Numerical simulation of spatiotemporal structure of hydrodynamics and water quality characteristics of Severnaya Sosva river

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The problems of development of base modeling complex for river ecosystem are discussed and the obtained results are presented. This is illustrated by the example of Severnaya Sosva river, a large confluent of Lower Ob, whose basin is located on the territory of Ugra, Khanty-Mansiysk Autonomous Region.

Introduction

The choice of the object of simulation (a part of the Severnaya Sosva river between Sosva and Sartyn'ya villages) was made on the following counts:

– the Severnaya Sosva river has a unique natural ecosystem with endemics in the biota composition (including the tugun, the famous Sosva herring) and, simultaneously, with compounds of iron, copper, zinc, and manganese, many times exceeding the maximum permissible concentration;

– the basin of the river upper flow soon will be a zone of active industrial development, what makes particularly important the construction of the controlling system for utilization and protection of water and the river biologic resources on the basis of information-simulation systems.[1]

1. Data preparation

Using the ArcGIS system, we digitized pilot and topographic maps of the coastline and constructed a 3-D model of the river fragment, where the base simulation complex (BSC) was used. The heart of BSC is CE-QUAL-W2, the numerical hydrodynamic and water quality model, used by Ugra Research Institute of Information Technologies since 2004.[2,3]

Using these materials, we developed a method of construction of the calculation grid for water objects, to which BSC is applied. For instance, the modeled region of Severnaya Sosva river, from Sosva gauge station to Sartyn'ya gauge station, is divided into 177 segments, each 400 m long (the length of the river section is 70 800 m).

Using the Rosgidromet data from the meteorological station and above-mentioned two gauge stations for 2003, databases "Meteorologiya" (8 measurements/day), "Gidrologiya" (1–2 measurements of water levels and water temperature per day, 33 measurements of annual water discharge), "Gidrokhimiya" (6 samples taken between March 4 and October 5, 2003, for 25 parameters at the Sosva gauge station).

2. Simulation of hydrodynamics of a region of Severnaya Sosva river

It can be confidently said that the BSC qualitatively well describes the dynamics of the phase change in the river hydrologic regime in 2003, including winter mean water (January – April), spring–summer flood (May – June), summer mean water (first half of August), fall flood (the end of August – the first half of September), and winter mean water (October–December). Some quantitative comparison of calculated and observational results is presented in Table 1, which includes the measured values of mean flow speed in the near-surface layer from Sosva and Sartyn'ya gauge stations and prognostic values of the longitudinal velocity (u) in the near-surface layer, calculated for segments 2 and 176, respectively.

Table 1. Comparison of calculated and observational data on mean river flow speed (m/s) for Sosva and Sartyn'ya gauge stations

Region	Date (2003)				
	Apr. 04	May 29	Aug. 08	Aug. 27	Oct. 21
Sosva gauge station	0.12	1.04	0.22	0.61	0.34
Segment 2	0.34	1.20	0.31	0.81	0.48
Sartyn'ya gauge station	0.14	0.83	0.25	0.49	0.48
Segment 176	0.31	0.92	0.31	0.61	0.45

The comparison shows a quite close coincidence of observed and model-predicted u values for the open water period.

We have analyzed the sensitivity of the river flow model in freeze-up period through comparison of

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u fields, calculated using the BSC on the MC1 grid (177 segments, a water layer depth of 0.2 m) for January 2003. As the varied BSC "parameters," the models for calculation of coefficients of vertical eddy turbulent viscosity RNG and W2N, traditionally used in CE-QUAL-W2 model were chosen. In addition, we used the modern TKE model (the so-called "$b - \varepsilon$" model). Table 2 presents the results of flow speed measurements in sub-ice water layer at Sosva and Sartyn'ya gauge stations and the results of *u* calculations for segments 2 and 176, using all above models.

Table 2. Simulation of flow speed in sub-ice water layer with the use of different calculation models of coefficients of the vertical turbulent viscosity

Site or segment	Speed, m/s	Site or segment	Speed, m/s
Sosva hydrologic gauge station	0.14	Sartyn'ya hydrologic gauge station	0.17
Segment 2 (RNG)	0.55	Segment 176 (RNG)	1.01
Segment 2 (W2N)	0.32	Segment 176 (W2N)	0.37
Segment 2 (TKE)	0.14	Segment 176 (TKE)	0.16

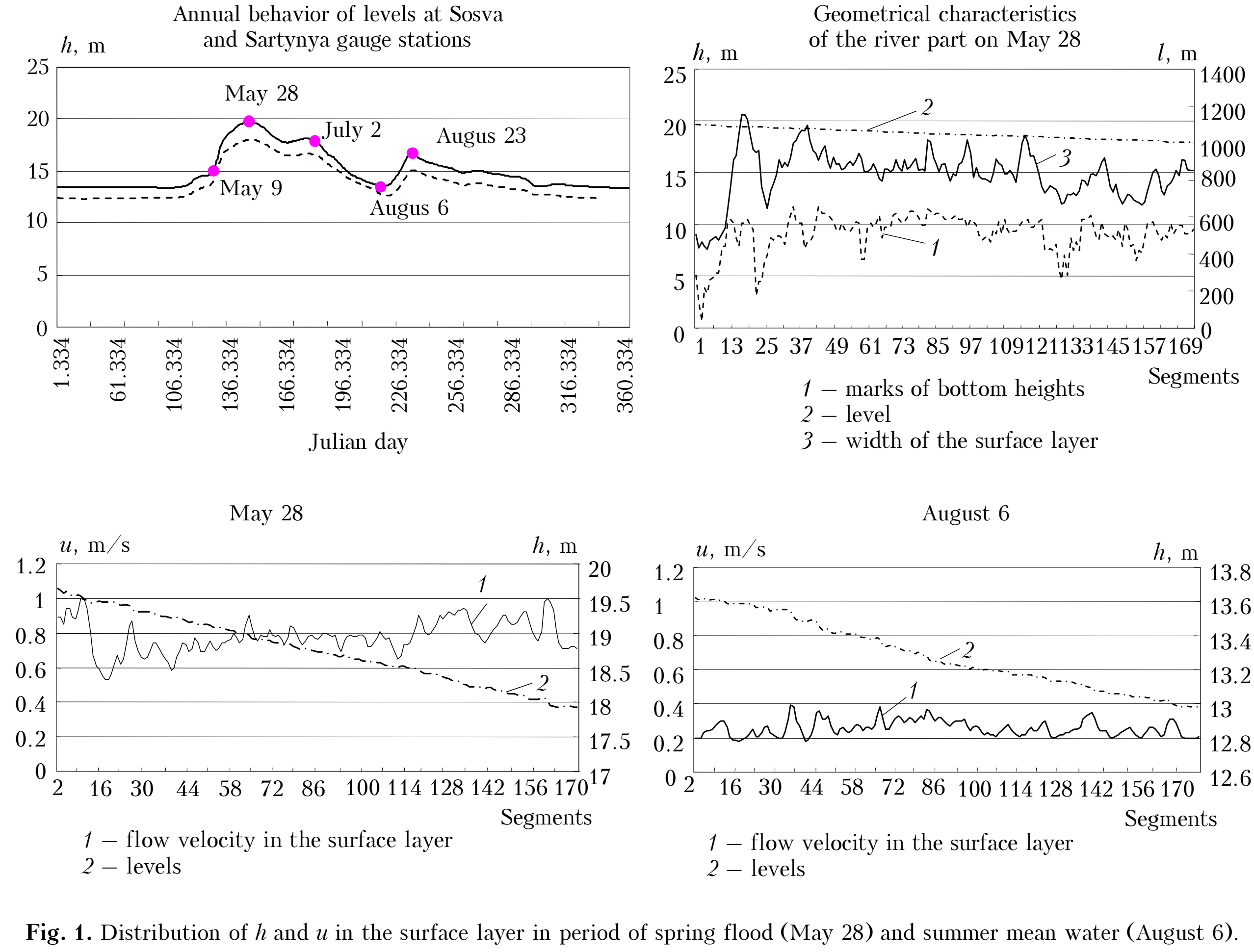
Table 2 shows a noticeable accuracy gain of TKE model in calculations of the *u* field. However, the total computation time increases by almost an order of magnitude because of the TKE model complexity as compared to RNG and W2N models.

The horizontal distribution of water levels *h* and *u* in the near-surface layer on May 28 (flood maximum) and on August 6 (summer mean water) is shown in Fig. 1.

The observation data for comparative analysis of *u* variability along the river are absent. At the same time, the calculations of *u* and *w* fields from MC1 and W2N models show a high variability of velocity fields along the water flow.

The results of numerical simulation of hydrodynamic characteristics (fields of longitudinal velocity and the coefficient of vertical eddy turbulence) at the flood maximum on May 28 and summer mean water on August 6 can be seen in more detail in Fig. 2.

Obviously, the velocities of the transport and diffusion of pollutants closely depend on longitudinal-vertical components of the flow velocity and the degree of the water current turbulization. Most 1-D models of velocity calculation use very coarse grid approximation along the river, leading to a number of disadvantages, considered in detail below.


Annual behavior of levels at Sosva and Sartynya gauge stations

Geometrical characteristics of the river part on May 28

1 – marks of bottom heights
2 – level
3 – width of the surface layer

May 28

1 – flow velocity in the surface layer
2 – levels

August 6

1 – flow velocity in the surface layer
2 – levels

Fig. 1. Distribution of *h* and *u* in the surface layer in period of spring flood (May 28) and summer mean water (August 6).

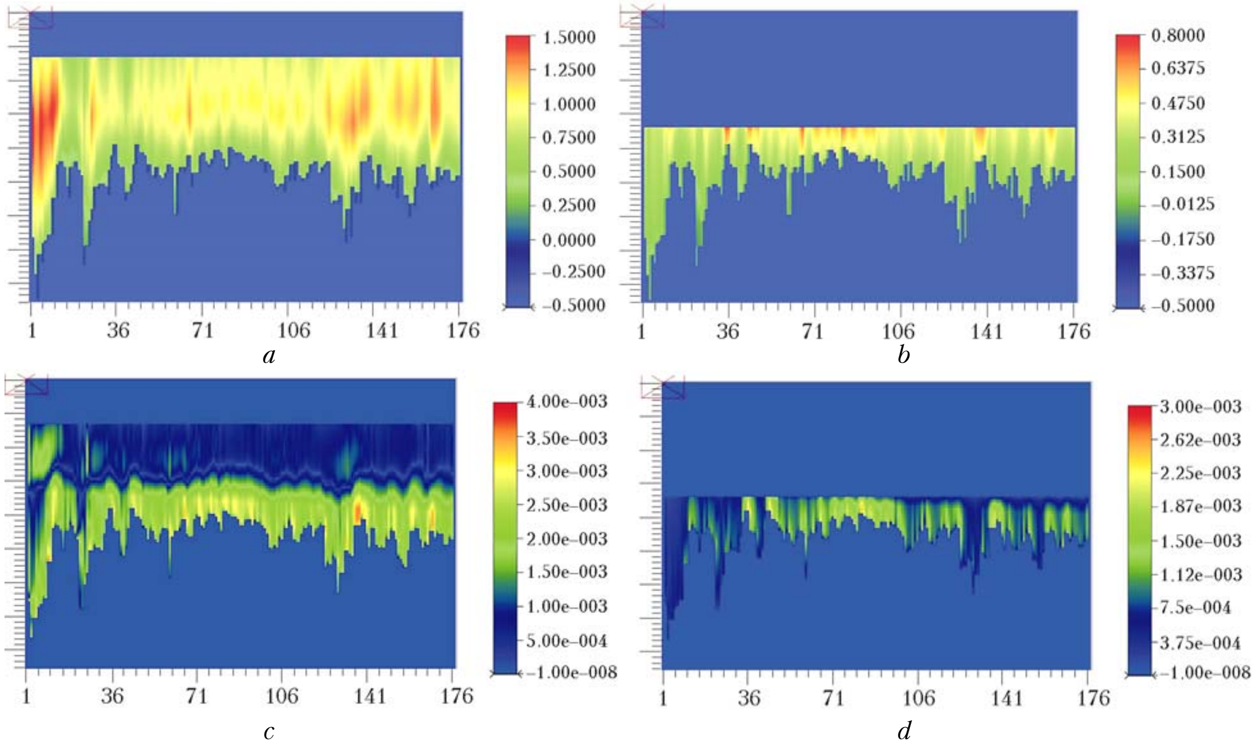


Fig. 2. Fields of longitudinal velocity, m/s (*a*), and coefficient of vertical turbulent viscosity, m^2/s (*c*), on May 28 at 12.00 of the local time, and the corresponding characteristics on August 6 (*b*, *d*). The horizontal axis shows the numbers of segments, and the vertical axis show the river depth.

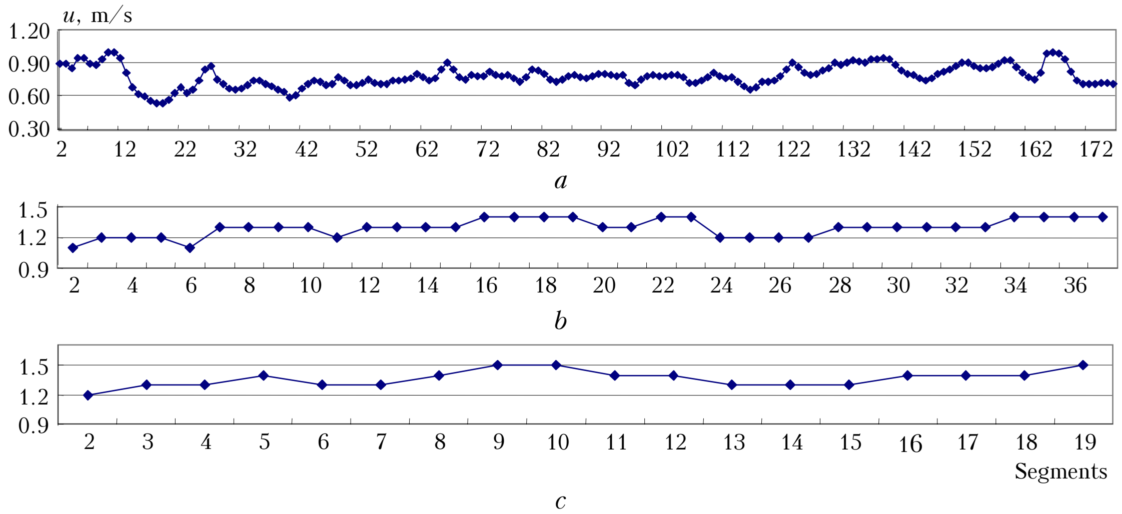


Fig. 3. The distribution of horizontal flow velocity in surface layer at flood maximum (on May 28), obtained with different grid models: MC1 (*a*), MC2 (*b*), and MC3 (*c*). Time of the run to Sartyn'ya village is 23.5 h at an average velocity of 0.78 m/s (*a*); 15.3 h at 1.29 m/s (*b*); and 14.4 h at 1.37 m/s (*c*).

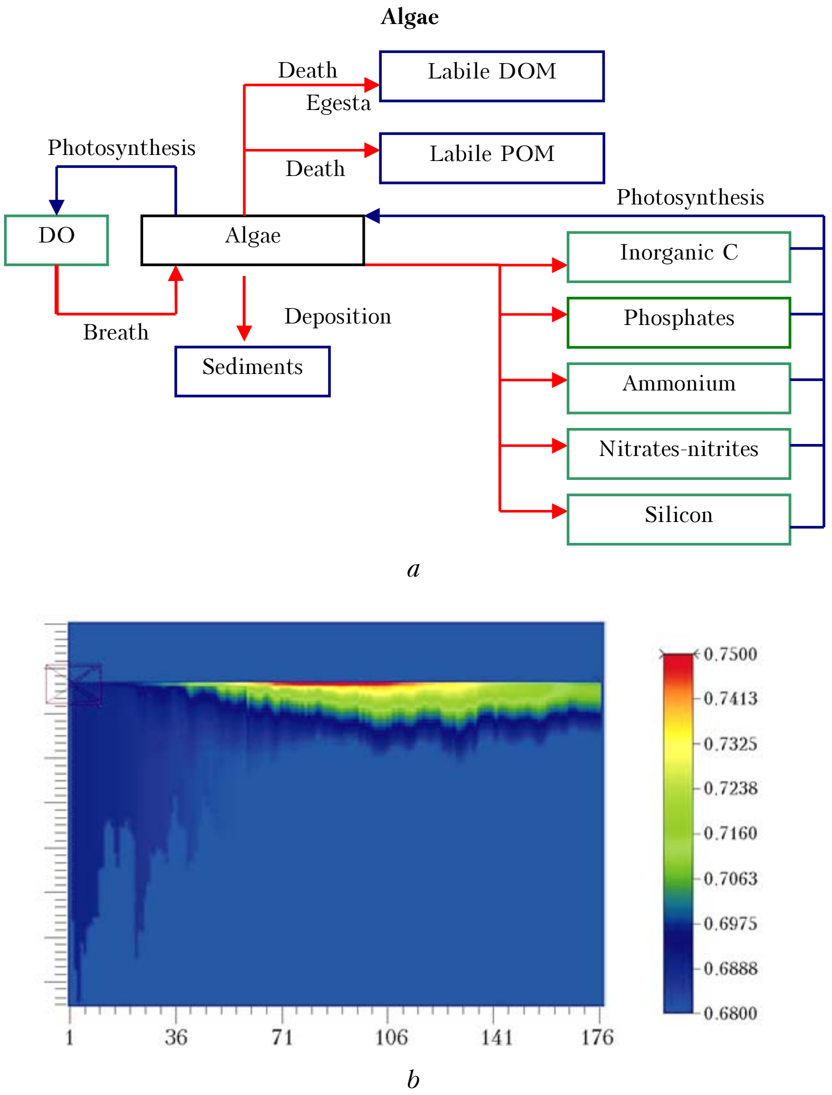
Is it possible to use so crude approximation when dealing, e.g., with the problem of prediction of the rate of pollutant propagation along the river during emergency volley discharges? To answer this question, we conducted three calculations using BSC on grids with different horizontal resolutions: the high-resolution MC1 grid (177 segments), the low-resolution MC2 grid (38 segments), and very-low-resolution MC3 grid (19 segments). An example of the flow velocity calculations for the surface layer during the flood maximum (on May 28) at different horizontal resolutions is shown in Fig. 3.

Analysis of Fig. 3 and other materials of this series of numerical experiments makes it possible to unambiguously conclude that the quantitative characteristics of the flow velocity field depend very strongly on detalization of the geometrical model of the river-bed channel. For instance, the use of an order of magnitude coarser horizontal approximation leads to almost doubled maximal values of the near-surface velocity. This in turn leads to errors in estimation of the velocity and run time, as well as large errors in the prediction of the velocity of the pollution transport.

3. Simulation of water quality characteristics

The model calculates many pararameters, the main of which are the following: the total dissolved substances (TDS); the tracer, i.e., passive pollutant with a zero deposition rate (Generic 1); the residence time, i.e., the characteristic of the hydrodynamics with right-hand part equal to −1 and zero boundary condition at the entrance (Generic 2); the enteric bacillus (Generic 3); inorganic suspended substances (ISS); the labile dissolved organic matter (Labile DOM); Refractory DOM; labile particulate organic matter (Labile POM); Algae; Phosphate; Ammonium; Nitrate-Nitrite; Dissolved Silica; Total Iron; and Dissolved Oxygen. The choice of some or other modeling parameters is determined by the availability of observational data. In addition, in some cases, as shown in Fig. 4*a*, simulation of some parameters necessitates inclusion of a number of other parameters, interconnected with each other in chain-cycles of substances.

Figure 4*b* shows the result of algae simulation in period of the flood maximum. The natural processes proceeding in nature are well seen, when the alga amount increases in a photic, well warmed water depth and then propagates to deeper layers due to the turbulent mixing and the gravitation.



a

b

Fig. 4. Diagram of interconnection between simulation of algae and other simulated parameters (*a*); alga concentration field (g/m^3) at 17:30 LT on May 28 (*b*). Horizontal axis shows segment numbers and vertical axis shows the river depth.

Conclusion

Ideally, the model should be used by water system researchers as a starting point, with subsequent continuous improvement of initial data and its algorithms aiming at the better understanding of the ecosystem structure and time dynamics of processes in it. Unfortunately, such an approach is rarely realized in practice because of large time consumption, high cost, and, regretfully, the absence of cooperation between different specialists: hydrobiologists, hydrophysicists, hydrochemists, and mathematicians.

Joint efforts of experimenters and modelers have led to notable achievements in physics, chemistry, and, to some degree, in biology (e.g., genetics) in the past century; however, such a cooperation is a rare phenomenon in the field of water quality simulation.

A deep insight into the modeled processes and the knowledge of the reproduced ecosystem are necessary for reaching the progress in this field. All this requires solution of the following problems:

– construction of the conceptual model of hydrodynamics and the water quality of the river system under study;

– implementation into practice of mathematical (numerical) model for solution of the problem of water control.

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