Influence of digital technologies on the quality of life by modelling the risk of flooding of territories by flood waters

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Abstract. Every year, there are many floods on the planet, which have a significant impact on ensuring the safety of people and affects the quality of life. The development of modern modelling technologies makes it possible to predict various scenarios for the development of the situation and reduce the likelihood of negative consequences. This issue is especially relevant for settlements located in the immediate vicinity of hydroelectric power plants, since by regulating discharge costs from hydroelectric power plants, it is possible to safely pass flood waters avoiding flooding of residential buildings and infrastructure, but this requires knowing the flooding zones at different water levels and discharge costs. This paper presents the results of solving the problem of modelling the dynamics of flood waters within the boundaries of the settlement of Krasnoyarsk. To calculate the flooded areas, the TUFLOW program was used in the Surface-water Modelling System modelling environment, as well as neural network forecasting using the NeuroPro software product. The simulation results made it possible to predict local flooding of the settlement during the flood of 2021 and take preventive measures to reduce the risk of flooding.

1. Introduction

Every year digitalization more and more penetrates the life of a person, regardless of where the person lives, improving the quality of life by automating routine processes and information processing. According to Maslow's pyramid, one of the main elements affecting the quality of life and the basic needs of modern society is security. The development of modern technologies makes it possible to improve security processes. One of the challenges of our time affecting the security of society is flooding caused by the flow of flood waters and rains. So, due to heavy rains on July 12, 2021, in the west and southwest of Germany, the tributaries of the Rhine Ahr and Moselle, as well as several small rivers, overflowed the banks. The main blow of the elements fell on the lands of North Rhine-Westphalia and Rhineland-Palatinate. More than 165,000 people were left without electricity, railways and infrastructure in the region were damaged. This issue is a global problem, as floods occur every year in various parts of the world, causing casualties, disruption to life and damage to infrastructure.

Catastrophic phenomena have their own pattern. During the period of preparation for the flood and the passage of the ice drift, hydrological forecasts, an effective warning system and evacuation of the population play a decisive role. Due to the constant change in hydrometeorological parameters, hydrological forecasts are being adjusted. Calculations show that the correct use of hydrological information on average reduces flood damage by 30 - 60% [1]. One of the ways to manage the risks of
natural emergencies caused by the influence of floods is the use of modern means of predicting risks and identifying areas of possible flooding under various negative scenarios of the situation.

At present, the introduction of big data and spawning forecasting technologies is widely used to solve the problem of determining the flooded areas of the territory [2-3], which allow predictive analysis with different forecasting horizons [4]. Weather forecasting, which is the basis for assessing the probability of floods, is subdivided into several ranges [5]: ultra-short-term forecasting: for 3 - 4 hours; short-term - for a day; medium-term up to 6 days and long-term forecasting for the entire flood season.

In the present work, the problem of determining the flooding zones of territories under various scenarios of the development of a flood situation was solved using the example of the city of Krasnoyarsk by applying the methods of mathematical modelling and neural network forecasting of flood waters in 2021.

2. Materials and methods

The inundation zones were calculated for the city of Krasnoyarsk, flooded at maximum water levels of 3, 5, 10, 25 and 50 percent availability (recurrence 3, 5, 10, 25 and 50 times per 100 years).

To determine the boundaries inundation zones flood zones are calculated by floods and floods of a given provision according to two mathematical models. The two-dimensional planning program TUFLOW in the SMS (Surface-water Modeling System) modeling environment, which builds planned two-dimensional flow models, is used to calculate the maximum water levels of the Yenisei. For the Kacha River, the Bazaikha River, the Bugach River, which have small cross-sectional dimensions in comparison with the flooded area, the modeling of the maximum water levels is carried out using the one-dimensional model of the HEC-RAS software package.

To determine the boundaries of flooded zones and their territories during modeling, [1] were used:

- digital elevation model (hereinafter - DEM) for the territory of work based on the results of topographic survey performed in August-September 2020 within the framework of engineering and geodetic surveys in accordance with the Federal Law "On Geodesy and Cartography" (figure 1);
- data on the marks of the characteristic water levels of the estimated supply at the points of the observational network of the FSBI "Central Siberian UGMS": the Yenisei River - the village of Bazaikha; the Yenisei river - Krasnoyarsk; the Kacha river - Krasnoyarsk; Bazaikha river - Bazaikha settlement;
- high water level marks (HLW) of the Yenisei River, obtained from interviews with local residents;
- estimated water consumption and the corresponding water levels of a given supply according to the data of hydrological posts;
- information from the Main Directorate of the Ministry of Emergency Situations of Russia for the Krasnoyarsk Territory, the Main Directorate for Civil Defense, Emergencies and Fire Safety of the City Administration Krasnoyarsk about information on the flooding zones of the territory of the city of Krasnoyarsk.

A digital elevation model (hereinafter - DEM) served as a cartometric basis for modelling. The modelling of the boundaries of the flooded zones was carried out in the local coordinate system (LCS-167) [2].
Figure 1. Digital elevation model of works in TIN format.

The TUFLOW computer program in the SMS (Surface-water Modeling System) simulation environment allows to build planned two-dimensional models of water flows averaged over their depth. This modelling environment has a graphical interface and allows you to manipulate and visualize data. The TUFLOW program was developed to simulate unsteady two-dimensional flows back in 1984 using equations for the laws of conservation of mass and momentum. This program was thoroughly tested by the US Army Corps of Engineers in 2001-2004 and is used in numerous calculations simulating sections of river systems.

The TUFLOW program constructs a solution to the water flow depth-averaged equations expressing the laws of conservation of mass and momentum in a two-dimensional rectangular coordinate system:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = 0,
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - c_f \nu + g \frac{\partial \zeta}{\partial x} + gu \left( \frac{n^2}{H^3} + \frac{f_1}{2g \Delta x} \right) \sqrt{u^2 + v^2} - \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + \frac{1}{\rho} \frac{\partial p}{\partial x} = F_x,
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} - c_f \nu + g \frac{\partial \zeta}{\partial y} + gv \left( \frac{n^2}{H^3} + \frac{f_1}{2g \Delta y} \right) \sqrt{u^2 + v^2} - \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \frac{1}{\rho} \frac{\partial p}{\partial y} = F_y,
\]

where \(u\) and \(v\) are depth-averaged \(x\) and \(y\) components of the velocity vector; \(\zeta\) - the level of the free surface of the water flow; \(H\) - its depth; \(\Delta x\) and \(\Delta y\) are the step of the computational grid along the \(x\) and \(y\) directions; \(c_f\) - Coriolis force factor; \(n\) is the Manning coefficient; \(f_1\) is the energy loss factor; \(\mu\) is the horizontal diffusion coefficient of the angular momentum; \(p\) - atmospheric pressure; \(\rho\) is the density of water; \(F_x\) and \(F_y\) are the components of the sum of external forces.

To solve this system of equations, an implicit scheme of the numerical alternating direction method is used for a finite-difference scheme using four fractional time steps and solving a tridiagonal matrix at each step.

The SMS system uses the so-called "conceptual modelling" approach, which is most effective for creating realistic models of high complexity. According to this approach, on the basis of a topographic map or a terrain plan using DEM and GIS objects (points, lines, polygons), a conceptual model is created. It is constructed independently of the computational grid and is a description of the study area,
including such geometrical characteristics as the channel, the coast, the boundary of the modelled area, water discharge and level as boundary conditions, as well as zones with different values of the roughness coefficients, turbulence indices and other characteristics of the channel, and flow in it.

After creating the conceptual model, the corresponding computational grid is automatically built and the data required for calculations is converted from the conceptual model to elements and grid nodes. This allows to automatically assign boundary conditions and design parameters. SMS includes tools for managing, editing and visualizing geometric and hydraulic data, creating and editing computational mesh data for use in numerical analysis.

Initial data for constructing a planned two-dimensional water flow model are given in table 1, are presented by the maximum water flow rates of the given provision of the Yenisei River and its tributaries - the Bazaikha River, the Kacha River in the upper sections of the calculated area and the water levels of the corresponding provision of the river Yenisei in the lower section of the computational area, predetermined by the slope of the water surface. The calculation is considered complete when the water flow reaches a stationary regime. The model enters a stationary mode when the water level changes during the calculated hour not exceeding 0.01 m.

Table 1. Maximum flow rates and water levels for building a two-dimensional model.

| Provision | Water consumption, m$^3$/s | Water level of the Yenisei River, m |
|-----------|-----------------------------|----------------------------------|
|           | Yenisei river | Bazaikha river | Kacha river | 32 km below the Krasnoyarsk g / p |
| 1%        | 13000         | 105            | 127         | 134.39          |
| 3%        | 10900         | 91             | 116         | 133.27          |
| 5%        | 9270          | 80.9           | 109         | 132.70          |
| 10%       | 7670          | 69.7           | 100         | 131.65          |
| 25%       | 5670          | 54.1           | 85.4        | 130.64          |
| 50%       | 4340          | 40.8           | 70.4        | 129.95          |

The size of the cells of the computational grid of the model after optimization of the configuration is minimized to 12 m with a total number of 1 million cells. The time step is set equal to 1 second.

To calibrate the model, we used water flow measurements in the range of levels from 900 to 380 cm above the "0" post.

The values of the roughness coefficients at the section of the Yenisei River station - the Bazaikha settlement vary from 0.018 to 0.03 at a flow rate of 21800 m$^3$/s (June 16, 1966) and 4230 m$^3$/s (October 22, 1974), respectively. In other sections of the river, the coefficients were selected for the best coincidence of the calculated and observed water levels on the date of a one-day connection of water levels during surveys with a flow rate of 3000 m$^3$/s. The values of the coefficients are 0.023 - 0.028. For floodplain areas, the coefficients are selected according to reference data, depending on the nature of the surface, they vary from 0.08 to 0.1; in built-up areas - 0.14.

For the tributaries of the Yenisei, the values of the roughness coefficients are taken equal to 0.03 - 0.04 for an ice-free channel and 0.025 - 0.028 for a stream flowing over the ice. In the latter case, hydraulic calculations were carried out on the basis of water consumption, taking into account the Kwin for the Bazaikha River, equal to an average of 0.6.

The slope of the water surface of the Yenisei in the lower design section was taken according to a one-day connection of the highest water levels in the sections of the hydrological posts of the village of Bazaikha, the city of Krasnoyarsk and the village of Atamanovo. The value of the slope is taken equal to 0.22%.

Table 2 shows the calculated water levels in the sections of the posts, obtained by the methods of hydrostatistics and mathematical modelling.
Table 2. Comparative characteristics of the water levels of the river Yenisei in the alignment of hydrological posts.

| Provision, % | the Yenisei river - Bazaikha village | the Yenisei river - the city of Krasnoyarsk |
|--------------|-------------------------------------|---------------------------------------------|
|              | statistically calculated | calculated by model | statistically calculated | calculated by model |
| 1            | 142.68                  | 142.54               | 141.43                  | 141.50               |
| 3            | 141.56                  | 141.39               | 140.31                  | 140.49               |
| 5            | 140.99                  | 140.87               | 139.74                  | 139.84               |
| 10           | 140.18                  | 140.13               | 139.01                  | 139.15               |
| 25           | 139.25                  | 139.20               | 138.00                  | 138.11               |
| 50           | 138.52                  | 138.62               | 137.31                  | 137.42               |

Also, the work carried out neural network modelling of the level of flooding of the territory of the city of Krasnoyarsk, depending on the discharge costs of the hydroelectric power plant. The simulation was performed using a neural network in accordance with the algorithm described in [8]. NeuroPro 0.25 developed at the Federal Research Centre of the KSC SB RAS [9] was used as a neuroimitator. The data set for forecasting was obtained from the data of operational monitoring of the flood situation and archival data on flooding of the territory for the last 30 years, taken from the database of the Main Directorate of the Ministry of Emergency Situations of Russia for the Krasnoyarsk Territory and the Federal State Budgetary Institution "Central Siberian UGMS". The input parameters were selected empirically. The dimension of the feature vectors was established empirically. In the calculation, a multilayer neural network with 12 layers and the number of neurons in hidden layers equal to 204 was used, which shows good results in practice. The percentage of reliability of the results varied and was in the range of 70-75%.

3. Results and discussion

Calculations for modelling the water flow of the Yenisei River were carried out to determine the boundaries of the flooding zones of the territories adjacent to the regulated Yenisei River with the estuaries of the Bazaikha River, the Kacha River in the downstream of the Krasnoyarsk hydroelectric complex, flooded when the hydrosystem passes floods 1%, 3%, 5%, 10%, 25%, 50% security.

For illustration, figure 2-4 shows the graphical results of modelling the flooded areas and their territories adjacent to the regulated Yenisei River in the downstream of the Krasnoyarsk hydroelectric complex.

Figure 2. Areas of flooding within the boundaries of the flooding zone, flooded when the Krasnoyarsk hydroelectric complex passes 50% of floods.
**Figure 3.** Water depth of flooded areas, flooded when the Krasnoyarsk hydroelectric complex passes floods of 50% of availability.

**Figure 4.** Flooded areas adjacent to the regulated river Yenisei with the mouths of the Kacha and Bazaikha rivers in the downstream of the Krasnoyarsk hydroelectric complex within the boundaries of the city of Krasnoyarsk, flooded when the hydroelectric complex passes floods of 1% of availability.

Figure 5 shows the longitudinal profile of the river's water surface of the Yenisei on the simulated site when the Krasnoyarsk hydroelectric complex passes floods of 1%, 3%, 5%, 10%, 25% and 50% of the availability, obtained from the calculation results.
Figure 5. Longitudinal profile of the water surface of the Yenisei River at floods of 1%, 3%, 5%, 10%, 25% and 50% of availability.

Comparative characteristics of the observed (survey) and calculated levels of the high-water horizon along the length of the Yenisei River within the boundaries of the city of Krasnoyarsk is shown in table 3.

Table 3. Comparison of water levels of 3% availability (2006).

| Location            | Level, m BS observed | Level, m BS calculated |
|---------------------|----------------------|------------------------|
| g / p Yenisei-Bazaikha | 141.58              | 141.96                 |
| g / p Yenisei-Krasnoyarsk | 140.35              | 140.47                 |
| st. Irbeyskaya      | 136.75              | 138.28                 |
| Peschanka village   | 138.45              | 136.46                 |
| Berezovka village   | 136.44              | 136.0                  |

The excess of the calculated water levels of 3% of the Yenisei supply over the high-water survey marks in 2019 on Irbeyskaya street by 1.5 m is caused by the narrowing of the floodplain flow due to the change in the relief of the urban area (filling up the road embankments) on the right bank after 2019, the flooding boundary 3% of water levels do not reach Irbeyskaya street.

The discrepancy between the calculated and observed water levels in the Peschanka village can probably be explained by the inaccuracy of the indicated survey mark of high waters in 2006 on the steep Yenisei bank.

Flooding zones of the territories adjacent to the Yenisei River, the mouths of the Kacha River, the Bazaikha River within the boundaries of the city of Krasnoyarsk are also determined taking into account the planning projects:

- the territory of the Historical Centre with the Kachinsky and Kombainovy districts on both banks of the river Kacha and the left bank of the Yenisei River opposite the Ostrov Otdlyha;
• the territory of the New Centre in the Soviet district on the left bank of the Tatyshhev channel opposite the Ostrov Otdlyha;
• territories the Ostrov Otdlyha and Ostrov Molokov in the river Yenisei;
• the territory of the "Pashenny" residential area in the Sverdlovsk district with the "Belye Rosy" residential area on the right bank of the Abakanskaya channel and part of the adjacent territory of Ostrov Otdlyha;
• the territory of the residential area "Yuzhnyi Bereg" within the former industrial zone of the Shipyard named after G.T. Pobezhimov on the right bank of the Abakanskaya channel in the area of Ostrov Otdlyha and Ostrov Molokov;
• the territory of Ostrov Tatyshhev to create a recreational complex of three large planning zones: the Oktyabrsky Bridge complex, the Strelka complex, and the Coastal complex.

The calculations, taking into account the location of the indicated territorial planning projects (figure 6), providing for the construction of sections of bank protection, embankments with a rise of the coastline and protrusions into the channel, show an increase in the water level of the river. Yenisei, not exceeding 0.16 m within the central part of Krasnoyarsk in conditions of narrowing of the flooded floodplain (figure 7).
Figure 7. Change in the calculated water levels of the river Yenisei with floods of 1%, 3%, 5%, 10%, 25%, 50% availability, taking into account the prospective development.

Neural network modelling was carried out in accordance with data on snow storage and predicted water level, depending on the discharge flow of the Krasnoyarsk hydroelectric power station. With discharges of the hydroelectric power plant (discharge 9000 m$^3$/s, water level 140.76 m according to the Baltic system of heights), at this level, the flooded area will be 25.0 sq. km., in this case, 96 private residential buildings will fall into the flooding zone. The simulation results are shown in figure 8.

Figure 8. Model of flood passage on the Yenisei River near the city of Krasnoyarsk.
The results obtained showed a high probability of flooding on the territory of Krasnoyarsk and the need for a complex of preventive measures in order to prevent flooding of residential buildings.

4. Conclusion

In this work, a method for increasing the protection of large settlements from the risk of flooding of the territory was demonstrated using the example of Krasnoyarsk. The demonstrated approach to solving the problem of the impact of flood waters on settlements using modelling and neural network forecasting methods has shown its effectiveness when the flood passes in 2021, since due to the large amount of precipitation in 2021, the city of Krasnoyarsk experienced a flood of 1% probability of passage. As part of this work, scenarios were developed for the passage of flood waters with the calculation of possible consequences. The boundaries of the estimated flood zones, obtained as a result of modelling, are confirmed by the data of surveys of local residents and information from the Department for Civil Defense and Emergencies on the flood zones of the city.

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