of research. Hydrometeorological research and forecasts, (2), 92-116. (in Russian)

Volodin, E. M. et al. (2017). Simulation of the present-day climate with the climate model INMCM5. Climate dynamics, 49(11), 3715-3734.

Yegorov, V. A., Bartalev, S. A., Kolbudaev, P. A., Plotnikov, D. Ye., & Khvostikov, S. A. (2018). Map of Russia's vegetation cover, obtained from data from the Proba-V satellite system. Contemporary problems of remote sensing of Earth from space, 15(2), 282-286. (in Russian)