Two-dimensional mathematical modeling of 2013 and 2020 Amur River floods

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Abstract. Predicting river flooding of the territory where people live and engage in economic activities is urgent. The most problematic area in the Russian Far East is the territory through which the Amur River and its tributaries flow. The article considers the calculations of two Amur River floods: 2013 – catastrophic flood and 2020 – low flood. The simulation was carried out using a system of two-dimensional Saint-Venant equations using the Stream 2D CUDA program. The solution of the system of equations by numerical methods is based on the original author's methodology. Channel depth maps and WordDEM™ (Airbus Defense and Space, Intelligence) data at 24 m resolution were used as a digital elevation model. Calculations of river floods in 2013 and 2020 were performed on a built-in and calibrated mathematical model, which matches the observational data well.

1 Introduction

Climate change and the development of economic activity in river valleys requires the development of operational methods for predicting the spread of high water and river flood. Such forecasts aim to prevent river floods or minimize their consequences. To assess the consequences of river floods, it is necessary to understand the speed of water distribution, levels of flooding, etc. The numerical simulation methods of the propagation of the flood/high water wave, described by the system of Saint-Venant equations in one-dimensional or two-dimensional formulation, show the greatest efficiency. The development of computer technology [1, 2] and methods of remote acquisition of initial information about the environment [3] makes it possible to make extended models of large rivers, for example, Lena [4], Northern Dvina [5], Don [6], Amazon [7]. Yangtze [8].

The Amur River is located in the Far East of the Russian Federation, one of the world's twenty largest rivers. The area through which the Amur River flows is in the zone of active cyclones and typhoons. Floods occur every second year and every 8-10 years; their consequences are catastrophic.

Catastrophic floods cover several large basins simultaneously; they flood almost all floodplain lands that are being withdrawn from agricultural use, cities, and settlements,

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transport communications are disrupted, and economic activity is completely paralyzed. In addition, as a result of the passage of the river flood, the riverbed and tributaries change, i.e., dangerous riverbed processes for objects of economic activity arise.

The last catastrophic flood on the Amur River caused great damage in 2013 [9-10].

In addition to the hydrological regime of the river, local physical and geographical factors influence the occurrence of flood hazards:

- a large density of the river network, which contributes to the rapid flow of rain and meltwater into the rivers;
- abrupt transitions from mountainous parts of river basins to plains, which is the reason for a long period of standing high waters;
- the presence of sharp local narrows of river valleys of natural and artificial origin, creating additional support during the passage of floods.

The difficulty of predicting the spread of a flood wave along the Amur River is primarily due to its length, wide and branched floodplain in the middle and lower parts. In addition, the river is a cross-border between Russia and China, and part of the water flow is regulated.

In separate sections of the Amur River basin, numerical methods of water movement in the riverbed were simulated at different periods [11-13], including models of precipitation forecast in the catchment area [14-16], together with a hydraulic model of the river [17-18]. The longest model in one-dimensional formulation on the DHI Mike Hydro River program with the NAM rainwater runoff model (Nielson and Hansen, 1973) was created jointly by the Technical University of Denmark, Maynooth University, Ireland Southern University of Science and Technology, Shenzhen, China [18]. The model was created from the Pokrovka village to Nikolaevsk-on-Amur along the Amur River and along the Sunghuai River from the inflow of the Nenjiang River in Sunghuai near Harbin to its inflow in Amur.

This article discusses the first experience of creating an extended two-dimensional numerical model of the Amur River.

2 Methods

2.1 Digital elevation model of the Amur River

As the geometric basis of the model, a digital elevation model was used, which was built for the Amur River from the Pokrovka village to Komsomolsk-on-Amur, including tributaries of the Zeya River (from the Zeya HPP to the mouth), the Bureya River (from the Nizhne-Bureysky HPP to the mouth), the Sunghuai River (from Jiamusa to the mouth), Ussuri river (from the village of Sheremetyevo to the mouth), Tunguska river (from the village of Archangelovka to the mouth). Cartographic information and data from WordDEM ^{TM} (Airbus Defense and Space, Intelligence) with a resolution of 24 m were used for this area in the floodplain part to build the channel of the depth map, the cutting line, space survey materials by domestic spacecraft "Resurs-P" and "Canopus-V" (with a spatial resolution of 2.1 m). [19].

A fragment of the DEM that is used in the model is shown in Fig. 1

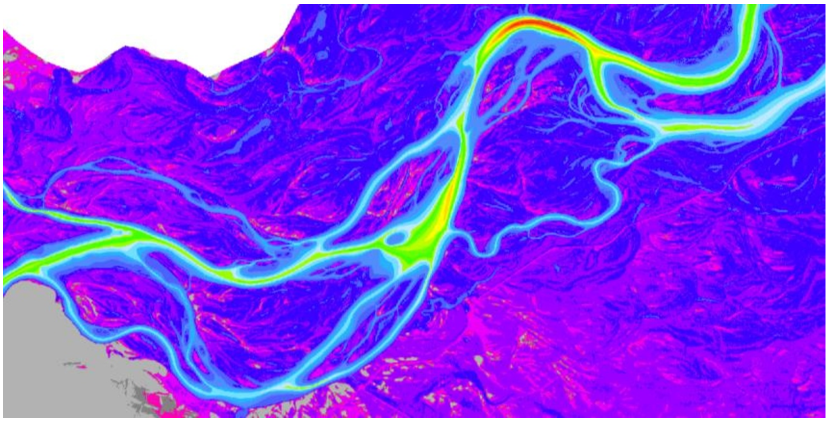


Fig. 1. Digital elevation model (fragment) of channel and floodplain of Amur River (middle course)

2.2 Building a model

To calculate the hydrodynamic parameters of the water flow, the domestic STREAM 2D CUDA software package [20] was used based on an original numerical algorithm for solving two-dimensional shallow water equations on an uneven bottom. The latest version of the STREAM 2D CUDA software package implements the new algorithm described in [1, 21, 22], which ensures the uniqueness and high accuracy of the solution in areas with complex bottom relief and hydraulic structures [23] and parallelizes on an NVIDIA GPU using CUDA technology to speed up calculations. The algorithm, validation of the numerical model, and numerous examples of applications to various problems of river hydraulics and hydrodynamics are presented in the monograph [23].

During 2019-2020 (fig.2), a mathematical model of the Amur River was constructed from Blagoveshchensk to Nikolaevsk-on-Amur and the left-bank tributary of the Zeya River from the inflow in the Selemdzha River to the inflow in Amur. The model also included estuaries of the Selemdzha (60 km), Bureya (32 km), Sunghuai (42 km), and Ussuri (45 km) rivers. In 2021, the model was completed in the upper part: sections were added along the Amur River from Blagoveshchensk to the Pokrovka village and along the Zeya River to the Zeya HPP. Subsequently, the section (520 km) below Komsomolsk-on-Amur was excluded from the calculations since, in that area, there was relief only along the floodplain, and digitization along the riverbed has not yet been completed. There are plans to add 45 km along the Bureya River to the Nizhne-Bureysky HPP and 320 km along the Ussuri River to the city of Dalnerechensk. The current model has a length of 2.2 thousand km along the Amur River and 590 km along the tributaries. In the future, with the addition of the lower section of the Amur River, as well as the Amur Estuary, the model of which was built and calibrated in 2016 [13], the length of the model along the Amur River will exceed 3000 km.

The calculation grid of the model is constructed in two stages. In the first stage, the calculated area is divided into polygons so that the relief forms and man-made objects are drawn correctly in the model. In the second stage, grids are built inside each polygon, combined into a single model, and smoothed. In total, about 2000 polygons were built.

Quadrangular curved grids were built along watercourses, roads, embankments, and dams, and a triangular grid of irregular structures was built along the floodplain. The minimum cell size in the model is about 50 m; the maximum is 500-700 m. Some embankments (roads, dams), according to the results of the analysis of the flood of 2013, were not accepted as overflow. Figure 3 shows a fragment of the constructed computational grid. The final grid size of the model up to Komsomolsk-on-Amur is 402048 cells. The section from Komsomolsk-on-Amur to Nikolaevsk-on-Amur contains more than 200 thousand cells, Amur estuary - 67391 cells. The expected size of the model after adding sections on the Bureya and Ussuri rivers will not exceed 1 million cells.

The model adopted 7 boundary conditions, on which the parameters of the hydrological regime were set: 6 - at the input, 1 - at the output. In addition, control gates and points were set to detail the calculation.

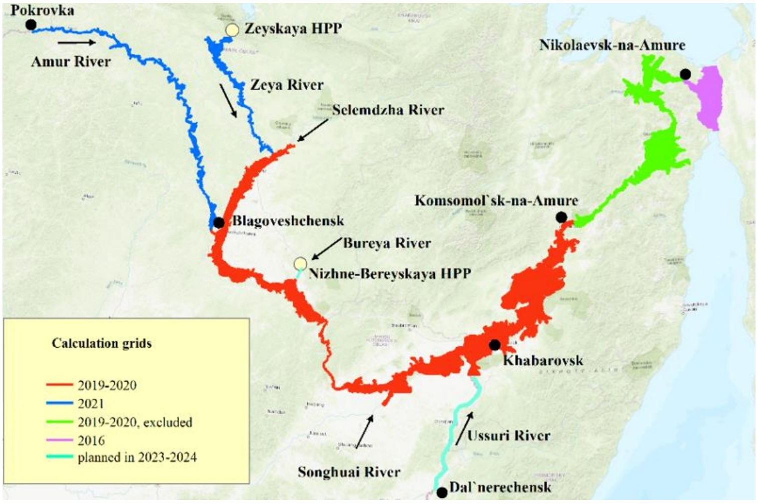


Fig. 2. Layout of models' location along Amur River and tributaries

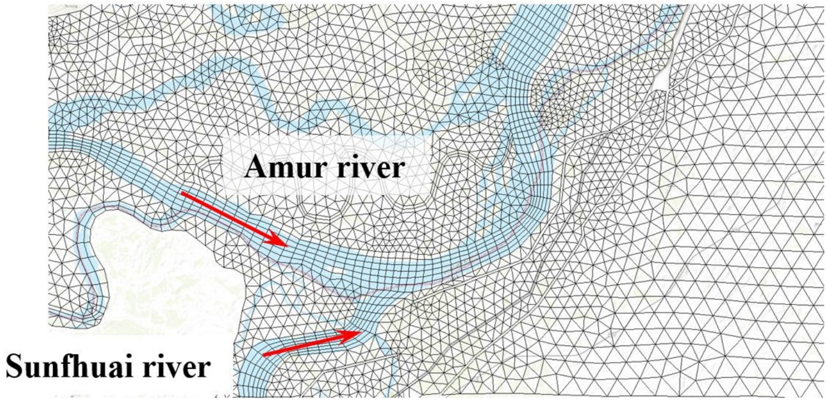


Fig. 3. Fragment of calculation grid in Sunghuai River inflow area

2.3 Calibration of the model

Before starting calculations, it is necessary to calibrate (verify) the model to be sure of the correctness of the results.

At the initial calibration stage, the roughness coefficient values were taken for the entire model: 0.025 for the riverbed and 0.05 for the floodplain. Hydrological conditions were taken as boundary values (Table 1), which reproduced the following phenomena on the model:

- the water flows below the riverbed edges;
- the water is close to the riverbed edges with a small exit to the floodplain;
- water flows through the floodplain (catastrophic flooding).

Table 1. Boundary conditions of the model during calibration

Calculation option	Maximum discharge at the model boundary, m^3/s						
	Amur River (Pokrovka)	R.Zeya	R.Bureya	R. Sunghuai	R.Ussuri	R.Selemdzha	R.Amur Komsomolsk-on-Amur
below the edges	4845	1740	900	1740	1435	670	11330
in the edges with exit to the floodplain	9700	1200	850	7500	3750	2000	25000
catastrophic flooding	11610	12900	2150	12900	3440	0	43000

At the output boundary of the model (in the area of Komsomolsk-on-Amur), a graph of the dependence of discharge on the level was set based on observations at a hydrometric post from 2002 to 2014 (fig. 4).

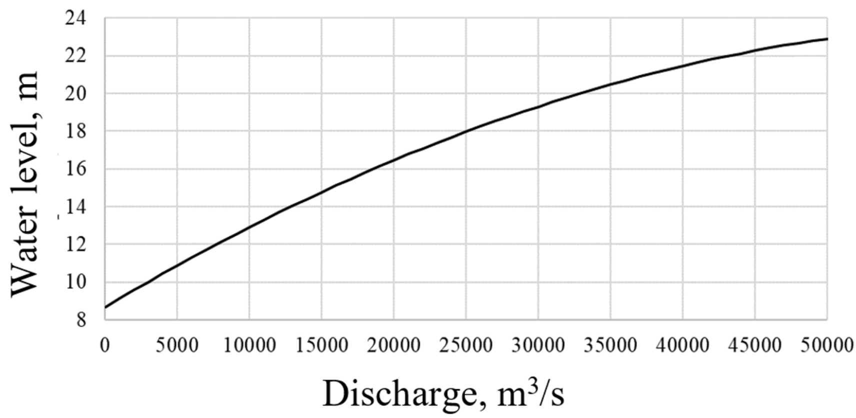


Fig.4. Dependence of *Z(Q)* on the output boundary of the model in Komsomolsk-on-Amur

Calculations were compared with the data from stream flow measuring stations. According to the calibration results, the values of roughness coefficients were obtained in the range from 0.017 to 0.03 in the riverbed and from 0.04-0.06 in the floodplain (Table 2).

Table 2. Values of channel roughness coefficients based on calibration results under stationary conditions

Morphometric part of the watercourse	Value of the roughness coefficient	Riverbed section
riverbed	0.017	Middle Amur from Khabarovsk to the end of the model
	0.02	Roads, embankments, the riverbed of the Amur River, and tributaries on the site of the Middle Amur from the village of Nagibovo to Khabarovsk
	0.022	Upper Amur to the Pompeevka village, the mouth of the Bureya River
	0.023	R.Zeya
	0.03	Amur River between the Pompeevka village and Nagibovo village
floodplain	0.04	Upper Amur and part of the Middle Amur to the Nagibovo village
	0.05	the Zeya River, on the site of the Middle Amur from the village of Nagibovo to Khabarovsk
	0.06	Middle Amur from Khabarovsk to the end of the model

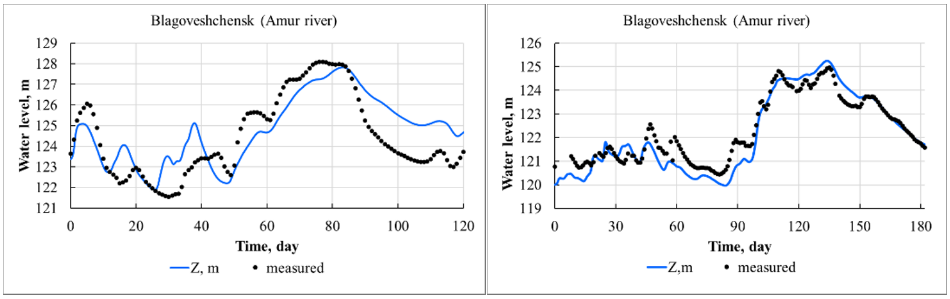
3 Results

3.1 Modeling of floods in 2013 and 2020

To verify the correctness of the model calculations in non-stationary conditions, the floods of 2013 (catastrophic) and 2020 were modeled.

For the first option, the period from 01.06.2013 to 30.09.2013 (121 days) was selected, and for the second – from 01.05.2020 to 30.10.2020 (183 days). Flow hydrographs were set at the input boundaries and at the output (in Komsomolsk-on-Amur), the dependence curve Q(Z) (Fig. 4).

The daily calculated water levels were compared with those observed at 24 posts and showed good calculation convergence with the observational data (Fig. 5).



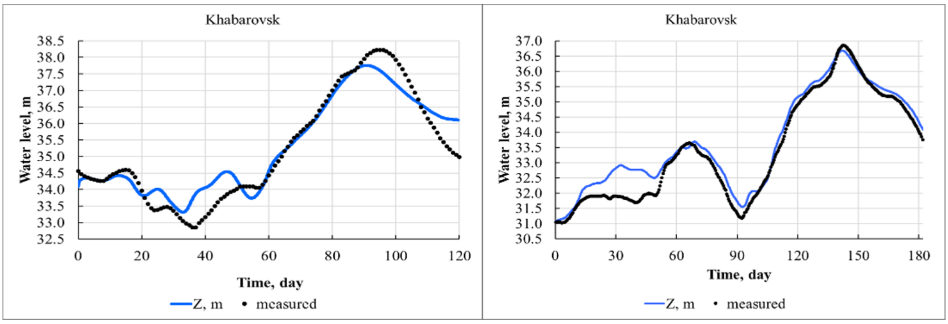


Fig. 5. Water levels (measured and calculated) depending on time: left – 2013, right – 2020

The estimation of the error of calculations of water levels was carried out according to the formula:

$S/\sigma = \sqrt{\frac{\sum(Z_i-R_i)^2}{\sum(Z_i-\bar{Z})^2}}$ where

Z_i is observed water levels at the stream flow measuring station;

R_i is water levels obtained as a result of the calculation at the same time points

$\bar{Z} = \frac{1}{n}\sqrt{\sum_{i=1}^{n} Z_i}$ is the arithmetic mean of the values of *n* observations,

The results obtained for three stream flow measuring stations (for Blagoveshchensk, Khabarovsk, and Komsomolsk-on-Amur) are presented in Table 3.

Table 3. Calculation results of the simulation error estimation for selected water measuring posts

Year of modeling	S/σ for stream flow measuring stations		
	Blagoveshchensk	**Khabarovsk**	**Komsomolsk-on-Amur**
2013	0.62	0.28	0.43
2020	0.36	0.32	0.23

4 Discussion

At the final stage of work on creating the Amur River model, it is planned to integrate a hydrodynamic model with a model for calculating water flow from the catchment - ECOMAG. Work in this direction is already underway. A software block has been developed in STREAM 2D CUDA, which transmits lateral inflow flows to the hydrodynamic model through "integration points".

A tool is also being developed to visualize the results of calculations in the form of maps of flooding areas and fast-moving fields.

Both directions are currently at the stage of testing and verification.

5 Conclusions

A hydrodynamic model of the Amur River and its tributaries was developed for flood forecasting and operational decision-making: operating for more than 2 thousand km and promising for more than 3 thousand km.

The model is based on the numerical solution of a system of two-dimensional Saint-Venant equations.

The model was calibrated according to three variants of the hydrological situation on the river: low level (low water), the river in edges and the exit to the floodplain (channelforming), and catastrophic flooding. The obtained values of the roughness coefficients for the riverbed in the range 0.017-0.03 for the floodplain 0.04-0.06 are consistent with the recommended regulatory documents.

The calculations for floods in 2013 and 2020 showed good convergence with the measured data.

Research on this scale in the Russian Federation has been carried out for the first time and has good prospects for practical use.

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