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Modeling the risk of territories flooding by flood waters on the Kan River

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Abstract. Throughout the existence of human civilization, flooding of territories as a result of the influence of flood and ground waters has threatened normal life. One of the ways to prevent negative impact of floods is the use of mathematical modeling methods using modern software. The paper presents the results of solving the problem of modeling the dynamics of flood waters within the boundaries of the settlement of Kansk and making a forecast of possible flooding for 2021. To calculate flooding zones of territories within the boundaries of Kansk by spring waters, the TUFLOW program was used in the Surface-water Modeling System modeling environment, as well as neural network forecasting using the NeuroPro software product and visualization of forecasting results in the AIMS RSChS-2030 software environment. Simulation of the passage of floods within the boundaries of Kansk was carried out under the condition that the timing of the onset of the maximum flow on the Kan River and its tributaries coincide. 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 in the world and in the Krasnoyarsk Territory in particular, there are many natural and man-made emergencies. The greatest risks of natural and man-made emergencies occur in the central and southern regions of the Krasnoyarsk Territory, which are characterized by a high population density and developed infrastructure. Most of hazardous industries are concentrated in the cities, there are transport hubs and large life support facilities.

Floods are one of the most tangible in terms of the scale of consequences on the territory of Siberia. So, in the period of 2019, as a result of heavy rains in the southern and eastern group of districts of the Krasnoyarsk Territory, there was a sharp rise in the water level in the rivers, as a result of which 24 settlements were flooded. The greatest flooding was recorded in the city of Kansk on the Kan River, where over 300 residential buildings were flooded, in which over 3000 people lived. In total, on the territory of Kansk in the period from 2016 to 2021, more than 1,300 residential buildings were flooded, in which 6,716 people live, which determines the importance and significance of solving this problem.

It is known that there is no absolutely reliable protection and there is always the possibility of exceeding the parameters of the most difficult (from a human point of view) scenario. For natural disasters, this is an event below 1% coverage. The multiplicity of factors contributing to the scale of an emergency makes it difficult to predict. Analysis of preventive measures carried out in different parts of the world demonstrates the need to predict hydrological conditions of river opening and a correct assessment of the situation for effective artificial impact on the processes of passage of flood waters.

Countermeasures may not be effective. In some cases, they can even contribute to the compaction of mash ice accumulation and a further rise in water levels.

The maximum water rise levels depend on many factors: on the amount of accumulated snow, on the intensity of snow melting and precipitation in the catchment area, on formation of ice jams and presence of autumn ice jams. A very important element is the weather during the snowmelt period.

Catastrophic phenomena have their own pattern. During the period of preparation for flood and 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 corrected. Calculations show that the correct use of hydrological information on average reduces flood damage by 30-60% [1].

Despite the development of modern technologies of predictive analysis and preventive measures, numerous natural and man-made emergencies continue to occur, causing irreparable damage to the economy and infrastructure of settlements and threatening life and health of citizens.

Eliminating the cause of floods at current level of development of science and technology is a difficult task, however, using modern methods of mathematical modeling, it is possible to calculate various scenarios for the development of situation, depending on specified parameters and thereby increase effectiveness of preventive measures.

One of the promising methods for predicting dynamics of flooding of the territory is implementation of mathematical modeling methods using neural network algorithms [2-3], which allow predictive analysis with a different forecast horizon [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 this work, mathematical modeling of the dynamics of water rise in the Kan River in the settlement of Kansk and neural network forecasting of the maximum level of flood waters in 2021 are carried out.

2. Materials and methods

To develop preventive measures in the event of an emergency and determine a flood zone, problems are solved with many variables that take into account a wide range of environmental factors; therefore, software tools were used, the algorithms of which are based on methods of mathematical modeling [6].

To determine the boundaries of flooding zones, the following were used:

- digital assessment model of the territory of work, performed according to the results of topographic survey in August-September 2016 (Figure 1);
- data on the marks of characteristic water levels at the points of the Kan and Ilanka rivers of observational network of the Federal State Budgetary Institution "Central Siberian UGMS" in the area of the city of Kansk;
- marks of the level of high waters (air-blast) of the river Kahn obtained from a local residents survey;
- estimated flow rates of the water flow and corresponding water levels of a given supply according to the data of hydrological posts;
- information of the Department for Civil Defense and Emergencies of the Administration of the city of Kansk about information on the flooded zones of the territory of the city of Kansk. Modeling of the boundaries of the flooded areas was carried out in the local coordinate system (local coordinate system of the Krasnoyarsk Territory (MSK) -168).

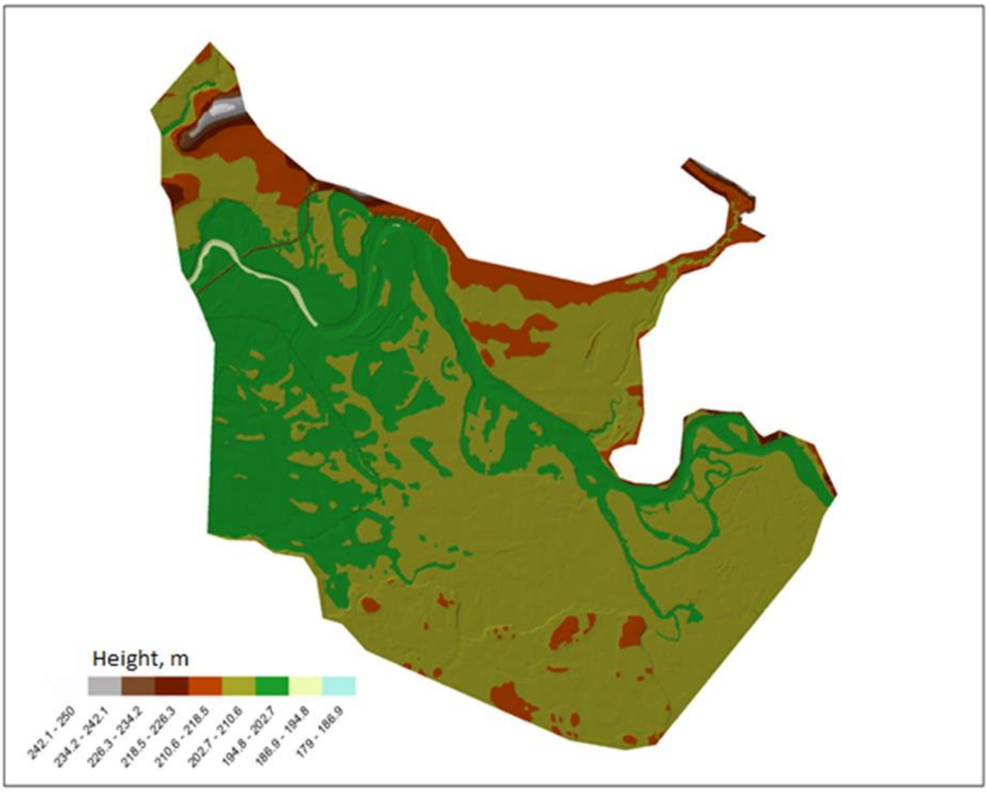

Figure 1. Digital elevation model of the work area in TIN format.

The simulation was carried out using the TUFLOW computer program [7] in the Surface-water Modeling System simulation environment. The program allows you to build two-dimensional models of water flows, which are further averaged over depth. The program includes tools for managing, editing and visualizing geometric and hydraulic data, creating and editing computational mesh data for use in numerical analysis. The program has a graphical interface and allows you to visualize calculation data.

The TUFLOW program in the Surface-waterModeling System simulation environment uses the law of conservation of mass and momentum in a two-dimensional rectangular coordinate system to solve the water flow equations:

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

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-c_f v+g\frac{\partial \zeta}{\partial x}+gu\left(\frac{n^2}{H^{\frac{4}{3}}}+\frac{f_1}{2g\Delta x}\right)\sqrt{u^2+v^2}-\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{1}{\rho}\frac{\partial p}{\partial x}=F_x$$

(1)

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}-c_f u+g\frac{\partial \zeta}{\partial y}+gv\left(\frac{n^2}{H^{\frac{4}{3}}}+\frac{f_1}{2g\Delta y}\right)\sqrt{u^2+v^2}-\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{1}{\rho}\frac{\partial p}{\partial y}=F_y$$

where u and υ are averaged according to the depth x and y which are velocity vector components; ζ is free surface level of water flow; H is its depth; Δx and Δy is a step of the computational grid along the directions x and y; c_f is Coriolis force factor; n is Manning coefficient; f_1 is energy loss factor; μ is horizontal diffusion coefficient of angular momentum; p is Atmosphere pressure; ρ is density of water; F_x and F_y are components of the sum of external forces.

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

The Surface-water Modeling System uses the so-called "conceptual modeling" approach, which is effective for creating realistic models of great complexity. According to this approach, on the basis of a topographic map, or a terrain plan using a digital elevation model and data from a geographic information system (GIS: points, lines, polygons), a conceptual model is created. This model is built independently of the computational grid and is a description of the study area, including such boundary conditions, geometric characteristics as: channel, coast, border of the territory, discharge and water level. It is possible to mark zones with different values of the roughness coefficients, turbulence indices and other characteristics of a channel and flow in it.

After creating a conceptual model, the corresponding computational grid is automatically built and the data required for calculations is converted from a conceptual model to elements and grid nodes. This allows you to automatically assign boundary conditions and obtain design parameters.

The initial data for constructing a two-dimensional model are given in Table 1, which presents the values of maximum water flow rates for a given supply of the river Kan, the river Ilanka in upper section of the area used in calculations and corresponding water levels of the river Kan - in the lower section, previously determined by the slope of water surface. The model, in which calculations are considered complete when water flow enters a stationary regime, assumes a change in the water level for a calculated hour of no more than 0.01 m.

Table 1. Values of maximum flow and water level of the river Khn, the river Ilanca used to build a two-dimensional model.

Availability	Water consumption, m^3 / s upper section of computational domain		Water level, m lower section of computational domain
	r. Kahn	r. Ilanka	r. Kahn
1%	3010	48.4	202.63
3%	2440	39.5	202.06
5%	2290	33.8	201.81
10%	1880	27.2	201.2
25%	1480	18.2	200.51
50%	1270	10.9	200.11

The size of cells of computational grid of the model after configuration optimization is minimized to 7.4 m with a total number of 1 million cells. The time step is set to 0.75 seconds.

The model is calibrated based on measured water flow rates. Values of roughness coefficients in the Kan channel were obtained from the low-water flow rate of 464 m^3 / s (July 2016) and the flow rate of 1840 m^3 / s (May 1965), measured at the marks of water outlet on the floodplain. Values of the coefficients are 0.023-0.024. For floodplain areas, the coefficients are selected according to reference data, depending on the nature of the surface in undeveloped areas, they vary from 0.08 to 0.1 and in built-up areas - 0.14. For the river Ilanka, a coefficient of 0.04 is adopted.

Long-term forecasting of the risk of flooding in Kansk, Krasnoyarsk Territory, was carried out using a neural network in accordance with the algorithm described in [8]. NeuroPro 0.25 developed at the Federal Research Center of the KSC SB RAS [9] was used as a neuroimmitator. The data set for forecasting was obtained from the data of operational monitoring of flood situation and archival data on flooding of the territory over the past 30 years, taken from the database of the Main Directorate of the Ministry of Emergencies of Russia for the Krasnoyarsk Territory and the Federal State Budgetary Institution "Central Siberian UGMS" The input parameters were selected empirically. 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. Percentage of reliability of the results obtained was in range of 70-75%.

3. Results and discussion

To determine the boundaries of the flooded areas adjacent to unregulated areas on the Kan and Ilanka within Kansk, a water flow simulation was carried out at water flow rates of 1%, 3%, 5%, 10%, 25%, 50% of the maximum availability.

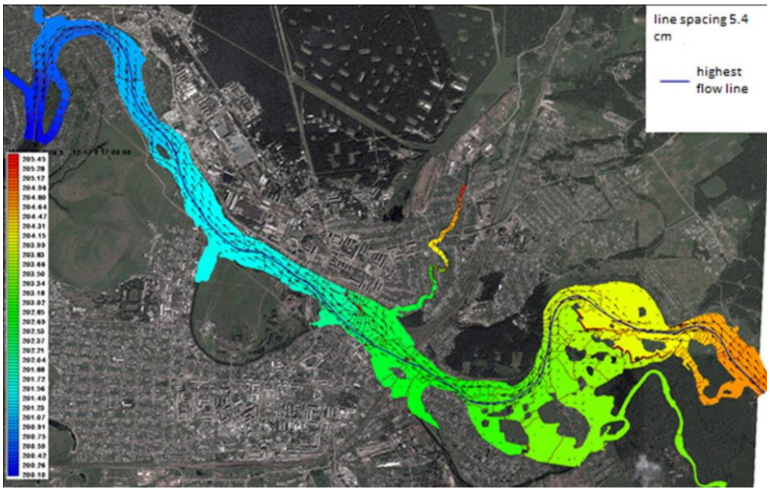

Figure 2. Flooding zone of territories adjacent to Kansk, flooded during high water and high flows of 50% availability.

Figure 2 shows the results of modeling the flooding zones of territories adjacent to unregulated areas within Kansk, flooded during high water and high flows, provided 50% of the maximum availability.

Figures 3-5 show the results of modeling the flooding zones of territories adjacent to unregulated areas within Kansk, flooded during high water and high flows of 1% availability in absolute heights, depths and velocities field.

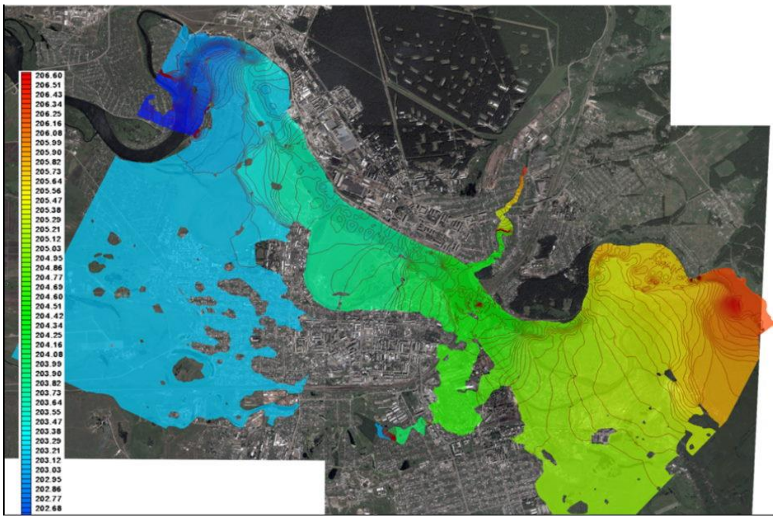

Figure 3. Levels of the free surface of the water in the flooding zone of the territories adjacent to the rivers Kan and Ilanka within the town of Kansk, flooded during high water and high flows 1% of availability.

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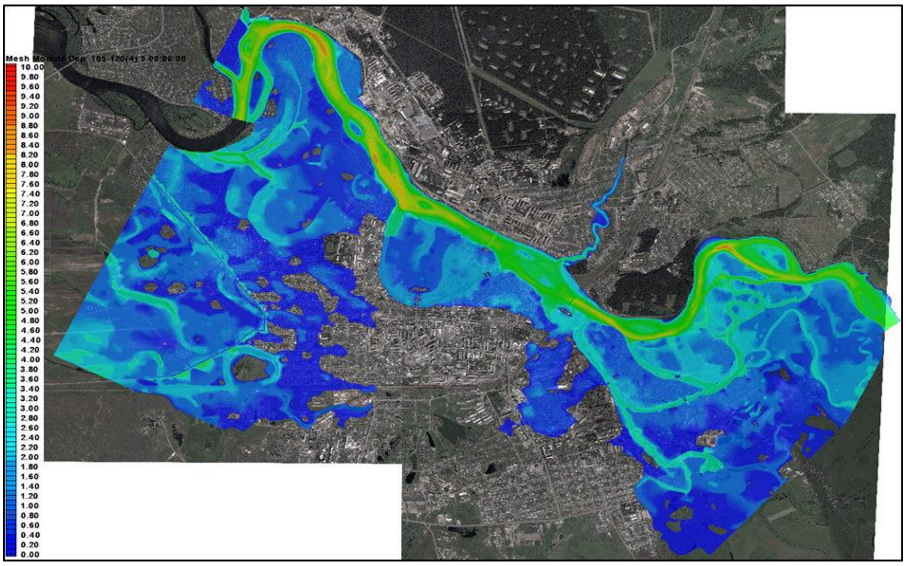

Figure 4. Water depth in the flooding zone of the territories adjacent to the rivers Kan snd Ilanka within the city of Kansk, flooded during high water and high flows 1% of availability.

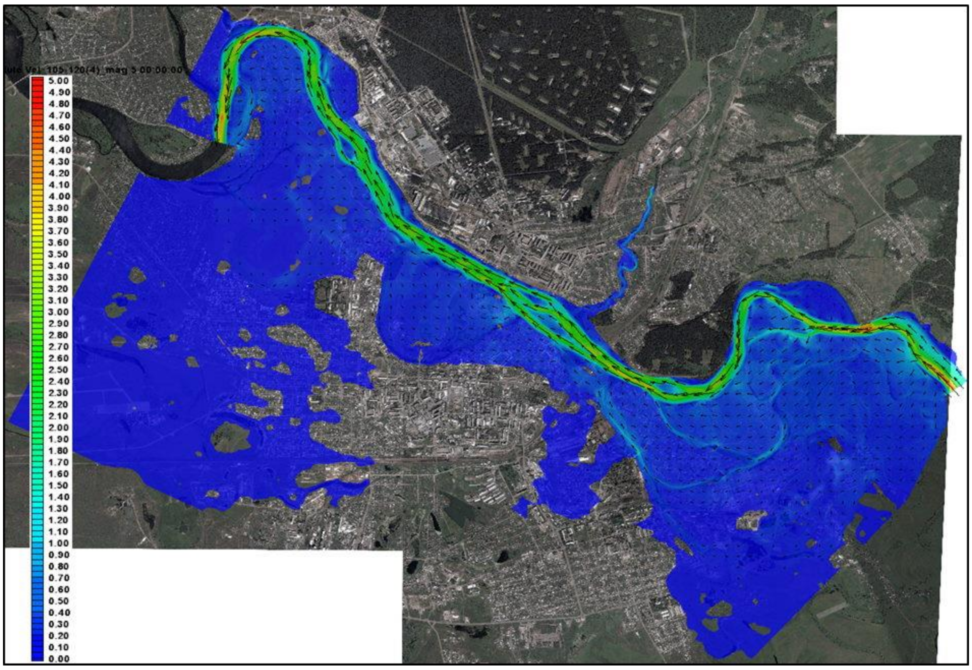

Figure 5. The field of velocities in the flooding zone of the territories adjacent to the rivers Kan and Ilanka within the city of Kansk flooded during high water and high flows 1% of availability.

Figure 6 shows the longitudinal profile of the river's water surface of the river Kan during high water and high flows of 1%, 3%, 5%, 10%, 25% and 50% of the availability obtained from the modeling results.

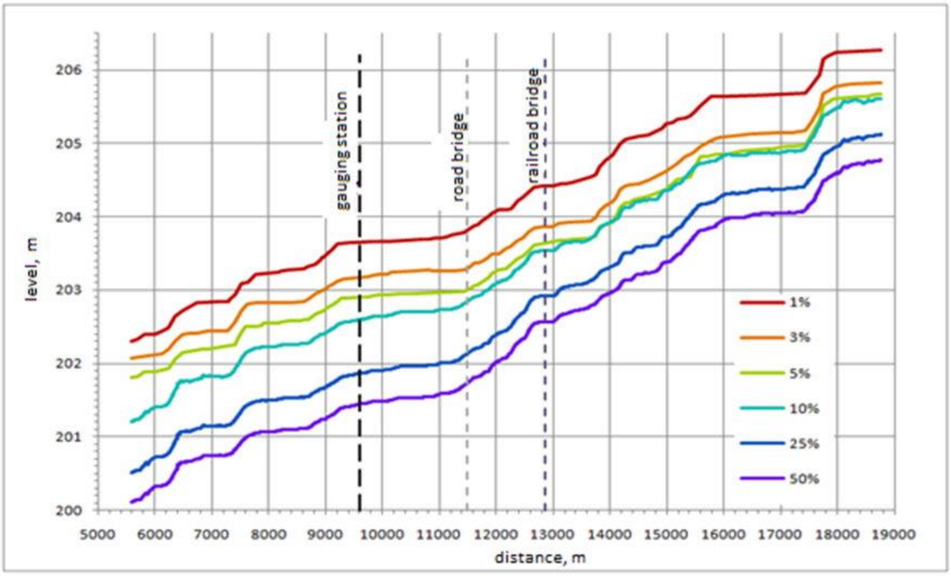

Figure 6. Longitudinal profile of the water surface of the river Kahn with high water and high flows 1%, 3%, 5%, 10%, 25% and 50%.

The boundaries of estimated flood zones obtained as a result of modeling are confirmed by the data of surveys of local residents and information from the Civil Defense and Emergencies Department on the flood zones of the city.

Difference between the calculated levels in model and in alignment of a hydrological station on the river Kan varies from –6 to +41 cm (table 2).

Table 2. Values of water levels in the section of the hydrological station of the river Kan, the town Kansk.

Availability	Level in the section of the hydrological station, m	
	calculated according to observations	calculated according to model
1 %	203.31	203.62
3 %	203.02	203.43
5 %	202.74	202.89
10 %	202.45	202.6
25 %	201.98	201.86
50 %	201.5	201.44

The calculated levels of rare availabilities obtained for different sections along the length of the river are partially confirmed by the marks of high waters indicated by local residents, with te exception of water levels of more than 50% of the abundance (Table 3). In 5 out of 6 cases, indicated water levels are 0.5 - 3 m higher than calculated levels of 50% supply. Probably, extreme levels are better remembered.

Table 3. Comparative characteristics of observed and calculated water levels along the length of the river Kan within the city of Kansk.

Flooding	Year	Water level, m BS (Baltic system)					Note
		observed	availability	calculated	availability	Neural network modeling	
128 residential houses	2005	202.23	8	202.6	5	202.28	downstream flooding
102 residential houses	1978	204.15	>50	202.1	50	204.12	
	2000	202.62	>50	202.1	50	202.54	
25 residential houses	1987	204.25	3	204.8	3	204.11	Stariy Kan stream
	2000	203.86	>50	203.1	50	203.74	
87 residential houses	2001	204.85	4	204.43	3	204.64	Stariy Kan stream
303 residential houses	2019	205.55	1	205.10	1	205.85	downstream flooding

Duration of the flood and its characteristic levels on the river Ilanka in high-water years were determined from observations of a hydrological station. The flood in Ilanka usually begins with a flow of water over the ice, the water levels during this period and the highest for the year are of a retaining nature. Fluctuations in the water levels of Ilanka are schematized by one flood wave with the coordinates indicated in Table 4. Fluctuations in water levels of the river Kurysh are schematized in a similar way.

Table 4. Typical points of a calculated graph of fluctuations in water levels of a high-water year in sections of hydrological posts.

river Kan - town Kansk		river Ilanka - town Kansk	
date	level, m BS	date	level, m BS
April 9	198.54	April 9	206.74
April 30	200.06	April 21	208.88
May 22	203.3	May 30	205.62
July 5	200.07	-	-
August 6	200.76	-	-
September 1	199.72	-	-
September 20	199.7	-	-

As a result of simulation, the results of influence of groundwater on the development of floods in the border of the territory of the city of Kansk were obtained:

- areas of severe flooding (with a groundwater depth of less than 0.3 m);
- areas of moderate flooding (with a depth of groundwater from 0.3-0.7 to 1.2-2.0 m from the surface);
- areas of weak flooding (with a depth of groundwater from 2.0 to 3.0 m).

Modeling of groundwater levels was carried out within an annual period with discreteness from several days to decades for situations of presence and absence of floods. In the latter case, water levels

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of the river and its tributaries are assumed constant throughout the year and equal to the minimum levels of calculated schedule of a high-water year.

The boundaries of individual periods of modeling in the presence of a maximum flood are shown in Table 4 (excluding the low-water period). Within the simulation periods, river water levels are assumed to vary linearly with time. During the period of the main flood wave (April 30 - June 5 for the Kan River, April 9 - May 30 for the Ilanka River), it is taken to be equal to days, in other periods equal to 10 days. In the absence of a flood, the modeling step is equal to 10 days for the entire modeling period.

The calculated surface of the maximum groundwater levels in the year of a flood of 1% availability is compared with the surface of maximum groundwater levels in the absence of flood effect. An area where the level difference does not exceed 0.1 m is not considered when determining the area of flooding induced by the river.

Graphic description of the boundaries of flooding zones in the territories adjacent to flooding zones with a maximum water level of 1% of availability of unregulated rivers Kan, Ilanka, Kurysh within the boundaries of Kansk is shown in Figure 7. The territory bounded by the western part of the city is not subject to direct flooding by high waters of the river Kahn due to the closure of most culverts. The territory under consideration contains a large number of lakes with a total area of about 0.3 km^2. The main source of replenishment of water reserves in these lakes before the development of the territory was high water and high flow on the river Kan. After the development and creation of structures to protect the territory from flooding, the inflow of water from the Kan River began to be of a ground nature and its volume (up to 30-50 thousand m^3 in high floods) is currently only enough to maintain the level of the lakes at elevations approximately corresponding to elevations of the level of groundwater in low water season. The main source of increase in the level of lakes is currently the runoff from snow melting and rainfall from the slopes of the river Kan valley (estimated up to several hundred thousand m^3 per year).

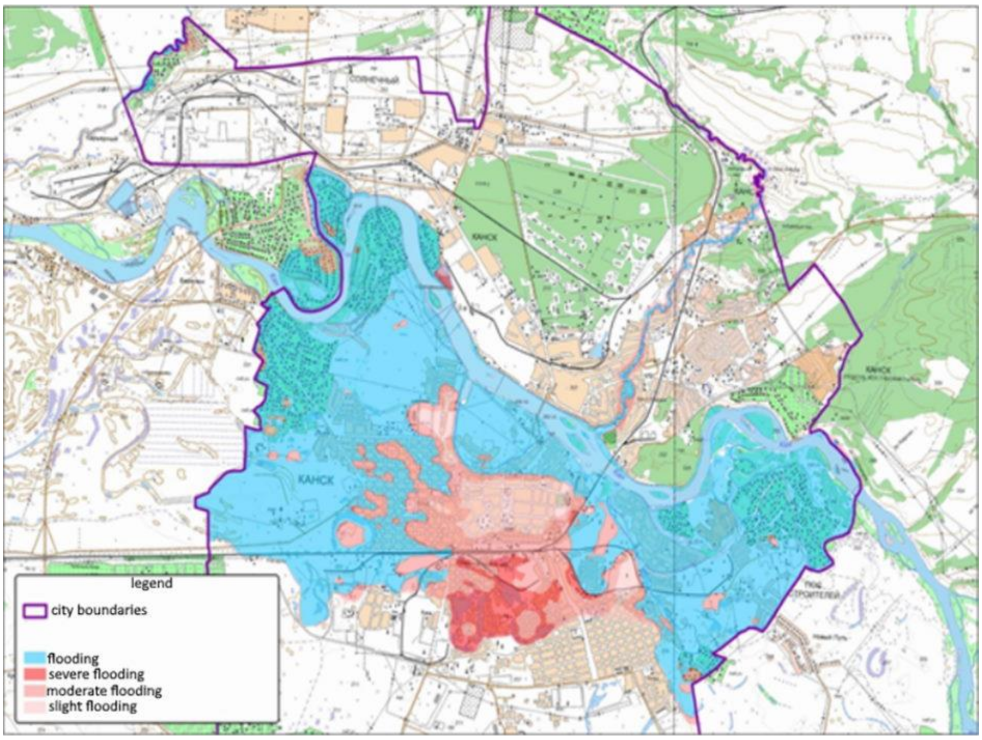

Figure 7. Graphic representation of the boundaries of areas of flooding of territories during high water and high flow of 1% of the rivers Kan, Ilanka, Kurysh within Kansk.

Based on the data obtained as a result of modeling, taking into account snow reserves in the Kan River basins, which in 2021 exceed the standard indicators by 100-200%, based on the methodology described in the work, forecasting of flood waters on the Kan River was carried out. In accordance with the model, the maximum values of water rise in 2021 can reach 204.2 cm in the Baltic system of heights, at this level the flooded area will be 5.0 sq. km., in this case, 24 private residential buildings will be in the flooding zone. The data obtained as a result of calculation were imported into the AIMS RSChS-2030 system and a model of flood at this level was developed, the results are shown in Figure 8.

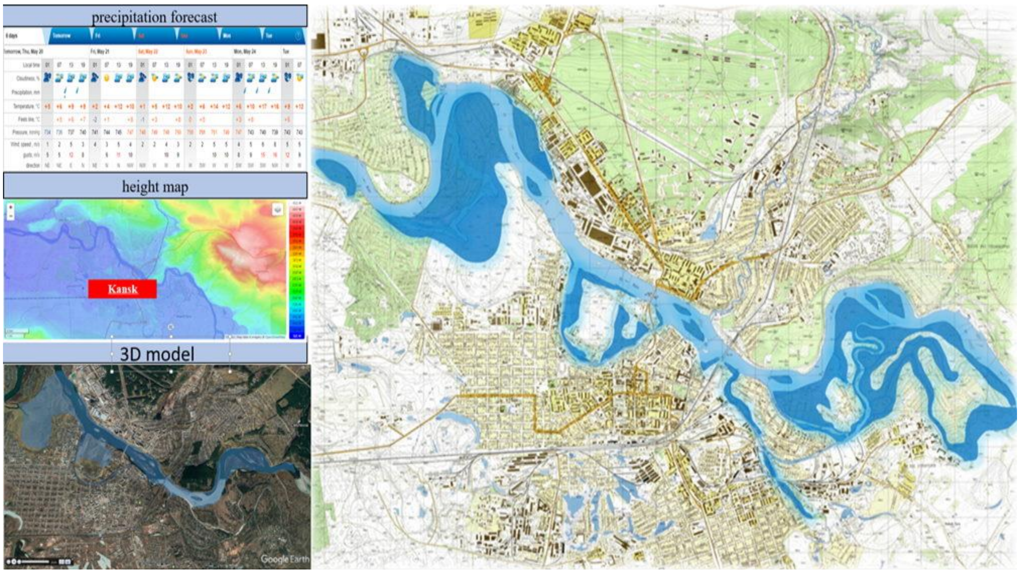

Figure 8. Model of flood on the Kan River near Kansk.

The results obtained showed a high probability of flooding in the territory of Kansk and the need for a complex of preventive measures in order to prevent flooding of residential buildings.

4. Conclusion

In this work, an approach to solving the problem of influence of flood waters on settlements was presented by methods of modeling and neural network forecasting. The boundaries of estimated flood zones obtained as a result of the modeling are confirmed by the data of surveys of local residents and information from the Civil Defense and Emergencies Department on the flood zones of the city.

The maximum flooding of territories within the boundaries of Kansk was observed in July 2019, in the alignment of the hydrological station the water level rose to 205.5 m BS, as a result of which 380 residential buildings got into the flooding zone.

As a result of the study, a forecast was made for flood waters on the Kan River, in the area of Kansk. The forecast indicates the likelihood of local flooding of the territory of the city of Kansk, the water level can reach 204.20 cm in the Baltic system of heights, at this level the flooded area will be 5.0 sq. km., in this case, 24 private residential buildings will be in the flooding zone.

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