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Modeling the scenarios of catastrophic flood on the river of the Northern

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Abstract. Calculation of the maximum possible water discharge is one of the most important applied tasks. Its main feature is a high social and economic responsibility. Currently, the regulatory documents apply extrapolation of the empirical curve to the area of rare frequency, taking into account a guarantee correction. This method is quite reliable in terms of security, but not always economically feasible. One of the possible ways to estimate the maximum discharge for the river under study is to use a stochastic model along with a “weather generator” and a physico-mathematical model for the formation of a runoff. The weather generator is a stochastic model that predicts time series of several interconnected meteorological variables based on the statistical characteristics of the values observed at meteorological stations. This paper assesses the maximum possible water discharge for the Northern Dvina river near the city of Velikiy Ustyug and the worst-case scenario of the flood.

1. Introduction

Floods on the Northern Dvina river are the most serious natural disaster since the time people settled in these places. The main feature of the formation of floods and as a consequence of high water levels is ice jams that occur in the river bars and in places of narrowing of the channel. According to archival sources, 14 floods were recorded from 1500 to 1877. The water level during them rose to 7 meters, and during two of them, the water mark exceeded 10 meters. During instrumental observations, from 1877 to 2018, seven floods occurred in Velikiy Ustyug, the water level during which exceeded the 8-meter mark, and five floods, the level of which exceeded the 9-meter mark [1]. However, the floods that are not associated with ice jams can also cause significant damage. This raises the question of studying the nature of floods and predicting possible consequences.

Currently, the most reliable and detailed way to predict the possible consequences of floods is mathematical modeling. It enables prediction of the main hydrological characteristics of flooding: the maximum discharge at the peak of the flood, the depth of flooding, the flow rate vector and the duration of standing water. The application of a set of models for the study of runoff-genesis floods is due to two factors:

- Known cases of occurring of large water discharges in the Northern Dvina River in the area of the city of Velikiy Ustyug without the formation of ice jams, for example, the flood of 1984 when the total water discharge of the Sukhona and the Yug rivers reached 4090 m3/s.
- When water discharge of frequency of 1% or less passes, ice jams are not formed, as the water goes to the floodplain, the cross-sectional area of the stream increases and as a result, conveying capacity of the riverbed increases.

2. Object of research

The study section of the Northern Dvina, Sukhona and Yug rivers is located in the northeast of the European territory of Russia. The Northern Dvina valley from the junction of the Sukhona and Yug rivers to the mouth of the Vychegda river has a length of 65 km (72 km along the riverbed), extending almost in the meridional direction from South to North from the city of Velikiy Ustyug to Kotlas. The region under consideration is located in a zone of temperate continental climate (with cold winters and moderately warm summers). The water regime of the Sukhona river is characterized mainly by snow feeding, high spring flood and low winter low water. There are frequent rain floods in the summer-autumn period. The maximum water discharge, up to 40–60% of the annual flow, is formed during the spring flood [2]. The Yug river has a mixed feeding on the background of the predominance of snow feed. By the nature of the water regime, it also belongs to the rivers of the Eastern European type. The water regime of this river is characterized by a well-defined spring flood with a rapid rise and fall of levels. The largest annual amplitude of water levels in the Yug river is about 6.5 m. Powerful jams – a piles of ice in the form of ice floes and small fields – occur almost every year on Sukhona, Yug and Northern Dvina rivers. Ice clogging the cross-section of the river forms dams that cause a sharp rise in water level upstream their location. Ice jamming is typical for the initial stage of break-up, when the energy of flood water is still small, there are many large floes (on the Sukhona – ice fields) among the floating ice, which are the basis of jams.

3. Data and methods

The peculiarity of the calculations of maximum water discharge is a high degree of socio-economic responsibility, since extrapolation occurs in the area of rare frequency. Errors in the calculations can lead either to an overspending of funds in the construction of a hydraulic structure, or to human casualties in case of underestimation of the true value. When calculating the maximum water discharge, sometimes there are difficulties associated with approximation of the empirical probability curve by estimating statistical parameters from the actual series of observations. This is due to the presence of heterogeneity within the sample, for example, the discharge of low frequency can be associated with both the abundance of snow in the basin, and a small loss during infiltration or concurrent snow cover melting.

The problem of extrapolation of the empirical curve to the area beyond the area covered by actual data increases as the percentage of probability decreases. A.V. Khristoforov theoretically substantiated in 1993 that even with an ideal correspondence of the analytical and empirical curve, the errors in the field of rare repetitions can reach the order of several dozens of percent [3]. The problem of calculating the discharges of low probability is not completely solved yet in applied hydrology. However, the proposed approach focuses on statistical justification rather than intentional overstatement of parameters as a precaution, such as setting Cs/Cv equal to 3-4.

To simulate the characteristics of low-probability flooding, a set of models consisting of three blocks was used: the stochastic model FRAGM WG by A.N. Gelfan, ECOMAG flow formation model by Yu.G. Motovilov and STREAM-2D two-dimensional hydrodynamic model of V.V.Belikov et al.

The basis for obtaining data on meteorological elements was a "weather generator" stochastic model. The term "weather generator" introduced by Richardson [4] designates a class of stochastic models based on simulation of pseudo-time series. Richardson's model reproduced the combined course of maximum and minimum temperature, daily precipitation and total solar radiation. In 1990s, with the development of computing resources, various stochastic models appeared that based on the principles laid down by Richardson, such as WXGEN [10]. In 1991, the LARS-WG [9] model was developed in the UK. This model reproduced the intra-annual course of the same elements as the Richardson's model: daily precipitation, total solar radiation, daily maxima and minima of air temperatures. Precipitation was set on the basis of empirical distributions, multiple autoregression 1st order model was used to describe air temperature. However, unlike the Richardson's model, Fourier series were used to specify the seasonal variations of parameters. CLIGEN model [8] was developed for the needs of US Department of Agriculture. In addition to the four parameters described above, the CLIGEN model reproduces the average daily wind speed, which is subject to the Weibull distribution, as well as the minimum and maximum values of the humidity deficit, estimated from temperature data using the linear regression equation.

In the monograph "Dynamics-stochastic simulation of thaw flow" (2007) A.N. Gelfan notes that such weather generators reproduce well the main climatic features of the region under study due to the use of a large number of parameters set on the basis of actual data, but also notes two shortcomings:

- There is a problem in providing the weather generator with initial meteorological information that would allow obtaining stable estimates of statistical parameters;
- The second problem of using a weather generator is the existence of local weather conditions, which are not typical for a large area, but will nevertheless be recorded by weather stations

The stochastic model FRAGM WG, which is such "weather generator", was used to model the main meteorological values in the Northern Dvina river basin. A feature of this weather generator is a structure containing embedded generators that describe sequences of meteorological variables with yearly, monthly and daily time averaging [5].

The algorithm of this model consists of three stages:

- Average annual values of air temperature, precipitation probability, precipitation intensity and deficit of air humidity for days without precipitation are generated using the Monte Carlo method on the base of average annual parameters at the observed meteorological stations.
- With the help of periodic functions, the intra-annual course of meteorological variables is modeled. The values of variables generated in the first paragraph are used as a parameter of vertical displacement of the corresponding function.
- Daily averages of meteorological variables are generated using models of air temperature, precipitation and humidity deficit. Note that a simple first-order Markov chain was used for the precipitation model, the parameters of which were estimated for each month separately. All other sequences of meteorological variables were described using a first-order autoregression model, the parameters of which were described separately for each month and for days with and without precipitation.

The series of meteorological observations at 35 stations were used as initial data for stochastic modeling. The duration of the observations series for each station was 42 years. Based on the actual data, statistical values were calculated (mathematical expectation and standard deviation for each simulated value, as well as the correlation coefficient between precipitation values and air humidity deficit). Further, using the FRAGM WG model based on the Monte Carlo method, artificial 1000 years series of average daily values of temperature, precipitation intensity and a deficit of air humidity were generated.

Quality control of the model was carried out by comparing the simulated and the actual values for each station for each month. Special attention was paid to the months in which the floods occur, namely April, May and June (figure 1).

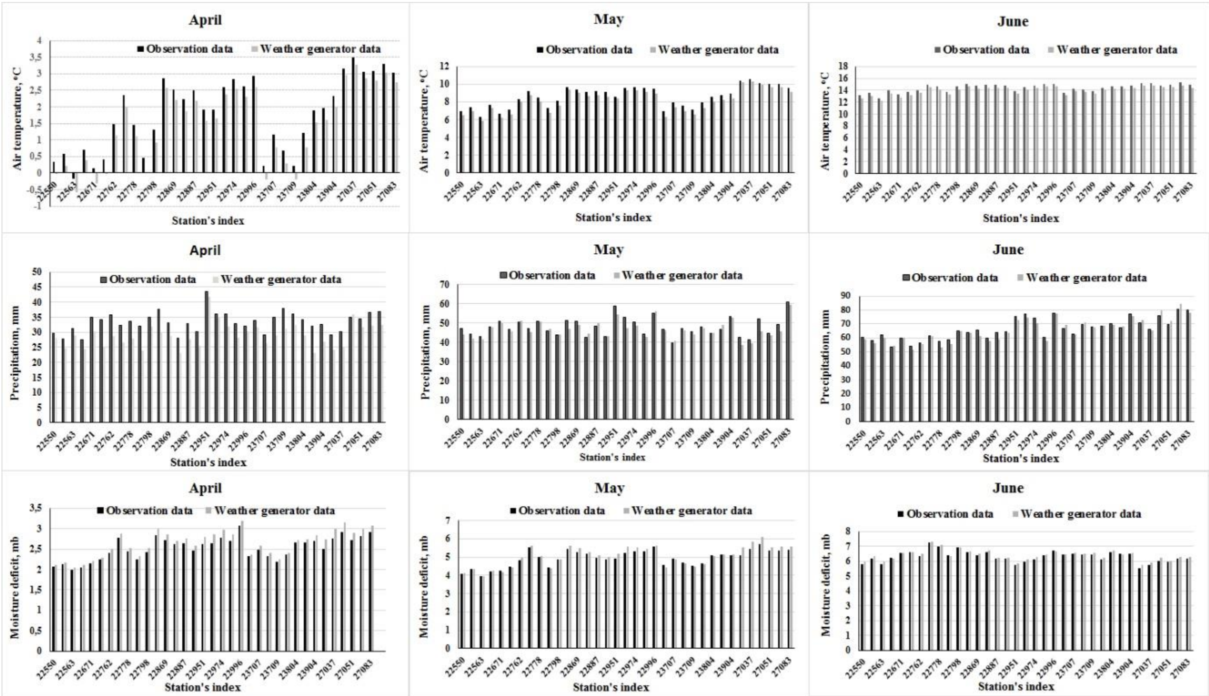

Figure 1. Comparison of actual and simulated values of average daily air temperature, monthly precipitation and average daily humidity deficit for April, May and June.

The comparison results showed a good agreement between the actual data. However, there are discrepancies when comparing the temperature in April, which can be explained by the fact that it is in April that the temperature passes through 0 °C, which complicates the modeling process.
Then, after the series was modeled, the obtained values of meteorological parameters were used as input data in the ECOMAG flow formation model.

The ECOMAG (ECOlogical Model for Applied Geophysics) Information and Modeling Complex (IMC) was developed by Yu.G. Motovilov [6] and includes: ECOMAG mathematical model; the specialized geographic information system (GIS), which is used to schematize a basin; the database of archive data on soil characteristics, vegetation, land use, pollutants; the database of operational hydrometeorological data; the information on the characteristics of the territory; the control shell that links the GIS and databases and allows for calculations.
The modeling of hydrological processes on each landscape element is performed for four levels: for the surface layer of soil (horizon A), the underlying deeper layer (horizon B), groundwater capacity and capacity in the zone of formation of surface runoff. In the cold period, the snow cover capacity is added. The scheme is completed with the consideration of water transformation processes in the river network.

It is worth noting that the use of the ECOMAG model is particularly relevant when studying floods in the area of the city of Velikiy Ustyug, since in 1989 the hydrological post in Gavrino village, which gave information on the Yug River its flow, was closed.

Since 1989, ECOMAG model data has been the best option for recovering water discharge data. Given this fact, the calibration of the model was carried out on the basis of data for 1969–1984, verification – for the period 1985–2014. A good correspondence was obtained between the simulated and observed hydrographs at the posts Kalikino (Sukhona River) and Gavrino (Yug River), which determine the water discharges at Velikiy Ustyug. After that, the analysis of the obtained values of water discharge was carried out and the most adverse option was chosen, namely, when the peak of the flood on the Sukhona River occurs at the same time with the peak on the Yug River (figure 2). The total discharge of 0,1% probability (according to the simulation results) was 13,585 m3/s, the

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maximum value for 1,000 years for the Yug River was 5,994 m3/s, and for the Sukhona River – 8,141 m3/s.

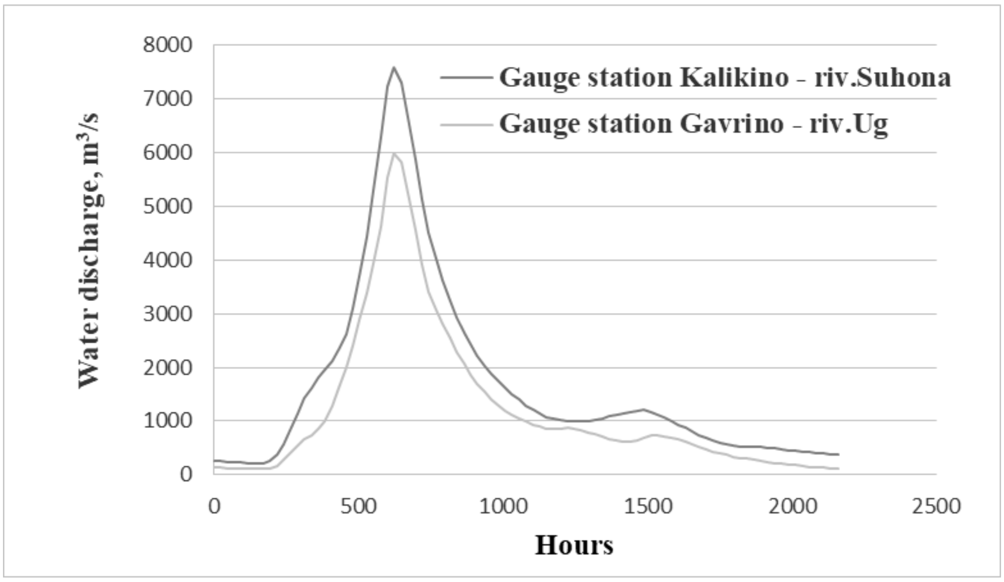

Figure 2. The most adverse hydrograph for the development of flooding, obtained on the basis of the joint use of the FRAGM WG weather generator and the ECOMAG flow formation model.

In addition to identifying an adverse hydrograph, an empirical water discharge curve was constructed based on the data obtained. In total, 365,000 values of average daily water discharge were used to construct the curve. For the Sukhona River, the range is from 8141 m^3/s to 6.7 m^3/s (data for the Kalikino hydrological station), and for the Yug River, the range is from 5994 m^3/s to 1.28 m^3/s. The resulting curve is shown in figure 3.

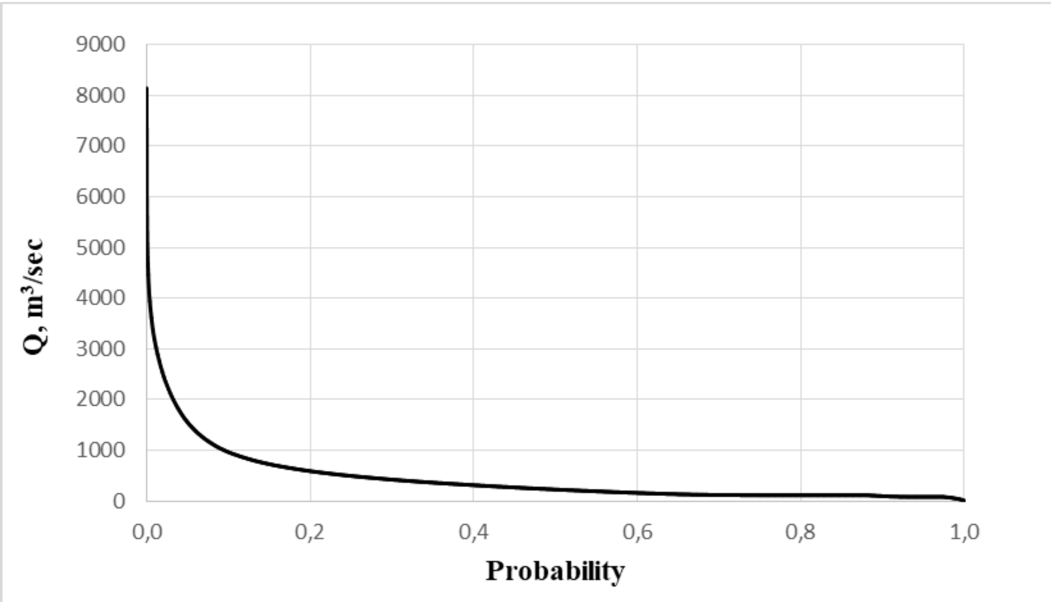

Figure 3. The empirical curve of probability built on the basis of the 1000-year series of water discharge pseudo-values.

For a detailed study of the water flow at the peak of the simulated flood, the two-dimensional hydrodynamic model STREAM-2D was applied. The model was developed by V.V. Belikov and A.N. Militeev [7]. It is based on the solution of the Saint-Venant equation, known as the shallow water equation. The equation is obtained by integrating over the depth of the Navier-Stokes equation, provided that the horizontal scale is much larger than the vertical one:

$$\begin{cases} \frac{1}{g}\cdot\frac{\partial u}{\partial t}+\frac{u}{g}\cdot\frac{\partial u}{\partial x}+\frac{v}{g}\cdot\frac{\partial u}{\partial y}+\frac{u^2}{C^2\cdot h}=-\frac{\partial z}{\partial x} \\ \frac{1}{g}\cdot\frac{\partial v}{\partial t}+\frac{u}{g}\cdot\frac{\partial v}{\partial x}+\frac{v}{g}\cdot\frac{\partial v}{\partial y}+\frac{|u v|}{C^2\cdot h}=-\frac{\partial z}{\partial y} \\ \frac{\partial(u\cdot h)}{\partial x}+\frac{\partial(v\cdot h)}{\partial y}=-\frac{\partial z}{\partial t} \end{cases}$$

where u is the velocity along the x axis, v is the velocity along the y axis, h is the depth, g is the acceleration of gravity, C is the roughness coefficient.

The initial conditions for the simulation are the initial bottom surface Z (x, y, 0), the corresponding instantaneous velocity fields V (x, y, 0), depth h (x, y, 0); water and sediment discharges and/or water surface levels are set at liquid boundaries.

The calculation trough two-dimensional hydrodynamic model was carried out for the period of 3 months, from April 1 to June 30. This period was chosen because when considering a long series of observations, various options should be taken into account for the beginning and end of the flood. The maximum level mark when simulating the passage of the most adverse hydrograph was 57.36 m at the hydrological station of Velikiy Ustyug (figure 4).

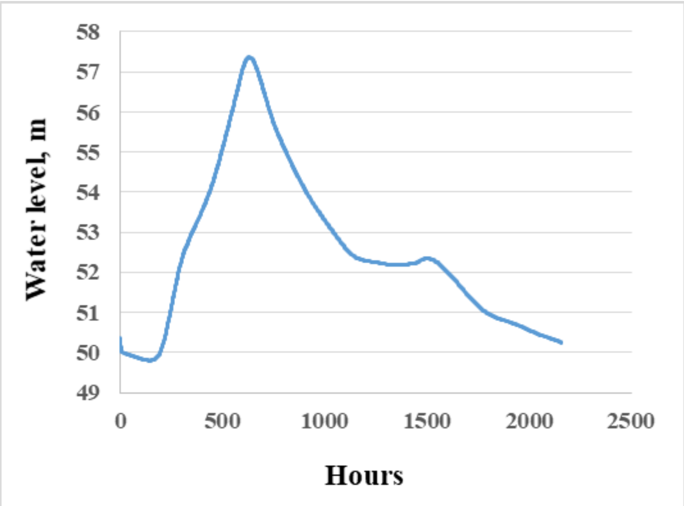

Figure 4. Chart of the level of the Northern Dvina river near the city of Great Ustyug during the passage of the 0.1% probability water discharge.

It is interesting that the flooded areas of 1% probability flooding of ice-jam genesis are greater than the flooded areas of 0.1% probability flooding of runoff genesis (figure 5).

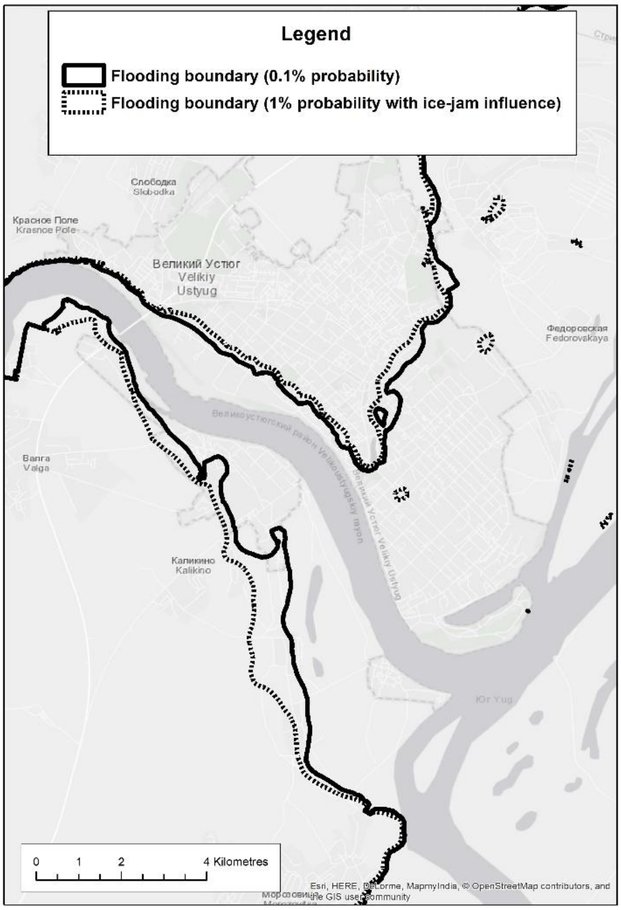

Figure 5. Comparison of the flooded area of 0.1% probability flooding of runoff genesis and the area of 1% probability flooding of ice-jam genesis (shown in bold line).

4. Conclusions

Based on the available archive data on temperature, precipitation and humidity deficit, the FRAGM WG stochastic weather generator was set up. Using the Monte Carlo method, the corresponding pseudo-values were simulated, the length of each row was 1000 values. Using the ECOMAG flow formation model, the average daily water discharges for every year from 1000 years were calculated. This allowed us to construct probability curves both for all water discharges available, and only for maximum ones. For the Sukhona River, the range is from 8141 m^3/s to 6.7 m^3/s (data for the Kalikino hydrological station), and for the Yug River, the range is from 5994 m^3/s to 1.28 m^3/s. Using the ECOMAG model, the most adverse hydrograph was revealed when the peak of the flood on the Sukhona River occurs at the same time with the peak on the Yug River, which is quite a real thing. The maximum level mark at Velikiy Ustyug is 57.36 m.

Assessment the boundaries of the flooded areas based on the simulation results revealed that the flooding of the runoff genesis of even a small probability of 0.1% is less compared to the flooding due to ice-jams with water level increases of 1% probability. Water discharge of 0.1% probability causes the flooding of the embankment, and the depth of flooding will be about 1.5 meters. In addition, the south-eastern part of the city is also subject to flooding, the depth of flooding according to the model is 0.5 m.

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