Investigation of the influence of wind stress in autumn leading to unstable stratification in a meromictic lake using three-dimensional numerical modeling

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Abstract. Currents in lakes affect the distribution of hydrophysical and hydrobiological characteristics. Three-dimensional model study is an important step toward an improved understanding and reliable prediction of the distribution of hydrophysical fields. Salt stratified lake Shira refers to meromictic reservoirs. The depth of the upper mixed layer depends on many factors (even a few isolated, fairly rare facts of its complete mixing are known). The study of the influence of each of them separately is the task of mathematical modeling. The model results indicate that strong wind stress in the autumn can result in unstable density stratification, leading to intense vertical circulation.

1. Introduction
Studies of the hydrophysics of lakes is an important task of enviromental management. Lakes hydrophysics study is an important task of land hydrology. It allows us to understand the patterns of both the formation of the quality of water in lake ecosystems and their functioning [1].

Many salt lakes are meromictic [2]. Water column is not mixed to the bottom for at least one year in them. In the stratified lake, the upper (epilimnion) and deep (hypolimnion) layers are distinguished, where the density gradients are small. A layer of water (metalimnion), within which the density gradient is great, is between them. In the near-bottom layer, hydrogen sulphide accumulates and there is no oxygen. In the autumn, the water reservoir cools down; before the formation of ice, the water temperature changes little with depth and the density stratification is mainly determined by the salinity gradient. In this period, the stability of the lake against mixing becomes the lowest. The complete mixing of a meromictic lake can lead to an environmental disaster [3].

Lake Shira (54°29′N and 90°14′E) is located in the Republic of Khakassia, Russia (figure 1). It is a closed inland basin without islands, with the river Son flowing into it. Due to the smallness of the river influx its influence is concentrated in the mouth area, so the main external factor determining the flow in the lake is the wind stress. Lake Shira is 5 km wide and 9 km long with the maximum depth about 25 m, and the average depth of the middle part is 21 m. The underground water input constitutes about 9% of the total water input of the lake. The salt stratified Lake Shira refers to meromictic type reservoirs. A few rare cases of its complete mixing are known. The last one occurred in winter 2014-2015.

The water temperatures are much higher in the epilimnion (15–20°C) than in the hypolimnion (2–3°C) in summer. The salinity is higher in the hypolimnion. The summer stratification is very stable.
because of the temperature stratification and the high salinity of the lake. The distinct density stratification is defined by both the decrease of the water temperature and increase of salinity with the lake depth. So mixing between the top and bottom layers is very low—this fact was repeatedly proved by measurements and was confirmed during simulations [4]. Lake Shira features unique therapeutic properties, which are largely determined by the specific chemical composition of the water [5].

Figure 1. Lake Shira.

Salinity is one of the main factors that determines the mixing status of Lake Shira. The salinity gradient is formed in spring because of introducing fresh water due to melting of ice and snow. Later, this salinity gradient prevents the lake from being mixed by wind. In summer, the water is stratified because of both the temperature and the salinity gradients. In autumn, only the salinity gradient maintains the stratification. Using the three-dimensional numerical model, we have calculated the effect of wind force on the change in the salinity distribution in depth, depending on the shape of the bottom and the shoreline of the reservoir. the change in salinity gradient depending on wind stress, which the minimum value of salinity necessary to prevent Lake Shira from mixing by wind.

2. Materials and methods
To evaluate the dynamics of the vertical structure of the stratified water reservoir, we take into account the following simplified statement of the problem. A stratified water reservoir is schematized by a three-layer fluid. In the upper water layer that adjoins the free surface, the water density has a constant value due to mixing (epilimnion); in a pycnocline, the density changes linearly with depth (metalimnion); in the bottom layer, the density changes little, \( \rho \approx \text{const} \) (hypolimnion).

We carried out computations using GETM [6]. The General Estuarine Transport Model (GETM) is a primitive equation numerical model for studies of lakes, estuaries and coastal seas. GETM was initiated by Hans Burchard and Karsten Bolding in 1998 and has been further developed and feature enhanced by a number of people over the last years. GETM solves the 3D hydrostatic equations of motion applying the Boussinesq approximation. Governing equations are the following:

\[
\frac{\partial u}{\partial t} + \frac{\partial (uv)}{\partial z} - \frac{\partial}{\partial z}((v_1 + v) \frac{\partial u}{\partial z}) = \alpha \left( \frac{\partial}{\partial x}(u^2) + \frac{\partial}{\partial y}(uv) - \frac{\partial}{\partial z}((v_1 + v) \frac{\partial u}{\partial z}) \right) - f v - \int_0^z \frac{\partial b dz'}{g} = -g \frac{\partial x}{x},
\]

\[
\frac{\partial v}{\partial t} + \frac{\partial (v^2)}{\partial z} - \frac{\partial}{\partial z}((v_1 + v) \frac{\partial v}{\partial z}) = \alpha \left( \frac{\partial}{\partial x}(v u) + \frac{\partial}{\partial y}(v^2) - \frac{\partial}{\partial z}((v_1 + v) \frac{\partial v}{\partial z}) \right) + f u - \int_0^z \frac{\partial b dz'}{g} = -g \frac{\partial y}{y},
\]

The vertical velocity is calculated from the incompressibility condition: \( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \).
Here, $u$, $v$ and $w$ are the ensemble averaged velocity components with respect to the $x$, $y$ and $z$ direction, respectively. The vertical coordinate $z$ ranges from the bottom $-H(x,y)$ to the surface $\zeta(t,x,y)$ with $t$ denoting time. $\nu_t$ is the vertical eddy viscosity, $\nu$ the kinematic viscosity, $f$ the Coriolis parameter, and $g$ is the gravitational acceleration. The horizontal mixing is parameterised by terms containing the horizontal eddy viscosity $A_h^M$. The buoyancy $b$ is defined as $b = -g \frac{\rho - \rho_0}{\rho_0}$ with the density $\rho$ and a reference density $\rho_0$.

At the surface and at the bottom, kinematic boundary conditions are:

$$w = \partial_z \zeta + u \partial_z \zeta + v \partial_z \zeta \quad \text{for} \quad z = \zeta,$$
$$w = -u \partial_z H - v \partial_z H \quad \text{for} \quad z = H,$$

at the bottom boundaries, no-slip conditions are prescribed for the horizontal velocity components:

$$u = 0, v = 0.$$

At the surface, the dynamic boundary conditions are:

$$(\nu_t + v) \partial_z u = \alpha \tau_s^x,$$
$$(\nu_t + v) \partial_z v = \alpha \tau_s^y,$$

where the surface stresses (normalised by the reference density) $\tau_s^x$ and $\tau_s^y$ are calculated as functions of wind speed, wind direction, surface roughness etc. Also here, the drying parameter $\alpha$ is included in order to provide an easy handling of drying and flooding.

The lateral boundary conditions at closed boundaries are following: the flow must be parallel to the boundary, i.e. for an eastern or a western closed boundary $u=0$, for a southern or a northern closed boundary $v=0$.

Discretization is performed on the basis of the finite volume method. The initial distribution of temperature and salinity in the lake, which determines the density distribution, are taken from field measurements. They differ significantly in the summer and autumn (figure 2). In the autumn, salinity gradient under strong winds decreases substantially and in winter due to freezing of salt water the layer of convective mixing under the ice cover can propagate to the bottom. That was happened in winter 2014-2015 on Lake Shira as we know from field observations [7].

![Figure 2. Salinity distribution with depth in summer and in autumn.](image-url)
Various forms of reservoirs have been taken for computations: rectangular pond with flat bottom of 24 m depth; model pond with configuration of Lake Shira and flat bottom of 24 m depth; Lake Shira with real bathymetry. A horizontal resolution for all configurations was 200 m × 200 m including 40 vertical layers.

The GETM configuration for Lake Shira has been initially forced at surface with various wind velocities and wind directions during different time periods. Model internal (barotropic) integration time step is 0.5 s while external (baroclinic) time step is 2.5 s. Mean values of all hydrodynamics variables has been stored throughout the entire simulation time span. The initial salinity distribution is shown on figure 3 (according to the results of field observations in October 2014). The initial temperature distribution is constant in depth (3°C), which is quite typical for the autumn period.

![Figure 3. Initial salinity distribution in computations.](image)

Let’s denote the value characterizing the change in the salinity gradient, a “variation $S$” for a point with fixed spatial coordinates $(x_0, y_0)$, as follows: $\text{variation } S = \Delta S(t_1) - \Delta S(t_0)$, where $\Delta S(t_1) = S_{\text{max}}(t_1) - S_{\text{min}}(t_1)$. $t_1$ is end time of calculation, $S_{\text{max}}(t_1)$ is the maximum salinity in depth at a given point $(x_0, y_0)$ at time $t_1$, $S_{\text{min}}(t_1)$ is the smallest salinity value at this point. $\Delta S(t_0)$ is similarly defined at time $t_0$ (start time of calculation). The larger the value $\text{variation } S$, the greater the probability of mixing the lake in the winter [8].

3. Results
Calculations has been carried out in the rectangular basin with a depth of 24 m, a length of 10 km, a width of 7.6 km for 24 hours. All results in Table 1 are shown in the central point of the basin to exclude the influence of boundaries. Table 1 shows a comparison of the salinity gradient change depending on wind stress. If the wind is greater than 17 m/s, we can see a strong increasing of the “variation $S$”. Dependence on the length of the basin was also obtained. Since from the east to the west the pool has a length of 10 km, and from the north to the south - 7.4 km, then with the west wind the pool can be considered as longer one than with the south or north wind. When a wind force is less than 20 m/s in a longer basin, a change in the salinity gradient is greater.

| Wind stress (m/s) | Time (h) | Variation $\Delta S$ (PSU) | Time (h) | Variation $\Delta S$ (PSU) |
|-----------------|----------|-----------------------------|----------|-----------------------------|
| 15              | 10       | 0.12                        | 15       | 0.13                        |
| 17              | 10       | 0.2                         | 15       | 0.25                        |
Calculations have been carried out in a model water body with a rugged coastline and a flat bottom 24 m depth. Results are shown in the central basin point. We can see a comparison of the “variation $S$” depending on wind strength in the Table 2.

**Table 2.** Change of the salinity gradient depending on wind stress in a model water body with a rugged coastline and a flat bottom.

| Wind stress (m/s) | Time (h) | Variation $\Delta S$ (PSU) | Time (h) | Variation $\Delta S$ (PSU) |
|-------------------|----------|----------------------------|----------|-----------------------------|
| 15                | 10       | 0.1                        | 15       | 0.13                        |
| 20                | 10       | 0.3                        | 15       | 0.38                        |

The “variation $S$” is reduced by almost 1.5 times with wind force greater than 17 m/s compared to a rectangular pool. The tables show calculations with the same wind direction.

A number of calculations for a reservoir with real bathymetry of Lake Shira have been carried out. The results in the Table 3 are shown in the central point of the basin with a depth of 24 m. “Variation $S$” in a reservoir with real bathymetry is much less than in a pond with a flat bottom (0.15 in a reservoir with real bathymetry compared to 0.38 in a reservoir with a flat bottom with the same force and direction of the wind).

**Table 3.** Change of the salinity gradient depending on wind stress in a reservoir with real bathymetry of Lake Shira.

| Wind stress (m/s) | Time (h) | Variation $\Delta S$ (PSU) | Time (h) | Variation $\Delta S$ (PSU) |
|-------------------|----------|----------------------------|----------|-----------------------------|
| 15                | 10       | 0.06                       | 15       | 0.08                        |
| 17                | 10       | 0.08                       | 15       | 0.13                        |
| 20                | 10       | 0.13                       | 15       | 0.15                        |

Calculations have been also carried out in the absence of the Coriolis force. Figure 6 shows the change in the salinity gradient in calculations without Coriolis. The presence of the Coriolis force reduces the “variation $S$” and, consequently, increases the stability of the stratified reservoir to the mixing.

**Table 4.** Change of the salinity gradient depending on wind stress in a reservoir with real bathymetry of Lake Shira excluding Coriolis force.

| Wind stress (m/s) | Time (h) | Variation $\Delta S$ (PSU) | Time (h) | Variation $\Delta S$ (PSU) |
|-------------------|----------|----------------------------|----------|-----------------------------|
| 15                | 10       | 0.08                       | 15       | 0.1                         |
| 17                | 10       | 0.09                       | 15       | 0.12                        |
| 20                | 10       | 0.12                       | 15       | 0.16                        |

With prolonged exposure of strong winds, the Coriolis force is a deterrent to the rate of change in the salinity gradient.

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