Computer modeling of a non-stationary regime of distribution of the wastewater of Togliatti city in the coastal zone of the Bakhilovsky Island of the Middle Volga Integrated Biosphere Reserve (Saratov Reservoir, the Volga River, Russia)

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Abstract. The formation of the pollution zones in the coastal water area of the Bakhilovsky Island belonging to the Middle Volga Integrated Biosphere Reserve was examined under the influence of a large source of wastewater discharge from the Togliatti city taking into account different phases of the daily flow regime of the Saratov Reservoir (the Volga River, Russia). Numerical simulation methods were used to calculate the flow fields and the transfer of the wastewater lenses at various water flow rates at the Zhigulevsk hydroelectric complex. Three typical scenarios for regulating water discharge were calculated: at night, during the day, and during the regulating releases. According to model calculations, the maximum pollution zone is formed in the area of wastewater discharge and in the vicinity of the Bakhilovsky Island during long-lasting regulating releases in the summer-autumn low-water period. The maps of the sewage plume distribution were developed, and vulnerable zones were defined for subsequent environmental monitoring of the water quality in the water area surrounding the protected island.

1. Introduction
Ecological state of the island ecosystems of the water reservoirs is formed under anthropogenic changes in natural hydrochemical and hydrological regime. The large wastewater discharge from Togliatti city and backwater regulation are the main factors adversely affecting the ecosystem of the Bakhilovsky Island. The island itself and the wastewater source upstream are located in the water area adjoining to the tail bay of the Zhigulevsk hydroelectric complex in the Saratov Reservoir, where the velocity regime and current vectors vary within a day. In such highly unstable hydrodynamic conditions at different phases of the water content, the wastewater plume is characterized by spatially inhomogeneous structure; as a result, local areas of water pollution with increased content of various compounds are formed around this protected island. Meanwhile, the size of a particular polluted area in the tail bay of the reservoir depends not only on the pollutant volume discharged and its concentration in the wastewaters and on the spillway pattern, but also on the peculiarities of the water circulation affected by the unstable flow pattern.
Studies of the dynamics of such highly polluted areas and defining their boundaries are of high ecological importance; alongside with field observations, this requires using the mathematical simulation technique in order to track the distribution pattern of certain pollutants.

The study aims to model the formation of pollution areas in the coastal waters of protected island taking into account a variety of daily backwater patterns in the Saratov Reservoir.

2. Materials and Methods

The Bakhilovsky Island is located in the tail bay of the Zhigulevsk hydroelectric complex, opposite the Bakhilova Polyana settlement. In 1967, as a result of the filling of the Saratov Reservoir, the water level in tail bay has increased by 3 meters, so a part of the island was covered by water [1]. Later, as the wastewater treatment facilities have appeared in Togliatti city, the wastewater discharge was directed to the course of the reservoir. The source of the sewage waters was established at the site located 4-km upstream the island and in 500-m distance from the left bank of the reservoir close to the Fedorovka settlement (figure 1). The width of the reservoir in this section is approximately 1–3 km nowadays, the depth at its waterway is 14–17 m at the right bank and 4-6 m at the left bank at the site of wastewater discharge.

![Figure 1. Location of the wastewater source of Togliatti city.](image)

In order to evaluate the patterns of the pollutants' distribution in the tail bay of the Saratov Reservoir in accordance to the Zhigulevsk HPP release regime, 2-D mathematical model was developed based on the system of equations of hydrodynamics and convective-diffusion transfer of impurities [2-6].

The model of the Saratov Reservoir comprises 10,125 nodes of rectangular computational grid with 100–500-m intervals. Calculations were performed with 60-s time intervals.
The model was calibrated at certain sections of the reservoir in vicinity of the Togliatti wastewater discharge site close to Pecherskoe settlement. The model was verified by comparing the simulation results with field data obtained on board of the research vessel "Biolog" during a daily stay in the channel section of the Saratov Reservoir. The calculation error was 20%, which served as a sufficient basis for carrying out subsequent numerical experiments on the model.

3. Results and Discussion

Daily and weekly changes in water discharge at the inlet and outlet hydropower facilities of the Saratov Reservoir lead to significant fluctuations in the water level in the tail bay and small fluctuations in the area of the dam reach. At such level variations, long forward and backward waves are formed along the entire length of water reservoir that complicate the wastewater flow pattern [2, 7]. Calculations show that water level mark in the tail bay of the Zhigulevsk hydroelectric complex is lower on working days from 2 a.m. to 5 a.m. comparing to that in Pecherskoe settlement (figure 2). At such a distribution of water levels in the upper section of the reservoir (from Zhigulevsk city to Pecherskoe settlement), in some places, stagnant zones are formed both in shallow waters and in the channel part of the reservoir, as well as week reverse flows (0.01–0.05 m s⁻¹).

![Figure 2](image-url)

**Figure 2.** Calculated longitudinal profile of the water surface of the Saratov Reservoir (H – water level relative to "0" on the graph; L – distance from the Zhigulevsk HPP).

Pollution zones were calculated together with calculation of water level fluctuations and unstable flow regime in the reservoir. The initial data on the discharge and concentration of wastewater from the Togliatti wastewater source are represented in table 1. The conservative indicator of specific water conductivity (SWC) was used as a calculated characteristic of pollution. The SWC background value in the Saratov Reservoir was 370 µS cm⁻¹. Three extreme operating modes for incoming and outgoing hydroelectric units were selected for the calculations:

- water flow pattern in working days, daylight and evening;
- water flow pattern in working days, night time;
- minimal sanitary water releases from the Zhigulevsk hydroelectric complex.
During the working day, there are two distinct water flow patterns at the site of the Togliatti wastewater discharge site. In the daytime and evening hours, the water discharge had a maximal value and ranges 7,000–8,000 m³ s⁻¹. At night and in the morning, water flow may decrease down to 300 m³ s⁻¹ and below. As a result of such variations in the wastewater discharge area, non-uniform water current pattern is observed, which affects the nature of the distribution of impurities in the tail bay.

When the load of the hydroelectric complex decreases in the area of Bakhilovsky Island, and so the main channel flow is divided into two branches, two weak backward currents appear along the right bank towards the dam and along the left bank from the dam (figure 3). This circulation of currents changes the direction of the spread of the sewage plume. Within 3–4 hours, while low water rate is maintained at the hydroelectric complex, a zone of increased pollution (SCW 390–425 μS cm⁻¹) is formed near the source of wastewater discharge. Due to low flow velocities (0.05–0.1 m s⁻¹), the plume of impurities stretches downstream to a distance of 0.8–1.0 km in width and 3–4 km along the length of the channel. During the maximum daily runoff phase, the pollution zone from the source narrows significantly (figure 4), and the flow velocity increases up to 0.5–1 m s⁻¹.

Table 1. Characteristics of the wastewater source in Togliatti

| Source | Wastewater flow rate (m³ s⁻¹) | SCW a (μS cm⁻¹) | Depth (m) | Distance from the left bank (m) |
|--------|-----------------------------|-----------------|-----------|-------------------------------|
| 1      | 3.20                        | 828             |           |                               |
| 2      | 2.06                        | 1488            | 4–6       | 500                           |
| 3      | 0.65                        | 2621            |           |                               |
| Total source | 5.91                | 1255            |           |                               |

a Specific conductivity of water

As a result of such daily fluctuations in water discharge, the spread of pollutants in the Saratov Reservoir proceeds in portions, accumulating in the areas where wastewater is discharged at a low-water phase and moving downstream at a high-water phase.

Figure 3. Distribution of wastewater of Togliatti city downstream the Zhigulevsk hydroelectric complex at night (a — distribution of SCW in μS cm⁻¹, b — flow rate in cm s⁻¹).
Figure 4. Distribution of wastewater of Togliatti city downstream the Zhigulevsk hydroelectric complex during daytime and in the evening (a — distribution of SCW, μS cm$^{-1}$, b — flow rate, cm s$^{-1}$).

On weekends, especially during regulating releases, when the flow rate can decrease down to the sensitivity of the measuring devices, the wastewater distribution zone significantly increases in the area of the discharge source and around the Bakhilovsky Island. A weak unidirectional flow from the dam of Zhigulevsk hydroelectric complex carries a slick of impurity practically along the entire width of the channel. A model calculation of the formation of a pollution zone during regulating releases (Q=300 m$^3$ s$^{-1}$) at a 24-h duration is presented at figure 5.

Figure 5. Distribution of wastewater of Togliatti city downstream the Zhigulevsk hydroelectric complex during minimal sanitary water releases (a — distribution of SCW, μS cm$^{-1}$, b — flow rate, cm s$^{-1}$).

According to our calculations, during summer-autumn low-water period, the maximum pollution zone from the source of wastewater discharge in Togliatti is formed during long-term regulating releases and occupies the area of 5 km$^2$. At a daily mode of operation of hydroelectric facilities, the pollution area covers 0.5 km$^2$ during daytime and in the evening, and up to 1 km$^2$ at night.

4. Conclusion
As a result of the daily water releases from Zhigulevsk hydroelectric complex in the tail bay of the Saratov Reservoir, the hydrodynamic regime has a significant effect on the nature of the distribution and formation of pollution zones in the coastal water area of the protected Bakhilovsky Island. Model calculations were carried out for the modes of minimum and maximum water releases; in all cases, the
patterns of wastewater distribution were fundamentally different. During the low-water phase, there is an increase of the area of pollution zone at the discharge site and in the vicinity of the island; during the high-water phase, the wastewater is carried downstream from the source by a strong current.

Weak backwards currents arising along the right bank under conditions of daily flow regulation still do not significantly affect the drift of the wastewater plume from the Togliatti wastewater source towards hydroelectric complex, as previously expected. The pollution plume is always directed downstream along the left bank and spreads along the entire width of the reservoir channel until it is completely mixed only if the water release is low.

References
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