Application of the synthesis of mathematical models to study the characteristics of flooding of the Northern Dvina River

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Abstract. The flood on the Northern Dvina River is one of the key and vital natural phenomena for the residents of the Vologda and Arkhangelsk regions. The ability to quickly predict the characteristics of flooding through the use of different types of models allows for more efficient rescue operations, protect residential and commercial buildings, to assess potential damage. The PROSTOR software complex (on-line forecasting of dangerous situations in the territory), developed jointly by Moscow state University named after M. V. Lomonosov, SPII RAS and IWP RAS, combines the ECOMAG model of flow formation and the STREAM-2D two-dimensional hydrodynamic model. To study the possible critical values of flood characteristics, 37 floods were modeled from 1980 to 2016, with subsequent analysis of changes in characteristics for selected representative points.

1. Introduction

In Russia, floods are among the most serious natural disasters because of damage they cause to residential and commercial buildings located on the floodplains. The Northern regions are particularly susceptible to the negative impact of the waters, as the floods in the spring-summer period are influenced not only by the melting of ice and snow, but also by the occurrence of ice jams.

It is impossible to avoid floods completely, it is possible only to weaken or prevent a negative impact. In order to assess the potential damage, to identify possible flood zones, the influence of certain factors affecting the river during the flood passage, mathematical modeling methods are being increasingly used.

Advanced models enable to perform the calculations faster, make a forecast earlier, leaving more time to take measures to prevent flooding of the territory developed by man.

An example of such a technology is the PROSTOR complex [1] (on-line forecasting of dangerous situations in the territory), developed as a joint project of SPII RAS, Lomonosov Moscow State University and IWP RAS. This system can automatically download data from weather and hydrological stations, automatically predict the characteristics of flooding in real time. To create an...
automatic complex that allows obtaining prognostic information about the characteristics of flooding, the ECOMAG model of flow formation and the STREAM-2D two-dimensional hydrodynamic model were used.

2. Object of research
The Northern Dvina River at the confluence of the Sukhona and Yug rivers was chosen as an object for the development of a complex for predicting the characteristics of flooding. 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. In accordance with the terminology adopted until recently, this section of the channel was called the Little Northern Dvina.

This choice of object is justified by the following factors:
• 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. The water rise reaches 7 meters or more.
• This site has been sufficiently studied by hydrologists, but the coverage with hydrological posts is not enough. There is the only station measuring water discharge available on the Sukhona River, and on the Yug River the station was closed in the late 1980s.

3. Data and methods
The ECOMAG (ECOlogical Model for Applied Geophysics) Information and Modeling Complex (IMC) was developed by Yu.G. Motovilov. It includes: ECOMAG mathematical model; the specialized geographic information system (GIS), which is used to schematize a basin; the databases 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.

The STREAM-2D model was developed by V.V. Belikov and A.N. Militeev. It is based on the solution of the Saint-Venant equation, known as the shallow water equation.

\[
\begin{align*}
\frac{1}{g} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{u^2}{C^2 h} &= -\frac{\partial z}{\partial x} \\
\frac{1}{g} \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \left|\frac{uv}{C^2 h}\right| &= -\frac{\partial z}{\partial y} \\
\frac{\partial (u \cdot h)}{\partial x} + \frac{\partial (v \cdot h)}{\partial y} &= -\frac{\partial z}{\partial t}
\end{align*}
\]

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.
4. The study of the sensitivity of the STREAM-2D two-dimensional hydrodynamic model to the calibration parameters

The main parameter affecting the regime of the river flow being modeled is the roughness coefficient, which characterizes the state of the underlying surface of the riverbed and floodplain.

In this paper, using the example of a two-dimensional hydrodynamic model of a key section at the confluence of the Sukhona and Yug rivers (from Velikiy Ustyug to Kotlas), implemented on the basis of the STREAM_2D software complex [2-3], numerical experiments were carried out to assess the sensitivity of the main simulated characteristics, such as the depth of the flow (m), flow velocity (m/s), water surface area (km²), to changes in the riverbeds and floodplains roughness coefficients. All flow characteristics obtained in the course of modeling for each computational cell of the model were averaged on the basis of the ADREM program developed by A.A. Sazonov and A.N. Amerbayev (WPI RAS Laboratory of River Basins Hydrology). A total of 99 scenario calculations were performed. As input data, the discharges of the Sukhona and Yug rivers were set within the range of their changes over the observation period. The total discharge of the Little Northern Dvina River ranged from 1000 to 11,000 m³/s. The water level at the lower boundary was automatically calculated by the STREAM-2D model based on the Q = f (H) dependence curve, which was constructed from daily data on water discharge during the passage of the free-flowing (non-ice-jam) flood.

For each specified water discharge, 9 different calculation options were carried out with different roughness coefficients: the roughness coefficients of riverbed successively changed from 0.02 to 0.032 in increments of 0.04. Then, a roughness coefficient of riverbed was set at 0.028 and the roughness coefficients of floodplain changed successively. For this experiment, 5 roughness coefficients were chosen: 0.04, 0.05, 0.06, 0.08 and 0.1. This set of coefficients was specified to consider the entire range of changes in the types of underlying surface from vegetation on undeveloped floodplain to urban areas. As a result of numerical experiments, graphs of dependence on the input water discharge at different values of the roughness coefficient were plotted for each hydrological characteristic.

![Graphs](image)

**Figure 1.** The dependence of the average depth (a) and average speed (b) on the water flow at different coefficients of roughness of the riverbed.

The graph of dependence of average depth on water discharge at different riverbed roughness shows that at water discharges up to 4000 m³/s, the differences are insignificant and are within the error of determination. Starting from 4000 m³/s, the roughness coefficient of the riverbed begins to affect the difference in depth of the flow by a value of more than 40–50 cm. On average, when the roughness coefficient of the channel changes by 0.04, the depth of flooding changes by 17 cm. The maximum depth of 4.04 m will be observed at a discharge of 11,000 m³/s and a roughness coefficient of 0.032.
The difference in depth at a discharge of 11,000 m$^3$/s at a roughness coefficient of 0.02 and 0.032 is 53 cm, which is quite a large difference when using a two-dimensional hydrodynamic model in solving problems associated with flooding of the territory.

The change in flow velocity depending on the roughness coefficient occurs exponentially. At the maximum water discharge, 11,000 m$^3$/s, the difference between the flow velocity with a roughness coefficient of 0.02 and 0.032 is 0.16 m/s, which is a small change in speed.

5. **The use of a complex of models for a free-flowing flood (on the example of 1981)**

1981 was chosen as the representative year, since no ice-jam was observed in this year, but at the same time the total maximum discharge reached 8860 m$^3$/s. Archival information on precipitation, humidity deficit and temperature was used as input data.

After modeling the runoff in ECOMAG, the obtained data were transferred to STREAM-2D. On the basis of the calculations performed, a comparison was made of actual data, data modeled using STREAM-2D based on actual data, and calculations obtained using the joint use of the ECOMAG flow formation model and the STREAM-2D hydrodynamic model. The result is shown in the figure 2.

![Figure 2](image)

**Figure 2.** Changes in water level during flood. 1 – actual level, 2 – STREAM-2D model based on actual data, 3 – STREAM-2D model based on ECOMAG data.

The graph shows a good match between the actual level and the level modeled using STREAM-2D. The difference is from 10 to 15 cm, which is a good compliance.

In general, the course of the actual level and the modeled level correspond to each other. The level obtained by joint use of ECOMAG and STREAM-2D is underestimated relative to the actual one by 0.5 m and shifted by 1.5 days in terms of the onset of the maximum. This result is considered satisfactory.

The difference between the simulated level and the actual one can be explained by two factors:
- an error is inevitable in the flow formation modeling, as the flow process is not well understood;
In the STREAM-2D model, the level is determined using the dependence curve $Q=f(H)$ based on the data of ice-jam-free years. According to the simulation data, the hydrological characteristics were averaged: the depth of flooding, the flow velocity, the flooded area (Fig. 3).

In general, the graph of changes in the average depth of flooding follows the hydrograph. Starting from May 4, a sharp increase in the depth of flooding is observed; it reaches its maximum (3.2 meters) on May 14, after which a gradual decrease in the depth of flooding began. It is interesting to note that three steps are visible on the depth change graph, where a short and a slight, by about 30 cm, increase in the average depth of flooding is observed.

The change in the average flow velocity is described by a linear dependence on the water flow. The flow velocity, since the beginning of the flood, increased by 2 times, from 0.37 m/s to 0.66 m/s. After passing the peak of the flood, the flow velocity began to decrease evenly, reaching its minimum mark, 0.11 m/s, on July 25.

The average flooded area or average water surface area during the flood period increases 2.5 times, from 110 km$^2$ to 255 km$^2$. The graph shows three phases characterized by a characteristic change in the area of flooding. At the first stage, since the beginning of the flood, there is a sharp increase in the flooded area. Starting from May 14, it is possible to distinguish the second phase, during which the flood falls. The decrease in the flooded area occurs in waves, this is due to the release from water of wide flooded areas of the floodplain and the drying out of islands.

From June 10, the third phase begins, characterized by a gradual and slight decrease in the flooded area and a return to the low-water surface.

6. Sequential flood simulation for the period 1980–2016 using ECOMAG-STREAM-2D

Modern software complex STREAM-2D allows you to process not a single value of water discharge, but long periods of time, corresponding to the passage of high water. To analyze the long-term variability of flooding characteristics, a series of average daily discharges for the period from 1980 to 2016 were collected and analyzed using the ECOMAG flow formation model. For a correct comparison, the time period was taken from April 1 to June 30 for each year. This period was chosen due to the fact that regardless of the change in the time of the beginning and end of the flood, it somehow fell into it. For each year, using the archival data, a level graph was plotted for the hydrological stations of Velikiy Ustyug and the village of Medvedki. On the basis of the graph (Fig. 4), the time of the beginning and end of the standing of the ice jam and its presence was distinguished.
After collecting all the necessary data on water discharges, the time of the beginning and end of the ice jam standing, its location, the flow motion was calculated using the STREAM-2D hydrodynamic model. For the analysis and identification of temporal patterns, 6 representative points were selected: Velikiy Ustyug and Koromyslovo village on the Sukhona River, Morozovitsa and Koromyslovo villages on the Yug river, Medvedki village and Kotlas city on the North Dvina river. Using the author's ADREM program for processing the results of the modeling, the average long-term values of the depth of flooding and maximum depths for floods in these settlements were obtained. The results of systematization are presented in the table.

Long-term values of the average depth of flooding and the maximum depth of flooding were analyzed for the presence of a trend using the Spearman criterion at the level of significance of 5%. The analysis showed that changes in the maximum depth of flooding in all six settlements are not statistically significant. Changes in average depth of flooding, with the exception of the city of Kotlas, are also not statistically significant. In the area of Kotlas, a decrease in the average depth of flooding is observed. Analysis of the maximum depths showed that the greatest depth was observed during the flood in 1998 in the village of Koromyslovo, located at the confluence of the Sukhona and Yug rivers. According to model calculations, it was 11.6 meters. Also in Koromyslovo, the highest average long-term value of depth is registered – 9 meters. The most flooded settlement is Medvedki village, where the average depth of flooding exceeds the average long-term value every 2 years 2 months. Frequent overflooding of the average long-term depth is due to the regular occurrence of ice jam in the area. The maximum value of the flow velocity, 2.1 m/s, is also observed in the village of Medvedki. This value is also associated with the presence of ice jam, which narrows the cross section, compresses the water flow, thereby increasing the flow velocity.
| Location                  | Average long-term value of the maximum flooding depth, m | Average long-term value of flooding depth, m | Maximum flooding depth, m | Frequency of exceeding the average long-term maximum value, 1 time / number of years | Maximum flow velocity, m/s |
|---------------------------|----------------------------------------------------------|--------------------------------------------|---------------------------|------------------------------------------------------------------------------------------|----------------------------|
| Velikiy Ustyug, the Sukhona River | 8.0                                                      | 4.0                                       | 11.0                      | 2.3                                                                                       | 1.6                        |
| Koromyslovo, the Sukhona River | 9.0                                                      | 5.1                                       | 11.6                      | 2.3                                                                                       | 1.2                        |
| Morozovitsa, the Yug River | 5.0                                                      | 1.8                                       | 7.5                       | 2.3                                                                                       | 1.0                        |
| Demyanovo, the Yug River | 7.8                                                      | 4.3                                       | 9.7                       | 2.3                                                                                       | 1.4                        |
| Medvedki, The Northern Dvina River | 7.2                                                     | 3.6                                       | 9.2                       | 2.2                                                                                       | 2.1                        |
| Kotlas, The Northern Dvina River | 7.1                                                     | 4.4                                       | 7.6                       | 2.3                                                                                       | 1.0                        |

7. Conclusions
The joint use of physical and mathematical models provides the basis for the development of a system of operational forecasting of the floods, including in urban areas.

Analysis of the results of 99 scenario calculations showed that the most sensitive characteristic of flooding to changes in the roughness coefficient is the depth of flooding.

The water level obtained by simulation was compared with the actual level, the result is considered satisfactory. In general, the graph of changes in the average depth of flooding follows the hydrograph. With the help of the PROSTOR system, flood hydrographs were calculated with subsequent hydrodynamic modeling from 1980 to 2016. Based on the ADREM results processing program, the averaged and maximum depths for the 6 selected locations were obtained. The analysis of the results showed that the changes in the maximum depths are not statistically significant, and the excess of the average long-term value of the average and maximum depth of flooding occurs approximately every two years.

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