Transportation of wastewater over long distances in the central ecological zone of lake Baikal

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Abstract. Almost 150 thousand people live in the central ecological zone of Lake Baikal. However, there are no sewage treatment facilities that would meet the requirements for the discharge of treated effluents into Lake Baikal. The analysis has shown that there are no existing wastewater treatment technologies as applied to Lake Baikal. The work proposes to transfer treated wastewater to other watersheds. For these purposes, we have developed a methodology and methods for optimizing the parameters of pressure-gravity systems for the transportation of wastewater. For this, we have developed a general concept of wastewater disposal from the territory of the central ecological zone of Lake Baikal to other watersheds. We have given the examples and shown the economic efficiency of the proposed methods and programs.

1. Introduction

Lake Baikal is a unique creation of nature. It stores almost a quarter of the world's fresh water, which is the purest and clear. The state pays great attention to its protection and preservation. The Federal Law No. 94 “On the Protection of Lake Baikal”, Government Decree No. 643 “On Approval of the List of Activities” and others have been developed, approved and are functioning. The Central Ecological Zone of the Baikal Natural Territory (CEZ BNT) has been organized, which encircles Lake Baikal and stretches from southwest to northeast for 700 km. In 2017, the federal target program “Baikal is a Great Lake of a Great Country” was launched.

Within the boundaries of the CEZ BNT there are 183 settlements with a population of 150 thousand people. More than 2.5 million people visit Lake Baikal and live in 1000 tourist camps every year. Every day, 10 thousand m³ of untreated wastewater gets into the lake. There are sewage treatment facilities in five settlements, while the quality of wastewater treatment does not meet the requirements for the discharge of treated wastewater into Lake Baikal. These requirements are regulated by the Order of the Ministry of Natural Resources of Russia dated February 21, 2020 No. 83 “On the Approval of Standards for Maximum Permissible Impacts on the Unique System of Lake Baikal...”. This order was preceded by the Order of the Ministry of Natural Resources of the Russian Federation dated March 5, 2010 No. 63, which imposed special increased requirements on the treatment facilities, the achievement of which turned out to be impossible [1-5]. There was simply no such technology for reasonable means, the use of which would allow the construction of treatment facilities. Therefore, in the course of ten years, not a single treatment facility has appeared on Lake Baikal that would meet the requirements of the Order of the Ministry of Natural Resources of the Russian Federation No. 63. Under the pressure of the scientific community and local authorities, changes were made to the Order No. 63, which were reflected
in the Order No. 83 of the Ministry of Natural Resources of the Russian Federation. However, these changes still do not allow the use of existing technologies and actually prohibit the direct discharge of treated wastewater into Lake Baikal. Although more than 300 rivers flow into Lake Baikal, most of them have an estimated flow rate that is insufficient to dilute treated wastewater. In connection with the listed factors, it is necessary to develop a new technology for wastewater treatment, and to address the issues of organizing the discharge of treated wastewater into the water area of Lake Baikal. Another alternative is the transfer of treated wastewater to other watersheds, for which the requirements for water bodies correspond, for example, to fishery purposes.

However, when transferring wastewater to other watersheds, it is necessary to overcome hills and other natural and artificial barriers. To do this, it is necessary to arrange cascades of pumping stations, rapid flows and drops. In this case, substantiating the locations and parameters of such structures becomes an issue.

2. Methods
Gravity drainage systems according to SP 32.13330.2012 are designed, as a rule, in one line (clause 6.1.1), intended in long-term planning for the maximum possible flow rate and with the highest filling [6,7]. The slopes of the collectors are within in the following interval: K/d < I < 0.15, where d is the collector diameter in mm, K is the correction factor, takes on a value depending on the size of the collector diameter, for example, K = 1 at d < 300 mm, K = 3 at d > 1000 mm. The minimum flow rates of wastewater depend on the diameter of the collector and have a range: 0.7 - 1.5 m/s. The maximum velocities are limited, for example, for domestic and rainwater drainage systems, respectively - 8 and 10 m/s. At high flow rates, drops and rapid flows are arranged. The filling (the ratio of the depth of the drains to the value of the collector diameter) is in the range: 0.3 - 0.8. At 0.8 filling, the collector is considered to be operating at full cross-section. The subsequent diameter of the next section of the network downstream of the wastewater flow is considered not less than the previous one. The connection of the collectors is carried out at “soffit to soffit” level. At the initial stage of the development of sewerage networks, the flow rates are assumed to be the minimum permissible, and with the development of networks and the connection of new consumers, the filling and velocities grow. For example, a collector with a diameter of d 500 mm, with a slope of 0.019, can pass a maximum flow rate of 0.45 m³/s in a non-pressure mode (at 0.78 filling and 2.8 m/s velocity). The minimum flow rate will be 0.085 m³/s (at 0.3 filling and 1.84 m/s velocity). Therefore, the collector can operate in gravity mode in the flow rate range from 0.085 to 0.45 m³/s. If the wastewater flow rate is more than 0.45 m³/s and less than 0.085 m³/s, this collector will need to be reconstructed. The listed standards are the basis for choosing the optimal profile of a gravity drainage system.

Figure 1a shows one of the possible profiles for the transportation of wastewater, according to which the movement of wastewater occurs under the action of gravitational forces with a piezometric pressure $P_1$ in well 1. Then, as the wastewater moves to node 3, part of this pressure is spent to overcome the friction forces of the pipeline operating in gravity mode: $P_1 - P_3 = h_1 + h_2 = l_1 \cdot i_1 + l_2 \cdot i_2$, $l$ is the length of the pipeline, $i$ is the slope. Further, in node 3, the wastewater rises (with the help of a pumping station) to level $P_3$ and is transported through a pressure pipeline with a head loss $h_3$, in section 4, the wastewater flows in gravity mode, and in node 5, the pressure decreases (with the help of a junction well), then in section 5, the wastewater moves in gravity mode.

The piezometric head at the P1 node will be related to P6 by the following ratio:

$$P_1 = P_6 + h_6 + H_5 + h_4 - (H_3 + h_3) + h_2 + h_1.$$  

(1)

Well-defined diameters of pipelines and their slopes, parameters of pumping stations and pressure pipelines, estimated costs for the construction and operation of these structures will correspond to this piezometric surface. Of course, the option shown in Figure 1a is not the only one.
Figure 1. Possible piezometric surfaces of the drainage system.

For example, with the same restrictions on the construction of a drainage system, it is possible to arrange all five sections in a gravity mode (see Figure 1b). Although this option will require extensive earthwork, the operating costs will be minimal. By varying, for example, the slopes of the pipelines, the heads of pumping stations and the height of the junction wells, or rapid flows, it is possible to determine the optimal profile (in terms of the criterion of reduced costs or life cycle costs) and select the best parameters of the drainage system structures, taking into account their reliability and seismic resistance.

The search for the optimal piezometric surface of drainage systems (1) is proposed to be organized as a multi-step process to control and build up conditionally optimal solutions according to the dynamic programming scheme [9-12]. The life cycle costs of the system are proposed as an optimization criterion [8]. Figure 2 illustrates such a computational process and shows the optimal territory in pink. Figure 3 shows the optimal profile and composition of transport structures.
The process of building up conditionally optimal solutions is carried out starting from the pendant vertices - consumers in the direction of the wastewater flow. At the root (last) vertex, of all locally optimal solutions, the best one is selected and the backward move restores the optimal trajectory and parameters of the system. In this case, the area of admissible solutions is formed in the range of freezing depth “plus” 0.5 m and the maximum depth of occurrence (for example, 8 m). This interval for each computational node is divided into a number of subintervals and the computational process is organized as follows. From the upper subintervals of the initial node of the rated section, a transition is made to all possible subintervals of the final node of the rated section by installing gravity collectors. For each transition, the slope is calculated, on the basis of which, for a given filling (0.7), the diameter of the collector is selected and its cost is determined, including the cost of earthwork. If the designer has chosen the diameter of the collector, then its filling is to be determined. If this filling is in the range of 0.3 - 0.7 and the design velocity corresponds to the non-silting one, it is considered that the transition to the final node (state) of the considered subinterval of the rated section has been made. After considering in this way all possible transitions by a gravity collector from the initial subintervals to the final ones, the arrangement of pressure pipelines and pumping stations is attempted according to the scheme described.
in [14]. Then the transition to the next section is carried out. The final states of the previous section are taken as initial for the next section and all calculations are repeated. For example, for a flow rate of 0.5 m$^3$/s, for a section 1 km long, the possible parameters of a pipeline with a diameter of 0.7 m are presented in Table 1.

Table 1. Collector parameters with increasing slope.

| Slope, m (d) | Diameter, m (d) | Velocity, m/s | Normal depth, m | Filling, h/d | Critical depth, m | Critical slope | Nominal diameter |
|--------------|----------------|---------------|-----------------|-------------|------------------|----------------|-----------------|
| 1            | 0.005          | 0.7           | 1.75            | 0.53        | 0.7              | 0.46           | 0.006           | 0.66            |
| 2            | 0.01           | 0.7           | 2.23            | 0.46        | 0.66             | 0.48           | 0.006           | 0.58            |
| 3            | 0.015          | 0.7           | 2.60            | 0.43        | 0.62             | 0.48           | 0.006           | 0.53            |
| 4            | 0.02           | 0.7           | 2.9             | 0.41        | 0.59             | 0.47           | 0.0164          | 0.51            |
| 5            | 0.025          | 0.7           | 3.16            | 0.39        | 0.56             | 0.46           | 0.021           | 0.49            |
| 6            | 0.03           | 0.7           | 3.38            | 0.37        | 0.53             | 0.45           | 0.0252          | 0.47            |
| 7            | 0.1            | 0.7           | 5.13            | 0.3         | 0.43             | 0.37           | 0.092           | 0.37            |

According to Table 1, in all cases there will be a steady uneven flow of wastewater with the formation of backwater and recession curves at the end of the section [13].

Let us show the effectiveness of this method using the example of substantiating the route of a prospective drainage scheme for the city of Irkutsk and the Irkutsk Municipality. According to the prospective plan for the development of the water supply and sewerage system (up to 2025), it is planned to drain wastewater from the village of Listvyanka located on the shore of Lake Baikal to the right-bank WWTPs in Irkutsk. The scheme provides for the arrangement of wastewater disposal from settlements located along the Baikalsky highway, starting from the area of Listvyanka (at elevation 456.10m BS), to Novaya-Lisikha, then to Pivovarikha, Dzerzhinsk, to WWPS-20a in Irkutsk. The drainage system is supposed to be made with pressure and non-pressure collectors, pumping stations with receiving tanks. Pressure pipelines will be laid in two lines. The length of the entire main collector “Listvyanka - Novaya Lisikha - WWPS-20a” is 78 km. [15]. According to the optimal variant, the collector will run along the Baikalsky highway, with 8 WWPSs with pressure pipelines arranged in two lines 31 km long and with gravity collectors 41 km long. The schematic diagram and optimal profile are shown in Figure 4.
Figure 4. Optimal profile of the main collector from Lake Baikal (the village of Listvyanka) to the WWTP in Irkutsk.

Based on the developed concept of wastewater disposal at Lake Baikal [3,5], it is proposed to build a centralized WWTP in the Slyudyanka Municipality in the village of Kultuk for the population of the entire municipality. It is proposed to transport wastewater from the town of Slyudyanka to the WWTP in a pressure pipeline 4.5 km long in two lines with a diameter of 315 mm each. After the wastewater treatment at the centralized WWTP of the Kultuk village, it is proposed to transport it to the Bystraya River, a watershed other than Lake Baikal, at a distance of 16.1 km by two pressure pipelines with a diameter of 315 mm each. In Figure 5, the pipeline route is shown with blue lines, and the road traffic routes are shown with red lines. Figure 6 shows the optimal profile and composition of the structures of the pressure pipeline route.
Figure 5. Logistic scheme for collection, treatment and transportation of wastewater to the Bystraya River watershed.

Figure 6. Pressure sewerage profile from the town of Slyudyanka to the Bystraya River with the arrangement of four WWPS.

3. Conclusion and Discussion
In this work, based on the multistep optimization methodology, we have developed an approach to substantiate the parameters and composition of structures for transporting wastewater over long distances. This approach and its software implementation in the form of software package Трасе-ВК [16] made it possible to develop options for the discharge of wastewater from populated areas of the central ecological zone of Lake Baikal to other rivers and watersheds. These options were the basis for the concept of wastewater disposal at Lake Baikal [3, 17-20], which is currently accepted for implementation.

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