RESEARCH PAPER

MODELLING OF POTENTIAL IMPACT OF CLIMATE CHANGE ON WATER REGIME AND CHANNEL PROCESSES IN THE RIVER LENA NEAR CITY YAKUTSK: POSSIBILITIES AND LIMITATIONS

Inna N. Krylenko[1,2*], Ekaterina D. Pavlyukevich (Kornilova)[1,2], Aleksandr S. Zavadskii[1], Pavel P. Golovlyov[1], Eugenia A. Fingert[1], Natalya M. Borisova[2], Vitaly V. Belikov[2]

[1] Lomonosov Moscow State University, Faculty of Geography, Moscow, 119991, Russia

[2] Water Problems Institute of the Russian Academy of Sciences, Moscow, 119333, Russia

*Corresponding author: krylenko_i@mail.ru

Received: May 12th 2024 / Accepted: November 22nd 2024 / Published: December 31st 2024

https://doi.org/10.24057/2071-9388-2024-3723

ABSTRACT. STREAM_2D software package was applied for retrospective and predictive simulations of the Lena River hydraulic and channel changes during ice-free period near the city of Yakutsk. The modelling results indicate significant correspondence of simulated water discharges distribution and water levels with observed one, the model also has captured main erosion and accumulation zones, according to the 2009–2016 years observations. Runoff hydrographs of the ECOMAG runoff model simulations based on the global climate model MIROC-ESM-CHEM data were used as input for the hydrodynamic model with daily time step for two climate scenarios RCP2.6 and RCP8.5.

Comparison of scenario, based on modern hydrographs, and two scenarios, based on climate projections, have shown the changes in the range of channel-forming discharges and their duration. According to the results of 20-year simulation of channel evolution for three scenarios, the position of the main areas of erosion and deposition under scenario RCP2.6 and RCP8.5 retained the same as under actual scenario, but some additional new local areas of erosion can be formed during peak flows near the banks. Erosion can increase by up to 1 - 2 meters and even more in some areas, but the shifting of some large erosion-accumulative forms is slower than according to the scenario, based on the modern hydrographs, due to the reduced duration of channel-forming flood discharges.

KEYWORDS: hydrodynamic modeling, channel processes, STREAM 2D, climate change, ECOMAG, runoff change

CITATION: Krylenko I. N., Pavlyukevich (Kornilova) E. D., Zavadskii A. S., Golovlyov P. P., Fingert E. A., Borisova N. M., Belikov V. V. (2024). Modelling Of Potential Impact Of Climate Change On Water Regime And Channel Processes In The River Lena Near City Yakutsk: Possibilities And Limitations. Geography, Environment, Sustainability, 4(17), 112-120

https://doi.org/10.24057/2071-9388-2024-3723

ACKNOWLEDGEMENTS: The authors are grateful to the participants of fieldwork, including the team of the Makkaveev laboratory of Soil Erosion and Fluvial Processes of the geographical faculty of Moscow State University. The authors express their gratitude to the Academy of Sciences of the Republic of Sakha (Yakutia) for scientific and information assistance in conducting research.

The study was carried out under the Governmental Order to the Water Problems Institute of RAS, subject FMWZ-2022-0001 (flow dynamic estimation) and under the state assignment of Faculty of Geography, Lomonosov Moscow State University part 1.10, CITIS 121051100166-4 (bathymetric survey), 121051400038-1 (Lena river regime data collection), the part of research, concerning Lena runoff modeling was supported by RSF project №24-17-00084, transport of sediments was analyzed with support by the Ministry of Science and Higher Education of Russian Federation under the Agreement 075-15-2024-614, date 13.06.2024.

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

The analysis of flow hydraulics at sites with complex topography, taking into account the large number of structures in the channel (incisions, diversion dams, water intakes) and in the floodplain (bridge crossings, flood protection dams, etc.) has been carried out last decades using hydrodynamic modeling methods (Jodhani, 2021). Calibration and validation of the hydraulics at different flow rates (e.g. with and without floodplain inundation) is mandatory for such modeling. Although nowadays there are some examples of models for long sections of large rivers such as the Parana (Guererro et al., 2015), Mississippi (Scott et al., 2008), Nile (Saeed et al., 2020), usually due to their complexity, moving-bottom hydrodynamic models are mainly used for non-extended channel reaches and/or for non-extended time periods (Sloff et al, 2012; Horvat et al., 2015; Zhang et al., 2014). Moving-bottom simulations are very computationally demanding, so there is a difficulty to perform calculations for complex computational meshes for long periods. Often the data on real channel changes are not available for the validation of the modeled channel evolution for long periods or for all modeling area.

At the same time, the need for prospective long periods modeling of channel evolution is driven by the requirement of comparative hydromorphological processes analyzing in the river section both under modern conditions and in the future, in order to assess the degree of anthropogenic impact on the water and channel regimes. Mathematical modelling has becoming one of the powerful tools in this case, which, combined with traditional hydrological and morphological approaches, gives opportunity for the rate and direction of channel changes assessment and developing of medium and long-term channel evolution forecasts, both in existent conditions and also taken into consideration various feasible infrastructure projects in river channels and on the floodplains.

An important issue in predictive modelling is the choice of computational scenarios. The most traditional approach to the problem is to use schematic hydrographs based on modern runoff series as input, sometimes taking into account discharges of low repeatability (for example, 1% probability discharge) (Vijay et al.,2007; Golovlyov et al., 2019). However, in the climate changes context, this approach does not allow to consider the impact of expected changes on the water regime and channel deformation, which is particularly relevant for the areas, where modern trends are clearly expressed and further runoff growth is projected. At the same time, demand on the assessments of the possible climate changes impact on water regime and channel processes is very high and such tasks require the development of new approaches, based on mathematical modelling methods.

Runoff is one of the key factors determining the intensity of channel evolution. Estimation of runoff changes based on runoff formation models grounded on global climate model data is now widespread (Gelfan et. al., 2021). A number of studies has also demonstrated the possibility of combining flow generation models with other types of models, including hydrodynamic ones (Grimaldi et al., 2019, Krylenko, 2023), to assess changes in the hydrodynamic characteristics of flow and flooding. The including of hydrodynamic models with channel bottom deformation module in this model chains is not so often, for example (Nones et al., 2014) due to complexity of the task. Thus, it is possible to perform scenario calculations taking into account runoff changes for the period of the climate forecast if the block of channel deformations is included.

The possibilities and limitations of this approach are considered in our paper on the example of the Lena River near Yakutsk city. The city of Yakutsk (which is administrative, culture and industrial center of the North East of Russia) is situated on the left bank of the Lena River. The city has faced with many problems, concerning intensive channel processes last decades. Sediment accumulation near the main water intake structure, supplying Yakutsk city by the drinking water, and deterioration in conditions of navigation roots to the main city ports are the most dramatic problems. This region is characterized by a significant increase in annual runoff volumes and growing anthropogenic pressures, including the bridge construction and floodplain development projects.

This study is performed on the base of STREAM 2D hydrodynamic model (Belikov and Aleksyuk, 2020), adapted for the 75 km long River Lena section near Yakutsk. The first task was to perform detailed model hydraulic calibration and validation to apply the model for a complex channel and floodplains system of the Lena River near Yakutsk. Validation of the channel deformation modeling through continuous simulation for the period between repeated channel surveys of 2009 and 2016 was the next goal in order to assess the quality of the model's reproduction of the main trends in vertical channel changes. The final parts of the research consider the possible channel changes for 20-year forecast period taking into account projected the Lena River runoff changes under the RCP2.6 and RCP 8.5 climate scenarios, especially regarding the difficult situation with the city's water supply due to the shallowing of the Adamovskaya channel, which is closest to Yakutsk city.

STUDY AREA

The city of Yakutsk, which is now the administrative center of the Sakha Republic, is an old Russian city (founded in the 17th century) located in the Lena River valley in the area under study. The city's population is about 300 thousand people. Three hydrological gauges are in operation within the considered section of the Lena River near Yakutsk city. The measuring discharges and water levels gauge in the village of Tabaga is located in the upper part of the studied reach. The Lena River basin area for the Tabaga gauge is 897 000 km^2. The water level measuring gauge of the Yakutsk city is situated in the middle part of the study area, and Kangalassy gauge (Fig. 1) is located at the lower boundary of the area. The river section under study is characterized by numerous ramifications, and is located between the Tabaginsky cliff at upstream and the Kangalassky cliff in the lower reaches (which limit the spread of the left bank floodplain) and low terraces above the floodplain, as they are rocky capes. The width of the main channel of the Lena River in this section is 3.5-4 km.

Numerous engineering and water facilities exist in the city of Yakutsk on the Lena River, so it is necessary to take into account the peculiarities of the water and channel regime of the river for their safe operation. An unfavourable situation has been created in recent years for the entire water infrastructure of the city in the territory, due to the fact that the river channel near the left bank, where the city is located, grows shallower, while the right branch develops and large forms of the channel topography also shift (Chalov et al., 2016). The above-mentioned re-formations of the channel lead to the displacement of the navigable fairway, which complicates the work of the port, leads to failure of the city water intake, and complications associated with the ferry crossing. The adverse channel changes effect on this section of the Lena River was discovered for the first time as early as the 1970s by the expedition of the Lomonosov Moscow State University, and even then forecasts, according to which the shallowing of the branches near the city was expected, were made (Zaitsev and Chalov, 1989; Chalov et al., 2012). Different projects were performed for the preserving of the main flow in the city area in connection with the existing problems of water use, including hydrodynamic model application (Belikov et al., 2002).

MATERIALS AND METHODS

Hydrodynamic modeling

STREAM 2D software package, based on the numerical solution of two-dimensional Saint-Venant equations in the "shallow water" approximation and widespread in Russia, was used for modeling. Hybrid computational grids of irregular structure and original topography interpolation algorithms have been applied for the task. This software showed high efficiency in modelling both for flow hydraulics and channel changes, including those for different key

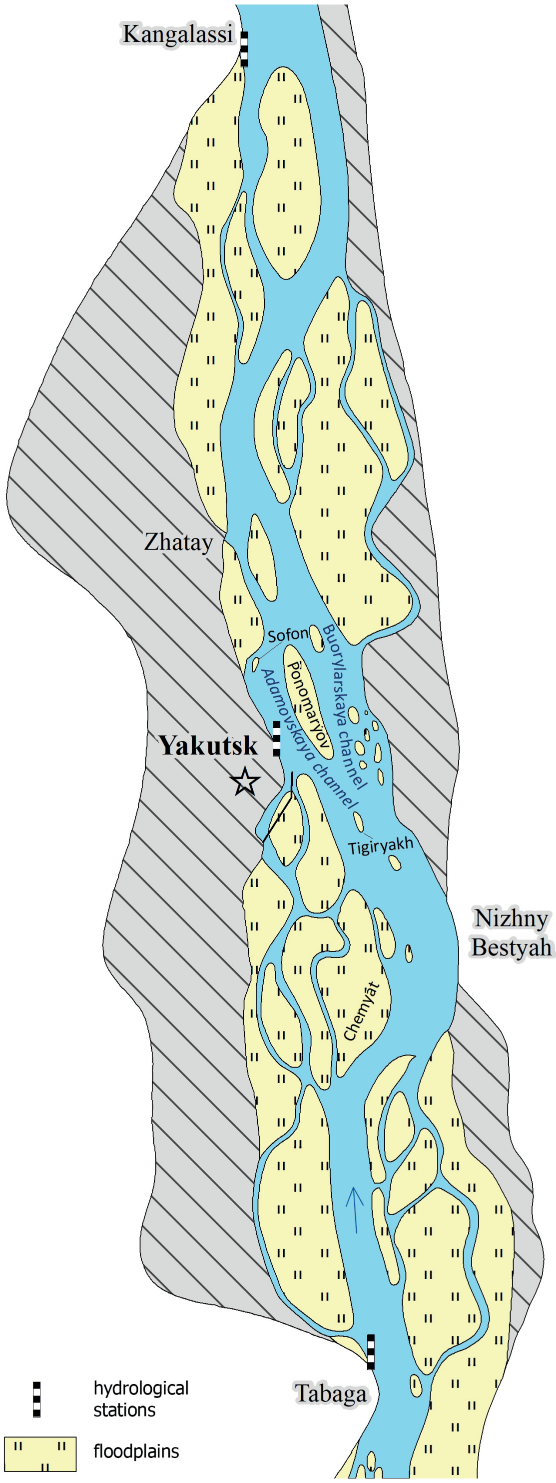

Fig. 1. Study area

area in Russia (Volga, Ob, Lena, Kolyma, Vilyuy, Yana, Amur etc.) (Belikov and Aleksyuk, 2020; Belikov et al, 2023). The description of the mathematical equations included in the numerical scheme of the model is presented, for example, in (Aleksyuk and Belikov, 2017). When modelling, a block of channel changes was involved, taking into account the convective transport of soil particles by flow, soaking up and sedimentation of sediments in an uneven flow, changing the bottom levels over time, taking into account the effect of flattening (transverse diffusion) of the underwater slope in a direction orthogonal to the velocity vector.

Model area is cover 75 km of the Lena River valley including branched channels and wide floodplain from Tabaga to Kangalassy gauge cites. Data of these stations were used for model boundary conditions assigning. Data of Yakutsk city gauge station as well as measured during field campaign water levels and flow velocities was taken into account for model calibration and validation. Model based on irregular hybrid curvilinear quadrangular and triangular mesh, which includes more than 50 thousands sells.

The initial data for the application of the hydrodynamic model were the materials of field researches of the soil erosion and channel processes laboratory at the Geography Faculty of Moscow State University, including the results of repeated bathymetric surveys, measurements of water discharges, water levels and water slopes and daily regime observation data of hydrological gauges on the Lena rivers - Tabaga, Yakutsk, Kangalassi. The bathymetric survey data for 2009, 2016, 2021 were integrated with the digital model of the floodplain topography to create the integrated digital topography models. The map of jam-hazardous part of river channels was compiled on the basis of historical data and satellite images to set the places of ice jams formation, the dates of the ice jams formation were taken according to the hydrological gauges data.

The field data obtained during the expedition researches in 2016 was used to set the parameters of the channel-forming sediments fractions. Mainly the channel sediments are represented by the sand with an average diameter of 0.36 mm, so the average diameter of the channel sediments was taken into account in the simulations. Initial model hydraulic calibration was performed based on data of the same field campaign. Model calibration and validation was done on the second step, based on long-term data of hydrological gauges Tabaga and Yakutsk from 2001 up to 2016 year. Due to the presence of multi-temporal bathymetric surveys, actual and modelled bottom evolution for the period 2009-2016 were compared for validation of channel deformation block.

Input runoff scenarios for the channel evolution forecast

Modeling of flow dynamics and channel changes was performed for the 20-year forecast period with a daily step. Modern bottom topography from 2021 year was used as a starting point. To save computation time, the modelling was carried out only for the warm period from May 1 to October 1 of each year, which covered the passage of the most important for the formation and displacement of the main channel forms, winter periods were excluded from the simulations.

As the base scenario 1, we used combination of modern hydrographs for the last years 2010 - 2020, repeated twice, to represent the modern conditions of channel formations. On the peak of one flood, 1% probability discharge was added.

We used outputs of ECOMAG runoff model (Motovilov, 2016) based on the data of the global climate models with daily time step to take into account possible runoff change at the 21st century. Ensemble of five models and different climate scenarios for the Lena River - for Tabaga gauge were considered during flooding characteristic modeling at separate research (Krylenko, 2023). We examined in detail the results of scenario modeling based on data from the MIROC-ESM-CHEM climate model (Nozawa et al., 2004) in this study, because the estimates of the runoff characteristics of the Lena River using this model as climate forcing well correspond to observed ones for the historical period and are closest to the ensemble average.

Climate projections for two greenhouse gas emission scenarios were taken into account, "soft" scenario rcp2.6 and "hard" scenario rcp8.5. Projected long-term flow hydrographs for the period from 2046 to 2065 from ECOMAG runoff model, forced by data of the MIROC-ESM-CHEM climate model, for the scenarios RCP2.6 and RCP8.5 were used as input data for the STREAM 2D hydrodynamic model. As result, three input runoff scenarios for the Lena River bottom change simulations was considered: 1. modern runoff input; 2. runoff change according scenario RCP2.6; 3. runoff change according scenario RCP8.5.

RESULTS

Results of model calibration and validation

Calibration and validation of hydraulic characteristics based on field data

The calibration and verification of the model was originally carried out based on data from 2016 field surveys, including a comparison of the water level marks along the longitudinal profiles and the distribution of the water discharges along the branches for various water discharges. When the roughness coefficients equal to 0.015–0.017 for the channels and 0.05 for the floodplain, a good compliance between the measured and calculated water levels at the control points was reached. The difference between the modelled and observed water levels at the Yakutsk gauge was 1–4 cm. The difference between the values obtained during special expeditionary surveys (instantaneous water level measurements) and the results of modelling at control points did not exceed 10–18 cm on the average along the length of the study section.

The model reproduces well the distribution of water discharges among the main branches. In the main branching point near the Yakutsk city, which determines the water situation of the city, the Adamovskaya channel, closest to the city, receives 37-39 % of the input water discharge in the flow range from 9560 to 30000 m^3 s-1 according to measurement data, the right Buorylarskaya channel gets up to 55 % of the input flow, which reproduces the model. The remaining 7 % of the input water flow goes along the Khatykhstakhaya channel, and the model slightly underestimates the water discharge in it (modelling value is 5 % of the total water flow), due to the small detailing of the computational grid in this channel because of its insignificant width in comparison with the main channel.

Calibration and validation of hydraulic characteristics based on long-term data of hydrological gauges

Additional refinement of the roughness coefficients for the ice jams periods at the hazardous sections according to the data for 2009-2015 was made to simulate water flow dynamics for the flood periods, and it was found that the best compliance of the water levels is provided with the roughness coefficients of the ice jams sections equal to 0.073.

The simulation, based on data for the period from 2001 to 2015, showed that the hydrodynamic model, adapted according to the field and regime observations data for 2009-2015, provides a steady good quality of water levels modelling over a long-term period, which confirms both by visual match of the graphs of the observed and simulated water levels (Fig. 2), and high values of the simulation quality criterion. The criterion of Nash-Sutcliffe (NSE) for the studied periods for the Lena River gauge in Yakutsk was 0.90 for 2001–2008 and 0.93 for 2009–2015 years (it is assumed that the results with NSE> 0.75 can be considered as good in the hydrological modelling practice).

Validation of inundation zones based on data of satellite images

An additional validation of the model was carried out by comparing the simulated flooding boundaries with the flooding boundaries provided by satellite images (more than 20 images). It was found that the relative error for the divergence of flooded areas does not exceed 10 % during floods and high waters and the maximum divergence reaches 18 % during ice jams when comparing the real hydrological situations observed by modeling and interpreting satellite images (Kornilova et al., 2018).

Validation of channel changes modeling results for the historical period

Due to the presence of multi-temporal bathymetric surveys, both actual and model bottom evolution were evaluated for the period 2009-2016. Despite some limitations of model simulations (only the warm period

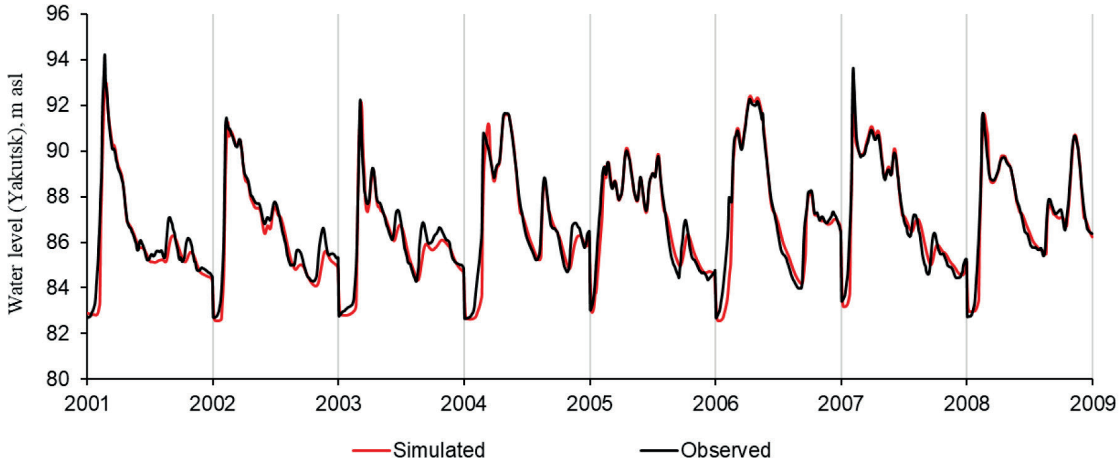

Fig. 2. Observed and modelled water levels at the Yakutsk gauge at 2001-2008 (ice-free periods)

of the years were modelled, sediments were considered as homogenous), the main positive result was the correspondence of the simulated and observed main zones of erosion and deposition (Fig. 3). Totally, in the 70 % of modeling sells inside the channels deposition or erosion zones coincide with estimated according bathymetry surveys. But one can notice some alternation of sections with almost complete coincidence of the situation of the simulated and actual changes and areas, where the model reproduced not so good.

The model adequate showed the channel changes in the upstream part of the studied section from the Tabaga until the Chemyat island. The model indicated erosion zone near the right steep bank downstream from this part of the channel, but in reality there are deposition zone. The possible reason of this discrepancy can be that the model is underestimated planform channel changes, which took more flow energy. There is the vast deposition zone near the Tigiryakh island. The stable two-stream system has formed near this island in the last decade, which is of decisive importance for the channel processes within the Yakutsk. The model again showed a situation close to reality in this area. The obtained distribution of water flow along the branches corresponds to that observed in the 2016 year (the flow discharge was distributed equally among the right and left main branches). In the next section from the Tigiryakh island to Ponomarev island, which is the most difficult for modelling because of the diversity channel processes factors, the simulation results can only be called partially successful. The model showed erosion along the left bank, but did not identify it in the central part of the channel. Despite the strong

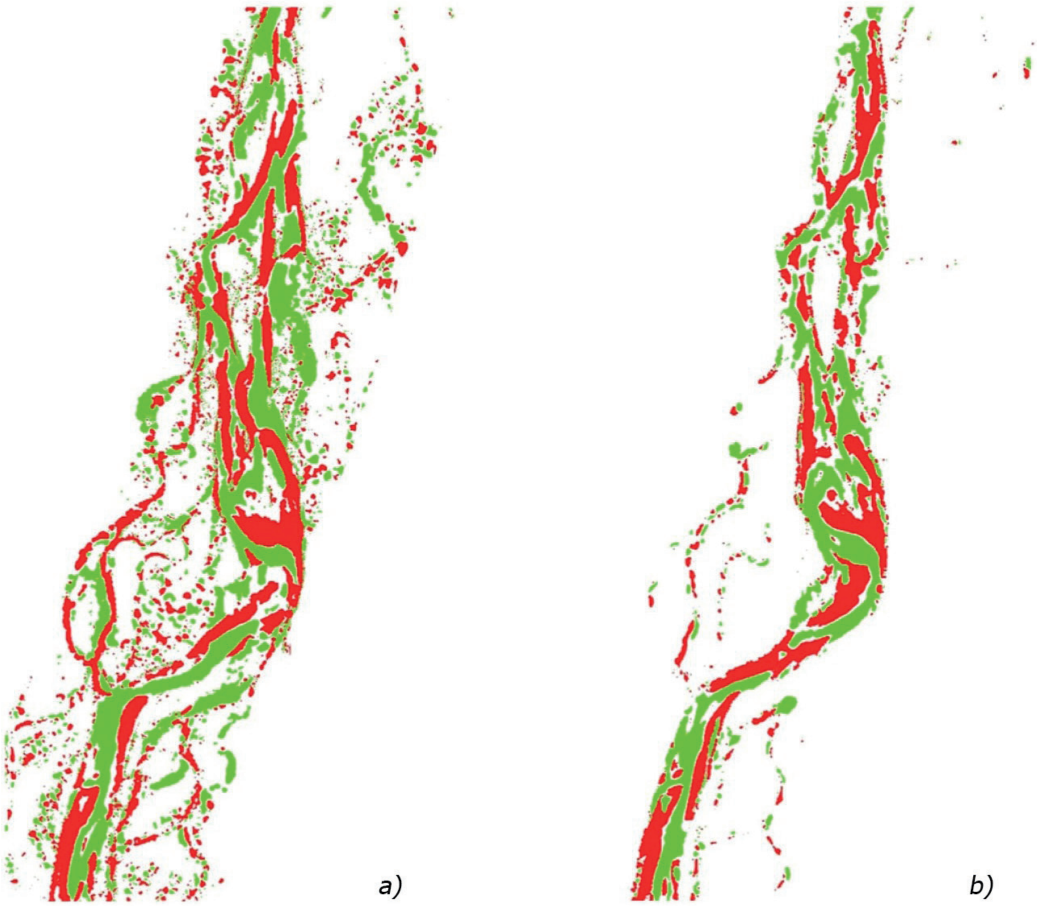

Fig. 3. Deposition (shown in green colour) and erosion (shown in red colour) zones in the Lena River channel for the period 2009 – 2016 year according observation data (a) and modelling (b)

discrepancy between the actual and model data, the distribution of water flow between Adamovskaya and Buorylarskaya branches coincides with the observed (39 % and 51 % correspondingly). Along the Adamovskaya and Buorylarskaya channels, the model has demonstrated quite realistic results. In the downstream section of the Lena River near Zhatay 75 % of the flow is going in the main stream. Modelling on this section showed a result that is different from the observed one. This section is characterized by the maximum rate of planform changes.

Water regime and channel processes under climate change scenarios

According to the analysis of the input hydrographs, it is expected that both the annual and peak runoff of the Lena River will increase during the 21st century, under both "soft" and "hard" climate scenarios (Fig. 4a). The increase in annual runoff could be up to 18% by the middle of the century and 19% at the end of the century under a "soft" scenario. Under a "hard" scenario, the increase could be as high as 23%. A significant increase in maximum discharges and a shift of floods to earlier dates are expected (Figure 4b). Thus, the maximum discharge during the second half of the 21st century under the RCP2.6 scenario could reach 57 000 $m^3 s^{-1}$, and under the RCP8.5 scenario, it could reach 72 000 $m^3 s^{-1}$. This would be by 7% and 35% higher, respectively, than the present-day 1% probability discharge, which is estimated based on a long-term series of observations at 53 100 $m^3 s^{-1}$. This increase in water discharge would lead to a corresponding increase in the depths and areas of flooding in riverine territories. In addition to an increase in the maximum discharge during snow-melt flood, the predicted hydrographs are characterized by a decrease in the discharge during the rain flood period, which is particularly pronounced for the hardest scenario RCP8.5.

Changes in runoff hydrographs are reflected in changes in the channel-forming discharge curve for the climate projection period. The channel-forming water discharges are those which have the most significant impact on the channel over a multi-year period (20-25 years) and at which the greatest sediment discharge is observed. They correspond to the maximums of the function f(P*Q^2). The calculated product (P*Q^2) for determining channel-forming discharge accounts for changes in water content of a river through the recurrence P of observed water discharges (Borshchenko, Chalov, 2010; Chalov, 1987). According analysis of modelled discharges, the main channel-forming discharge shifts from a range of 26000-27000 $m^3 s^{-1}$ to a range of 36000-40000 $m^3 s^{-1}$ even under the mild climate scenario, and two peaks in the range of 38000-42000 $m^3 s^{-1}$ are observed under the RCP8.5 scenario (fig. 5).

The main Adamovskaya and Buorylarskaya branches, which determine the situation near Yakutsk city, under RCP2.6 scenario, develop similarly to the trends shown in the current channel forecasts. The water content of the Adamovskaya branch increases significantly relative to the

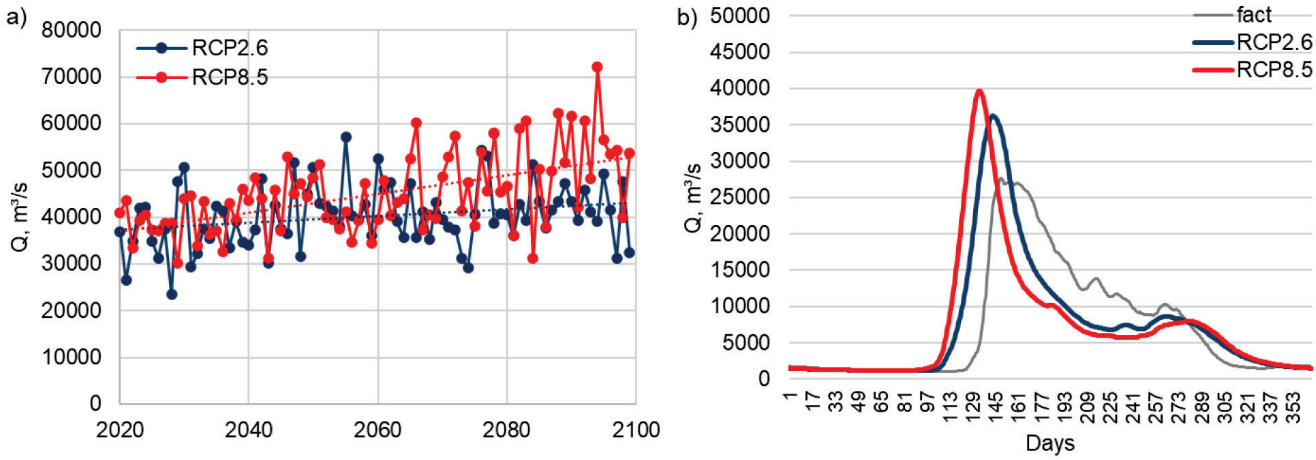

Fig. 4. Maximum discharge based on modeling results (a) and multiyear averaged predicted runoff hydrographs obtained from the ECOMAG model using data from the global climate model MIROC-ESM-CHEM for the middle of the XXI century (b), Lena River (Tabaga) for two climatic scenarios

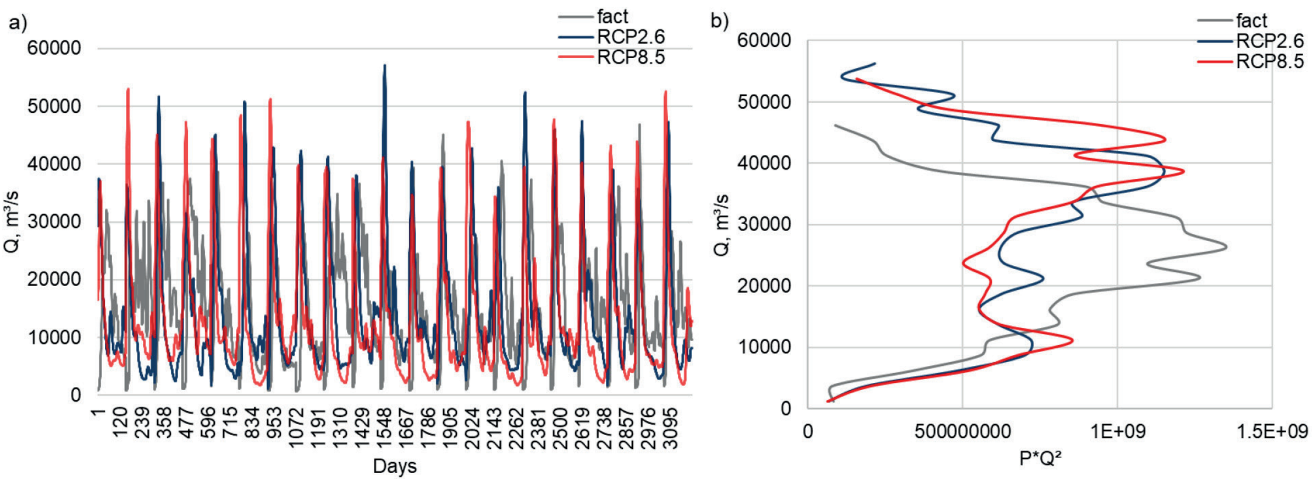

Fig. 5. Predicted runoff hydrographs derived from the ECOMAG model using data from the global climate model MIROC-ESM-CHEM, used as input data for assessing trends in changes in channel reshapes (a); channel-forming water discharge in the present period and under climate change under RCP2.5 and RCP8.5 scenarios simulated with MIROC-ESM-CHEM climate model data (b)

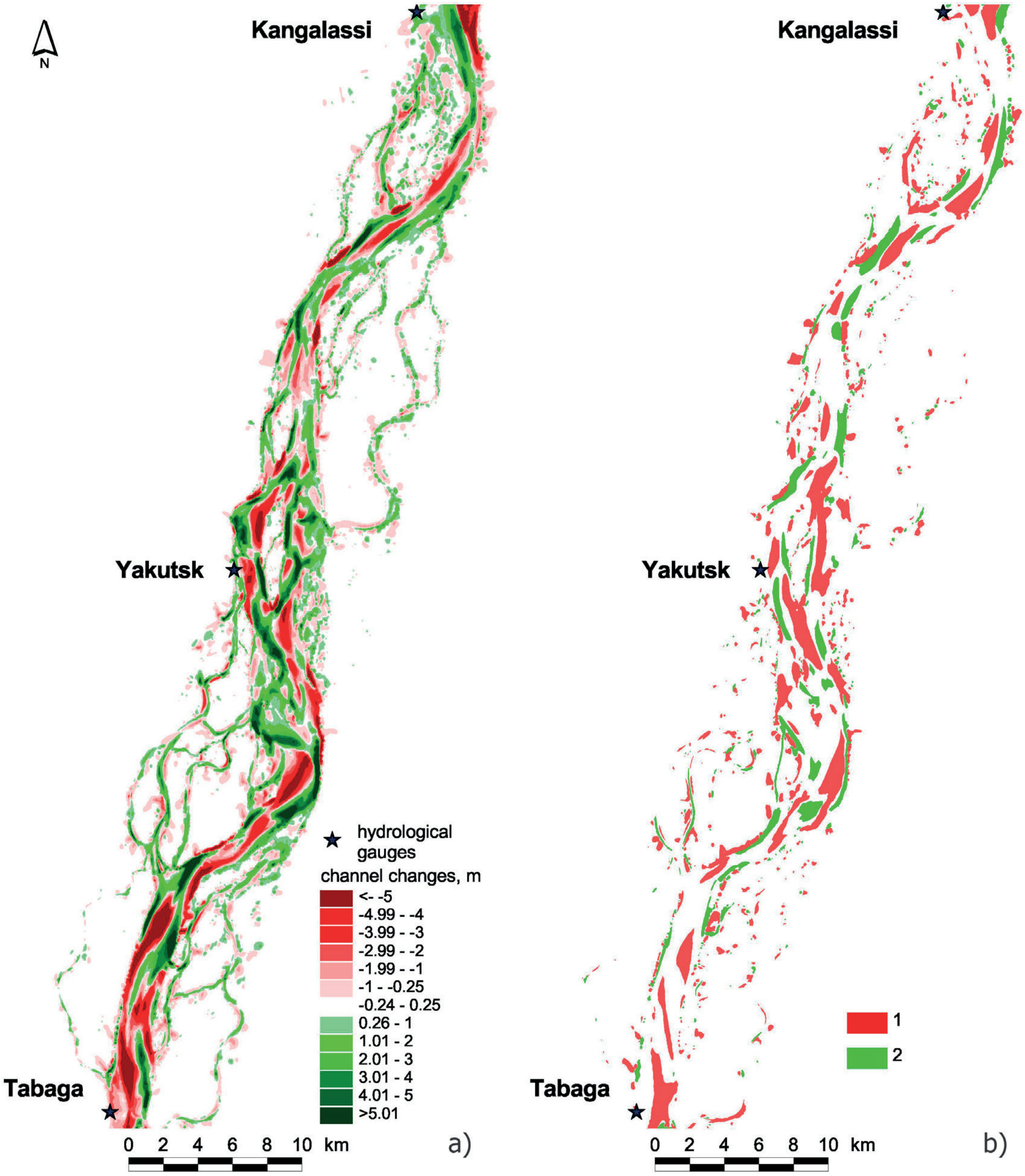

Fig. 6. Projected channel changes for scenario 3 (under RCP8.5 runoff input) (a); zones of negative (1) and positive (2) differences (more than 1 m) between final channel bottom from scenario 3 (under RCP8.5 runoff input) in comparison with scenario 1 based on modern runoff after 20-year period of channel deformations (b)

Buorylarskaya branch by the end of the 20-year forecast period (Fig. 7a). Under scenario RCP8.5, the Adamovskaya and Buorylarskaya branches retain almost equal water capacity under the maximum discharge during the whole forecast period. However, there is a positive trend is the growth of low-water discharge in the Adamovskaya branch (Fig. 7b), which will favourably affect the situation with water supply in Yakutsk.

DISCUSSIONS

Comparison of modelled bottom changes with the observed ones for the period 2009-2015 has demonstrated that in the 70 % of channel grid sells model adequately reproduce the erosion and deposition trends. In connection with the novelty of such studies for large sections of lowland rivers, these results should be considered as positive. At the same time, the use of a hydrodynamic model to reproduce channel evolution has a number of limitations. In general, the accuracy of channel changes estimates based on modelling methods is determined by a number of objective factors. The most important factors are:

- Accuracy of hydrometeorological scenarios selection for the period under study (including annual runoff hydrographs), taking into account the peculiarities of ice phenomena passage, etc;

- Variability of the river channel evolution process itself (occurrence of so-called bifurcations of the solution). It is well known that repeated replication of the same physical experiment with a deformable bed under identical initial and boundary conditions can lead to different results;

- Difficulty in taking into account in the modelling, for objective and subjective reasons (inadequacy and inaccuracy of the initial data, complexity of a number of physical processes, etc.), a number of factors that significantly influence the process of evolution of the river channel (heterogeneity of the bed materials; presence in some areas of an underlying surface that is difficult to erode; presence of various types of vegetation that hinder erosion; presence of permafrost and frozen ground after winter);

- Difficulty in accounting for bank erosion and planform changes.

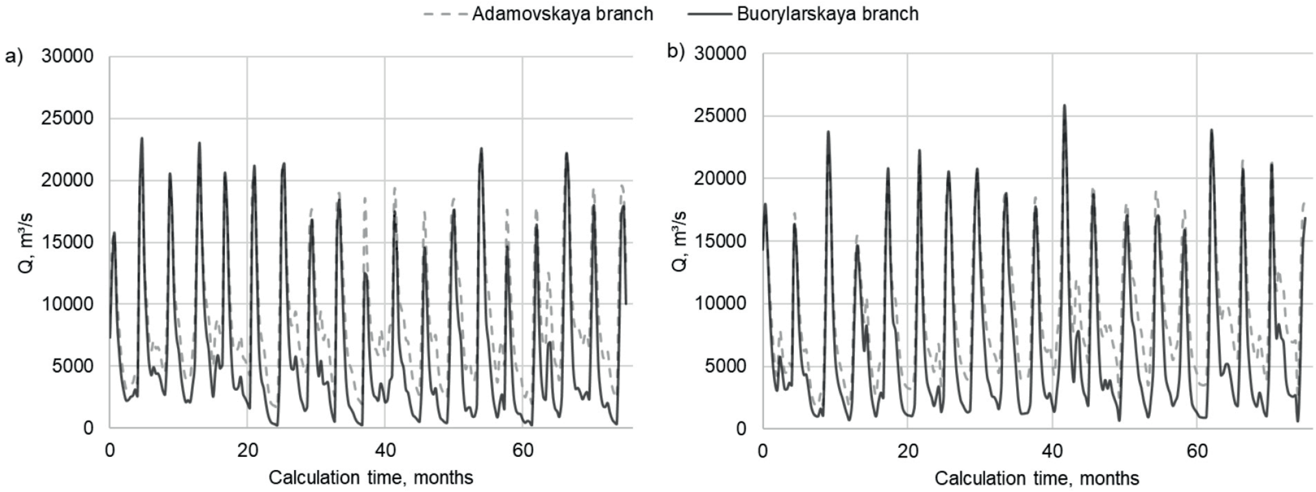

Fig. 7. Discharge in the Adamovskaya and Buorylarskaya branches under modeling based on predicted hydrographs: a) under the RCP2.6 scenario, b) under the RCP8.5 scenario

For the Lena River section under study discrepancies of simulation results with observed one in some sections is connected with the determining role of planform changes there. The further development of the model should take into account planform channel deformation block improvement. More attention should be pay also for the ice-covered period and ice jams periods, for which channel bottom changes have not been investigated enough.

In case of climate projection, the complex consideration of mentioned above factors, in particular planform changes due to bank erosion and permafrost degradation, is currently difficult to implement in practice. Long-term simulations of channel evolution (over a period of more than 50 years) without accurate estimations of planform changes can lead to unrealistic results.

Possibility to consider changing of the input hydrographs due to climate change is demonstrated in this work. The obtained estimates of changes in the hydrographs of the Lena River at Tabaga gauge for the period of climate forecast have shown, that simple extrapolation on the basis of existing trends does not give an idea of changes in the shape of hydrographs and, as a consequence, changes in the range of channel-forming discharges. It is also shown, that due to the change of channel-forming discharges, new local areas of erosion occur during peak flows, especially near the banks.

Also it will be important to take into considerations further the contribution of the catchment component of sediment load, to improve the modelling approach for simulation of the river channel evolution. Economic development of the area and intensification of erosion due to thawing permafrost under different climate warming scenarios will increase the contribution of sediment inflow from the catchment to the Lena River channel. According to (Maltsev and Ivanov, 2022), soil erosion losses in the catchment near the city of Yakutsk have increased by 4% over the last decade. This additional material may influence channel incision and redistribution of runoff along the branches.

CONCLUSION

The numerical two-dimensional hydrodynamic model of the Lena River near Yakutsk city was developed, calibrated, and verified using field data. The model successfully reproduce the distribution of water discharges among the channels, the water level regime for a long-term period and zones of inundation.

Comparison of modelled bottom changes with the observed ones for the period 2009-2016 has demonstrated that in the 70 % of channel grid sells model adequately reproduce the erosion and deposition trends. The aim of the future directions of the study is further improving of modeling, taking into account planform changes, ice cover, permafrost and contribution of the catchment component of sediment load.

The obtained estimates of changes in the hydrographs of the Lena River at Tabaga gauge for the period of climate forecast have shown, that simple extrapolation on the basis of existing trends does not give an idea of changes in the range of channel-forming discharges and consequently in the channel evolution over long-term period. In this case, an integrated approach, described in the paper, using input hydrographs from the runoff formation model offers a number of advantages for a better-grounded choice of simulations scenarios.

REFERENCES

Aleksyuk, A.I. and Belikov, V.V. (2017). Simulation of shallow water flow with areas and bottom discontinuities, Computational Mathematics and Mathematical Physics, Vol. 57, no. 2, p. 318–339. DOI: 10.1134/s0965542517020026, 2017.

Belikov, V.V. and Aleksyuk, A.I. (2020). Modeli melkoi vody v zadachakh rechnoi gidrodinamiki (Shallow-Water Models in Problems of River Hydrodynamics), Moscow: RAN, ISBN 978-5-907036-22-2, 346p.

Belikov, V.V., Aleksyuk, A.I., Borisova, N.M., Vasil'eva E. S. and Glotko A.V. (2023). Experience in Numerical Hydrodynamic Simulation of Long River Reaches. Water Resour 50, 465–481. https://doi.org/10.1134/S0097807823040036

Belikov, V.V., Zaitsev, A.A. and Militeev, A.N. (2002). Mathematical modeling of complex sections of large rivers channels, Water resources, V. 29, № 6, p. 698–705. (in Russian)

Borshchenko E., Chalov R. (2010). Channel-forming water flow rates and morphodynamics of river channels in the Russian part of the Amur basin. Geography and Natural Resources. 31. 148-158. 10.1016/j.gnr.2010.06.010.

Chalov R.S. (1987). Channel-forming water discharges and their significance for the study of channel processes in rivers. Dynamics of channel flows. Collection of scientific papers (interuniversity). LPI named after M.I. Kalinin Leningrad, p 103-108

Chalov, R.S., Kirik, OM., Ilyasov, A.K. and Botavin D.V. (2012).Yakutsk water junction on the Lena river: problems of channel processes, history, modern times, prospects, management possibilities, Water Industry of Russia: problems, technologies, management, № 3, p. 44–56 (in Russian).

Chalov, R.S., Zavadsky, A.S., Ruleva, S.N., Kirik, O.M., Prokop'ev, V.P., Androsov, I.M. and Sakharov, A.I. (2016). Morphology, deformations, temporary changes in the channel of the Lena river and their influence on the economic infrastructure in the Yakutsk region, Geomorphology, № 3, p. 22–35 (in Russian).

Gamal H. El Saeed, Neveen A. Badway, Hossam M. Elsersawy and Fatma S. Ahmed (2020). Evaluate the Nile River Confluence Morphological Changes on the Shear Layer// Journal of Scientific and Engineering Research, 7(2):220-229

Gelfan, A.N., Frolova, N.L., Magritskii, D.V., Kireeva, M.B., Grigor'ev, V.Yu., Motovilov, Yu.G. and Gusev, E.M.(2021) Effect of climate changes on the annual and maximal runoff of the Russian rivers: assessment and forecasts, Fundam. Prikl. Klimatol., vol. 7, no. 1, pp. 36–79.

Golovlyov, P., Kornilova, E., Krylenko, I., Belikov, V., Zavadskii, A., Fingert, E., Borisova, N., and Morozova, E.(2019) Numerical modeling and forecast of channel changes on the river Lena near city Yakutsk, Proc. IAHS, 381, 65–71, https://doi.org/10.5194/piahs-381-65-2019.

Grimaldi, S., Schumann, G. J.-P., Shokri, A., Walker, J. P. and Pauwels, V. R. N. (2019). Challenges, opportunities and pitfalls for global coupled hydrologic-hydraulic modeling of floods. Water Resources Research, 55, 5277–5300. https://doi.org/10.1029/2018WR024289

Guerrero, M., Latosinski, F., Nones, M., Szupiany, R. N., Re, M. and Gaeta, M. G. (2015). A sediment fluxes investigation for the 2-D modelling of large river morphodynamics. Advances in Water Resources, 81, 186–198. Doi:10.1016/j.advwatres.2015.01.017

Horvat, Z, Horvat, M. and Spasojevic, M. (2015). Two dimensional river flow and sediment transport model. Environmental Fluid Mechanics. 15. 595-625. 10.1007/s10652-014-9375-y.

Jodhani, K. H., Patel, D. and Madhavan, N. (2021). A review on analysis of flood modelling using different numerical models. Materials Today: Proceedings. doi:10.1016/j.matpr.2021.07.4

Kornilova, E.D., Krylenko, I.N., Golovlyov, P.P., Sazonov, A.A. and Nikitsky, A.N. (2018). Verification of the two-dimensional hydrodynamic model of the Lena River near Yakutsk according to time-based space imagery data, Modern problems of remote sensing of the Earth from space, V. 15, № 5, p. 169 - 178. (in Russian). DOI: 10.21046/2070-7401-2018-15-5-169-178

Krylenko, I.N. (2023) Evaluating Inundation Characteristics under Climate Changes. Water Resour 50, 577–582. https://doi.org/10.1134/S0097807823040152

Maltsev, K. and Ivanov, M. (2022). Comparative Study on Sediment Delivery from Two Small Catchments within the Lena River, Siberia. Water. 14, 3055. https://doi.org/10.3390/w14193055

Motovilov Y.G. (2016) Hydrological simulation of river basins at different spatial scales: 1. Generalization and averaging algorithms. Water Resour 43(3):429-437. https://doi.org/10.1134/S0097807816030118

Nones, M., Guerrero, M. and Ronco, P. (2014). Opportunities from low-resolution modelling of river morphology in remote parts of the world, Earth Surf. Dynam., 2, 9–19, https://doi.org/10.5194/esurf-2 9-2014.

Sloff, K. and Mosselman, E. (2012). Bifurcation modelling in a meandering gravel-sand bed river. Earth Surface Processes and Landforms, 37(14), 1556–1566. doi:10.1002/esp.3305

Vijay, R., Sargoankar, A. and Gupta, A. (2007). Hydrodynamic Simulation of River Yamuna for Riverbed Assessment: A Case Study of Delhi Region. Environ Monit Assess 130, 381–387. https://doi.org/10.1007/s10661-006-9405-4

Zaitsev, A.A. and Chalov, R.S. (1989). Channel processes and regulation of the river Lena in the area of Yakutsk, Water resources, № 5, pp. 75-81 (in Russian).

Zhang, W., Xu, Y., Wang, Y. and Peng, H. (2014) Modeling Sediment Transport and River Bed Evolution in River System. Journal of Clean Energy Technologies, Vol. 2, No. 2