

# Mathematical modelling of Krasnoyarsk HPS intake regime influence on the ice and temperature downstream of the dam

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**Abstract** Mathematical model was developed for simulation of Krasnoyarsk hydropower station (HPS) intake regime influence on ice and water temperature downstream of the dam. Current reservoir vertical temperature profile and water temperatures of downstream river were used for the verification of the model. Using this model we estimated influence of stratification, withdrawal position and discharge on temperature of water inflow into HPS. It was estimated that changeover to upper-layer intake from current deep-layers intake allows to increase water temperature of Yenisey at Krasnoyarsk city on 6-8 °C at summer period.

**Keywords:** numerical modelling, hydrophysics, Krasnoyarsk reservoir, stratified flows

## 1. Introduction

The construction of the Krasnoyarsk HPS on the Yenisei River has caused considerable changes in the thermal regimes downstream of the dam. The Krasnoyarsk Dam is a 124-metre high concrete gravity dam located about 30 km upstream from Krasnoyarsk city (figure 1). It was constructed from 1956 to 1972 and supplies 6,000 MW of power.

As a result of the damming, the Krasnoyarsk Reservoir was created. This reservoir, informally known as the Krasnoyarsk Sea, has an area of 2,000 square km and a volume of 73.3 cubic km. It is 388 km in length and 15 km in width at its widest, has an average depth of 36.6 m, and a depth of 105 m near the dam.

The dam significantly influences the local climate; normally the river would freeze over in the bitterly-cold Siberian winter, but because the dam releases unfrozen water year-round, the river never freezes in the 200 to 300 km stretch of river immediately downstream of the dam. In winter, the frigid air interacts with the warm river water to produce fog, which shrouds Krasnoyarsk and other downstream areas. In contrast, summer water temperatures are very cold – not more than 14 °C even during hottest summer days with air temperatures higher than 30 °C. Thirty kilometers downstream of dam Yenisei is crossing Krasnoyarsk – city with more than million people population. Low temperatures make Yenisei uncomfortable for swimming and recreation purposes.

The main reason of such significant thermal changes is that average depth of water inflowing from the reservoir into HPS is 20-40m. This below thermocline water is colder than surface water at summer and warmer – at winter. Negative impacts of hydropower operation on the downstream area can be offset with operational strategies such as selective withdrawal. Thus, various projects were suggested for modification of inflow regime for the intake of water from upper reservoir layer.

The flow regime from the dam can influence hydraulic and geomorphic processes that in turn may impact the ecology of the downstream. Different researchers investigated various features of hydrophysical regimes upstream and downstream of hydropower stations (e.g. Atavin *et al.* (2014)).

Effects of HPS water intake on the downstream water is evident but more detailed calculations are needed for more precise estimate of influence. Most recently, Caissie (2006) has reviewed the literature to describe the factors and underlying physical processes related to river temperatures, to provide a general overview of water temperature models, and to discuss natural and human-modified thermal conditions and their potential implications for aquatic habitats. Many different approaches of varying sophistication have been developed to model different aspects of thermal behaviour in space and in time (Moore, 2005; Caissie, 2006). In this study we used simple mathematical model in order to estimate potential temperature effect of selective withdrawal.

### 3. Methods

Temperature profiles were determined in the reservoir with in situ measurements near the intake tower. Continuous in situ monitoring of temperature downstream of the HPS were conducted at several locations from the dam to Krasnoyarsk.

Mathematical model of stratified flows at reservoir close to the dam is based on flow equations under the Boussinesq approximation (Imberger and Ivey, 1993):

$$\frac{\partial \omega}{\partial t} + U \frac{\partial \omega}{\partial x} + W \frac{\partial \omega}{\partial z} = K_x \frac{\partial^2 \omega}{\partial x^2} + K_z \frac{\partial^2 \omega}{\partial z^2} + g \frac{\partial \rho_1}{\partial x},$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = -\omega \quad U = \frac{\partial \psi}{\partial z}, \quad W = -\frac{\partial \psi}{\partial x}$$

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} + W \frac{\partial T}{\partial z} = K_{xr} \frac{\partial^2 T}{\partial x^2} + K_{zr} \frac{\partial^2 T}{\partial z^2}$$

$$\rho = \rho_0 [1 + \rho_1(T)]$$

Here T is water temperature; V= (U , W) is the flow velocity vector; omega and psi are correspondently swirl and current function; z is the downward coordinate axis, x is the coordinate directed on horizontal lengthways of the reservoir; K is the turbulence exchange coefficient.

We considered the stationary flow regimes of stratified fluid in the two-dimensional vertical plane schematization of a reservoir, at one end of which water is input, and at the other water is output from the diversion opening, located at distance h from the free surface.

The main processes, affecting the formation of the turbulence structure of reservoirs, are the fall of surface and internal waves, turbulence energy diffusion, convective processes, and shearing effects. For estimating the vertical turbulence exchange coefficient, accounting for shearing effects and stratification, the Prandtl-Obukhov formula is used (Belolipetsky and Genova, 1998).

### 4. Results

HPS inflow water temperature depends on relative amount of water taken from different depths and vertical temperature profile. Temperature distribution at the reservoir behind the dam is shown on figure 3a. Significant stratification is observed – temperatures higher than 10 °C

are reached at August from surface to 40-50 m depth; at the bottom (60-100 m) water temperatures are not higher than 5 °C during whole year. Figure 2 shows flow patterns for current withdrawal and modification to selective withdrawal of surface layers.

We have performed calculations for three basic scenarios concerning the wind: direction of wind is to the dam, direction is – opposite, and no wind is present. We considered 5 m/sec constant wind force and performed calculations until stationary conditions are reached.

Vertical distributions of horizontal velocity under current HPS withdrawal are shown on figure 3b. It is seen that the worst case is than wind direction is opposite to the dam – most of the inflow water is from the layers under thermocline. The average depth of inflow water among these scenarios is about 20-40 m.

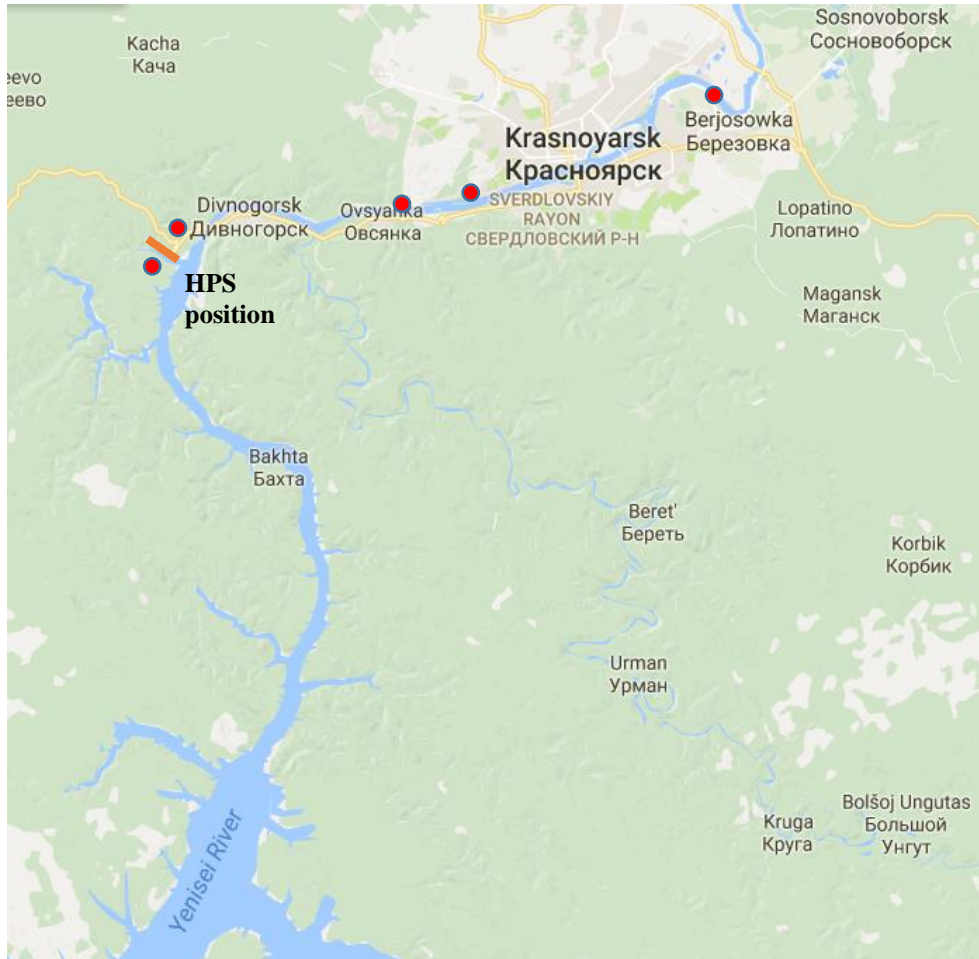
Horizontal velocity profiles for selective withdrawal from surface layers is shown on figure 3c. It is seen that in all considered wind scenarios most of water inflow from surface layers with higher temperature. This modification by our estimates will increase water temperature of Yenisey at Krasnoyarsk city on 6-8 °C at summer period.

### 5. Conclusion

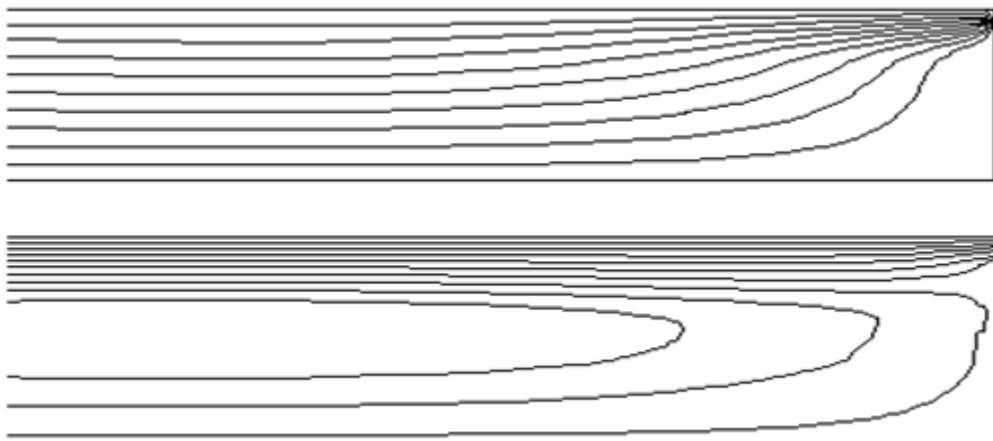
The low temperatures of Yenisei water in the bounds of Krasnoyarsk at the summer period were the primary concern of this study. Current HPS operations include the release of deep layers cold water to downstream. We tested if selective withdrawal of surface reservoir waters could maintain comfortable water temperatures downstream of dam. Calculations showed that selective withdrawal allows to increase Yenisei temperatures near Krasnoyarsk up to 15-17 °C at July and 17-19 °C at August.

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**Figure 1.** Map showing the Krasnoyarsk HPS position and monitoring points of temperature (red circles).



**Figure 2.** Flow currents from the reservoir into the Krasnoyarsk HPS. Upper regime is the operation of current withdrawal. Bottom regime – projected selective withdrawal operation.

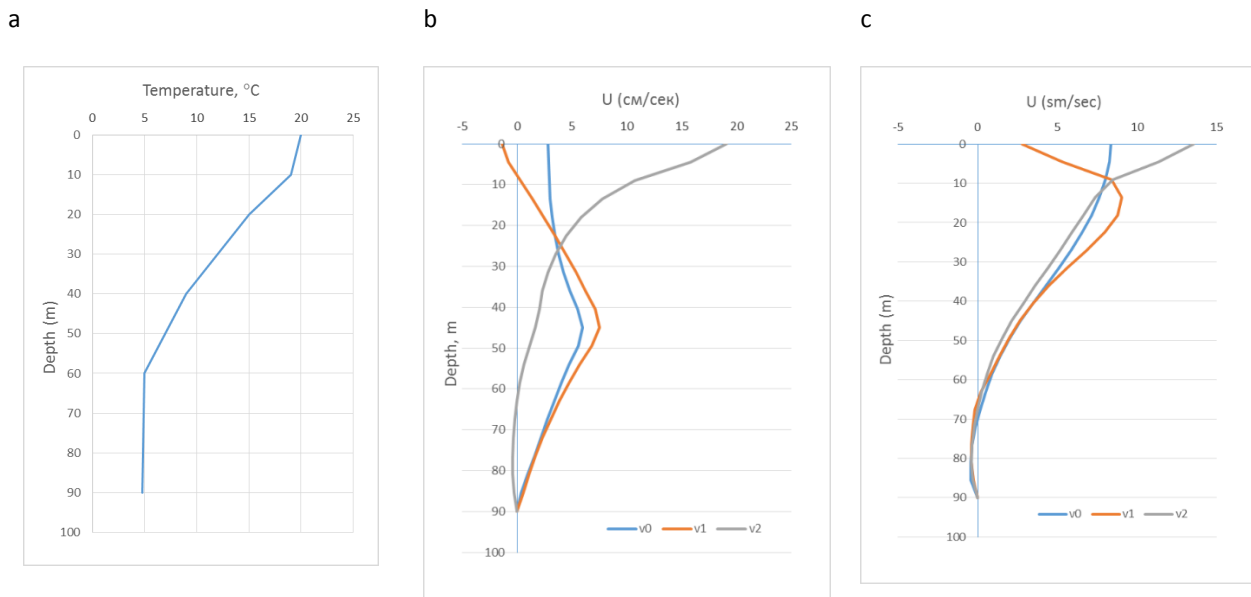


Figure 3. Temperature and horizontal velocity at the reservoir behind Krasnoyarsk HPS dam. (a) Current temperature profile at summer (July-August). (b) Calculated horizontal inflow velocities for the current withdrawal depending on wind scenario: blue line – no wind, orange line – wind is opposite to the dam, gray line – wind is blowing to the dam. (c) The same as b but for selective withdrawal from the surface layers.

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