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Analysis of the Impact of Hydrotechnical Construction on the Amur River near Blagoveshchensk and Heihe Cities Using a Two-Dimensional Hydrodynamic Model

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Abstract—Water flow and sediment transport under the effect of hydrotechnical constructions on the Amur River near Blagoveshchensk and Heihe cities was analyzed based on two-dimensional hydrodynamic modeling using STREAM_2D software (the authors V. Belikov et al., Russia). Three modeling scenarios were considered: without constructions, with the embankment of Blagoveshchensk, with the embankment of Blagoveshchensk and a system of dams near the Chinese island of Big Heihe. Modeling results have shown that the embankment has only a local effect on the part of the Amur R. upstream from confluence with the Zeya R. The construction of dams in the side channels near the island of Big Heihe can lead to significant flow redistribution, providing the flow concentration in the main river channel and reduction of the water flow, entering the island system. An increase in erosion in the main channel downstream of the confluence near the left bank and a simultaneous increase in accumulation near the right bank of the Amur R. below the island system can take place as the result of side channels shutting by dams from the right bank.

Keywords: hydrodynamics, channel deformations, modeling, Amur, Blagoveshchensk, Heihe

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INTRODUCTION

The geographical location of the Amur R. causes a high dependence of its water regime on the natural and anthropogenic factors. The instability of river channels in the border areas between Russia and China, due to the high activity of channel deformations, is an important regional problem. The intense erosion of river banks, the formation of new islands and branches, the redistribution of water flow, and changing the position of channel area are common here. The annual irretrievable loss of valuable floodplain and valley lands can reach up to 100 hectares along the Russian border alone [13].

The studies of the water regime and channel processes for the cross-border rivers are often complicated because of problems with data acquisition in the bordering countries. So, for example, although many researches are devoted to the channel processes for the problem sections of the Amur R. [10–12, 14], there exist just a few works on the water flow modeling for this area, above all, they are generally based on less comprehensive one-dimensional water flow models [9, 15].

The construction on the floodplains and in the channels, which induced additional impact on the hydrological regime and channel processes, makes the problem of their estimation for the cross-border territories even more complicated.

One of the most vulnerable area is located along the transboundary reach of the Amur R. between Blagoveshchensk (Russia), with the population of about 200 thousand, and Heihe (China) City with the population of over 1.5 billion. The main flood protective levees had existed here since the mid-20th century, but a new wave of active construction has started here in the last 5–10 years, including the embankment of the Blagoveshchensk and a complex of dams around the Chinese Big Heihe island (Fig. 1). The main purpose of the study was to identify the impact of these structures on the channel deformation and flow distribution.

The first version of the model of the study area was developed by authors in 2011 based on the field survey

Fig. 1. (a) Location of the embankment of Blagoveshchensk City and dams around the Chinese island of Big Heihe (red lines) and years of the beginning of their construction; (b) photo of the island of Big Heihe from the embankment of Blagoveshchensk City.

of 2011, and the modeling results had shown a weak effect of the embankment, which is still under construction, on flow velocities and channel deformations [5, 6]. Some studies and simulations for this area were also carried out by the Chinese Institute of Water Resources and Hydropower Engineering (IWHR) at the same time.

In this study, the development of a new model was initiated, due to the active construction of dams from the Chinese side in the last years. The model area was significantly expanded, including the Amur R. downstream of the confluence and the Zeya R. upstream of the Blagoveshchensk; new topographic data were added to digital terrain model; and the hydrological observations of 2011–2015 were taken into account in the simulations.

The simulations, both in 2011 and at present, were carried out on the basis of program complex STREAM_2D, which is widely used in Russia and based on the numerical solution of two-dimensional water and sediment motion equations. This software has been applied to solving various problems, connected with the economic activity on the major rivers of Russia: the Neva, Volga, Northern Dvina, Ob, Lena, etc. [1, 2, 6, 17], and represents the hydrodynamic core of the intelligent information systems for operational flood forecasting being under development in Russia [3].

THE STUDY AREA

The study area is situated at the confluence of the Amur and Zeya rivers between the Russian city of Blagoveshchensk on the left bank of the Amur and the Chinese city Heihe on the its right bank (Fig. 1). The Amur basin above Blagoveshchensk has an area of 493000 km^2, the basin area of the Zeya R. is 223000 km^2. The river basins are characterized by different types of landscapes: from taiga to steppe and mountainous regions and continental moderate monsoon climate with cold and long winters and warm and short summers. The annual precipitation here is about 200–400 mm/year with a maximum during summer monsoon.

The mean annual discharges of the Amur and Zeya rivers above the confluence is 1522 and 1807 m^3/s, respectively. The floods on these rivers are induced by rains. The maximum water discharges of the Amur and the Zeya rivers at their confluence were observed in August, 1984, and were 16700 and 12800 m^3/s, respectively. The hydrological regime was affected by the construction of the Zeya Reservoir in 1985. A few small reservoirs are located in the Chinese part of the Amur basin, but they have no effect on the water regime.

The study area included 15 km of the Amur R. and 20 km of the Zeya River upstream from their confluence and 15 km of the Amur R. downstream from the confluence. The width of the Amur R. near Blagoveshchensk is above 600 m in the main channel, and the width of the Zeya R. is about 1000 m. There are many islands on this reach, especially in the area of rivers confluence. The redistribution of the water flow and bank erosion leads to changes in the positions of the islands and, accordingly, changes of the border between Russia and China, which passes along the Amur R. midstream.

The reaches under study show spatially heterogeneous composition of sediments, including sand, gravel, and pebble. There are many hard rock spots on the Amur R. above the river confluence, while the Zeya R. has mostly sandy sediments.

The main flood protective levees in Blagoveshchensk and Heihe cities appeared in the middle of 20th century, and, nowadays, they are being reconstructed and extended. The major portion of Blagoveshchensk embankment was constructed in 2009–2011 years. The dams around the Chinese Big Heihe island and the dams in the channel branches between the island of Big Heihe and nearby islands have been constructed since 2014 till present. In addition, one of the dams crossed the channel between the island of Big Heihe and the right bank of the Amur R. (Fig. 1). Dams in the side channels have crest height about 124.5 m BS, and they are overflowed during high-flow periods, but reduce the discharges.

MATERIAL AND METHODS

Data Used

Maps at scales of 1 : 25000 and 1 : 10000 were digitized for the Amur floodplain and actualized according to high-resolution satellite images. The data of engineering survey of 2017, including the bathymetry, measured water discharges, and water surface slopes, were used for model adaptation. New data was also supplemented with the results of 2011 field survey. More than ten line structures in river channels and floodplains, including the dams from the Chinese side, the embankments of Blagoveshchensk, existing bridges and those under construction, and the road embankments on the floodplain were taken into account in the model grid and relief.

Several digital terrain models with bathymetry of 2011 and 2017 years and different sets of engineering structures were prepared.

Data from hydrological gauges Zeya–Belogorie, Amur–Kumara, and Amur–Grodekovo were used as the boundary conditions. The water levels at gauges, located in the cities (Blagoveshchensk on the Amur and on the Zeya), were used as control points for the model calibration and validation.

The analyses of the inundation during the high-flood period in August 2013 was made by the comparison of the flooded areas from satellite images Radarsat and Landsat with the results of simulation.

The parameters of channel sediment was specified according to the field data; the average diameter of the channel sediment was set at 0.9 mm, and the diameter of the 90%-probability, at 2.5 mm (90% of particles is less than 2.5 mm). The position of the erosion-resistant layer (the surface of clay sediments and rocky cliffs) was taken according the geological survey data. The crests of engineering structures were specified as erosion-resistant in the model.

Model Description

STREAM_2D program complex [4], which is based on the numerical solution of two-dimensional Saint-Venant equations and which takes into account sediment transport, was used for the simulations.

The Saint-Venant equations consider the main forces that affect a stream with a free surface (gravity, friction, pressure, and inertia; the Coriolis force and wind influence can be considered in addition), and three-dimensional orography of the land surface.

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

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

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

where G is the area on the horizontal plane (x,y); dG is an element of an area G; σ is the area G of the border; $d\sigma$ 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 the stream depth; t is time; g is the acceleration of gravity; $z = z(x, y)$ is the topographic elevation; f are external forces, in the actual model, the friction force $f = \lambda\vec{w}|\vec{w}|/2$, λ is the hydraulic resistance (roughness) coefficient.

For solving the system of equations (1), (2) the corresponding initial and boundary conditions are needed. At an initial point in time $t = 0$: $\vec{w}(x,y,0) = \vec{w}_0(x,y)$ and $h(x, y, 0) = h_0(x, y)$. The boundary conditions should be established along the borders of the modeled area, for example, water discharge, water level, or no flow condition.

The Saint-Venant equations are supplemented with sediment transportation, roiling and sedimentation equations, and bottom diffusion equations:

$$(hS)_{,t} + \nabla\cdot(\vec{w}hS) = -F_w, \quad (3)$$

$$(1-\rho)z_{,t} = F_w + \nabla\cdot(D\nabla z), \quad (4)$$

where F_w is the mass flow, z is the bottom surface; h is water depth; w is velocity; S is sediment concentration; D is diffusion coefficient; and ρ is porosty.

The mass flow can be described by the expression ($F_w > 0$ is for sedimentation, $F_w < 0$ is for roiling)

$$F_w = K(S - S_s), \quad (5)$$

where S_s is the balance sediment concentration under saturation; K is the coefficient of vertical exchange between sediment and flow.

Coefficient K is defined by the formula:

$$K = \begin{cases}\alpha U_* + (1-\alpha)W, \text{ if } U_* > W \\ W, \text{ if } U_* \le W\end{cases}, \quad (6)$$

where α is a weight coefficient ($0 < \alpha < 1$); W is sedimentation velocity (the steady velocity of sedimentation in a stationary liquid); U_* is the dynamic velocity.

The rate of the start of particles movement is defined by Goncharov formula [15]:

$$U_N = \min\left(U_N^{\max},\ \log\left[\frac{8.8h}{D_{90}}\right] \times\sqrt{\frac{2\left(\left(\frac{\rho_s}{\rho_l}-1\right)gD_{50} + 1.75C_y\right)}{3.5}}\right), \quad (7)$$

where U_n is non-sliding flow velocity, D_{90} is the boundary of particle diameters of 90% probability, D_{50} is the average diameter of particles, ρ_s is the density of sediments, ρ_l is the density of water, C_y is the cohesive coefficient for cohesive sediments.

The discretization of the modelling area in STREAM_2D was performed using an irregular hybrid computational mesh with more than 72 thousand cells. We used curvilinear quadrangular grids for line structures and a curvilinear triangular grid with a spatial resolution from about 20 × 30 m and less for channels to 150 × 200 m for the remote sites of the floodplain. All floodplain topography and river channel relief data were interpolated into the centers of grid cells using an original algorithm [7].

Model Calibration and Validation

The calibration and validation of the model was carried out based on the data of engineering surveys of 2017; an additional validation was made for the extreme floods of 2013 and 1984 (Table 1). The model reproduces water level and flood area fairly well for all hydrological situations with channel and floodplain roughness coefficient of 0.020 and 0.050, respectively; the differences between the simulated and observed water levels at Blagoveshchensk were less than 30 cm.

An additional validation was carried out for the outstanding floods of 1984 and 2013 using riverbed bathymetry of 2011 and 2017 surveys. On August 15, 1984, a flood of 1% exceedance probability took place near Blagoveshchensk; water levels at the gauge Amur–Blagoveshchensk came up to a maximum height of 868 cm (128.56 m BS), some streets of the city near the river were inundated. For the simulation based on the channel relief by 2017, the obtained water level at the gauge Amur–Blagoveshchensk is 20 cm higher and that at the gauge Zeya–Blagoveshchensk is 14 cm lower than the respective observed values. With the bed relief of 2011 used for the same simulation, the deviations of 6 and –28 cm were obtained, respectively.

The recent extreme flood of 2013 featured a long period of flooding in the entire Amur basin [8, 9]. The maximum water level at the gauge Amur–Blagoveshchensk during this flood exceeded the height 822 cm above the gauge zero (128.10 m BS) on August 16; this is only 73 cm less than the absolute historical maximum (895 cm above gauge zero level), which was observed there on August 20–21, 1958. The continuous simulation of the high flood period from August 10 to 20, 2013, has shown a good agreement between the simulated and observed water levels and flooding zones. The model slightly underestimates the levels compared to their actual values, the mean difference between the simulated and observed water levels on gauge station on the Amur R. is 13 cm, and that on the Zeya R. is 15 cm. The flooded areas, simulated

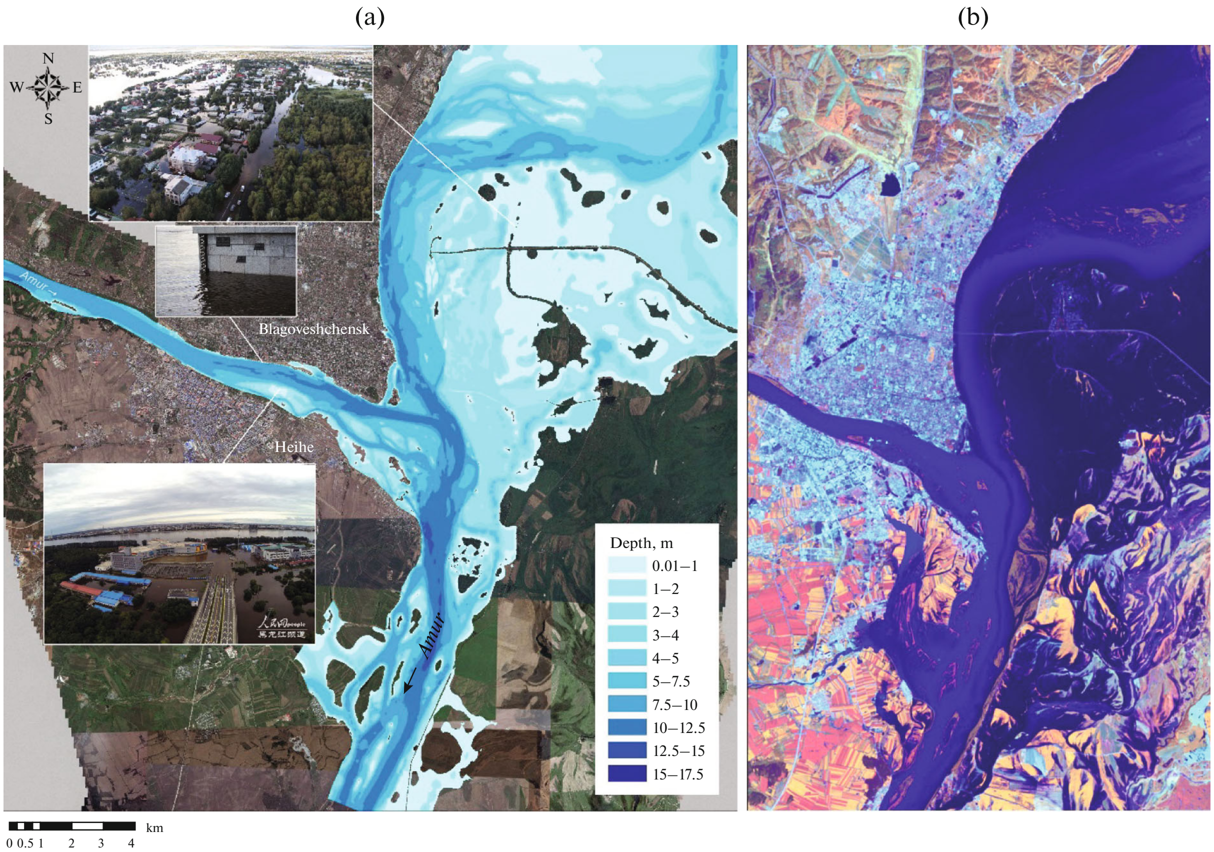

Fig. 2. Flooding zones at the peak of the flood of 2013 (a) simulated using two-dimensional hydrodynamic model STREAM_2D and (b) observed in Landsat satellite image.

using the hydrodynamic model and determined by satellite images (Radarsat from August 14, 2013 and Landsat 8 from August 20, 2013), are in good agreement, the difference between them being about 10%. Blagoveshchensk was not flooded in 2013 due to the appropriate protection structures and the regulation by the reservoir on the Zeya River, but the most part of floodplains, including settlements near Blagoveshchensk and Chinese island of Big Heihe, were flooded significantly with water depths over 2 m (Fig. 2).

RESULTS OF SCENARIOS MODELING

The modelling of water regime and sediment transport was carried out continuously for a long-term period from 2011 until the end 2015. We have not carried out simulation for 2016 and 2017 years because data of water level and discharges are not available. For the estimation of the effect of hydrotechnical construction on the river flow and channel deformations, three modeling scenarios were considered:

I. without dams and embankment,

II. with embankment of Blagoveshchensk,

III. with embankment of Blagoveshchensk and complex of dams around Big Heihe Island.

The embankment of Blagoveshchensk was taken into account for the scenarios II and III from the beginning of the simulation. The influence of the dams from the Chinese side in the third scenario was considered as follows: since the beginning of April 2014, the dams blocking side channels with heights 124.5 m BS and the protective dam around the Big Heihe Island (with a height of 129.5 m BS) have been incorporated into the model bottom relief, obtained by the results of simulation for 2011–2014 according to scenario II. Thus, for 2014–2015, scenario II was carried out taking into account only the embankment, and the third scenario took into account the effect of dams and the embankment. Such approach has allowed us to consider most fully the effect on water flow and sediment transport of the different hydraulic conditions at the confluence of the Zeya and Amur rivers in the last years, including the extreme flood of 2013.

The exact quantitative comparison of the simulated values of the vertical channel deformations with the actual values is complicated, because the modeling there did not take into account the years of 2016 and 2017 because of the lack of hydrological data, and the bathymetry data for 2011 cover much smaller area than

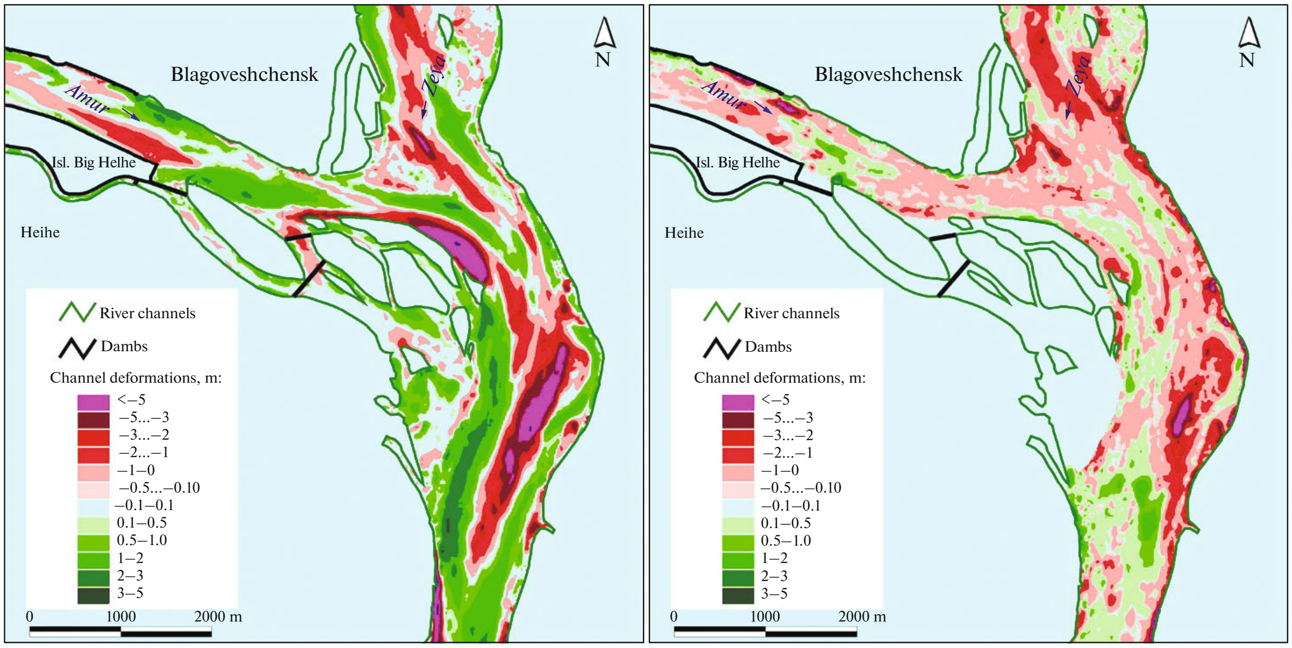

Fig. 3. (a) Modelled channel deformations at the confluence of the Amur and Zeya rivers for the period of 2011–2015 taking into account dam constructions in the 2014 (scenario III); (b) channel bottom deformations, estimated as the difference between the channel bathymetry surveys of 2017 and 2011 years.

those for 2017. However, a visual comparison of the deformations obtained by the modeling and the results of comparison of two bathymetrical surveys looks rather promising. The model has clearly captured the main erosion zones at the Muraviev Island and in the area at the mainstream line of the Amur R. downstream from the confluence, and the downstream accumulation zone (Fig. 3).

The comparison of the results of simulation by scenarios I and II confirmed the results of previous studies [5, 6], in that the construction of the embankment in Blagoveshchensk has only a local impact on the flow of the Amur R. upstream from the confluence (Fig. 4a). The strongest restriction of the stream by the construction of the embankment is about 250 m, which leads to an increase in the flow velocity of the Amur R. in the embankment area and within 1.5 km downstream of it by 0.15–0.2 m/s. This causes a decrease in sediments accumulation in this area, but does not lead to additional channel erosion. However the results of modeling show that the midstream line of the Amur R. can shift by 100 m toward the right bank within a 1-km-long reach from the downstream part of the Big Heihe Island to the confluence. Downstream from the confluence of the Amur and Zeya rivers, there is no impact of the embankment on the flow and channel deformations in any way.

The simulation has shown, that the presence of dams at the islands from the Chinese side of the river influences the entire system of islands at the confluence of the Amur and Zeya rivers, and this influence can be traced over more than 8 km downstream of the confluence. This is attributed to the significant increase in water discharges in the main channel of the Amur R. due to the closing of the side channels, the effect of which is especially significant in the flood water discharges, varying in the range of 1500–5000 m^3/s, because the largest water discharges cause the overflow of the dams. Based on the simulation results, the water discharges in the main river channel upstream from the confluence during the flood period with input discharges of 1500–5000 m^3/s can increase by 15–25%; and those during peak flow, by 5–6% (Fig. 5).

The increase in water discharges in the specified area of the Amur R. causes an increase in flow velocities, especially high downstream from the confluence at the system of islands, where such increase is about 0.25–0.3 m/s, with a local increase of 0.5 m/s. The mainstream line is found to shift by 60 m to the left (concave) bank of the Amur R. within a reach more than 1 km long downstream from the confluence. The increase in water discharges in the main channel of the Amur R. does not lead to significant changes in the flooded zones, because, during peak flow, the changes in water discharges are not so significant.

The comparison of the results of simulation by scenarios II and III, the effect of the dams during 2014–2015 causes an increase in the erosion in the mainstream below the confluence near the left bank and a simultaneous increase in accumulation near the right bank of the Amur R. downstream from the island sys-

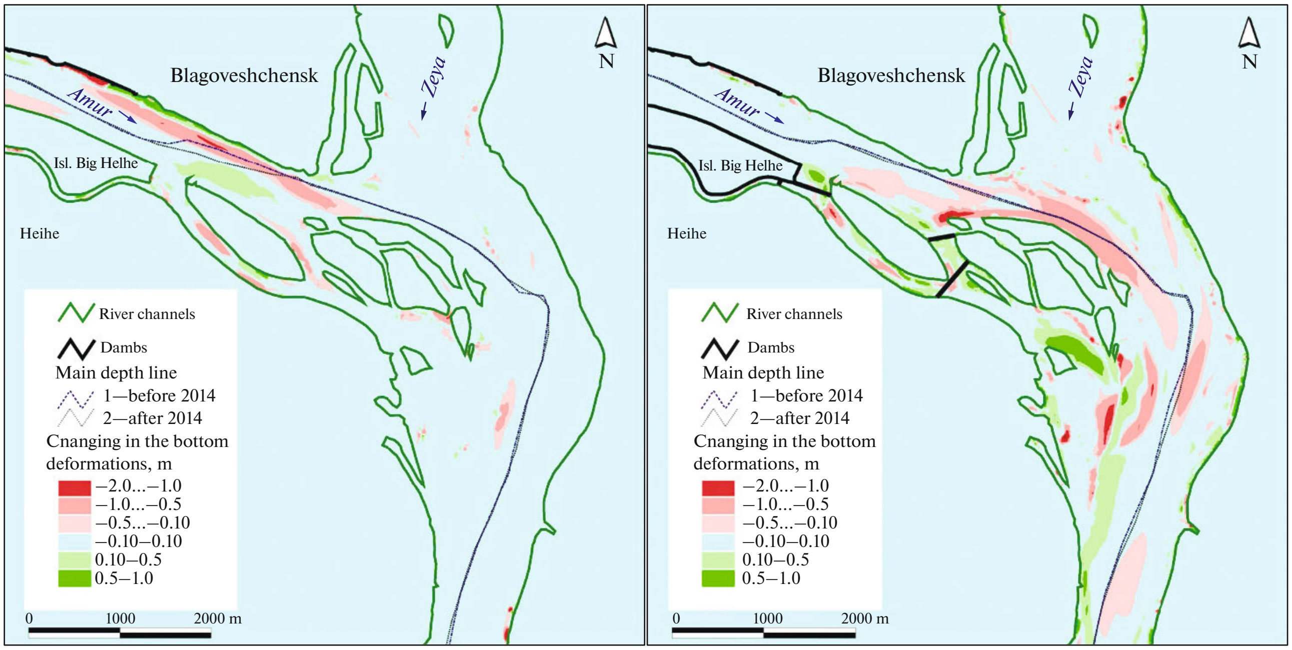

Fig. 4. Changes in channel bottom deformations due to hydrotechnical constructions: (a) the embankment of Blagoveshchensk (difference in deformations between scenarios II and I), (b) dams near island of Big Heihe (difference in deformations between scenario III and II).

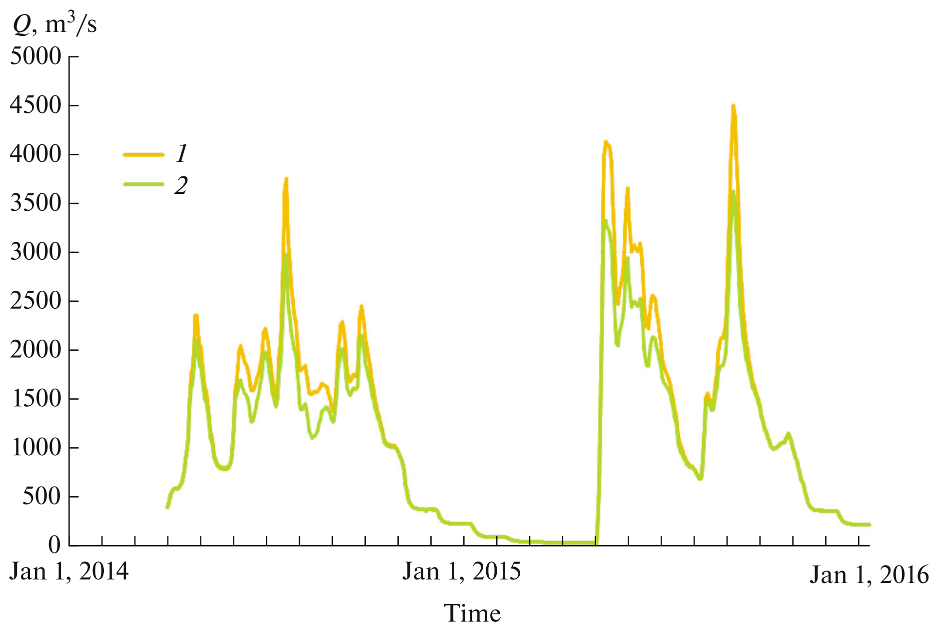

Fig 5. Simulated water discharges in the main river channel of the Amur River upstream from the confluence in 2014–2015: (*1*) with dams near island Big Heihe (scenario III), (*2*) without dams near island Big Heihe (scenario II).

tem at an amount of up to 0.5–1 m (Fig. 4b). In the area near the bridge on the Russia–China cross-border road under construction on the Amur R., the main trend is accumulation, which exceeds 3–4 m, except for the areas near both banks, where erosion zones exist, especially, at the right bank. Due to the dams,

Table 1. Comparison of water levels for calibration and validation scenarios

Dates	Input discharges of the rivers, m^3/s		Water levels (m BS)					
			observed	simulated	difference between simulated and observed level, cm	observed	simulated	difference between modeled and observed level, cm
	Amur	Zeya	Blagoveshchensk – Amur			Blagoveshchensk – Zeya		
September 23, 2017 (low flow)	3110	2340	122.35	122.33	–2	121.49	121.68	19
September 8, 2017 (rain flood)	5640	4660	124.59	124.53	–6	123.44	123.57	13
August 16, 2013 (extreme rain flood)	12288	13400	128.09	128.04	–5	127.92	127.82	–10
August 15, 1984 (extreme rain flood)	16700	12800	128.56	128.75	20	128.52	128.37	–14

the accumulation in the middle part of the channel slightly decreased, as well as the erosion in the right-bank area.

DISCUSSION

This study showed that the model used is a good tool for scenario estimations and monitoring of possible changes in stream hydraulics, flooded areas, and the transport of sediments. The model reproduces water levels, flow velocities, and flooding zones fairly good for all hydrological situations at the confluence of the Amur and Zeya rivers, considered during calibration and validation, with the difference between the observed and modelled data never exceeding 30 cm for water levels and 10% for flooded areas.

The most demanding task is sediment transport modeling, considering that the correctness of channel deformations estimations is defined by a number of objective factors, including the accuracy of selection of hydrometeorological scenarios for the studied period, accounting of ice phenomena, the inhomogeneity of channel sediments, the existence of flow-resistant channel beds in specific areas, the presence of vegetation, which complicates the erosion process, the existence of the sediments that are frozen after winter period.

In this model version, the inhomogeneity of sediments in the interflowing waterways was not considered; therefore, for calculating, it was necessary to set effective diameter of particles for the entire explored area. This assumption, under the conditions of more sandy channel bed of the Zeya R. and the larger sizes of sediments of the Amur R. at Blagoveshchensk, leads to the fact that the erosion and accumulation can be overestimated in the Amur R. upstream from the confluence. From the modeling results, we can also see some overestimation of the accumulation values by the model for the Amur R. channel downstream from the confluence and an underestimation of the erosion values in the Zeya R., due to the fact, that the modeling uses homogeneous sediments of an average diameter, while, actually, the sediments of the Amur R. are coarser, and the sediments of the Zeya R. are smaller than the average. At the same time, the comparison of results showed, that the change of sediment effective diameter had no effect on the spatial location of the erosion and accumulation zones, but affect only the values of possible deformation change. This means that the diameter of the sediments in this case has worked to some extent as a calibration parameter, because setting of an appropriate average value of sediment diameter makes it possible to minimize the differences between the modeled and observed channel deformations in the whole area.

For the further studies, it may be expedient to change the model to the multi-fraction one, which is being developed now; however, it will require more detailed initial maps of the channel sediment distributions.

Downstream from the island of Big Heihe in the Amur R. channel there is an accumulation zone, which the model results show to be longer than it actually is. The reason is, most likely, both the insufficient length of the modeling period and the changes in the operating modes of the dams during their construction.

Although the dams were considered in the model with a constant crest mark, in reality they have been in the process of construction. This fact also could lead to some differences in the simulated and actual riverbed elevations. Further, it will be necessary to obtain the specifications of the final project for the constructions of the Chinese riverside, since, till present, all of them exist only as ground cofferdams without any concrete reinforcements and, probably, their marks and a configuration are changing. If the final heights of dam crests will be higher than it was assumed in the model, the changes in water discharge redistribution and channel deformations can be larger.

CONCLUSIONS

A two-dimensional hydrodynamic model of the confluence zone of the Amur and Zeya rivers was developed based on the program complex STREAM_2D. The model takes into account both the existing engineering structures and those under construction on the floodplain and in the channel and branches of the Amur R. on both its Russian and Chinese sides.

The results of scenario modeling showed a local influence of the embankment of Blagoveshchensk on the changes in the velocity field of the stream and channel deformations.

The construction of dams in the branches near the Big Heihe Island can lead to an increase in water discharges in the main channel of the Amur R. upstream of the confluence by 15–25% during the flood period with input discharges of 1500–5000 m^3/c, and by 5–6% during peak flow. No substantial changes in the flooding zones are expected to be caused by the construction of dams in the side channels at the existing elevations of the dam crests (about 124.5 m BS), because, during high flow, the dams ensure water flow through these channels.

From the point of view of the possible changes of channel deformations, the construction of dams from Chinese riverside can increase the erosion in the main channel of the Amur R. downstream from the confluence with the Zeya R. and increase the accumulation downstream from the system of islands at the right bank of the Amur R.

Under the present conditions, the Amur R. channel close to the cities of Blagoveshchensk and Heihe becomes more and more constrained, which requires monitoring and assessment of the consequences of construction impact on the hydraulics and channel processes from both Russian and Chinese sides, using field studies, remote sensing data, and mathematical models.

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