Vertical Density Inhomogeneity of Kama Reservoir Water Masses in the Region of Berezniki: Possible Genesis and Influence on the Stability of Water Use

A P Lepikhin1, T P Lyubimova2, A V Bogomolov1, Yu S Lyakhin1, A A Tiunov1, V Yu Kolchanov2, Ya N Parshakova2

1Mining Institute UB RAS, Sibirskaya 78a, Perm 614007, Russian Federation
2Institute of Continuous Media Mechanics UB RAS, 614013 Perm, Russian Federation

E-mail: a lepihin49@mail.ru

Abstract. The stability of water supply systems is one of the main factors that determine the reliability of the functioning of large industrial complexes. This problem is considered on the example of the “Azot” branch of URALCHEM JSC in the city of Berezniki, which takes fresh industrial water from the Kama river (Kama reservoir). A specific feature of this water body is the significant variability of its hydrological regime. During the summer dry season, it is characterized by low flow velocities. In winter, with a decrease in the water level in the reservoir, a typical river regime is observed. In addition, there is a strong technogenic impact on the water body. The impact is formed largely due to non-declared dispersed (diffuse) sources. Their characteristic feature is high mineralization and, accordingly, the density of the formed wastewater. Their behavior is fundamentally different from the processes of dilution and migration of effluents with neutral buoyancy. A two-layer structure is formed, when the content of the main ions in the surface horizon is more than an order of magnitude less than in the bottom layer. This circumstance must be taken into account when assessing the reliability of the functioning of water intakes. The most effective tool for solving such problems is the conjugation of a complex of field monitoring observations with computational experiments using hydrodynamic models in one-, two- and three-dimensional formulations.

1. Introduction

Traditionally, it is believed that the distribution of pollutants is fairly uniform over the depth of water bodies. This statement is reflected not only in the organization of the system of impact monitoring of water bodies, when it is considered acceptable to take water samples only from the surface horizon, but also in the regulatory and methodological documents for establishing VAT, where it is a priori assumed that the discharged wastewater is characterized by neutral buoyancy. This statement is quite acceptable for relatively shallow water bodies characterized by intense vertical turbulent sweep, for which the density Froude numbers \( Fr_{\rho} >> 1 \), and, accordingly, the Richardson numbers \( Ri << 1 \).

However, in water bodies with slow water exchange, primarily in lakes and reservoirs, these basic conditions may not be met and significant vertical density heterogeneities are formed in them, which fundamentally change the conditions of water use. However, unfortunately, the traditional concepts of the vertical homogeneity of water masses are widely used in the analysis of the stability of the functioning of systems for withdrawing water from water bodies. In the present paper, this problem is considered on the example of the technical water intake of the “Azot” branch of URALCHEM, JSC, Berezniki. This water intake is the largest technical water intake in the city of Berezniki. At the
beginning of June 2020, there was a significant increase in the limiting indicators of water quality - chlorine and sodium ions, significantly exceeding technological standards.

The stoppage of a large industrial enterprise for several days, due to the intake of water of substandard quality, had a very large public response. Several hypotheses were put forward for the possible causes of this incident:

- discharge of contaminated water from the downstream scattering wastewater outlet of OOO “Stok” due to back flows from the Kamskaya HPP, as well as wind drift;
- inflow of pollution from the technological complexes located on the left bank of the Kama reservoir (the Kama river);
- water intake from the lower bottom of the most polluted horizons.

This work analyzes the feasibility of these possible hypotheses based on the analysis of the peculiarities of the hydrological and hydrochemical regime of the Kama reservoir using the materials of field observations and performed computational experiments.

2. Materials and methods

The considered water intake is located in the upper part of the Kama reservoir in the industrial zone of Berezniki city. A general overview diagram of the area under consideration is shown in Figure 1.

Due to its design, the water intake of the “Azot” branch of URALCHEM JSC in Berezniki can take water from three different depth horizons at a normal back water horizon of the Kama reservoir: 0-2 m, 3-5 m, 7-9 m.

A characteristic feature of the hydrochemical regime of this section of the Kama river (Kama reservoir) is a strong technogenic impact within the Solikamsk-Bereznikovskiy industrial hub, and
technogenic load is formed in a dominant degree not due to point, declared sources of pollution, but due to the unloading of non-declared dispersed sources, called diffuse in modern literature [1].

As a result of these sources, in the area of Berezniki, during the summer dry season, a significant layer of water ~ 3–5 m thick with increased salinity is formed in the bottom area (Figure 2).

Figure 2. Distribution of electrical conductivity in depth along the left bank of the Kama River on separate verticals based on material from natural field studies 07/14/2020. This phenomenon was first described back in 1959 by G.S. Kulikov [2]. An increase in the content of chlorides in the intaken water at the considered water intake, which led to the shutdown of the enterprise, was recorded on 06/05/2020 and continued until 06/08/2020 (Figure 3).

Figure 3. Change in the content of chlorides and sodium at the water intake of the “Azot” branch of URALCHEM, JSC, Berezniki.

2.1. Used tools
To solve this problem, along with a series of detailed instrumental observations at the investigated section of the Kama reservoir, previously developed 1D-2D-3D hydrodynamic models were also actively used. Hydrodynamic models in 1D formulation were built using HEC RAS, 2D -SMS, 3D - ANSYS Fluent software.
The experience of using this complex of coupled hydrodynamic models for solving specific water management problems is considered in [3,4,5,6] and others.

3. Discussion of the results obtained

3.1. Analysis of the impact of the Kamskaya hydroelectric power station

In earlier studies it was shown that a significant intra-diurnal irregularity in the operation of the Kama hydroelectric power station can have a significant effect on the hydrodynamics in the upper dam section of the Kama reservoir [7, 8]. However, their significant influence extends only up to the wide part of the Kama reservoir. Inside the wide (lacustrine) part of the reservoir, starting from the mouth of the Obva river (Fig. 1), this influence is sharply reduced.

The performed computational experiments with the setting of specific discharge rates through the dam of Kam HPP for the period from 06/04/2020 to 06/08/2020 have shown that the change in the operation mode of the HPP could not form significant stable back flows in the area of Berezniki and, thus, to determine the observed increase in the chloride content in the intaken water. The calculations of drift flows based on hydrodynamic models in 2D formulation, using data from the Berezniki meteorological station for the period under consideration, have shown that these factors could also not be the cause of the observed abnormal situation at the water intake under consideration.

3.2. Emergency situations at technological facilities located above the water intake

Detailed surveys of technological facilities located on the left bank of the Kama reservoir above the water intake under consideration did not reveal traces of possible emergency situations associated with the ingress of significant volumes of pollutants into the reservoir. Therefore, the influence of possible emergency situations on the stability of the operation of the considered water intake was considered in a scenario setting.

In the initial section in the Kama river itself (Kama reservoir) water salinity was assumed to be uniformly distributed over depth. Numerical experiments in a 3D formulation were carried out for several variants of setting the boundary conditions. In the variant described in [5], the pollution source was in the bottom area along the left bank at the site of the sludge storage facility No. 2 of BSZ JSC (“White Sea”). This paper considers a possible emergency situation when the source of pollution is located directly at the mouth of the river. Tolych, with an intensity of q=161 kg/s, the salinity of water throughout the bay was taken to be the same: the maximum technically possible - 100 g/l.

At the same time, the mineralization of water in the background section of the Kama river was taken to be uniform over the entire flow section and equal to C ~ 0.2 g/l.

This problem was solved on the basis of conjugation of hydrodynamic models of this section of the reservoir in 2D and 3D formulations. Calculations using the model in a 2D setting were necessary to set the boundary conditions for modelling in a 3D formulation. The used computational domain of the 3D model is shown in Figure 4.

Three-dimensional numerical modelling was carried out using the ANSYS Fluent software package based on the implementation of the finite volume method. The non-uniform grid was built in accordance with the actual morphometry of the area under consideration.

Two-dimensional (in the horizontal plane) model for the section of the river Kama from the village Pyskor to the village Oryol, 24 km long, was made using a specialized hydrological package SMS v.11.1 of the American company AQUAVEO LLC. The RMA2 module was used to simulate the two-dimensional flow, and the RMA4 module was used to simulate the propagation of pollution. To correctly set the morphometry of the river Kama, from the village of Pyskor to the village of Oryol, a digital bottom relief model (DEM) was built for the water body under consideration.
Figure 4. Change in the content of chlorides and sodium at the water intake of the “Azot” branch of URALCHEM, JSC, Berezniki.

The velocities in the inlet sections on the Kama River and at the confluence of the Tolych River Bay and the Kama River were set in the form of velocity profiles obtained in two-dimensional calculations.

The results of the performed computational experiments are shown in Figure 5. As follows from Fig. 5 at the water intake of the “Azot” branch of URALCHEM JSC in Berezniki at distances of 50, 100, 150 meters from the coast, in the emergency situation under consideration, a significant vertical heterogeneity in the distribution of mineralization in depth should be observed.

Figure 5. Distribution of mineralization by depth for different control verticals at the water intake of the “Azot” branch of URALCHEM JSC, Berezniki at distances of 50, 100, 150 meters from the coast.

From the data presented by the calculation, it can be seen that the concentration in 700 mg / l is achieved only at a depth of more than 6 m. The concentration on the surface is less than 500 mg / l.

The main result of the performed computational experiments, when compared with the results of calculations presented in [5], is that when highly mineralized brines enter the reservoir, regardless of the location of their source, a significant vertical stratification of water masses is formed. At the same time,
a fairly stable layer of water with increased mineralization is located in the bottom area. Accordingly, the observed increase in the content of chlorides at the considered technical water intake can only be explained by the temporary intake of water from the bottom horizons.

4. Conclusion
The use of integrated 1D - 2D - 3D modeling makes it possible to analyze the possible causes of emergency situations at water intakes.

1. Under the observed hydrological regime of the Kama river and the operation of the Kama hydroelectric power station, as well as under the existing wind regime, significant back flows cannot be recorded and, accordingly, the water intake of the “Azot” branch of URALCHEM JSC in Berezniki cannot receive pollutants discharged through the scattering outlet of LLC Stoke “in the Kama river (Kama reservoir).

2. In the scenario setting, the emergency discharge into the mouth bay of the Tolych river with an intensity of 161 kg / s (based on total mineralization) was accepted as a possible source of pollution of the Kama river in the upper part of Berezniki.

      Calculations performed on a mathematical model in a three-dimensional formulation have shown that on the considered section of the Kama river and a source of pollution at the mouth of the Tolych river an increased mineralization of water in the area of the considered water intake up to 1 g / l can be observed. However, the distribution of water salinity is characterized by significant vertical density stratification and high concentrations are observed in the bottom layer, and in the surface horizon - by an order of magnitude less. The boundary between the water masses is at a depth of approximately 6 m.

      It is shown that even a significant emergency situation could not lead to the intake of water of substandard quality, provided that the intake of water is made from the surface horizons.

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