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Reproduction of runoff hydrograph in the Lena River basin with a hydrologically correct digital elevation model*

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Abstract. A hydrologically correct digital model of the bottom topography of the Lena River basin with a resolution of $(1/3)^\circ \times (1/3)^\circ$ is constructed. Based on the linear model of forming a water balance in the river-bed network and a model network of river channels schematized in the form of a graph of a model system of river channels, daily, monthly, and annual flow hydrographs in the closing range Kyusyur of the Lena River were calculated. As an information support for the model, the global MERRA reanalysis database for meteorological parameters for 1980–2011 was used.

It is shown that it is possible to attain a satisfactory quality of the river flow calculation (the correlation coefficient with the observed discharge values is 0.88 using the linear model) and a fairly good agreement between the real and the model catchments.

Keywords: hydrologically correct digital model, Lena River basin, linear formation model of water balance, channel network, surface runoff, river flow, discharge.

1. Introduction

It is known that several types of hydrological models have been developed for the simulation the river flow hydrograph, including linear models of the water balance in the channel network [1–4]. The purpose of this study is to investigate the possibility and quality of reproducing a river flow from the Lena River basin using the two types of linear flow models: a linear model for calculating the hydrological flow [5], in which the surface flow is parameterized by a cascade of equal linear reservoirs, and a simple linear model of the water balance formation in the river networks based on a hydrologically correct digital elevation model.

The use of the global MERRA reanalysis database [6] is due to the fact that initialization of linear models requires the input distributed runoff and drainage fields, which are usually not available for measurements. These variables are derived from the MERRA reanalysis data on precipitation and surface air temperature. In this regard, there is a need to investigate how to adequately reproduce the river flow hydrographs using the global MERRA

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database. The simulation results as compared to the measured values of the river flow for the period of 1980–2000 at the Kyusyur station of the Lena River flow have shown that the linear models adequately reproduce the annual course of the river flow with a high spring flood and the interannual dynamics of the river flow provided that a schematized network of river channels is in good agreement with a real river network.

2. Modeling of a river flow hydrograph

2.1. The simulation of runoff within a design cell or a small catchment. To obtain a flow hydrograph in the closing range of the river channel, it is necessary to convert the surface Q_0 (runoff) and underground Q_g (baseflow) flows into the river flow calculated with the use of the MERRA reanalysis database for each grid cell covering the Lena River basin. These flows represent instantaneous drains at the center of a computational cell, and for their propagation to the exit from the grid cell and for getting into certain sections of the river network, it takes additional travel time. To convert the surface runoff Q_0 into a river flow with allowance for the travel time, a linear two-parameter model is used in [5] — the surface runoff Q_0 is parameterized by a cascade of n equal linear reservoirs and the underground runoff Q_g is the only linear reservoir.

According to the Horton mechanism [7] or the Danne mechanism [8], there are various mechanisms of surface runoff formation. In the first case, a surface runoff is formed when the rate of moisture infiltration into the soil is lower than the rate of precipitation (the case of heavy rainfalls). In the second case, the surface runoff is formed as a result of raising the groundwater level to the soil surface, which is possible with a close occurrence of the groundwater and abundant moisture input into the soil (during the spring snowmelt or as a result of a large amount of precipitation).

The underground runoff in the linear model [5] is formed under the assumption of a free drainage and excess water after the complete saturation of the soil. It is assumed that there is a constant small underground flow called the baseflow. In the linear model, the runoff of volumes of water corresponding to both the surface and the underground runoff occurs as a continuous water layer on the cell surface. The runoff values from the calculated cells (with allowance for the areas calculated with real catchment areas connected to the cell) serve as input information runoff for the conversion into the river network.

2.2. The simulation of a river flow in a river network. To simulate a river flow in a channel network schematized in the form of channels that combines the calculated cells of the Lena River basin, a linear model of the water balance formation is used. This model is based on the equation of balance (continuity) within each river cell:

$$\frac{dW}{dt} = Q_{\text{in}} - Q_{\text{out}}, \tag{1}$$

where W is the water reserve in the calculated channel cell; Q_{in} is the flow rate of the water entering the channel cell both from the neighboring river cells and in the form of a lateral inflow; Q_{out} is the water flow rate at the outlet from the channel cell. The value of Q_{in} is assumed to be constant within a calculation time step. In the model in question, as in many similar linear models [2, 3, 9], the following parametrization is used:

$$Q_{\text{out}} = cW, \tag{2}$$

where $c = 1/k$ with a constant coefficient $k = d/u_e$ of the time dimensionality [10], where u_e is the effective velocity of the water motion in the channel (with allowance for the tortuosity of the channel) and d is the distance between the calculated cells [3].

Substituting (2) into (1) we obtain the ordinary differential equation whose numerical solution describing the water dynamics in the channel cell has the form

$$W(t_{i+1}) = D(\Delta t)W(t_i) + (1 - D(\Delta t))\frac{d}{u_e}Q_{\text{in}}, \tag{3}$$

$$D(\Delta t) = \exp\Bigl(-\frac{u_e}{d}\Delta t\Bigr), \qquad \Delta t = t_{i+1} - t_i.$$

According to (3) and with a network of river cells (channels) schematized in the form of a graph, the dynamics of the water reserves in each cell and the water flow in it are calculated.

As input information for obtaining the river flow in the Kyusyur closing range, we used the values of the surface runoff and drainage for 1980–2011 calculated from the data on precipitation and air temperature adopted from the global MERRA database.

3. Schematization of the Lena River basin

In order to quantitatively reproduce the basic transformation regularities of the water (precipitation) entered into the catchment based on the linear river flow models, it is necessary to schematize the basin and its hydrographic network. Within the basin under study, the schematization allows one to distinguish elementary watersheds entering the basin, the boundaries of the watersheds taken into account.

Figure 1 shows a schematic diagram of the Lena River basin up to the Kyusyur stock station with, totally, 3,735 spatial grid cells with a uniform

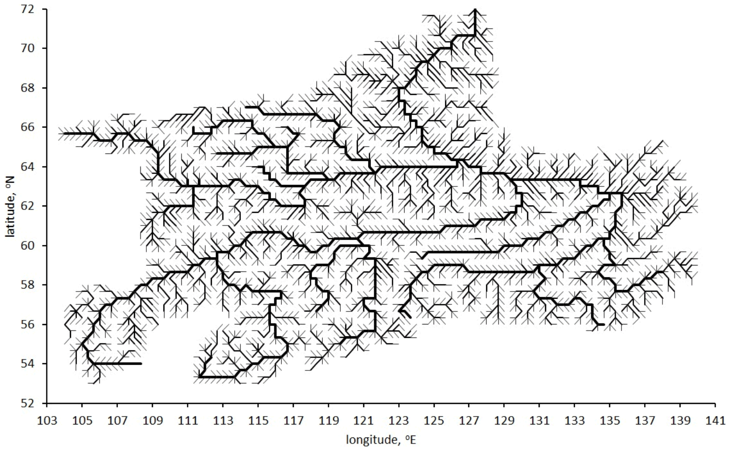

Figure 1. Schematization of the Lena River basin on a grid with uniform resolution of (1/3)°

resolution of (1/3)° × (1/3)° connected by a fairly developed model hydrographic network. In [11], the schematization of the Lena River basin, including 4,565 cells, early constructed on a grid with the same resolution, is presented. The comparison of the two schematizations between themselves and with the real area of the Lena River basin shows that with the Lena River basin area of 2,490 thousand km^2, according to the schematization [11], the excess of the basin area ranged up to 500 thousand km^2 (755 cells), and according to the schematization presented in this paper, 40 thousand km^2 (50 cells).

The surface topography is the most important characteristic for the modeling based on linear models of the surface and river flows. The topography gradient is directly introduced into the formulation of the delay coefficient for surface runoff in the model [5], which is used to calculate it. For each grid cell, only one direction of the outgoing flow from a cell is allowed. This direction is determined by the largest gradient of topography for eight neighboring cells surrounding each cell. Based on this information, a flow direction matrix is generated for the model catchment.

The catchment was schematized based on the digital terrain model SRTM30 supplemented with GTOPO30 data with a resolution of 30 seconds. A fragment from these data, including the entire basin of the Lena River: 52–72°N and 103–140°E was isolated. This dataset was transformed using the kriging procedure to a topographic dataset with a resolution of (1/3)° × (1/3)° with a height value at the center of a cell.

In addition to the SRTM data, topographic maps of the Lena River basin at the scale of 1:200,000, 1:1,000,000 were used. With the help of these maps, the channels of the Lena River and its four main tributaries

Vilyuya, Vitim, Olekma, and Aldan were routed, which ensured a constant decrease in height along the river channels. Then it appeared possible to proceed to constructing a hydrologically correct digital model of the basin topography. For this it was necessary, first of all, to fill in all the local depressions (incorrect areas of the internal runoff) and to eliminate errors and inaccuracies in the values of the heights of the catchment cells. If one does not carry out this procedure, then with a consequent simulation of the hydrographic river network could have breaks. After eliminating local depressions, the “total drain” for each of the cells of the spatial grid (i.e. the number of all the cells whose runoff falls into a given cell lying lower on the slope) was calculated. The cells with the highest value of the “total runoff” form the basis for constructing a network of watercourses covering the entire basin. If one sets the corresponding threshold value of the “total flow”, one can design a fairly complete model hydrographic network.

All the procedures described above made it possible to construct a hydrologically correct digital relief model of the Lena River basin with the boundaries of the catchment basins of the main tributaries (see Figure 1).

A comparative analysis of the schematization obtained with the river system of the Lena River basin (Figure 2) allows us to conclude that, on

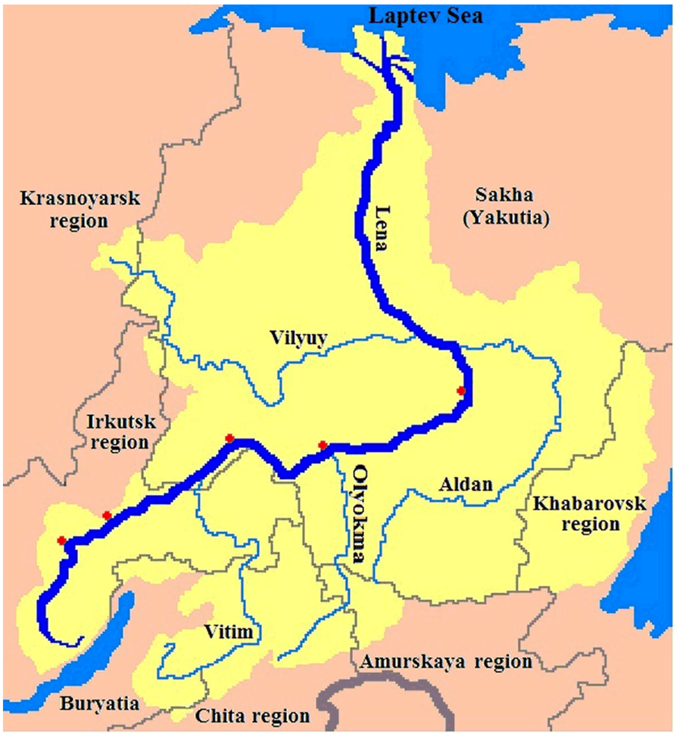

Figure 2. The Lena River basin

the whole, the shape of the watercourses corresponds to the shape of watercourses shown in the topographic maps. The constructed network of watercourses is more ramified, possibly, due to the fact that not only rivers, but also the entire erosion network in the Lena River basin are taken into account.

4. The results of linear models and improved topography

To assess the model reproduction of a river flow using the MERRA reanalysis database, the river flow from the Lena River basin was calculated with a 6-hour time step for 1980–2011. A time step equal to 6 hours provides the minimum time for the passage of a water stream through a grid cell of dimension $(1/3)^\circ \times (1/3)^\circ$.

Figure 3 shows a comparison between the annual cycles of the observed and model flows for the Lena River in the closing section of Kyusyur. It should be noted that the underground baseflow is not included in the calculation, since the mechanism of its formation is not fully implemented. And although it represents an insignificant stream in its value, its inclusion can affect the winter low water and the autumn rain floods. On the whole, the model results are in good agreement with the observational data, repeating the annual regime of the river flow with a high spring flood observed in the Lena River basin in the month of July of each year.

The results obtained in the coarse of the simulation were estimated according to the three statistical criteria between the calculated and observed values of the river runoff: the *bias calculation error* [13] (average deviation between the calculated and measured river flow values), the *correlation coefficient*, and the Nash–Sutcliff *efficiency* [14].

The quality of the calculations must be considered to be satisfactory, since the efficiency is 0.51 for 1980–2000. The bias calculation error for the month of June is observed in the range of 0.9–23 %. As for other months, it can reach 50 %.

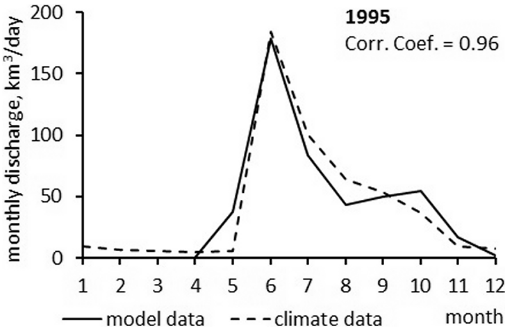

Figure 3. Comparison of the model hydrograph with the observational data at the Kyusyur stock station [12]

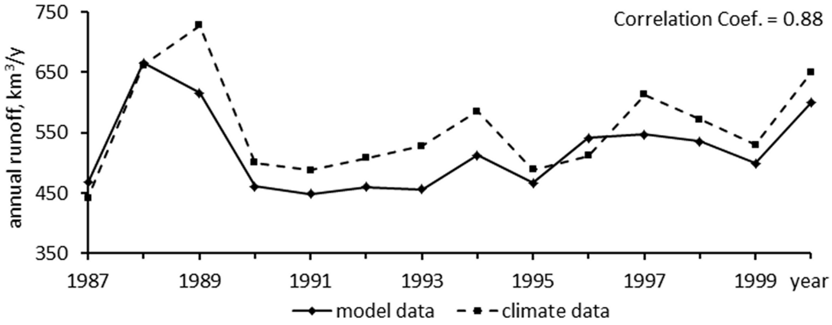

Figure 4. Comparison of the model annual runoff with the observational data at the Kyusyur stock station for the period of 1987–2000 [12]

5. Conclusion

The constructed model allows the determination of a more realistic model hydrographic network of the basin as compared to the previous version of the model [11].

In order to further improve the quality of the river flow calculation based on the linear model of the water balance formation in the channel network, a hydrologically correct digital relief model of the Lena River basin was constructed with a resolution of (1/3)° × (1/3)°. A fairly good agreement between the real and the model catchments (in the size, location and directions of the hydrographic network) provides an acceptable application of the delay coefficient parametrization using the characteristics of a mesh cell of a given resolution. A comparison of the observed and simulated discharges for the period of 1980–2011 shows an improved flow rate according to the linear model applied to a more realistic model catchment.

Further development of the linear model involves improving the parametrization of the surface and the river flows by incorporating the spatial heterogeneity of a cell in percent of wetlands. Since deviations of a natural flow from the observed one are also caused by the lake and the river regulation, when the information on natural objects (lakes) and river regulation processes (reservoirs) is accessible, their influence must be taken into account.

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