Numerical modelling of admixture transport in a turbulent flow at river confluence

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Abstract. The paper is concerned with the development of the hydrodynamic model of the Chusovskoy water intake located in the confluence zone of two rivers with essentially different hydrochemical regimes and in the backwater zone of the Kamskaya hydroelectric power station. The proposed model is used for numerical simulation in the framework of two-and three-dimensional approaches for the annual average, minimal and maximal values of the water flow rates in two rivers. The data for water mineralization in the water intake zone have been obtained. The recommendations for optimization of the water intake structure have been formulated.

1. Introduction
The objective of this paper is to develop a hydrodynamic model of the Chusovskoy water intake system, supplying most of Perm districts numbering about one million inhabitants with potable water. Numerous field observations have shown that in the region of the Chusovskoy water intake located in the confluence zone of the Chusovay and Sylva rivers with essentially different hydrochemical characteristics, water of the Sylva river is characterized by a higher degree of hardness and mineralization than water of the Chusovaya river. Moreover, the Chusovskoy intake system is located in the backwater zone of the dam of the Kamskay hydroelectric power station (HPS). Thus, the hydrodynamic regime of the water basin in the region of the water intake is defined by a rather complicated combination of the hydrological regimes of the Chusovaya and Sylva rivers, the water level of the Kamskiiy water storage reservoir and the operating regime of the Kamskay HPS. It should also be noted that the rivers’ regimes are characterized by high seasonal variability. Due to these factors and the limited possibilities of water monitoring, a numerical simulation of the above hydrological system is a matter of considerable importance for the environmental and engineering applications. Optimization of the water intake structure using the data of mathematical simulation may provide an alternative to the high-priced and time-consuming technological methods of lessening water hardness.

Simulation of the processes of the selective water intake from large water basins in the context of water-protective problems has been the subject of numerous studies by foreign and Russian researchers [1-7]. Simulation is generally done in the framework of a two-dimensional approach using the system of shallow water equations. A number of software products have been developed to realize numerically the two-dimensional Saint Venant equations.
A difference in the chemical composition of water is responsible for its density difference. Therefore, as the waters of two rivers are stirred, the more dense Sylva river water sinks to the bottom and the less dense Chusovaya river water rises to the surface. Since the non-uniform distribution of water density over the depth of the river is of fundamental importance for the examined problem, a numerical simulation in the framework of the two-dimensional approach including averaging over the depth is conceptually incorrect at least for part of the hydrological system, where the waters of two rivers are actively mixed.

On the other hand, in view of large dimensions and complicated geometry of the computational domain, a solution of this problem in the framework of a three-dimensional approach will require extensive computational resources.

To alleviate the problem, we used a combination of two- and three-dimensional computational schemes. The numerical simulations in the vicinity of the water intake head and the bottom barriers were made based on the three-dimensional model, whereas the hydrodynamics of the rest of the computational domain was computed based on the two-dimensional model.

To realize three- and two-dimensional simulations we used two different software products. The two-dimensional approach required application of the specialized hydrological software packet SMS v.10 produced by the American company AQUAVEO LLC (Donnell, 2009). For simulation of a three-dimensional problem we used the software packet for computational hydrodynamic Fluent v.6.3.26.

2. Two-dimensional model
Since the resource requirements for a two-dimensional simulation are relatively low we were able to examine the whole region of the Kamskiy water storage basin, which extends for about 100 km. The characteristic dimensions of the examined area are as follows: the length of the region from the Kamskaya HPS to the settlement of Palazna is ~ 40 km, from Kamskaya HPS to the place of the confluence of the Chusovaya and Sylva rivers ~23 km., from the confluence of the Chusovaya and Sylva rivers upstream the Chusovaya river ~ 22 km., from the confluence of the Chusovaya and Sylva rivers upstream the Sylva river ~ 17 km; the width of the water storage reservoir in the examined area ranges from 1.0 to 3.5 km and the average depth is about 15 m.

To set correctly the morphometry of the considered water basin (see fig.1) we used the technique of matching the data obtained from a detailed echo-sounding survey using GPS coupled sensors with satellite imagery. Raw data processing was accomplished using the Arc GIS software packet.

A two-dimensional (in a horizontal plane) model for the examined region of the water storage basin was constructed by making use of the software product SMS v.10 of the American company AQUAVEO LLC developed and manufactured by request and with participation of the USA Center of Hydraulic Investigations. The basis for this model is a set of modules (RMA2, RMA4, FESWMS, and others), which allow us to solve different problems. A brief outline of the RMA2 module which was used to analyze a two-dimensional flow [8] is given below.

RMA2 is a general-purpose module developed for a wide class of problems, in which the vertical acceleration is inessential and the velocity vectors have the same direction throughout the water basin depth at any time instant. It is used to calculate the eminences of water surface and horizontal velocity components in the laminar or turbulent flows with free surfaces in the two-dimensional domains.

The RMA2 module is designed to solve the Reynolds-type equations for turbulent flows derived from the Navier-Stokes equations by the finite element method. Friction is calculated by the Manning or Chezy formulas and the coefficients of the turbulent viscosity are used to determine the specific features of turbulence. It can be applied equally well to the stationary and non-stationary problems.
As the boundary conditions of the model we used the annual average flow rate of water in both rivers at the entrance to the water storage basin and the water level at the exit from the Kamskaya HPS, which is 108.5m. The data for the annual average flow rate and mineralization of water in the Chusovaya and Sylva rivers are given in Tables 1,2. Figs. 2,3 show the calculated fields of the velocity vector and distribution of water mineralization in the confluence region of two rivers and the location of the Chusavskoy water intake system.

| Water flow rate in Kamskiy water storage basin near the settlement of Polazna, Q, m³ /s | Water level in the Kamskiy water storage basin near the Kamskaya HPS, H, m | Water flow rate in the Chusovaya river, Q, m³ /s | Water flow rate in the Sylva river, Q, m³ /s |
|---|---|---|---|
| 1158.0 | 108.5 | 226.0 | 159.0 |

Table 1. Data for the flow rate and water level in the rivers of the Kamskiy water storage basin.

| Mineralization of water in the Kamckiy water storage basin near the settlement of Polazna, C, mg / l | Mineralization of water in the Sylva river, C, mg / l | Mineralization of water in the Chusovaya river, C, mg / l |
|---|---|---|
| 300.0 | 650.0 | 200.0 |

Table 2. Data for mineralization of water in the rivers of the Kamskiy water storage basin.
3. Three-dimensional model
As it has been mentioned above, our investigations would be far from complete, if only the results of numerical simulations made in the framework of two-dimensional model were not supplemented by the results of simulation of the three-dimensional flow region, which takes into account the vertical stratification of water mineralization and, accordingly, stirring of the Sylva and Chusovaya river waters due to the difference in water density.

The computations were made by applying the hydrodynamics software packet to one of the semi-empirical turbulence models. Since a tree-dimensional simulation requires extensive computational
resources it was restricted to the region extending upstream for about 10 km from the confluence of the Sylva and Chusovaya rivers to the Chusovskaya water intake system.

The rivers’ depth was taken to be constant over the whole length of the computational domain and was equal to 20 meters, which held 20 nodes of the mesh with adaptive refinement toward the bottom of the river. All in all, the mesh constructed with the aid of Gambit 2.3.16 packet consisted of 200000 nodes.

The flow was assumed to be isothermal and all changes in the water density were assumed to be caused by the difference in water mineralization found by the law $\rho = \rho_0 + 0.702 \times s \times 1000.196$ kg/m$^3$ and s is the mass concentration of the dissolved salts measured in promille.

At the inlet zone of the computational domain, (the place where the Chusovaya and Sylva rivers entered the domain) we used the boundary conditions of the VELOCITY-INLET type (the prescribed flow velocity was determined from the water flow rate) and for the outlet zone downstream from the Chusovskoy water intake we used the boundary conditions of the OUTFLOW type. The free surface of the river waters satisfied the boundary conditions of the WALL type with zero tangential stresses and other boundaries satisfied WALL-type conditions for a "solid wall".

The choice of the computational model is of critical importance for anticipated results. Out of the turbulence models of the Fluent software packet we chose the Reynolds Stress model and used the Coupled scheme with discretization of the SECOND UPWIND type providing the second-order accuracy. The under relaxation factors used in our computations were standard.

We carried out preliminary simulations to debug the scheme for construction of an adequate numerical solution by applying the Fluent packet to the examined problem. First, we found a stationary solution to the problem neglecting the effect of gravity. The convergence of the obtained solution was achieved already after several hundred iterations. The solution showed that the vertical stratification of water mineralization was absent. Then, the stationary solution was refined in the framework of the non-stationary approach using the time step of 1 second and the second-order time approximation.

The non-stationary simulation lasted for a hundred thousand seconds and revealed a redistribution of salt concentration in the waters of two rivers. Since water of the Sylva river is heavier than that of the Chusovaya river it drops lower and while doing this is mixed with the lighter water of the Chusovaya river.

| Flow rate type  | Water flow rate in the Chusovskaya river, $Q$, m$^3$/s | Water flow rate in the Sylva river, $Q$, m$^3$/s |
|-----------------|------------------------------------------------------|-----------------------------------------------|
| Annual average  | 226.0                                                | 159.0                                         |
| Minimum         | 16.0                                                 | 16.8                                          |
| Maximum         | 5250.0                                               | 3750.0                                        |

Table 3. Data for the water flow rate in the Chusovaya and Sylva rivers.

The simulations were made for three values of the water flow rate in the Chusovaya and Sylva rivers: the minimal, maximal and annual average (see table 3). The mass concentration of salts dissolved in water was assumed to have the same value for three variants of the flow rate (table 2). Fig.4 shows the profiles of distribution of water mineralization through the depth of the river obtained in the vicinity of the water intake head.
Figure 4. Profiles of distribution of water mineralization through the depth of the river. 1 – annual average flow rate; 2 – minimal flow rate; 3 – maximal flow rate.

4. Conclusions

The results of the two-dimensional simulations have shown that at typical values of the flow rates of the Sylva and Chusovaya rivers, their waters after confluence are intensively mixed in the horizontal direction. In the water intake zone, the admixture concentration in the horizontal direction is practically homogeneous. The three-dimensional simulations have supported this conclusion and revealed essential vertical inhomogeneity of admixture concentration through the water depth: water mineralization near the bottom a few times higher than water mineralization near the surface. Hence, the selective water intake from the near-surface layers can essentially reduce hardness of potable water consumed by the inhabitants of Perm.

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