A three-dimensional thermohydrodynamic model for Krasnoyarsk Reservoir

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Abstract. The paper presents a 3D model for a deep flowing water body based on the open software package Delft3D to describe and predict thermohydrodynamic (THD) processes in existing and projected reservoirs of Siberia. As an example, a 3D model for non-stationary THD processes of the Krasnoyarsk Reservoir was built and tested. For its construction, we developed a Digital Relief Model (DRM) for the Krasnoyarsk Reservoir basin, generated a finite-difference grid, identified the empirical constants and formulated the initial and boundary conditions. Numerical simulation of current velocity and water temperature of the reservoir for spring/summer of the scenario year was performed.

1. Introduction
Further development of hydropower engineering in Siberia calls for solving the challenging scientific and practical problems related to design, creation and operation of large and deep reservoirs under severe Siberian conditions. Fluctuations of hydrologic regime in regulated river sections as a result of construction of large energy complexes make a strong influence on the aquatic environment. In addition, complex natural conditions aggravate the situation as well. Therefore, adverse ecological impacts should be assessed at the stage of studying probable environmental consequences of large project implementation. Obviously, mathematical modeling is an effective approach to studying hydrological processes in regulated river sections [1].

Software packages MIKE, SMS, GETM, Delft3D and other computational models in 2D, 3D formulations are recently employed to numerically describe hydrothermal processes of large reservoirs [2-8]. The application of such packages ensures the refinement of mathematical models with due regard for specifics of water bodies and solution of important problems, i.e. assessments of thermal pollution of the aquatic environment by thermal or nuclear power plants, or forecasts of dissolved oxygen concentrations in waters of the projected reservoirs with allowance for the qualitative bed preparation to flooding. For example, Delft3D was originally created to specify the characteristics of the aquatic environment in the coastal areas of seas, estuaries and river mouths. Using the observational data, adaptation of the Delft3D - based mathematical model to deep and stratified conditions of Lake Teletskoye makes it possible to define temperature, ice regime [9] as well as a thermobar formation and its movement during spring-summer heating of the reservoir [10].

Nowadays, studies of Delft3D [7] application to THD processes in large water bodies of Siberia are in progress. For this purpose, the Delft3D - based model for non-stationary THD processes in the Krasnoyarsk Reservoir was built, and numerical simulation of flow velocity and water temperature for spring/summer of the scenario year was performed.
2. Study object
The Krasnoyarsk Reservoir (on the Yenisei River) appeared due to the Krasnoyarsk HPP construction. In terms of volume, it is among the world largest man-made reservoirs and the second in Russia after the Bratsk reservoir. The Krasnoyarsk Reservoir is a foothill water body of the valley type with water mass volume of 73.3 km$^3$. Its surface area is 2000 km$^2$. The upper location of the reservoir is near the city of Abakan, at the confluence of Rivers Abakan and Yenisei, while the down one is the dam of the Krasnoyarsk Reservoir, upper the city of Krasnoyarsk. The rectilinea r distance from the top point to the Krasnoyarsk HPP is approximately 250 km, while the total length of the reservoir is much longer, i.e. 388 km (figure 1). Its maximum width is as large as 15 km. The amplitude of water level fluctuations during the year makes up 6-18 m [11].

3. Materials and methods
For numerical simulation of nonstationary processes of heat and mass transfer in the Krasnoyarsk Reservoir, we employed the 3D THD model, the equations of which describe temperature fields and velocity of water in the hydrostatic approximation by using the (k-ε) turbulence model, which is the basis of a software package Delft3D-FLOW [12]. We modified Delft3D-FLOW to construct a model for the deep Krasnoyarsk Reservoir (its depth exceeds 100 m). For instance, the UNESCO state equation was replaced by the TEOS-10 formula, where water density was a function of temperature, salinity and pressure [13]. In the TEOS-10 formula used for low-mineralized Krasnoyarsk Reservoir (up to ~ 100 mg/dm$^3$ [11]) water salinity was assumed to be constant (S=0.1 kg/m$^3$). When constructing a computer model, DRM of the reservoir basin resting on the results of scientific research of 2013 was used as the input information [14]. Reservoir coordinates and time of day were considered in computations of solar radiation flux at the water-atmosphere border. The computation of the total heat flow at the water surface was done using a semi-empirical formula with parameters depending on weather conditions. In the boundary conditions for the reservoir surface, a wind load was allowed for the components of velocity and energy of turbulence. In the mouths of tributaries, water discharge and temperature (salinity of tributary and reservoir waters was assumed to be equal) and in the northern tail of the reservoir near the dam of the Krasnoyarsk HPP water surface level were set as time function. The details of setting the boundary conditions are given in [12].

In a general case, the 3D computer model for the Krasnoyarsk Reservoir does not involve additional calibration of internal parameters. Note that to determine roughness, the Manning model with a typical for large watercourses constant roughness coefficient of 0.025 is employed. When using the 3D flow model, the effect of the assigned roughness coefficient on computation of turbulence characteristics is negligible.

A water surface level and current velocity were set as the initial conditions. A key to setting a water level was a quasi-stationary computation performed with the use of constant discharges in the input sections, the constant water surface level in the output section, and the same initial level throughout the water plane. The obtained thereby surface level and velocity served as the initial condition for the non-stationary problem.

The boundary conditions were set for the input and output sections. In the input sections, the water discharge, while in the output section – the water surface level were set as time function. Cross-section of the R.Yenisei below the R.Abakan mouth and cross-sections of its tributaries (Tuba, Syda, Ubey, Sisim, and Biryusa) in their estuaries were considered to be the input sections.

Figure 1 presents the constructed DRM of the Krasnoyarsk Reservoir basin converted to a format suitable for using in Delft3D. Its spatial resolution is 30 m; the altitude system - Baltic; the coordinate system - SK-42; the model format is a regular grid (raster) Grid ArcGis. For DRM of the Krasnoyarsk Reservoir basin, a count off at the elevation scale starts from the 243 m BS and can be interpreted as a depth analog. The input section of the reservoir is located in the Yenisei channel, below the mouth of the R. Abakan. The Krasnoyarsk HPP dam is defined as the output section.
The computational grid in Delft3D is structured, i.e. each cell is a convex quadrilateral and each inner cell has exactly four adjacent cells. When generating a grid, conflicting objectives should be considered. On the one hand, the grid must be sufficiently detailed to ensure the accuracy of calculations, contain the optimal number of cells to minimize the calculation time, and be curved to account for a complex morphometry. On the other hand, cell faces must be close to orthogonal ones and the ratio of lengths of faces inside a cell - close to one; the ratio of face lengths of neighboring cells should not differ too much. Utilities RGFGRID and QUICKIN of Delft3D generate the grid with a focus on its quality along the main watercourse. A horizontal grid view (the "plane" grid) in QUICKIN utility is shown in figure 2.

We applied the so-called “sigma” model with vertical adding of nodes to those of the "plane" grid (distributed in line with a given law between the bottom and the actual water level) because maximum
depth of the Krasnoyarsk Reservoir is about 100 m. Besides, in major computations we used a regular grid of 258 x 1221 x 5 with a typical cell size in horizontal direction of about 50-200 m.

Among the challenging problems was the construction of a version of the 3D model for the Krasnoyarsk Reservoir with appropriate (in terms of available computational resources) physical computational time of one scenario year. In the first approximation, the computational time of the model year was assumed equal to 2-3 weeks of the workstation.

4. Results
Using the 3D model built for the Krasnoyarsk Reservoir, we performed computations for two scenarios. The first one was for solving a quasi-stationary problem with a discharge of 8500 m³/s and a water level at the Krasnoyarsk HPP dam equal to 240 m BS. The obtained results served as initial conditions for the second scenario involving the simulation of unsteady flow regime during the ice-free period.

We employed the actual data (1987) on discharges and water surface levels at the dam. The computations made for the spring-summer period of the scenario year revealed an extremely complex nature of flow near the input section. In the upper reaches of the reservoir, islands appeared and disappeared on the water surface during spring flood; width of the reservoir varied significantly.

To increase the computation efficiency, the input section was shifted downstream to avoid the problems described earlier and to minimize the errors in numerical calculations of flow in the main part of the reservoir basin. The grid was also optimized to exclude "bad" cells (too small, with poor aspect ratio and orthogonality parameters). Optimization enabled to increase a time step to 90 seconds and to reduce the actual computation time for the spring-summer period to 6 days.

Figure 3 shows the simulated distribution of water surface level near the input section for some dates of the scenario year. The difference is clearly noticeable both in the surface level slope along the riverbed (depending on the input flow rate) and in varying width of the water surface (depending mainly on water surface levels in the output section).

Figure 3. Simulated water surface levels near the input section: 01.04 (left), 23.05 flood peak, center) and 01.09; on the scale of 0, the level of 243 m BS.

Figure 4 shows absolute velocity at the surface of the upper layer of the Krasnoyarsk Reservoir. Velocity noticeably varies only near the input sections (for the main channel and tributaries).
Figure 4. Simulated velocity module for the water surface in the Krasnoyarsk Reservoir for 30.05.

Figure 5 presents simulation results of upper layer temperature at the upper part of the Krasnoyarsk Reservoir during flood peak.

Figure 5. Simulated water temperatures at the surface of the Krasnoyarsk Reservoir for 30.05.

5. Discussion
The analysis of simulation results verifies that the Delft3D-based hydrothermal model of a large flowing reservoir adapted to the Krasnoyarsk Reservoir conditions adequately reproduces variability of parameters (depth, velocity, water temperature). Therefore, the built 3D model can be applied in description and prediction of the aquatic environment state of reservoirs with a refined mesh for significant time periods. At the same time, it is not necessary to use 1D, 2D and 3D simulation in calculations for large water bodies and perform them on high-performance computing clusters. There is a good alternative, i.e. a multi-functional Delft3D, which was initially created for solving such
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6. Conclusions
The implemented studies on modeling hydrothermal processes in the Krasnoyarsk Reservoir suggest that Delft3D based hydrothermal model can be used to refine and detail spatial/temporal characteristics for large and deep water bodies (lakes and reservoirs) of Siberia. The constructed 3D model with a satisfactory accuracy reproduces intra-annual changes in surface levels and temperatures of water, including flow velocity in various parts of lengthy stratified reservoirs. The constructed model is quite efficient in solving challenging water and ecological problems when assessing the impact of large energy complexes on the aquatic environment of Siberian rivers.

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References
[1] Zinoviev A T 2009 The use of mathematical modeling methods for evaluating design solutions in the creation of large reservoirs ECO-bulletin of INEKA 4 (135) [Available online http://www.ineca.ru/?dr=bulletin/archiv/0135&pg=011]
[2] Lyubimova T, Lepikhin A, Parshakova Ya, Lyakhin Yu and Tiunov A 2018 The modeling of the formation of technogenic thermal pollution zones in large reservoirs International Journal of Heat and Mass Transfer 126 P 342–352 [Available online https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.017 0017-9310]
[3] Lyubimova T, Parshakova Ya, Lepikhin A, Lyakhin Yu and Tiunov A 2019 Application of hydrodynamic modeling in 2D and 3D approaches for the improvement of the recycled water supply systems of large energy complexes based on reservoirs-coolers International Journal of Heat and Mass Transfer 140 P 897-908 [Available online https://doi.org/10.1016/j.ijheatmasstransfer.2019.05.017 0017-9310]
[4] de Goede E, Wagner T, de Graaff R et al. 2014 Modelling of Ice Growth and Transport on a Regional Scale, With Application to Fountain Lake, Minnesota, USA. In: Proc. of the 33th International Conference on ocean, offshore and arctic engineering (ICONE-14), June 8–13, 2014 (San Francisco, CA, USA)
[5] Chantsev V Yu, Gudoshnikov Y P, Pleshanov D A, Skutin A A and Danshina A V 2018 Multifunctional integrated model of the water system of the Gulf of Ob News of gas science 4 (36) pp 139–148
[6] Symonds A M, Vijverberg T, Post S et al. 2016 Comparison between MIKE-21 FM, Delft3D and Delft3D FM FLOW models of Western Port Bay, Australia Coastal Engineering Proceedings 35 pp 34–45
[7] Delft3D-Flow, simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments: user manual. Version 3.15.34158. Deltares, 2014 P 684
[8] Büchmann B 2019 Dealing with discontinuous meteorological forcing in operational ocean modelling: a case study using ECMWF-IFS and GETM (v2.5) Geoscientific Model Development 12 pp 3915–3922 [Available online https://doi.org/10.5194/gmd-12-3915-2019]
[9] Koshelev K, de Goede E, Zinoviev A and de Graaff R 2021 Modelling of thermal stratification and ice dynamics with application to Lake Teletskoye, Altai Republic, Russia Water Resources 3 (in print)
[10] Zinoviev A T, Koshelev K B, Dyachenko A V and Marusin K V 2021 Numerical modeling and in situ studies of a thermobar in Teletskoye Lake Meteorology and Hydrology 5 (in print)
[11] Vyshegorodtsev A A, Kosmakov I V, Anufrieva T N, Kuznetsova O A 2005 Krasnoyarsk Reservoir. (Novosibirsk: Nauka) P 212

[12] Delft3D-FLOW User Manual. Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. Version: 3.15.52614. 1. Deltares, 2017. October 2017

[13] Thermodynamic Equation of Seawater – 2010 [Available online http://www.teos-10.org]

[14] Fedorova E A 2016 Features of sedimentation in basins of reservoirs of plain and foothill type by the example of the Novosibirsk and Krasnoyarsk Reservoirs: PhD thesis.: 25.00.25 Gelendzhik P 178