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Retrospective Simulation of an Extreme Flood on the Oka River at the City of Ryazan and Impact Assessment of Urban and Transport Infrastructure

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Abstract—Numerical modeling of flow dynamics of rivers with comprehensive channel patterns and wide floodplains during high water stage is considered to be one of the most effective methods for implementing both research and civil-engineering projects. However, realistic results of simulations can be obtained only if the model has been calibrated and validated against field observations and remote sensing data. This approach is realized for a 2D hydrodynamic model of the Oka River at the city of Ryazan (central European Russia). The Oka has a meandering channel and a wide floodplain with a complicated distributary network. The feasibility of allocating new residential quarters and infrastructure facilities on artificial "islands" on the floodplain was studied using STREAM_2D software package. Because of a significant decrease in the maximum runoff of the Oka in the recent decades, the simulations were made for the extreme spring snowmelt flood of 1970 for various scenarios of floodplain development in the past, present, and future.

Keywords: flood, flow dynamics, 2D model, the Oka River, STREAM_2D software, Ryazan—Vladimir motorway, embankment, bridge

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Introduction

The city of Ryazan is one of most ancient large settlements in Russia. It is located in the middle course of the Oka River (the main right-hand tributary of the Volga) on its high right bank at the inflow of the Trubezh River. Vast floodplain areas of the Oka, covered mainly by meadows, formerly often inundated during high spring floods, have not been used for settlements, except for several villages on terrace remnants surrounded by floodplain and distributaries. Lowlands were traditionally used for grazing and recreation. However, in the recent decades, the Oka floodplain was affected by serious anthropogenic impact, mainly as a result of the construction in 1971—1972 of the bridge across the Oka River and the Ryazan—Vladimir motorway embankment intersecting the valley (Fig. 1). The influence of the bridge and embankment construction on the flow pattern was not possible to assess by direct field measurements, because the latest extreme flood occurred there in 1970 when the floodplain has not been disturbed by these structures. Recently, various options of the concept of further floodplain development were investigated in the Department of Architecture and Urban Development of the Ryazan Region. One of the key issues of this investigation was solving the problem: "What will happen if a high flood like the one that occurred in the past takes place now, when the bridge and motorway already exist, or in the future floodplain, covered by residential areas and linear infrastructure facilities?"

The only way to solve this problem is mathematical modeling. Simulations were carried out using the software STREAM_2D, widely known in Russia and based on the numerical solution of two-dimensional water motion equation ns. This software has been used to solve various problems, relating to economic activity and flood risk assessment on the major rivers of Russia: the Neva, Volga, Ob, Lena, Northern Dvina, etc. [2, 3, 6], and represents the hydrodynamic core of an intelligent information system for operational flood forecasting, which is under development in Russia [1, 7].

STUDY OBJECT

The Oka River is the second largest tributary of the Volga next tothe Kama River. It originates from the confluence of the Oka and Ochka creeks near the village of Sen'kovskie Vyselki on the Central Russian Upland, 4 km west of the Maloarkhangel'skaya railway station in Orel oblast. The Oka crawls along the

Orel, Tula, Kaluga, Moscow, Ryazan, Vladimir, and Nizhny Novgorod oblasts and flows into the Volga from the right side at the city of Nizhny Novgorod. The total catchment area of the Oka is about 248 000 km^2, and its length is 1485 km. In its upper reaches, the Oka receives right-hand tributaries: the Zusha, Upa, Osetr, Zhizdra, Ugra, and Protva. Downstream from the confluence with the Moskva River, the middle course of the Oka begins, where the Pronya, Pra, Moksha from the right, and the Gus' from the left empty into it. Downstream of the inflow of the Moksha River, the lower Oka reach begins, where it receives the large left tributary, the Klyazma.

The Oka basin is located in the zone of transition from the mild temperate-maritime climate of Europe to the continental Asian climate. In general, the climate of the basin is moderately continental. January—the coldest month of the year—has an average temperature of −9.0 to −10.0°C. The warmest month of the year is July. Its average temperature varies between 17.5°C and 18.6°C increasing from northwest to southeast. The annual precipitation varies between 550 and 650 mm, governed mostly by the cyclonic activity over the East European Plain. The precipitation shows annual and seasonal variations.

By its water regime pattern, the Oka belongs to the East European type, which features a high spring flood (up to 60–70% of the annual runoff), low water stage in summer and winter, and minor rain floods in autumn. The share of rain and ground water recharge is approximately 15-20% each. The city of Ryazan is located in the middle course of the Oka River on its right bank at the inflow of the Trubezh River, 699 km upstream from the confluence of the Oka with the Volga. At the city of Ryazan, the Oka is 250–300 m wide with its channel meandering within a wide (10–12 km) floodplain, which abounds in distributaries, old channels, and lakes. The Oka in this section is navigable, and the port of Ryazan is located in the lower reach of Trubezh, 1.5 km upstream from its mouth. Previously the Trubezh was a floodplain anabranch of the Oka, but, at the present time, its initial source is blocked and its runoff is formed by its two tributaries—the Pavlovka and the Pletyonka—flowing through the city of Ryazan.

The gauge of the Federal Service for Hydrometeorology, recording Oka, is also situated in the mouth section of the Trubezh, where the water surface slope is believed to be negligible. Daily measurements of the water level are carried out there, but not the discharge of the Oka. The latter is being recorded 50 km downstream at Polovskoye hydrological gauge. The data of this gauge was used to analyze the Oka maximum flow at Ryazan, since there are no significant tributaries between Ryazan and this place. No regular runoff observations are carried out on the Trubezh, Pavlovka, and Pletenka rivers.

Historically, the main residential areas and the main infrastructure of the city were located on the high right bank of the Oka beyond the floodplain areas, which are prone to flooding during the spring high water (Fig. 2a). However, in recent years, the city administration has been investigating the possibility of locating residential quarters and infrastructure facilities on artificial "islands" on the floodplain terrain. Along with the objective needs to expand the territory of the city, an important factor in favor of such a decision was a clear tendency of the Oka spring runoff to decrease (Fig. 3), hence, the rarer and less significant cases of channel overfilling by snowmelt water and flooding of urban areas.

After the disastrous flood of 1908 (which in its time gave an impetus to the development of the Russian hydrometeorological service), the most significant was the flood of 1970, when the maximum water flow reached 12 200 m^3/s. In recent years, relatively high flood occurred in 2013, the maximum of which, being outstanding for the last decade, would has been quite ordinary for the first half of the 20th century.

MATERIALS AND METHODS

Model Description

STREAM_2D is a software package for two-dimensional numerical simulations certified by the Russian Federal Service for Intellectual Property [4]. It is well adapted to solving problems of flow dynamics in rivers with complicated channel pattern and wide floodplain, even with deficient field data. The hydrodynamic core of STREAM_2D is based on the numerical solution of the two-dimensional Saint-Venant equations also known as the shallow-water equations. These equations consider the main forces operating in a stream with a free surface (gravity, friction, pressure, and inertia; Coriolis force and wind effect can be considered in addition), as well as three-dimensional orography of the river bottom and floodplain surface.

The system of the Saint-Venant equations in an integrated divergent form (i.e. in the form of mass and momentum conservation laws) reads as follows:

$$\left[\iint h dG\right] + \oint h\left(d\sigma \cdot \vec{w}\right) = 0 \tag{1}$$

$$\left[\iint h\vec{w} dG\right] + \oint h\vec{w}\left(d\sigma \cdot \vec{w}\right) + \frac{1}{2} g \oint h^2 d\sigma + g \iint h \nabla z dG = \iint f dG \tag{2}$$

where G is the area on the horizontal plane (x, y); dG is an element of area G; σ is the border of the area G; $d\sigma$ is a vector element of the border; $\vec{w} = \vec{w}(x, y, t) = (u, y)^T$ is a velocity vector, averaged over depth; $(a \cdot b)$ is the scalar product of vectors a and b; $h = h(x, y, t)$ is stream depth; t is time; g is the acceleration of gravity; $z = z(x, y)$ is topographic elevation;

Fig. 1. Flooding of the Oka floodplain near Ryazan in April 2018; view from the northwest. Photo by Igor Shelaputin [5]. The modern bridge across the Oka River and the Ryazan–Vladimir motorway embankment intersecting the valley were built in 1971–1972.

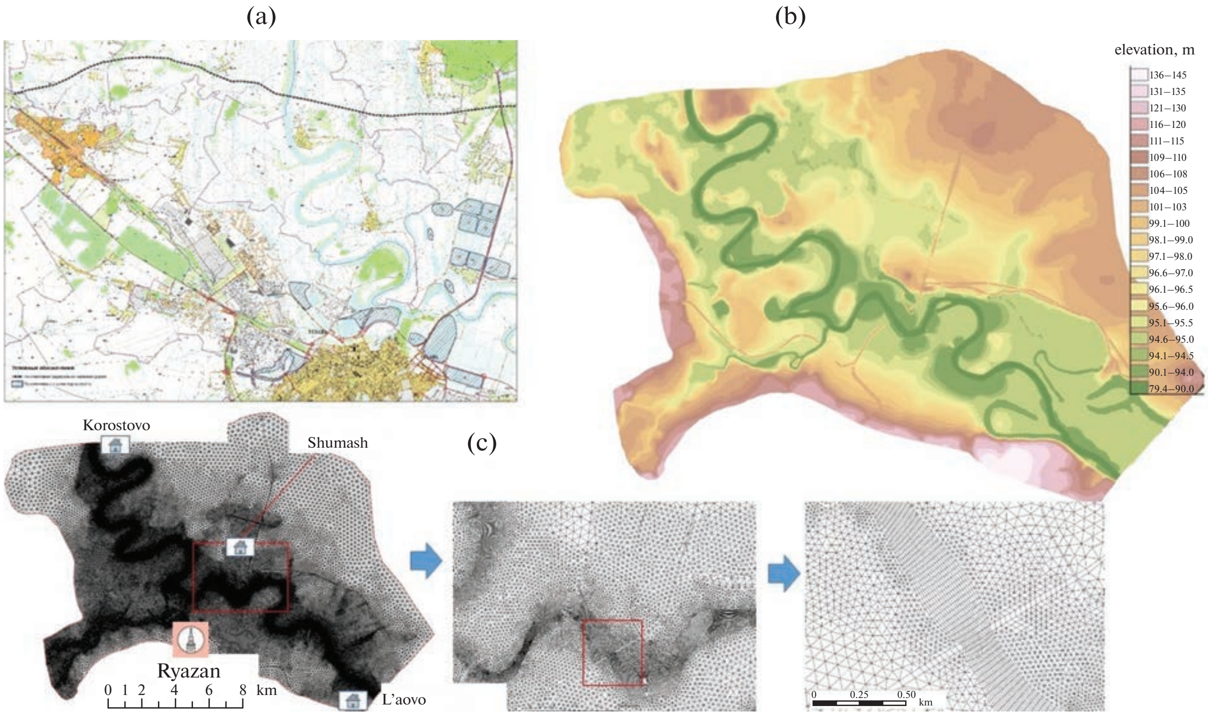

Fig. 2. Maximum (a) water level elevation and (b) discharge of the Oka River at the city of Ryazan.

f are external forces, in the actual version, represented only by the friction force $f = \lambda\vec{w}\left|\vec{w}\right|/2$, where λ is the hydraulic resistance (roughness) coefficient.

Flow intensity can be evaluated by the specific energy of flow P, which is calculated as

$$P = \rho h\frac{\left|\vec{w}\right|^2}{2}, \qquad (3)$$

where ρ is water density.

For solving the system of equations (1), (2), the corresponding initial and boundary conditions are needed. At the initial moment $t = 0$: $\vec{w}(x,y,0) = \vec{w}_0(x,y)$ and $h(x, y, 0) = h_0(x, y)$. Boundary conditions are to be specified along the borders of the model area, for example, water discharge, water level, or no-flow conditions.

Detailed information about the topography of the region and the river bed relief is necessary for model setup. Water discharges and water levels at model area boundaries are utilized as the model input. As a result of modeling, one can determine the flooded areas and obtain the spatial distribution of flow velocities, water levels, and depths at any point of the channel and the inundated floodplain for any time step in the modeling period.

The mesh generator of STREAM_2D allows the user to construct triangular, quadrangular, and hybrid (with both triangular and quadrangular cells) meshes for model areas of complicated shape.

The Data Used

Maps of scales 1 : 100000–1 : 50000 were digitized for the Oka floodplain and actualized according to high-resolution satellite images. Data of engineering survey of 2014, including bathymetry, measured water discharges and flow velocities of the Oka, Trubezh, Pavlovka and Pletyonka, as well as water surface slopes, were used to calculate river channel hydraulic resistance factors. Linear structures, including dams, levees, dykes and embankments on the floodplain were taken into account in the model meshand relief. The crests of engineering structures (both existing embankments and possible future artificial "islands") were set in the model as erosion-resistant.

Data from Ryazan and Polovskoye hydrological gauges were used to generate boundary conditions.The calibration and verification of the model were carried out by comparing the contours of flooded area at space images, as well as photos taken from balloons (Fig. 1) and other aircrafts with the flooding contours obtained from the model for the water discharge corresponding to the date of the photograph.

Modeling Strategy

Changes in the relief of floodplains accompanying an increase in anthropogenic impact, for example, because of the construction of dams, roads, embankments, or a rise of floodplain elevation marks for building residential quarters, can cause changes in flooding characteristics in local areas and, if the floodplains are highly developed, changes in flow regime over the entire nearby territory.

The feasibility of urban development of Oka floodplain for the extension of Ryazan was examined by simulating the modified river flow pattern. It was found that the anthropogenic changes in the underlying terrain would cause a redistribution of flood snowmelt water between the channel and floodplain parts of the valley cross-section. The most significant intervention in the hydrodynamic regime of the flood was made in 1971-1972, when a bridge across the Oka was built and Ryazan–Vladimir motorway crossing the valley was upgraded by lifting its embankment to marks exceeding the flood level.

Because no high flood comparable with that of 1970 has occurred after the construction of the bridge and reconstruction of the motorway, at the first stage it is necessary to knowas to what extent these activities will affect the water level over the flooded territory and the behavior of flows there.

The simulation area was the part of the Oka valley between the villages of Korostovo and L'govo (Fig. 2b), which corresponds to 674–719 km from the confluence of the Oka and the Volga. The hybrid triangular-quadrangular mesh (quadrangular cells with a size of 10-20 m for the channels of the Oka, its tributaries and branches, and triangular cells of 50-80 m for the floodplain) has been generated (Fig. 2c).

At the upper boundary of the simulation area, a steady-state water flow of the Oka and Trubezh was set, and at the lower boundary, a stationary water level corresponding to this flow was specified. This level was determined by linear interpolation between the gauges of Ryazan and Polovskoye. At the same time, the position of the lower boundary was chosen in such a manner that the floodplain infrastructure located upstream had no significant effect there.

The next step was to explore how the different stages of floodplain development under the past, present, and future conditions could alter the flow distribution and water level elevations. For this purpose, the flood of1970 was simulated and numerical experiments were carried out for the entirerange of observed water discharges.

The experiments were organized as follows: calculations were carried out over the entire range of observed water discharge with a constant step (1000 m^3/s, 2000 m^3/s, etc.). The maximum flow rate was set at 12200 m^3/s which corresponds to the maximum observed discharge in 1970. The water level at

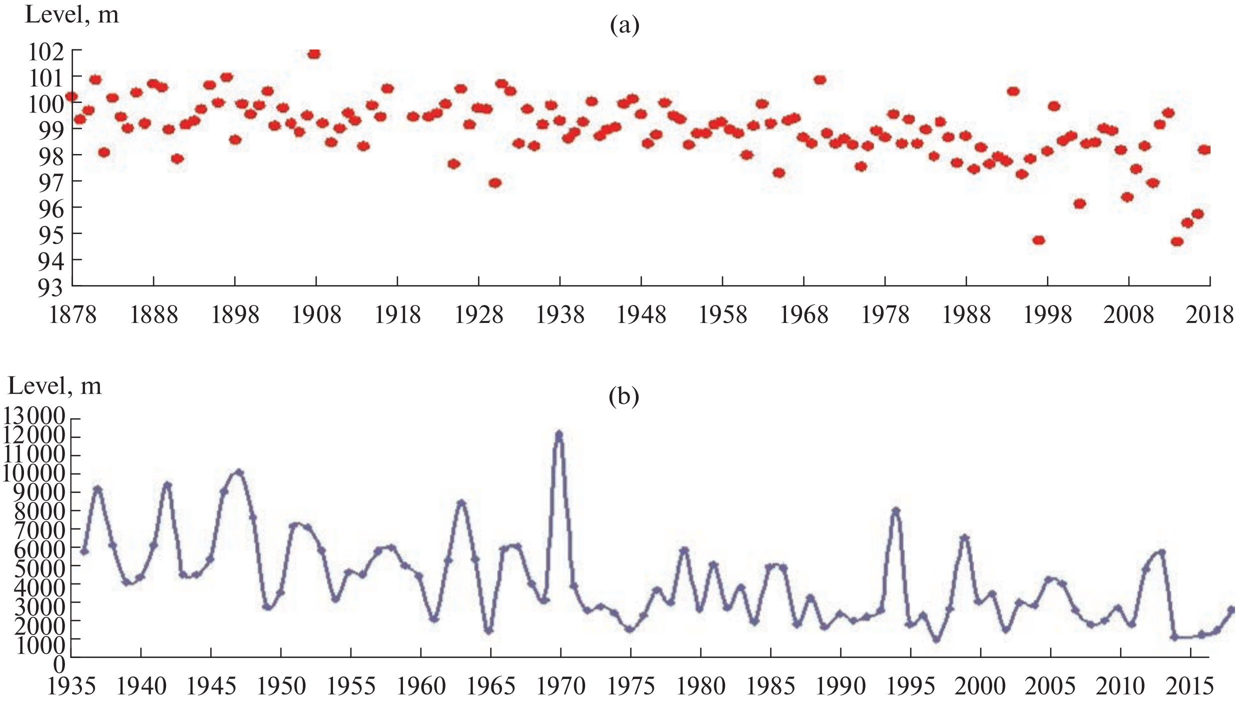

Fig. 3. (a) Model area, (b) digital elevation model, and (c) finite element mesh for the Oka valley near Ryazan.

the lower boundary of the model was given by the discharge rating curve. The simulation was carried out until the process became steady-state: constant water flow was simulated until all hydraulic characteristics of the flow ceased to change, the establishment time was 2 days.

Results and DISCUSSION

The following conditions (scenarios) of floodplain development were considered in modeling:

1. floodplain with neither Ryazan–Vladimir motorway embankment nor the bridge across the Oka River (the past conditions reflecting the situation of the flood of 1970, when these constructions had not yet been built);

2. floodplain relief including the Ryazan–Vladimir motorway and the bridge across the Oka River (present-day conditions);

3. floodplain relief including the Ryazan–Vladimir motorway and the bridge across the Oka River and the sites for new urban infrastructure (anticipated conditions).

The retrospective simulation of 1970 flood (scenario 1, Fig. 4) has shown that, under the former (natural) conditions without any constructions, the floodplain is flooded almost completely, except for a few hills (remnants of the terrace above the floodplain). Near the confluence of the Oka and Trubezh, the flow is evenly distributed over the inundated floodplain, and the current velocity is in the range of 0.2–0.4 m/s. Significant flow concentration in the flooded Oka main channel occurs only near the upper and lower boundaries of the model area (outside the territory of practical interest), and the flow velocities reach 1.0–1.5 m/s there. The water surface slope is relatively uniform without sharp changes in the level elevation in both longitudinal and transverse directions.

The simulation of 1970 flood with the incorporation of the Ryazan–Vladimir road with a bridge across the Oka, as well as several minor road embankments on the floodplain (scenario 2, Fig.5) has shown that the presence of these constructions leads to serious changes in the hydrodynamic regime of the submerged floodplain. Under these conditions, the entire Oka stream will be concentrated in the main channel and floodplain spans of the bridge, where the current velocity will exceed 2 m/s. At the same time, the level difference on the embankment of the motorway will be 0.5–0.7 m. These values suggest the need to monitor the river bottom and bank erosion near the bridge, as well as water seepage and suffosion through the body of the motorway embankment. In addition, the backwater effect from the embankment will influence floodplain inundation upstream up to the village of Korostovo along the Oka and up to the Ryazan Kremlin along the Trubezh. The water level marks there will be higher by 0.4-0.5 m, compared with the values that would have been at the same runoff, but before the construction of the motorway and bridge (Fig. 6).

The artificial “islands” with a total area of 12.5 km^2, which should raise a part of floodplain terrain

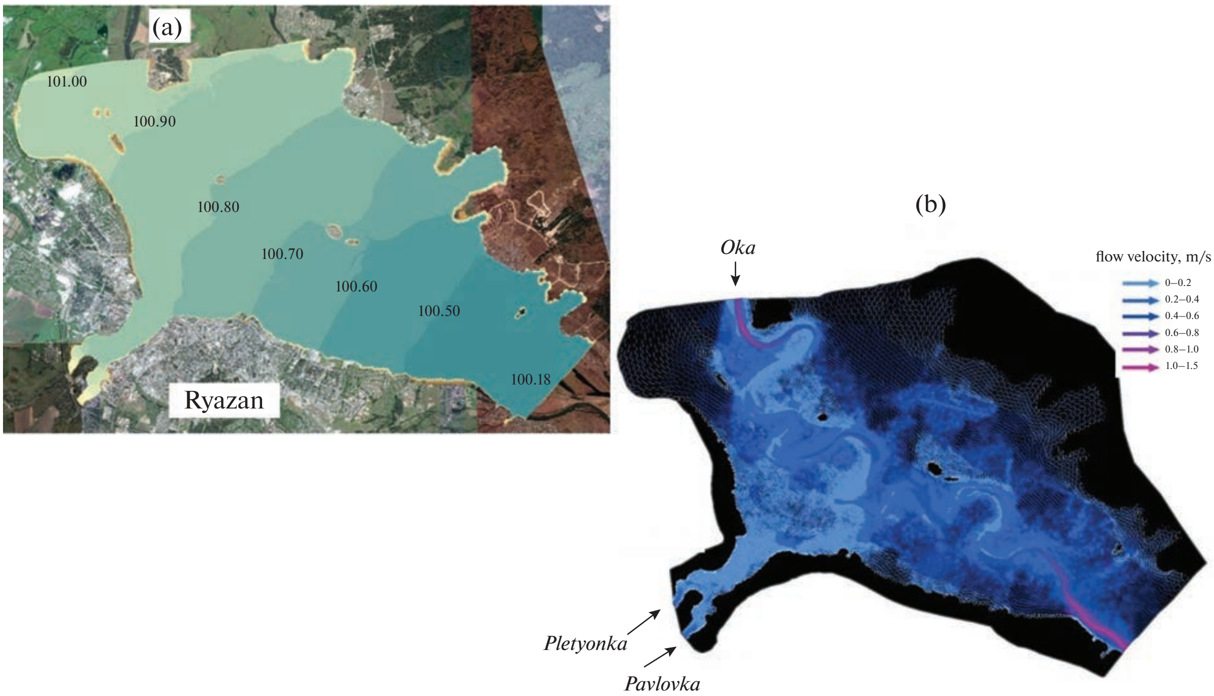

Fig. 4. Simulation of the 1970 flood under natural conditions. The embankment of the Ryazan–Vladimir motorway and the bridge across the Oka river have not been built yet (scenario 1).

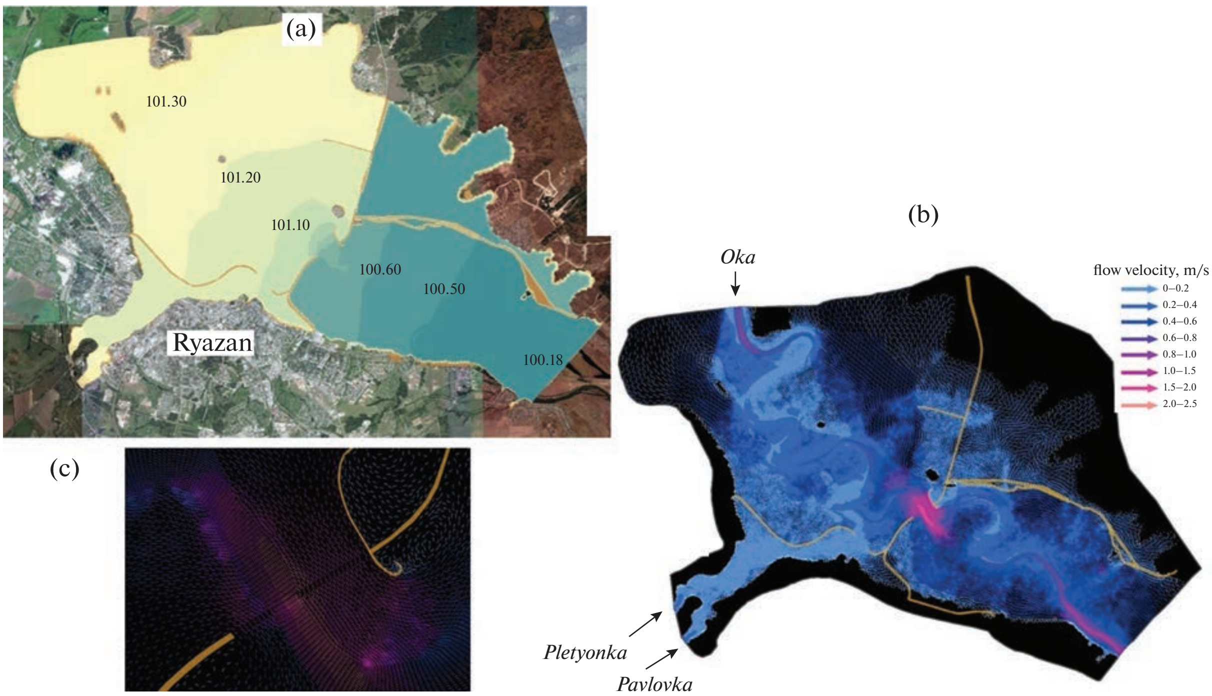

Fig. 5. Simulation of the 1970 flood, as if the Ryazan–Vladimir motorway and the bridge across the Oka river have been already built (scenario 2) with an enlarged fragment of the bridge area.

above the flooding level, will not have a global effect on the further change of the hydrodynamic regime in the case of a flood similar to that of 1970 year (Fig. 7). The most significant increase in the level (by 0.12 m) will occur only in the left-bank part of the floodplain near Shumash, where the adjacent minor branch

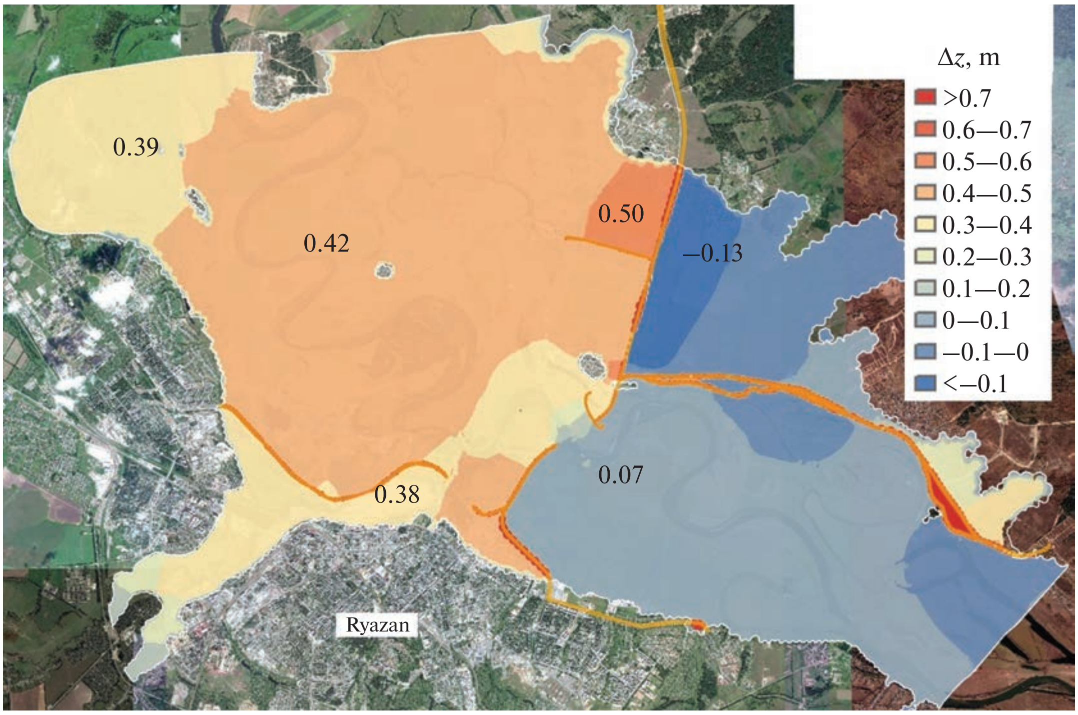

Fig. 6. The effect of the Ryazan–Vladimir motorway and the bridge across the Oka on water level elevations Δz on the inundated floodplain of the Oka (comparison of scenarios 1 and 2, the positive and negative values of Δz are for the rising and lowering water level, respectively).

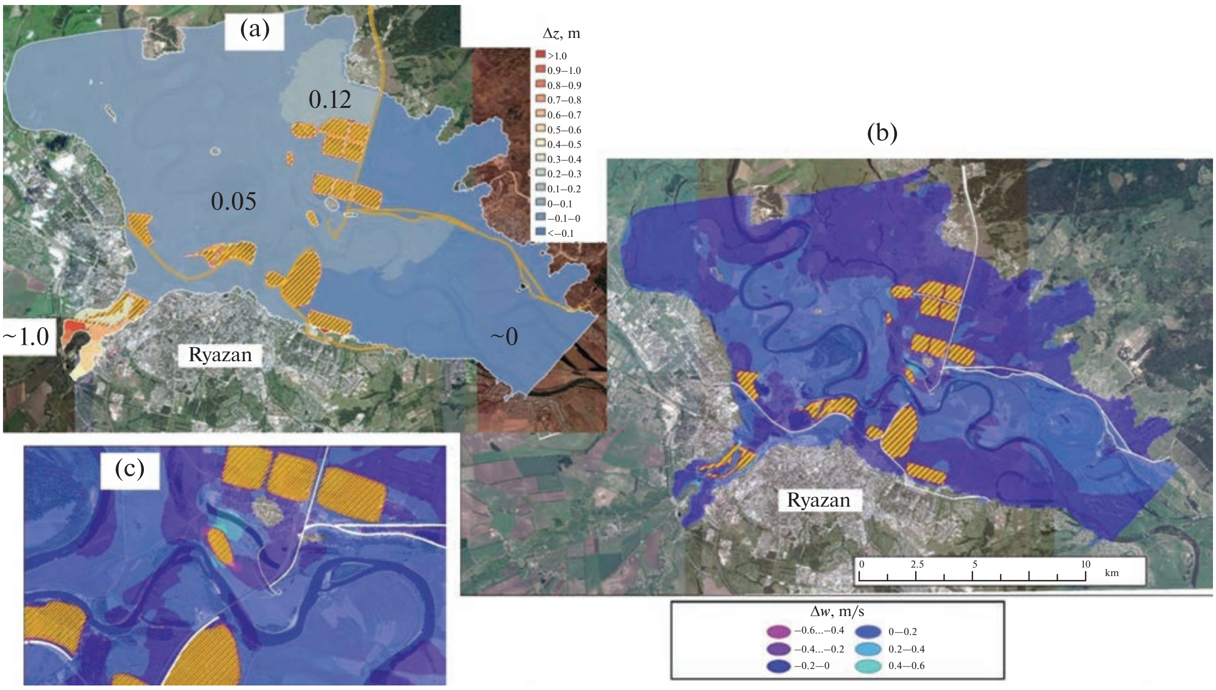

Fig. 7. The effect of artificial "island" location on the Oka floodplain on water level elevations and flow pattern (comparison of scenarios 2 and 3, the positive and negative values are for an increase and a decrease, respectively).

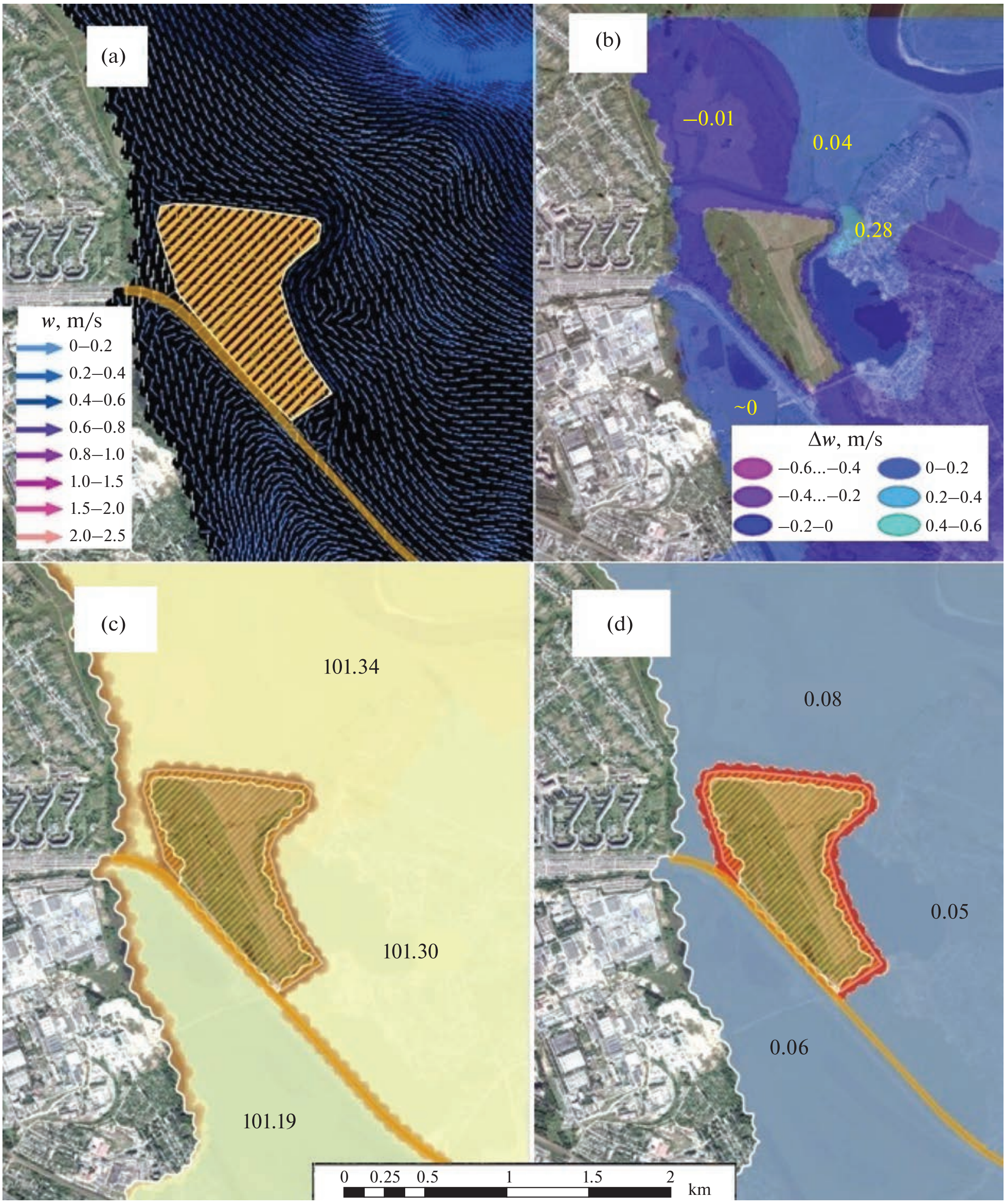

Fig. 8. (a) The flow field and (c) water level elevation around one of the artificial "islands" and the effect of its construction on (b) velocity magnitude and (d) level mark (the positive and negative values are for an increase and a decrease, respectively).

channel will be overfilled. It facilitates the diversion of water from the left-bank segments of the floodplain to the bridge spans. The velocity field of the flow will undergo local changes in zones close to the boundaries of the banquettes (Fig. 8).

Based on the results of numerical experiments for the entire range of water discharges, the flow characteristics were averaged and dependencies of flooding areas and specific flow energy from input water discharge were constructed (Fig. 9). The comparison of

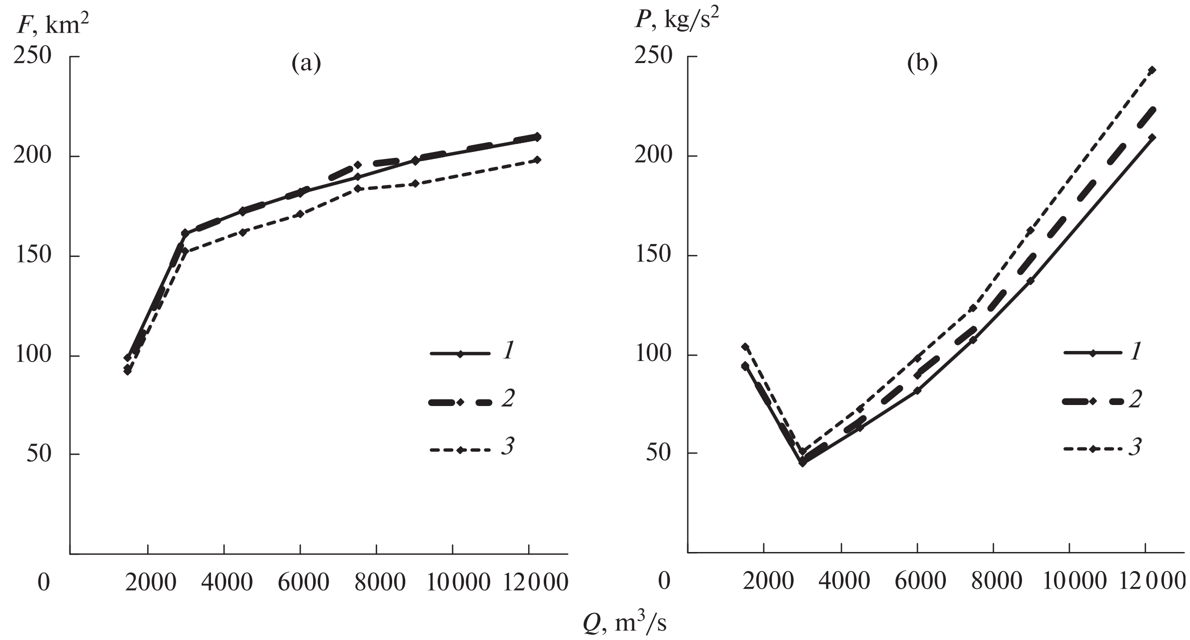

Fig. 9. Dependencies of (a) inundation area F and (b) flow intensity P on the flood discharge Q of the Oka river according to three scenarios of the modeling (the digits are scenario numbers).

the obtained dependencies for three scenarios of floodplain development has shown that, even averaged over entire modeled area, flow characteristics are sensitive to changes in the floodplain relief. Due to the presence of road embankments, including Ryazan–Vladimir motorway (scenario 2), the average flow intensity, determined by the specific energy of flow, increases on the average by 5–7% for the entire range of flood runoff corresponding to floodplain inundation in comparison with unchanged floodplain conditions (scenario 1). The mean water depth in this case increases by 20–30 cm, but the area of flooding and the flow velocities do not change significantly. The additional impact of the planned building of the artificial "islands" (scenario 3) can lead to an increase in mean flow velocities by5% in the entire range of observed water flow, because the inundation area will decrease by 5–6%. As a result, the intensity of the flow will increase by 9–10% compared to the present-day conditions (scenario 2). The common contribution of all infrastructure facilities to the difference between scenarios 1 and 3can cause an increase in the intensity of the flow by 15–20% as a result of flooding area decrease by 5–7%, an increase in the mean flow velocity by 4–5%, and an increase in the mean flow depth by about 40 cm.

CONCLUSIONS

Thus, the analysis of the obtained dependences shows that the values of flow characteristics, even averaged over the entire modeling area, are sensitive to changes in floodplain relief. The most vulnerable characteristic is flow intensity (the specific energy of the flow), which determines the potential flooding hazard. A decrease in the inundation areas by 5–6% when a part of the floodplain gets out from the flooding zones, leads to a significant (up to 20%) increase in the flow intensity on the remaining floodplains. Such effects should be taken into account for the planning of flood protection measures, especially for the case of extreme flood events, similar to that of 1970. The results of modeling can be used in designing the slopes of banquettes and their strengthening in the places most dangerous in terms of possible erosion. In addition, the simulation results allow us to justify the height of the artificial "islands", basing on the expected water levels.

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