Optimization of the sewerage systems scheme of cities and populated areas

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Abstract. Lake Baikal is a UNESCO World Heritage Site. This unique lake is by nature, by the purity and depth of the waters, by the diversity of the lake fauna and flora. The rules for the use of the Baikal waters, its territory, and the forest fund are strictly regulated by the Federal Law "On the Protection of Lake Baikal". This law restricts economic activity within 200 km of the guard zone. In a difficult situation there are settlements located on the shore of the lake, especially those found in the territory of national parks and reserves. However, the prohibitive measures are not able to stop the development of tourism, which is increasing every year. Only "Small" Sea and Olkhon Island are visited annually by over half a million visitors from different countries. The most attractive zone for the development of tourism and recreation is the middle zone of Baikal, the territory of which falls within the boundaries of the National Park. Many tourist centers arise spontaneously and do not correspond to modern technologies of their organization and the requirements of the protection of Baikal. Practically, nowhere there are no treatment facilities. Only cesspools are used, from which drains drain into the ground and enter Baikal. Therefore, the issues of water disposal for this area are relevant. The paper proposes a new method for substantiating options for centralization of wastewater treatment, including optimization of the technology for transporting effluents to sewage treatment plants. With the help of this technique, the system of wastewater disposal from the territory of Olkhon Island and the coast of the "Small Sea" has been justified.

1. Introduction

Lake Baikal is a UNESCO World Heritage Site. This unique lake is by nature, by the purity and depth of the waters, by the diversity of the lake fauna and flora. The rules for the use of the Baikal waters, its territory, and the forest fund are strictly regulated by the Federal Law "On the Protection of Lake Baikal". This law restricts economic activity within 200 km of the guard zone. In a difficult situation there are settlements located on the shore of the lake, especially those found in the territory of national parks and reserves. However, the prohibitive measures are not able to stop the development of tourism, which is increasing every year. Only "Small" Sea and Olkhon Island are visited annually by over half a million visitors from different countries. The most attractive zone for the development of tourism and recreation is
the middle zone of. The Baikal, the territory of which falls within the boundaries of the National Park. These are settlements: Khuzhir on the island of Olkhon (population 1,750 people), Chernorud, Sarma, Kurma (population 859 people) and 50 tourist centers, of which 25 on Olkhon (see fig.1). Many tourist centers arise spontaneously and do not correspond to modern technologies of their organization and the requirements of the protection of Baikal. Practically nowhere there are no treatment facilities. Only cesspools are used, from which drains drain into the ground and enter Baikal. Therefore, the issues of water disposal for this area are relevant.

![Figure 1. The main tourist bases on the small sea and Olkhon Island.](image)

2. Methods

The options for sewerage schemes can be as follows:

1. Each tourist base and localities can have local treatment facilities for deep purification of sewage (up to the required standards for discharge to Baikal Lake). Purified water will be discharged through the ground or directly into Baikal. Partially purified water can be reused for flushing toilet bowls, watering plantations and cleaning the premises.

2. Sewage that enter the cesspools can be transported by road to central sewage treatment facilities. There can be three such structures: One on island of Olkhon, the second is near the village of MRS and the third is near the village of Sarma.

3. From the camp site to these three wastewater treatment plants, effluents can be transported by pressure-gravity pipelines.

4. For these three treatment facilities, effluents can be delivered by specialized barges, i.e. by water transport.

5. Centralized drainage systems with a single wastewater treatment plant can be organized with the subsequent discharge of treated runoff to another watershed other than Baikal Lake.

6. Centralized drainage systems with one wastewater treatment plant with subsequent discharge of treated runoff to evaporation ponds.
There may be other variants representing a combination of the above.

3. Results and discussion

Option 1. The option of installing local wastewater treatment plants with subsequent discharge of sewage into Lake Baikal. Legislation prohibits all economic activity on Olkhon, including the discharge of treated sewage into Baikal, even if they have the same properties as Baikal water. However, four Alfa Bio-5 deep biochemical treatment stations have already been installed in the cordons of the forest districts of the National Park in the village of Khuzhir, Buguldeika, Bolshoy Goloustnoye and Listvyanka. The capacity of the station is 1 m³/day. Expenses for the construction of each station amounted to 1.250 million rubles. Only on Olkhon in the village of Khuzhir live 1750 people plus tourists. Now on Olkhon operates 25 tourist bases with a maximum load of 500 people each. Consequently, already the estimated number of people is: 13 850 people. The same number of people are resting at the tourist centers of the Small Sea. At a rate of 200 liters of sewage per person/day, the total amount of them is 5540 m³ per day. In the case of local treatment facilities of the firm "Alta Bio-5", the costs will be 6925.0 million rubles. The operating costs and costs of the reagents are estimated at 5% of the investment. In Figure 2, this variant is indicated by dot-dash lines and circles.

Figure 2. Option of local treatment facilities.

Option 2. Local treatment facilities are installed, after which 40% of the treated effluent goes into circulation for flushing the toilet bowls, and 60% enter vacuum-evaporators. It will be required for the evaporation of effluents 3334 m³/day, electricity in 92 MW. Question: Where to get this electricity. Accordingly, the cost of electricity will be 36.5 million rubles per year. For natural evaporation, ponds with a large area are needed. If such ponds are evaporation, then this option can be realized. The cost of vacuum evaporators is comparable with the facilities for treating wastewater "Alta Bio-5". The final costs, including vacuum evaporation, are 8536 million rubles.

Variant 3. It presupposes the removal of sewage from cesspools of tourist camps and their transportation by road to decentralized treatment facilities (see Fig. 3), the minimum number of which can
be three: First on the island of Olkhon, the second is near the village of MRS and the third is near the village of Sarma.

The productivity and cost of treatment facilities of the firm "Alta Bio" will be as follows: Olkhon - 2770 m³/day - 277 million rubles; in Sarma - 1385 m³/day - 138.5 million rubles and in the MRS - 1375 m³/day - 138.5 million rubles. The total cost of 554 million rubles. Annual operating costs are 5% of capital investment. When transporting by road, construction of roads with asphalt pavements will be required: on Olkhon - 52 km, on the small sea - 36 km; in the region of MRS - 14 km. The cost of 1 km of the road is 70 million rubles. The total cost will be 7140 million rubles.

It will take 30 cars with a capacity of 30 m³, each worth 5 million rubles. The total cost will be 900 million rubles. Annual costs associated with the transportation of sewage, per 1 m³ 123.5 rubles, will amount to 250 million rubles. Therefore, for the second variant, will be required 8646 million for one-time investments and 324 million rubles for annual operating costs. The variant is shown in figure 3.

![Figure 3](image_url)

**Figure 3.** The option of centralization of wastewater treatment.

Variant 4. It presupposes the transportation of drains from tourist camps to three decentralized treatment facilities by pipeline transport. It will be necessary to lay pressure pipelines in 2 strings: 2d300, l = 30 km; 2d200, l = 24 km; 2d150, l = 7 km. The total cost is 300 million rubles. In addition, it will be necessary to install six pumping stations for pumping sewage with a total cost of 18.6 million rubles. Taking into account the three STP investments will be as follows: 872.6 million rubles; annual operating costs amount to 36 million rubles. The variant is shown in figure 3.

Variant 5. It presupposes the transportation of sewage from tourist camps to three decentralized treatment facilities by water transport, specially equipped barges (see Fig. 4). It will be necessary to purchase 2 self-propelled barges of Project 292 with a displacement of 4,865 tons with the cost of each 500 million rubles. Transportation costs amount to 65 rubles for 1 ton, or 130 million rubles in year. Consequently, one-time costs amount to 1672 million rubles. Annual operating costs - 143 million rubles.
Figure 4. Variant of water transport of sewage.

Option 6. The installation of a centralized sewerage system with one sewage treatment plant and discharging the sewage into the watershed of the Lena River (see Figure 5). Another watershed is the district center of the village of Bayandai, located from Olkhon at a distance of 123 km (see Figure 6). The federal road has asphalt surface.

Figure 5. Centralized sewerage systems with one sewage treatment plant.
Figure 6. Transportation of sewage to the watershed of the Lena River.

In this case it is advisable to organize treatment facilities in the "Tazheranskaya steppe". The cost of treatment facilities for a capacity of 5540 m³ per day will be 310 million rubles. Before the treatment facilities, according to option 3, the delivery of effluents is expedient to be carried out by pipeline transport, with the installation of six pumping stations providing a rise of effluents from an elevation of 456 m to an elevation of 650-700 m. The length of pipelines with a diameter of 300 mm in two strings will be 112 km, costing 672 million rubles and six pumping stations for pumping waste 82 million rubles. It will be necessary to lay a 3 km long tube along the bottom of the Baikal. (the Olkhon Gates area). The cost of the tube is 36 million rubles. Sewage, after cleaning, can be dumped into lakes. As the lakes are filled, the settled waters can be transported to the district of Bayandai village. Enough two cars, 10 million worth and 5 million rubles for annual operating costs. Under option 5, one-time costs amount to 1354 million rubles. Annual operating costs - 32 million rubles.

Option 7. Organization of a centralized system for collection and transportation of sewage by pipeline to a sewage treatment plant located in the "Tazheranskaya steppe" with the subsequent discharge of treated effluent to evaporation ponds. This option for the cost will be close to option 5 and will be 1315 million rubles and 27 million rubles for operational costs.

In Table 1, from the calculation of the pay-back period at 6 years, the listed costs for each of the options.

Table 1. Comparison of the options of the sewage system on the island Olkhon and the Small Sea of Baikal/

| № Variant | One-time investment, million ruble. | Annual operating costs, million ruble. | The resulted expenses, million ruble. |
|-----------|------------------------------------|----------------------------------------|--------------------------------------|
| 1         | 6925.00                            | 364.00                                 | 1518.17                              |
| 2         | 8536.00                            | 36.50                                  | 1459.17                              |
| 3         | 8646.00                            | 324.00                                 | 1765.00                              |
| 4         | 872.60                             | 36.00                                  | 181.43                               |
| 5         | 1672.00                            | 143.00                                 | 421.67                               |
| 6         | 1354.00                            | 32.00                                  | 257.67                               |
| 7         | 1315.00                            | 27.00                                  | 246.17                               |
It can be seen from Table 1 that option 4 with pipeline transport of effluents to three treatment facilities located on the island of Olkhon, near the village of Sarma and near the village of the MRS, is economical. If, for environmental reasons, this option does not work, option 7 will be economical. However, as already noted above, other variants are possible, representing a combination of these 7 variants. Obviously, it is difficult to analyze and value other options on economic and environmental criteria.

At the same time, an effective approach is a technique based on the preliminary construction of redundant design schemes for sewerage systems and the solution of optimization structural and parametric problems on them. Redundant scheme can be formed by imposing in advance the designers worked out alternative options for laying reservoirs, reconstruction and development of sewerage systems. For example, the designers outlined two options for tracing the sewerage system, which are presented in Figure 7a, b. These two options can be replaced by one graph, shown in Figure 7c, in which there will already be 8 options for tracing the sewerage system.

![Figure 7](image)

**Figure 7.** Formation of redundant and transport network for searching for the optimal option of the structure and parameters of the sewerage system.

When constructing redundant schemes, deliberately non-optimal solutions can be avoided and it is possible to generate a set of permissible variants of the structure and parameters of the sewerage systems that differ from each other by the given costs. In the same way, it is possible to designate in advance in any given areas possible ways of their reconstruction (parallel laying, re-laying, laying of a new collector, arrangement of pumping stations, etc.). To find the best option, it is suggested to go from the redundant scheme to the transport network (see Figure 7d). When constructing a transport network, all nodes—wastewater collection point are closed to a common node—stream inputs, and all nodes—discharges of sewage, or possible sewage treatment plants (for example, STP 1 and STP 2 in Figure 7c), are closed to a common flow outlet node from transport network (see Figure 7d).

The carrying capacity of the branches of the transport network, which simulate the operation of existing sewers, is subject to bilateral restrictions. The first lower limit is assigned from the condition of unencumbered speeds, and the second upper limit is assigned based on the inadmissibility of gravity sewers in the pressure regime. The cost of a unit of flow is determined on the basis of enlarged norms of cost data on investment and operating costs. From a mathematical point of view, the problem is formulated as follows:

\[ \sum_{i=1}^{n} C_i \cdot K_{i,\text{min}} \cdot x_i \rightarrow \text{min}, \]  
\[ A \cdot x = q_{\text{tr}}^*, \]  
\[ g_1 \leq x_i \leq g_2, \]  
\[ a_i \geq 0. \]
where $C_i$ is the value of the flow, $x_i$ is the required flow on the branch of the redundant or transport network, $A$ - the matrix of contiguity of the nodes and sections of the transport network, $q_{ip}$ - the vector of average seconds of flow to the sewerage system, $q_{ii}$ - lower and upper flow restrictions, $K_{ общ}$ - overall maximum coefficient of uneven sewage movement through pipelines and sewers. The upper limit on the flows of fictitious branches corresponds to the calculated values of the discharge of effluents from the wastewater collection points and the productivity of STP. For new sections of the network, no flow restrictions are imposed.

If the amount of allocated investments in the construction of new and reconstruction of existing networks and structures is known, then the following restriction is added:

$$
\sum_{i=1}^{n} C_i \cdot K_{ общ} \cdot x_i \leq \mathcal{C}
$$

Where $C_i$ - allocated investments for the construction and reconstruction of the sewerage system. When solving problem (1) - (4), an algorithm is used to find the maximum flow of the minimum cost [1]. As a result, the allocated investments are optimally distributed in the construction of new and reconstruction of existing sewerage facilities. At the same time, the number of new consumer and their loads are determined, from which it is possible to build a sewerage system and divert wastewater from the allocated investments. As a result of the optimization, the route and parameters of the new sections of the network are determined, the options for reconstructing the existing sewers (open-method, or non-canal, or laying a parallel pipeline), the location and productivity of the treatment facilities (see Fig. 7e).

Using the above technique, we will superimpose all the seven options considered and get the redundant scheme shown in Figure 8. Based on the redundant scheme, a transport network is constructed in the form of a graph, shown in Fig. 9. As a result of the solution of the problem (1) - (3), i.e. finding the maximum flow of the minimum cost, the optimal variant shown in Figure 10 was obtained. This option is practically consistent with option 7 with the evaporation pond device.

![Figure 8](image_url)

**Figure 8.** The redundant scheme of the sewerage system from the territory of the "Small Sea" and Olkhon Island.
4. Conclusions

A new method for substantiating options for the centralization of wastewater treatment is proposed, including optimization of the technology for transporting effluents to treatment facilities. This technique allows solving complex problems of designing new ones, reconstruction and development of existing sewerage systems.
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