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Justification of Hydrological Safety Conditions in Residential Areas Using Numerical Modelling

V. V. Belikov[a, *], A. I. Aleksyuk[a, b], N. M. Borisova[a], E. S. Vasilieva[a], S. V. Norin[a], and A. B. Rumyantsev[a]

[a] *Water Problems Institute, Russian Academy of Sciences, Moscow, 119333 Russia*

[b] *Faculty of Mechanics and Mathematics, Moscow State University, Moscow, 119991 Russia*

**e-mail: belvv@bk.ru*

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Abstract—The present paper looks at the application of modern technology of numerical modelling to simulate natural and human-induced river floods of residential areas. The modelling is based on the use of 2D shallow-water equations and 3D digital terrain models. The application of adaptive mesh generator and effective algorithms of parallel computing using NVIDIA graphics processors with CUDA technology enables calculating the areas and depths of flooding in a big city, taking into account all residential, industrial, and road constructions. Each one of them is specifically singled out on the mesh. This enables the reproduction of the real course of a flood well.

Keywords: residential areas, flood, dam-break wave, flooded area, numerical modelling

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INTRODUCTION

People have settled along rivers from time immemorial. Nowadays, due to the growth of big cities, the increase in the number of summer houses and cottages, as well as the development of road infrastructure, the human impact on floodplains and river banks is becoming stronger. The authors of the present paper have recently been involved in hydrodynamic modelling of floods in order to ensure the hydrological safety of several large objects. These include Oktyabrsky island in the Pregolya River (the City of Kaliningrad), where a football stadium with the appropriate infrastructure was built for the 2018 FIFA World Cup; the left-bank floodplain of the lower Don (the City of Rostov-on-Don)—an area under active development where a football stadium for the 2018 FIFA World Cup was constructed; part of Kuznetsovsky boat-yard of the Belaya River floodplain, which will be transformed into a new district of the City of Ufa; Zakharovskaya floodplain of the Moskva River, where cottages will be built; ‘Kamskaya valley’—the prospective development area in the floodplain of the Kama River (the City of Perm); the City of Yaroslavl on the Volga River; etc. Almost all these objects, apart from being threatened by natural floods, can also be influenced by waves breaking through the hydropower structures upstream (not based on a real danger). This complicates calculating flood areas and their depth, and leads to stricter safety requirements in the prospective construction areas.

According to the existing standards, settlements along rivers must be protected against flash-floods, wind set-up, and groundwaters with filling or embanking. The edge of the reclaimed territory should be no less than 0.5 m above the predicted high-water level with regard to the wave height at wind set-up. The extent to which the crest of a flood-breaking dam exceeds the predicted level should be set depending on the class of structures pursuant to sets of rules Nos. 104.13330.2016 and 58.13330.2012 [8, 10]. According to set of rules No. 42.13330.2011 [9], the predicted high-water level should be set at the highest water level recurrent every 100 years for urban (or to-be built-up) areas with residential and public buildings, and every 10 years for parks and ‘plane’ sports venues [9]. It is forbidden to construct any buildings, facilities, utilities, or transport infrastructure in the flood-prone areas (with the flooding depth equal to or exceeding 1.5 m) that are not supplied with flood-prevention engineering systems [9].

Residential areas situated in river floodplains considerably influence the water level and flooding areas of natural or industry-induced river floods. This creates additional hydraulic resistance due to the flows around obstacles. Of vital importance here is the fact that the resistance that has to be considered in calculations is form drag, not friction. It cannot be described in simple relationships like the Manning formula. Dense residential areas and road dams across floodplains affect the water level and flood zones most significantly. If areas are protected by dams or filling, it is necessary to calculate the maximum flooding levels taking into account the fact that the flow is constricted by these objects. In some cases, due to historically formed housing development, localities are not protected against floods with any engineering systems. This can lead to natural disasters like the flooding of Krymsk in 2012 [1, 6]. That is why it is necessary to predict the maximum parameters of flooding and its dynamics in order to devise an evacuation plan and to alert the population.

The available data on the existing gauging stations (the number of which in Russia has been sufficiently reduced recently) does not allow the tasks in hand to be fully completed due to the following.

(1). The instrumental monitoring period may not witness extreme spates of low probability (1% or less).

(2) Even if such floods occurred long ago, due to the human-induced impact on the floodplain (e.g., the construction of reservoirs and roads, bottom deepening of river channels, etc.), the real correlation between water levels and discharge may considerably change (which is often the case in practice).

(3) In selecting high-altitude solutions for new development sites that comprise vast floodplain areas, one needs to take into account the way they may affect the hydrological regime, which is difficult to do based only on earlier observations.

(4) Observations at gauging stations alone are not enough to predict the parameters of waves breaking through the hydropower constructions upstream (not based on a real danger). In such a case it is necessary to calculate engineering constructions protecting residential areas.

Taking the above mentioned into account one can see the necessity to apply numerical simulation to complete the tasks in hand. A model must adequately reflect all the peculiarities of flood flows with respect to buildings, safety constructions, bridges, and the rest of the infrastructure in the floodplain; it must take into account the nonstationary character of the flow, as well as the deformation of the river channel (if needed), etc. The model should be calibrated against factual data, which, among other things, presupposes retrospective analysis when applied. The present paper illustrates a modern technology and methodology that can be applied to a numerical simulation of flooding of residential areas, as shown on a particular example.

THE OBJECT OF RESEARCH AND NUMERICAL HYDRODYNAMIC MODEL

The City of Yaroslavl, whose population amounts to 700 thousand, stretches along the banks of the Volga River (part of Gorky Reservoir) over 30 km (Fig. 1a). Rybinsk Hydroelectricpower Plant (HPP) is situated 100 km upstream. Its dam creates one of the biggest reservoirs in the European part of Russia—Rybinsk Reservoir, which holds 25.4 km^3 of water. After it was constructed, the maximum flood discharge in the lower pool, as well as the levels of a flood of 1%-probability, have dropped considerably. However, there is now a hypothetical danger that a dam-break wave may emerge at the waterfront of the hydropower construction. Considering the dense residential areas of the city, it is needed to single out the areas where construction is possible without security measures and the areas where such measures are necessary, and to what extent.

In order to simulate dam-break waves and to determine the hydrograph of outburst spates, a numerical model was designed representing a part of the Volga River valley from the upper reach of Rybinsk Reservoir down to the mouth of the Kuban' River (downstream of Kostroma). The river reach is over 300 km long (Fig. 1b) and includes Rybinsk HPP, residential and industrial areas, as well as Yaroslavl road infrastructure. The model includes both the upper pool (Rybinsk Reservoir) and the lower pool (Gorky Reservoir), which helps to accurately calculate the discharge through a dam (because of a dam-break) taking into consideration the influence of the lower pool. It is also necessary in order to realistically reproduce the dynamics of a dam-break wave.

The calculations were carried out based on 2D shallow-water equations according to a unique numerical algorithm [2] integrated in STREAM 2D CUDA software [3].

Digital Terrain Model

The first step in building up the computer model was to produce a digital elevation map. The electronic topographic map at a scale of 1 : 200000 was combined with vectored pilot charts of the Volga River valley and with the electronic isohypses, both vectored based on maps at a scale of 1 : 25000. The topography of Yaroslavl was determined by vectored topographic maps at a scale of 1 : 500 and at a scale of 1 : 2000. Rybinsk HPP was digitized based on its plans. Afterwards, a 3D digital terrain model (DTM) was formed composed of nodes and isohypses in Cartesian coordinates X, Y, Z (Fig. 1b).

The input data for the DTM of Yaroslavl was its large-scale topographic maps provided by the administration of the city. The maps showed the computational domains at a scale of 1 : 500 and at a scale of 1 : 5000 (in electronic vectored format).

The following data was additionally used.

—The DTM along the course of the Volga River from the site of Rybinsk HPP to the mouth of the Kuban' River at a scale of 1 : 25000 and 1 : 200000 (the floodplain) and 1 : 25000 (the river channel).

—The refined GIS of the morphometry of Gorky Reservoir from the site of Rybinsk HPP to the mouth of the Kuban' River. The map was provided by the Operations Division of Gorky Reservoir. It was

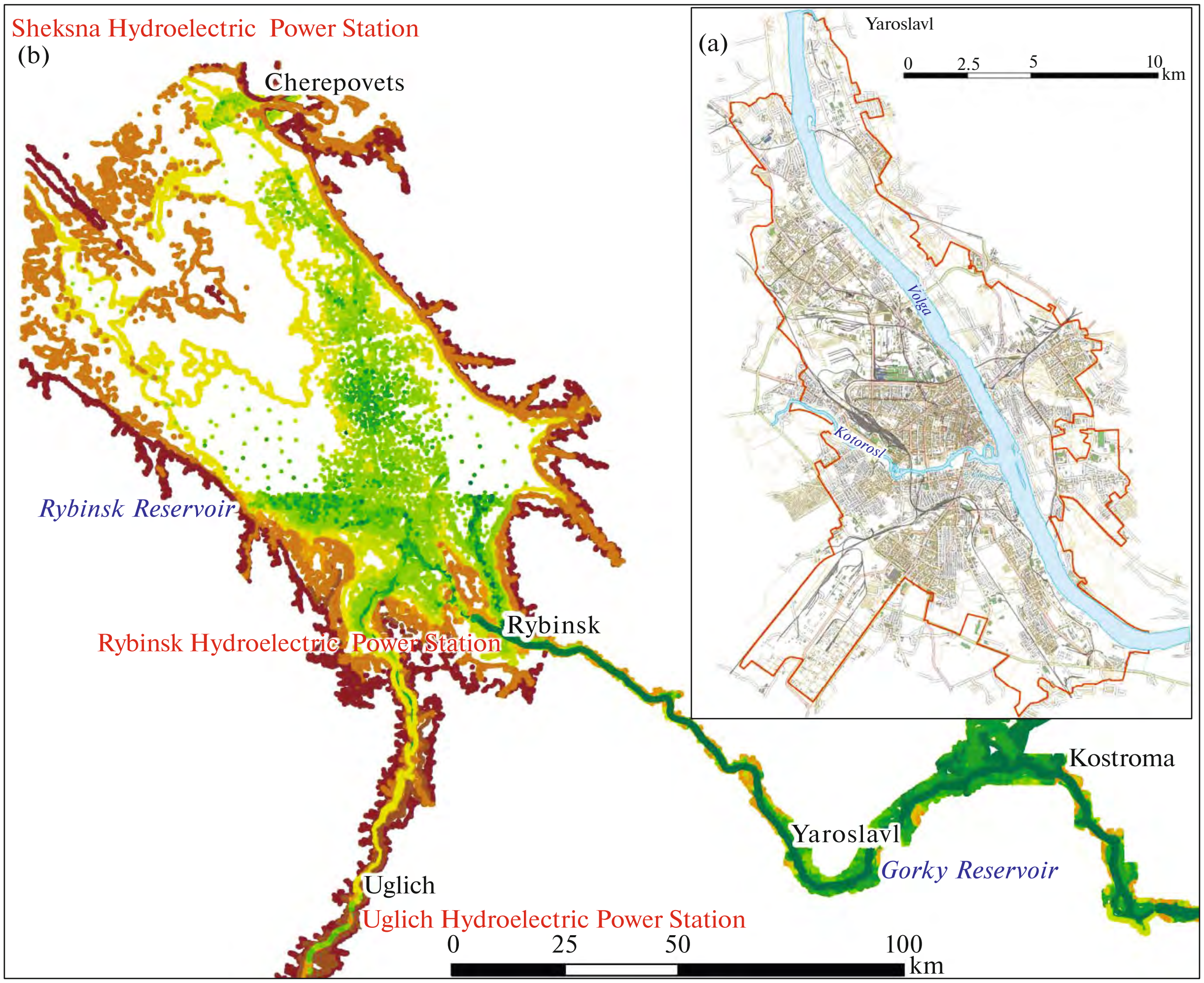


Fig. 1. (a) City borders of Yaroslavl, (b) DTM of the computational domain.

accompanied by the georeferenced pilot charts, data in cross-sections of the river channel, bathymetric results, and a digital model of the river bottom.

—Outlines of roads, water bodies, and buildings (obtained from Open Street Maps) in the area of the supposed flood in coordinates WGS 1984.

Computational Mesh

A unique automated procedure was used to generate a hybrid unstructured triangular–quadrangular mesh composed of more than 60000 cells. The mesh was refined with respect to the features of the borders and topography of the computational domain. It includes all the buildings and structures at the borders of a supposed flooding of the City of Yaroslavl.

In the area outside Yaroslavl, the Volga river channel was described by a mesh where a characteristic length of a cell edge was 60 m; in the floodplain, the characteristic length of a cell edge was 100 m at the bank line and up to 1000 m at the most distant locations (e.g. the water area of Rybinsk Reservoir). Inside the city on the Volga river channel, the mesh was condensed to 40 m, and the banks were described with the help of a specific method. To do that, a vectored city map was used to describe roads and buildings. The roads were described with the help of an adaptive mesh with the characteristic length of a cell edge of 10 m. The buildings were surrounded by a 50-meter zone where the characteristic length of a cell edge was 15 m, and the mesh edges were superimposed on the walls of the buildings. Areas inside the contours of the buildings were removed from the mesh. Thus, the walls of the buildings are the boundaries of the computational domain with free slip conditions which directly affect the velocity field. The rest of the city pool was described by a mesh with the characteristic length of a cell edge of 50 m. The schematic division into cells of different size can be seen in Fig. 2, while Figs. 3 and 4 show fragments of the computational mesh.

The mesh was generated with the help of BlueKenue software developed by the National

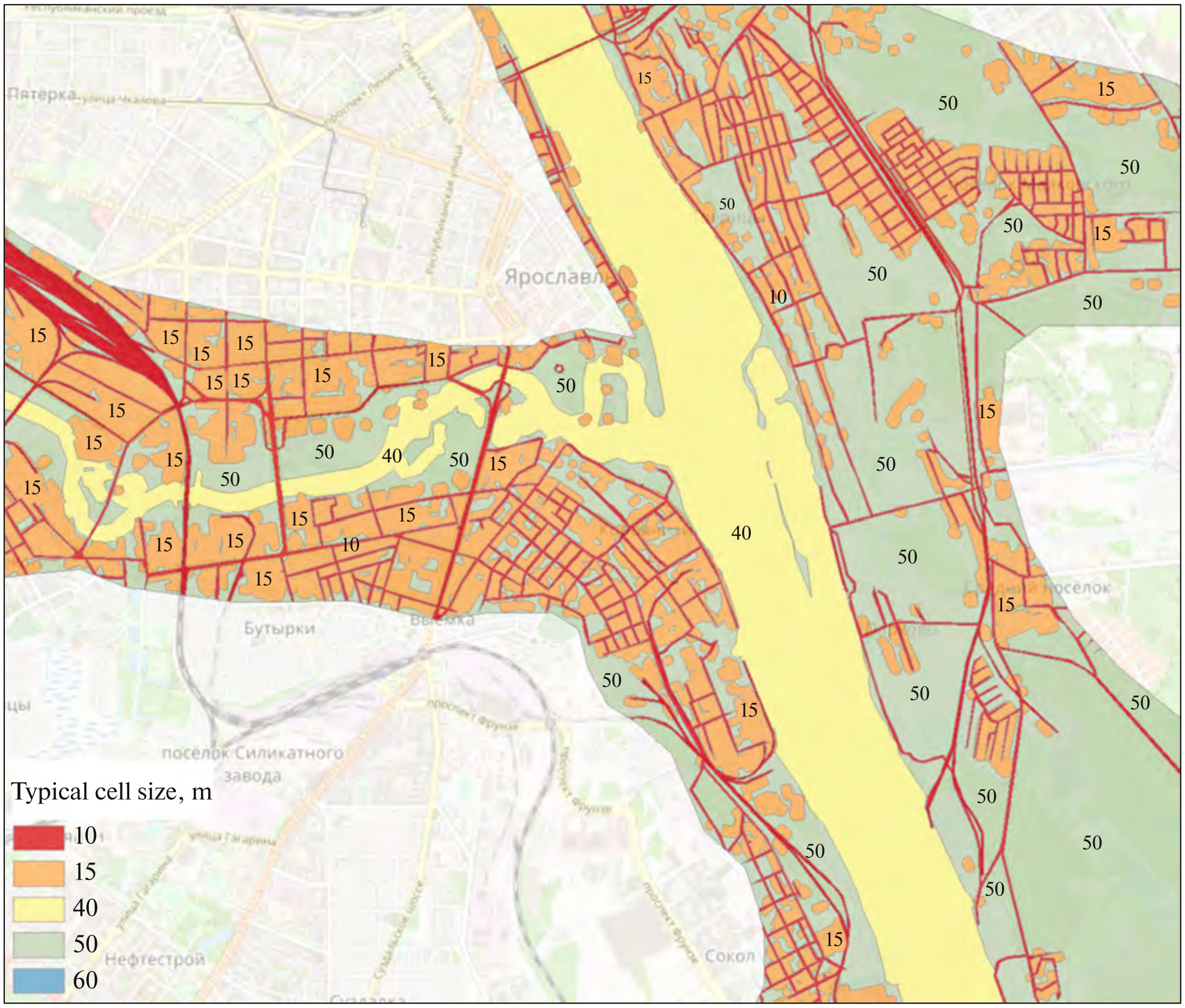


Fig. 2. Parts of the computational mesh with the typical cell size, m. The mouth of the Kotorosl' River.

Research Council of Canada for computational meshes in 2D numerical models.

After the mesh had been generated, the bottom levels were interpolated into the cell centres with the help of an original algorithm [4].

NUMERICAL MODEL CALIBRATION AND SIMULATION OF A RIVER FLOOD OF 1%-PROBABILITY

Calibration is an important stage in modelling an object. It implies picking up the parameters of the model that will agree with the field data. For the upper pool of Rybinsk HPP, the design curve showing the correlation between the reservoir volume and its level was compared to the one calculated with the help of the mathematical model to show a good agreement. In order to calculate an extreme spate in the lower pool, it is necessary to calibrate the model with respect to high floodwater discharge. For the purpose of calibration, the freshet of 1966 was chosen as it was the biggest one in the period of simultaneous existence of both Rybinsk and Gorky reservoirs. Based on the data of water discharge in the spring of 1966, the period from May 12, to May 17, was chosen as the one corresponding to the maximum and nearly regular water discharge at Rybinsk HPP (5376 m^3/s).

According to the measurements in the given period, the average water discharge of the Kotorosl' River was 71.63 m^3/s, which is 11.59% of the maximum discharge of 1%-probability (618 m^3/s). Since there is no available data on the subject, let us prima facie assume that this percentage ratio is also true for the rest of the inflows into Gorky Reservoir (from Rybinsk HPP to Yaroslavl). It can thus be calculated that the water discharge at the inflow between Rybinsk and Yaroslavl in the given period is 86 m^3/s (11.59% of 742 m^3/s). Water discharge at the interbasin flow in the same area is 79.4 m^3/s (11.59% of 685 m^3/s). The resulting total water discharge of the inflows (the flow

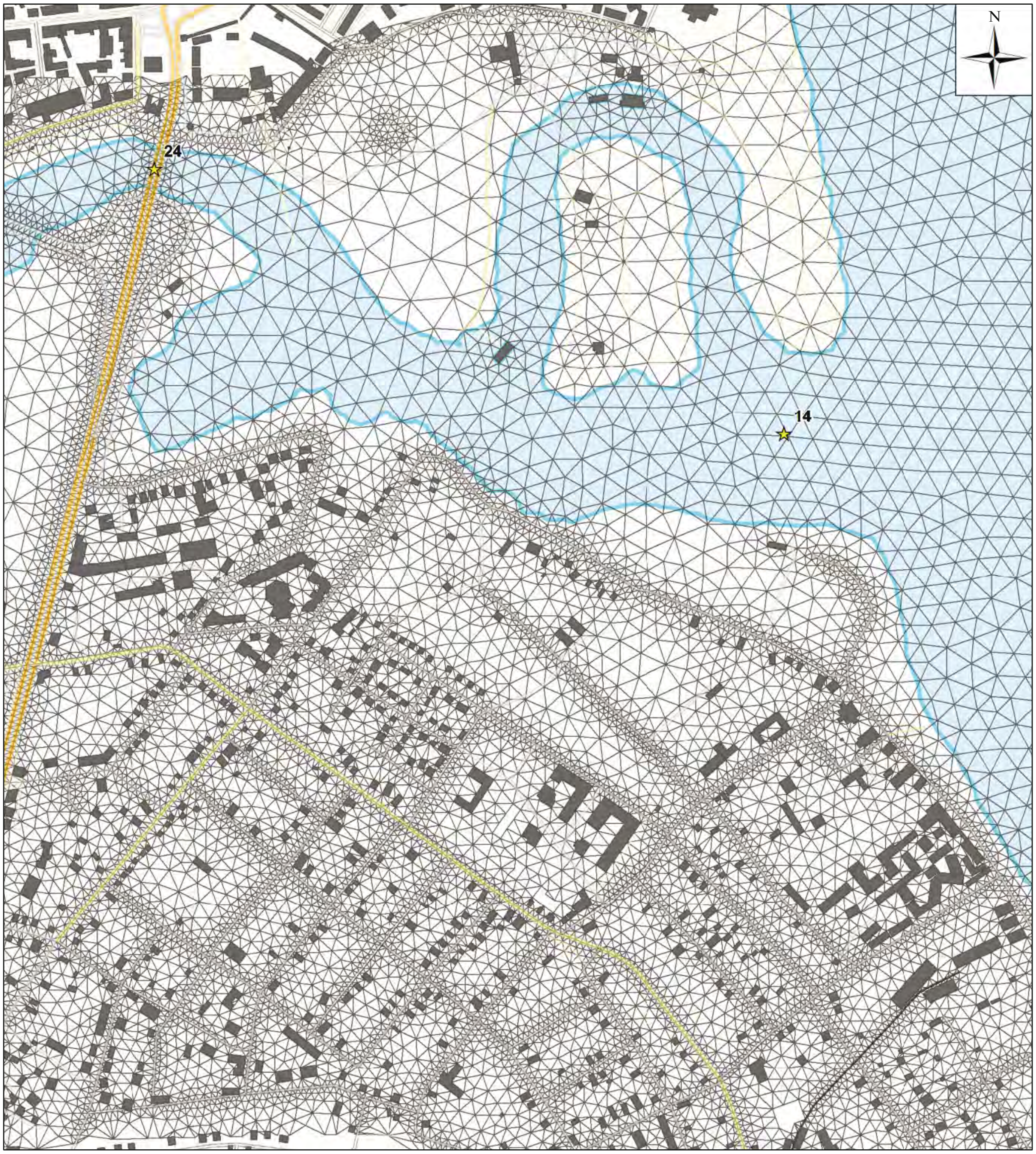


Fig. 3. The computational mesh. The mouth of the Kotorosl' River.

of the Kotorosl' River included) from May 12, to May 17, amounts to 237 m^3/s. Adding this value to the water discharge at Rybinsk HPP in the given period, we obtain the water discharge of the Volga River downstream of its confluence with the Kotorosl' River, which equals 5613 m^3/s.

The maximum water level at the hydrological station of Gorky Reservoir at Yaroslavl (the Volga River) in 1957–2014 amounted to 87.19 m and was observed on May 14, 16, and 17, 1966. The water level at the hydrological station of Yaroslavl obtained through calibrating calculations (with the river discharge being 5613 m^3/s) is 87.24 m, i.e. 5 cm more than the one observed. With such values of water discharge and water level, this deviation seems to be insignificant (especially, if one allows for a certain ambiguity in obtaining the total discharge of the lateral inflow). For the present calculations, as well as when calculating flooding by dam-break waves, the coefficients of

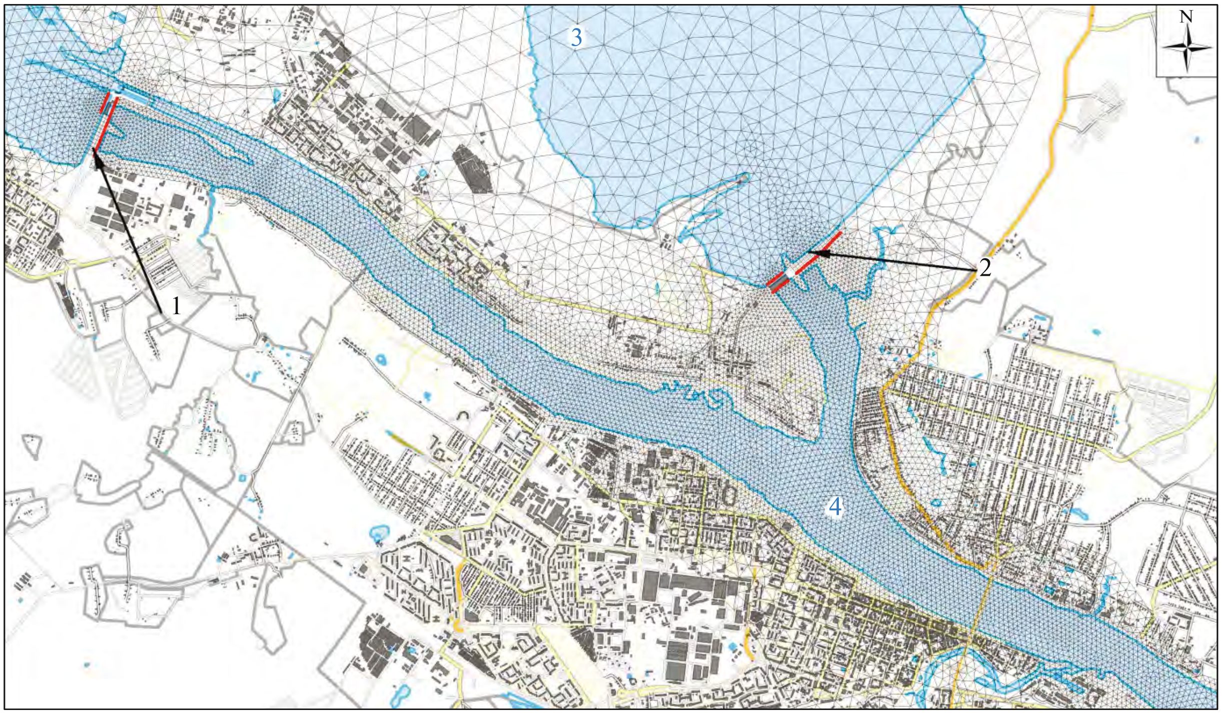


Fig. 4. Part of the computational mesh showing the floodplain and the river channel of the Volga near Rybinsk. (1) Volzhsky discharge site; (2) Sheksna discharge site; (3) Rybinsk Reservoir; (4) Gorky Reservoir (the Volga River).

roughness in the Manning formula were $n = 0.019$ (for the Volga river channel downstream of Rybinsk HPP) and $n = 0.05$ (in the floodplain).

Figure 5 shows the curve reflecting the correlation between water discharge and water level at the hydrological station in Yaroslavl. The discharge varies from 4000 to 15 000 m^3/s, if the normal headwater level in the upper pool of Gorky HPP is maintained at 84.0 m. The curve is the result of a numerical simulation. The red point shows the maximum flood level of 1966. The curve cannot be obtained empirically as there is no observation data on high water discharge at Gorky Reservoir.

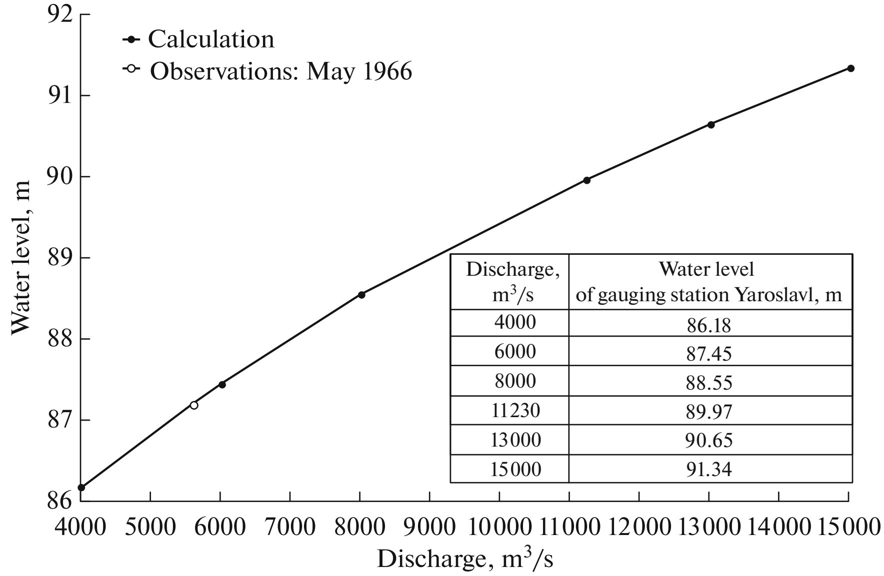
According to Yaroslavl Centre for Hydrometeorology and Environmental Monitoring one percent flood level at Yaroslavl gauging station is 87.22 m. The result of the calibrating calculations is 87.24 m, which is only 2 cm more. Thus, the result of the calculation can be regarded as the result of a river flood of 1%-probability.

Based on this, a longitudinal profile of the water surface in a 1%-probability flood around Yaroslavl was plotted. The difference in the 1%-level in the Volga River inside Yaroslavl is approximately 0.75 m. The maximum levels were also calculated, and those parts of Yaroslavl that could be flooded by a 1%-inundation were singled out. On the whole, one can say that the territory of the city could be flooded only insignificantly.

SCENARIOS OF A HYDRODYNAMIC ACCIDENT

The parameters of dam-break waves, the consequences of a hydrodynamic accident, the topography of the lower pool, the bathymetry of the reservoir, the accuracy of calculating methods—all this is determined, to a great extent, by the scenario of an accident at the hydropower structure and in the lower pool. The scenario depends on the design characteristics of the hydropower structure, the features of the upper and lower pools (for example, whether there is a cascade of hydroelectric schemes), as well as on the political and military situation in the country. Thus, at the time of the Cold War, it was necessary to take into consideration a scenario implying an instant destruction of the waterfront by a nuclear strike. Nowadays, it has become typical to consider various scenarios of a terrorist attack. However, while compiling the Declaration of Safety of Hydraulic Structures, a terrorist attack is not regarded as a cause of a hydrodynamic accident.

Field observations and monitoring of the technical condition of Rybinsk HPP have revealed that the failure of the waterfront at Sheksna discharge site is likely due to the increased filtering and washout on the upstream side of dam No. 46. Based on the analysis of accident data at similar objects, possible (not based on a real danger) scenarios were singled out—accidents at the earthworks of Rybinsk HPP. These scenarios are



Discharge, m^3/s	Water level of gauging station Yaroslavl, m
4000	86.18
6000	87.45
8000	88.55
11230	89.97
13000	90.65
15000	91.34

Fig. 5. The calculated curve showing the correlation between water levels and discharge at the gauging station in Gorky Reservoir (Yaroslavl).

presented in the Declaration of Safety of Rybinsk Hydroelectric Power Plant [11].

Scenario 1: failure of dam No. 46 (Sheksna discharge site). An accident occurs at the water level of the upper pool equal to the normal headwater level.

(1) Malfunction of drainage system with a raise in the depression curve, an intensive seepage in the body of the structure, and the irrigation of the downstream shell An increase in the pressure gradient at the dam site and the body of the dam, progressive suffosion, formation of suffosion vortices.

(2) Formation of subsidence zones at the crest and the downstream shell, collapse of the downstream shell with the formation of seepage or piping through the dam.

(3) An increase in water discharge, a collapse of the crest, breaking of the waterfront with the formation of a dam-break wave.

The estimated qualitative and quantitative likelihood of a hydrodynamic accident at individual hydraulic structures of Rybinsk HPP [11] is as follows.

—The average annual probability of an accident at dam No. 46 with a long-term average annual flow (scenario 1) is 3.47×10^{-4} 1/year, which is lower than the allowed value for structures of the second class (5×10^{-4} 1/year).

—Based on this, the most likely scenario is the breaking of the waterfront at the channel part of Sheksna discharge site with the average annual flow and the level of the upper pool equal to the normal headwater level.

Scenario 2: a break of the earth dam at Volzhsky discharge site with the upper pool level being the highest water level during a flood of 0.01%-probability (likely to happen once in 10 thousand years). It is important to point out that scenario 2 (the break of Volzhsky discharge site), being the gravest, has a very low average annual probability of an accident, i.e., 5.64×10^{-8} 1/year. This means that it may occur once in 20 million years! In comparison, all major structures of nuclear power plants are calculated with a probability of an accident being 10^{-6} 1/year, i.e. once in a million years. It is absolutely clear that it would be irrational and practically impossible to construct buildings that, theoretically, will not be affected by a flood that rare and unlikely. That is why the results of the calculations for this scenario are not discussed in the present paper.

CALCULATING PARAMETERS OF A DAM-BREAK WAVE RESULTING FROM A HYDRODYNAMIC ACCIDENT

To calculate the break at Sheksna discharge site, the initial conditions were the level of Rybinsk Reservoir being normal headwater level 102.0 m and the average annual flow of the Volga River at Rybinsk HPP being 431 m^3/s. At the outlet of the model domain downstream of Kostroma, a relationship was specified between water discharge and water levels $Q(H)$, which was taken from the previous calculations on 1D hydrodynamic model of the entire Gorky Reservoir [5]. The time of the dam breach is 24 hours after the calculation was started.

The development in time of the outlet in the earth dam was calculated following the method of Prudovsky [7] with the height of the dam assumed vari-

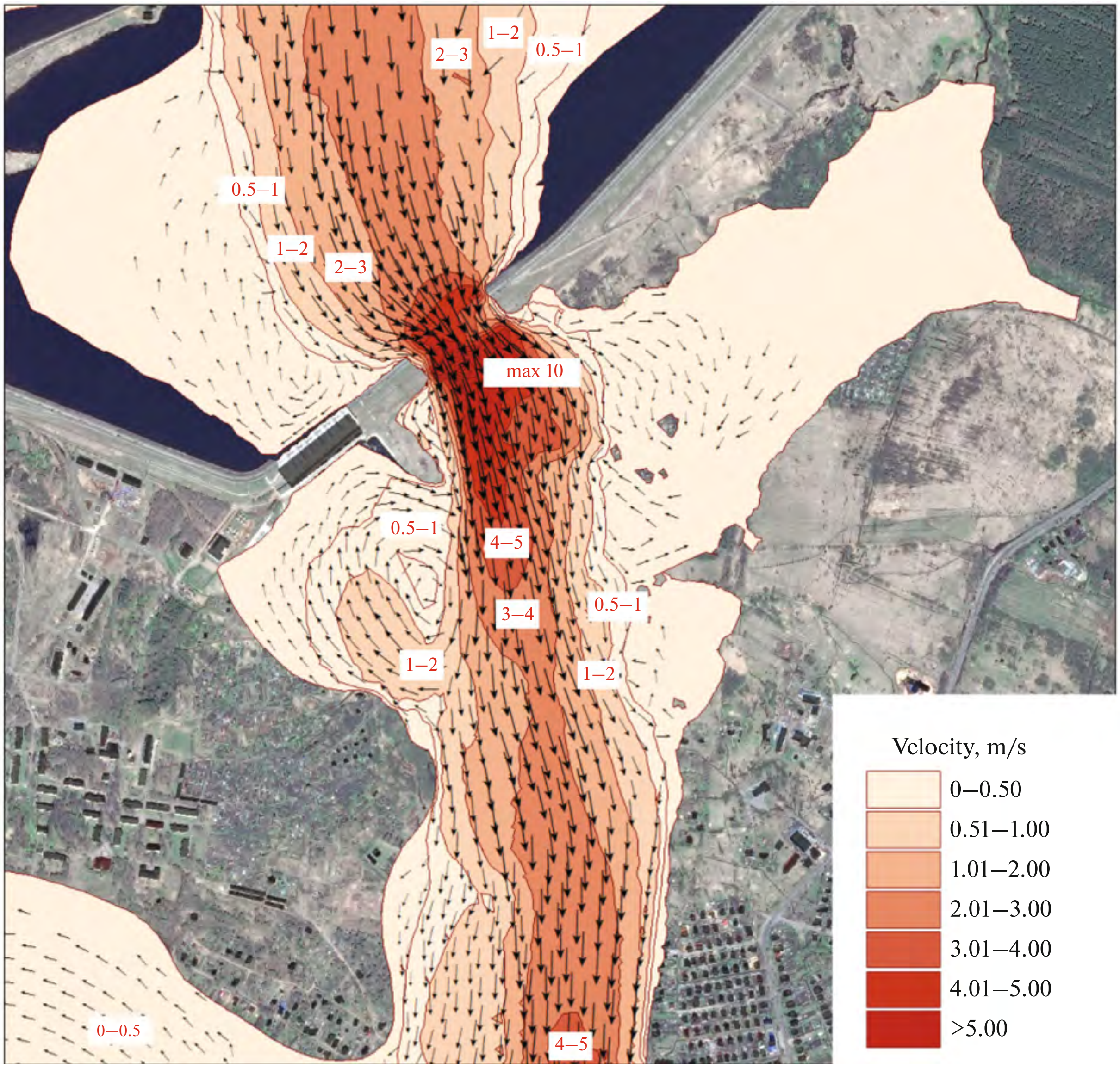


Fig. 6. The flow field 15 hours after the accident onset with the formation of an outlet in Sheksna discharge site of Rybinsk HPP.

able. According to the calculations, the maximum width of the outlet was 675 m. The maximum discharge at the outlet is achieved 15 hours after the accident started, and it reaches 13162 m^3/s. The flow field at Sheksna discharge site 15 hours after the accident started is shown in Fig. 6.

At the site of Yaroslavl hydrological station in the centre of the city, the rise in the water level will start 6.2 hours (the travel time of the dam-break wave front) after the accident onset. The maximum flood level (89.87 m) will be reached in 71 hours (the travel time of the wave ridge, Fig. 7). This excludes the surprise factor. It can be seen in Fig. 7 that the difference in the flood levels of the southern and northern parts of the city is more than 1 m. This should be taken into account when developing flood-prevention engineering systems. One must not use the same constant flood level for the entire city.

Large-scale plans (at a scale of 1 : 25000) were developed for the moment of maximum flooding (71 hours). The plans show the boundaries, levels, and depths of flooding over the entire city. The maps reflect the boundaries of the flooding caused by an accident, by a flood of 1%-probability. The contour lines of depth under 1.5 m are shown in red, those up to 3.0 are shown in blue (Fig. 8). In the residential areas of Yaroslavl, the maximum depths vary from 0 to 3 m. Topographically, the low areas along the banks of Gorky Reservoir are flooded by more than 3.0 m. The maximum depth here locally can reach 6 m. According to the calculations, the total flooding area of Yaroslavl equals 33.25 km^2, where 5.89 km^2 of the flood is 3 or

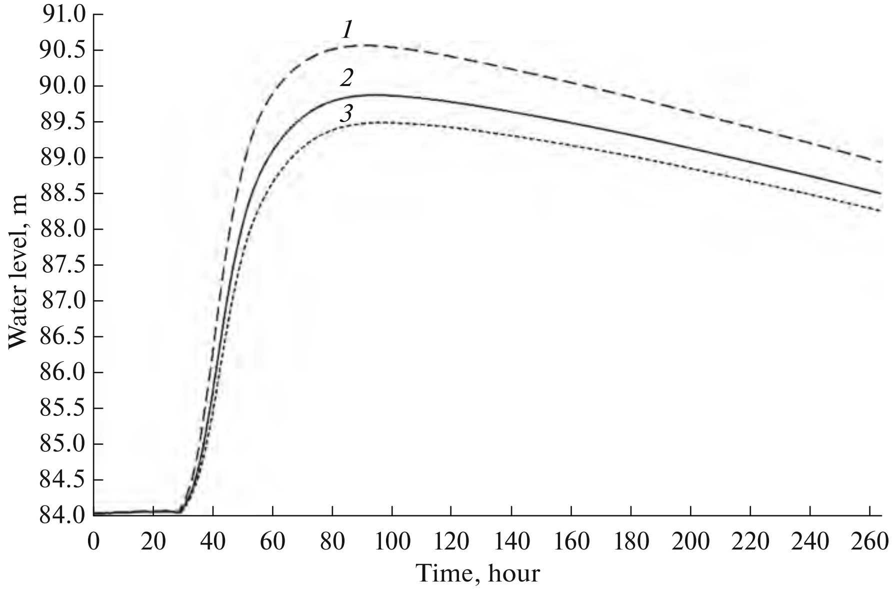


Fig. 7. Levels of the dam-break wave over time. (1) The northern boundary of Yaroslavl; (2) gauging station; (3) the southern boundary of Yaroslavl.

more meters deep; and 15.35 km^2, 1.5 or more meters deep. In total, the flood will last for more than 5 days.

The analysis of the flow field at the maximum flooding caused by an accident has shown that the flow velocity in the floodplain is insignificant and reaches from 0 to 0.2 m/s (which according to [9] allows residential buildings in the areas to be constructed with the depth of the flood being less than 1.5 m). In the Volga river channel, the velocity varies from 1 to 1.5 m/s, reaching locally up to 2 m/s. Both in the river channel and on the floodplain of the Kotorosl' River, the velocity is below 0.2 m/s.

CONCLUSIONS

(1) Modern computer technologies allow the development of 2D numerical models of extended parts of a river for adequately calculating the floods that may be either natural or human-induced. To obtain more accurate results for residential areas, it is necessary to take into account the city and road infrastructure that can significantly influence the levels and areas of flooding, as well as the distribution of flow velocity. When modelling a dam-break wave at a hydropower structure, it is important to consider a joint model of both the upper and the lower pool.

(2) The present paper describes a new technology allowing for a semiautomatic generation of unstructured adaptive meshes, which enables one to take into account and single out all structures (houses, roads, bridges, etc.) in the computation domain. This makes it possible to individually set the impermeability condition for each particular object (e.g., a house) or terrain (e.g., the upper part of the roadbed). It would be nearly impossible to manually produce such meshes for large urban areas containing dozens of thousands of structures subject to flooding.

(3) A numerical 2D model of the upper and lower pools of Rybinsk HPP was developed and calibrated. The model covers a large area and describes the terrain and the city infrastructure around Yaroslavl in detail. The model was used to calculate the possible flooding scenarios. In a flood of 1%-probability, the maximum flood level at the discharge site of Yaroslavl hydrological station will be 87.24 m. Inside the city, the flood areas are insignificant.

(4) With the movement of the dam-break wave at Sheksna discharge site of Rybinsk HPP (which is the most likely scenario, not based on a real danger), the rise in the water level at the site of Yaroslavl hydrological station will begin 6 hours after the accident onset. The maximum flood level (89.87 m) will be reached in 71 hours. It is mainly the left bank of the Volga River that is subject to flooding almost all the way through Yaroslavl, along with the right bank in the northern part of the city and at the mouth of the Kotorosl' River. The maximum flood depths vary from 0 to 3 m. According to calculations, the total area flooded in Yaroslavl because of a hydrodynamic accident at Rybinsk HPP will amount to 33.25 km^2, including areas with a depth of 3 or more meters (over 5.89 km^2), and areas with a depth of over 1.5 m (15.35 km^2). In total the flood will last for more than 5 days.

(5) When the dam-break wave that has formed at Rybinsk HPP passes through the urban area, the maximum flow velocity does not exceed 0.2 m/s, i.e., it cannot lead to the destruction of buildings by the

Fig. 8. Depths of flooding by a dam-break wave in Yaroslavl. The mouth of the Kotorosl' River. (*1*) Normal headwater level equals 84.0 m; (*2*) depths of 1.5 m; (*3*) depths of 3.0 m; (*4*) flood zone.

dynamic effect of the flow. That is why, according to [9], in the areas of disastrous flooding, buildings can be constructed only if the flood depth is no more than 1.5 m. Otherwise, it is necessary to raise the territory to the required level or to build dams. Due to the fact that the maximum levels across the city vary by more than 1 m, this needs to be considered when planning the prospective development sites in the city; engineering safety measures are to be taken, each object having its own maximum flood level.

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