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Optimizing the Structure and Parameters of Local Wastewater Disposal System Based on Flow Models

Victor Chupin[1], *Maria* Moroz[1,*], *Roman* Chupin[1], *Victor* Bober[1], and *Agegnehu K. Yoshe*[2]

[1]Irkutsk National Research Technical University, 664074, Lermontov St. 83, Irkutsk, Russia
[2]Arba Minch University, Arba Minch, Ethiopia

Abstract. The paper investigates the issues of transporting wastewater from small settlements to centralized sewage treatment facilities, taking into account the use of various modes of transport. For each mode of transport we determined the dependences of life cycle costs on the amount of wastewater flow and its transportation over different distances. Taking into account these dependences we obtained the ranges for the use of road and pipeline transport and developed methods for optimizing the structure and parameters of local wastewater disposal systems.

Introduction

Local wastewater disposal systems (LWDS) are designed to collect wastewater from small settlements and transport it to centralized treatment facilities, where this wastewater is treated to the required standards.

This poses the problem of choosing the location of treatment facilities, the method and ways of wastewater transportation. The most common modes of wastewater transportation are pipeline and road transport. At the same time the scope of road wastewater transport has not been studied and it needs to be justified depending on the range and volume of transported wastewater.

The most effective criterion for determining the scope of using road and pipeline transport is the life cycle cost (LCC), which allows you to consider both the one-time costs and operating costs for the period of operation of the system. Studies on the organization and optimization of local wastewater disposal systems based on the LCC criterion have not been carried out before. There are no methods for justifying the structure and parameters of local wastewater disposal systems. Therefore, the issues of feasibility study and solution of optimization and logistical tasks of organizing local wastewater disposal systems, increasing their reliability and environmental safety are relevant.

Issue

The existing methods and technologies of justifying the scheme and structure of local wastewater disposal systems do not take into account modern capabilities of computer technology and numerical simulation, the principles of investing in construction,

* Corresponding author: morozmariyav@gmail.com

reconstruction and development of wastewater transportation systems. Issues of justifying the route and structure of transportation, treatment and disposal of wastewater are insufficiently elaborated.

Defining the problem of improving the structure and parameters of LWDSs based on pipeline and automobile transportation of wastewater

We need to develop a new complex methodology of optimizing the parameters of LWDSs, allowing us to determine the types of transportation by pipeline and road, the location and parameters of wastewater treatment facilities, the routes between these facilities, including existing wastewater disposal facilities and proposals for their reconstruction. At the same time it is necessary to conduct research and develop functions of life cycle costs of LWDS facilities, including the dependence of one-time investments and operating costs on the length of routes and volumes of transported wastewater, to determine the scope for using pipeline and road transport in local wastewater disposal systems for areas with different seismic activity, with different cost of electricity and taking into account the use of different fuels.

As a result of this research it has been shown that the justification of design options for wastewater disposal systems should be based on their life cycle costs. The LCC of facilities and structures of local wastewater disposal systems can be represented as:

$$\mathrm{LCC} = R_1^0 \cdot T_1^0 \cdot \sum_{i=1}^{n} K_i^s \cdot KP_i^s + R_2^0 \cdot T_2^0 \cdot \sum_{i=1}^{n} (C_i^{op} + C_i^{em}), \quad (1)$$

$$\text{where } R_1^0 = \sum_{t=t_1}^{T} \left(\frac{1}{(1+r)^t}\right), R_2^0 = \sum_{t=t_2}^{T} \left(\frac{1}{(1+r)^t}\right) \quad (2)$$

R_1^0, R_2^0 are coefficients of discounting of capital investments and operating costs (the discount coefficient for 50 years is 0.141); T_1^0 is the service life of the main fund of water supply and sewage systems; n is the number of estimated sections of a wastewater disposal system (*i=1,...,n*); K_i^s are capital investments equal to one-time costs for each network section; KP_i^y is the capital investment multiplier (equal to the ratio between the estimated system service life and the service life of a specific system element, whose life is less than estimated); T_2^0 is the time interval in years, for which the operating costs are determined; C_i^{op} are the current annual operating costs for the network section i; C_i^{em} are the costs for the elimination of emergencies; r is the discount rate - the value of the refinancing rate of the Central Bank of the Russian Federation.

The paper studies and assesses the life cycle of wastewater disposal facilities in the Irkutsk Municipality, for which capital investments are taken on the basis of NCS-81-02-14-2020 and NCS-81-02-19-2020 (norms of construction prices). The annual operating costs C_i^{op} (thous. RUB/year) were calculated based on the Recommendations on Rationing the Number of Employees in Water Supply and Sewage Services dated June 15, 2020, # 316/pr and in accordance with the order of the Russian Ministry of Construction, Housing and Utilities dated March 23, 2020, # 154/pr On Approval of the Standard Industrial Norms for the Number of Employees in the Water Supply and Sewerage Sector.

Taking into account (1) and (2) the paper proposes a methodology for determining the scope of using vehicles for transportation of wastewater to LWDSs. Whereby:

- For each section of the network (*i*) based on capital investments (K_i^s) and operating costs (C_i^{op}), life cycle costs (1), (2) are calculated depending on the flow rate of transported wastewater (x_i) separately for pressure pipelines (including pumping stations) and unpressurized collectors;
- Based on capital investments and operating costs the life cycle costs for road transport depending on the volume and distance of transported wastewater are determined;

- Based on the obtained dependences the areas of using this or that mode of transport are determined by analytical or graphical methods (see Figure 1).

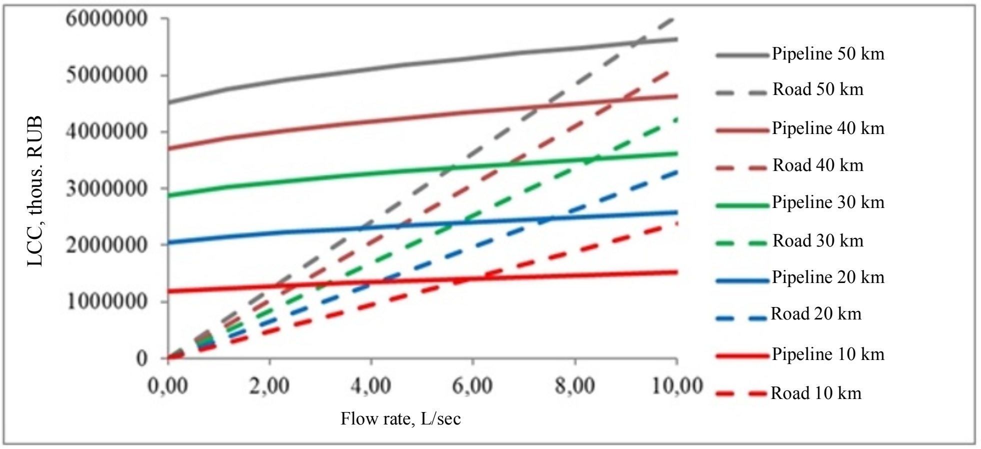

Fig. 1. Joint functions of the LCC of wastewater transportation.

Such ranges of using road transport are not difficult to obtain for different climatic and economic conditions, terrain and other features of the regions of the country. For example, for the Magadan Region, where the cost of electricity is 5.41 rubles/kW, the range of using road transport increases compared to the Irkutsk Region from 9.2 to 13.2 L/sec. For seismic areas the limits of using road transport are expanded by 25-30% due to the higher cost of measures to improve the reliability of the pipeline system. Transition to electric vehicles makes road transport environmentally friendly. Transition to autopilot vehicles significantly increases the scope of using road transport by reducing operating costs.

The obtained ranges of the use of road transport in the transportation of wastewater to LWDSs have an independent value and can be applied in the design of reconstruction and development of LWDSs. In our work, these ranges are the basis for developing new methods of optimization and conservation of LWDS wastewater disposal facilities, based on the preliminary construction of redundant design schemes. The paper shows that the redundant design scheme can be represented in the form of a graph where the edges model the possible pipeline and road sections of the network, the vertices of the graph model the possible locations of treatment facilities and discharges of treated water into ponds (storage tanks, evaporators) or directly into water bodies. Consumers are modeled by the vertices of the graph in which the flow enters (wastewater discharge to the sewerage system). The redundant scheme is formed by assigning or superimposing alternative options for the development of LWDSs. For example, at the design stage of the reconstruction and development of LWDSs, taking into account the possible housing, surveys, topography, etc., two options of wastewater disposal system routing were outlined, which are shown in Figure 2a and 2b. These two options can be replaced by a single graph, shown in Figure 2c, for which we can already count 8 options of wastewater disposal system routing.

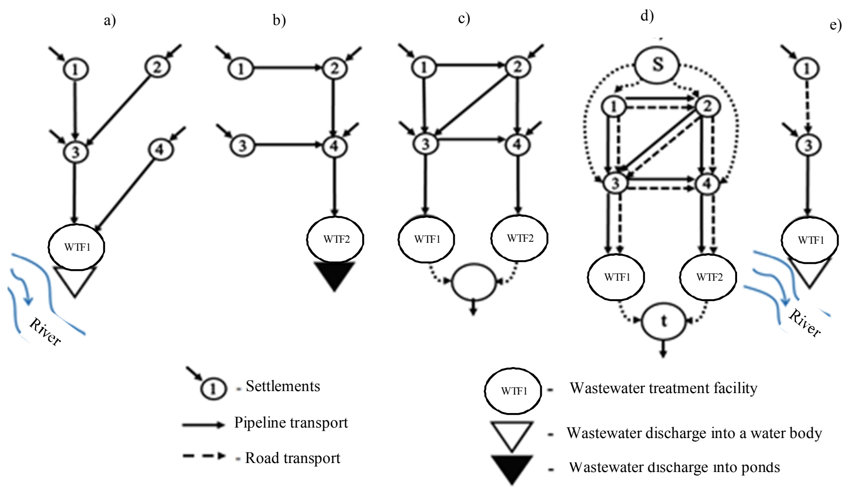

Fig. 2. Redundant and transport schemes of LWDS.

The optimization problem will consist only in finding in the redundant graph a subgraph corresponding to the minimum of function (1).

In this paper, we first developed an algorithm for transforming the redundant LWDS graph into a "transport network" as an intermediate graph necessary for solving the problem, and representing a wastewater disposal network with one inflow vertice and one outflow vertice of wastewater flows [1-10]. Figure 2d shows such a network, in which the nodes of wastewater discharge from the consumers are closed to the node of inflows S by arcs. These arcs are imposed with upper limits equal to the required estimated or actual volumes of wastewater from the consumers. Nodes, which model possible WTFs, are closed by arcs to the node of outflows t. These arcs are imposed with upper limits equal to the possible capacity of the WTF. The arcs are assigned weights equal to the specific costs of the WTF (per 1 m3 /s of capacity). The graph edges that model pipeline transport (solid lines in Figure 2d) and the graph edges that model road transport (dashed lines in Figure 2d) are assigned with the corresponding unit flow values. The upper flow limits corresponding to the intersection points of Figure 1 are assigned for road transport. Given the pipeline transport network thus constructed, the linear programming problem of the following form is solved:

$$\sum_{i=1}^{n} (Bi + C_i \cdot x_i) \rightarrow min, \text{ with } \underline{\underline{b}}_i \le x_i \le \overline{\overline{b}}_i,\ A \cdot x = q'_{av} \quad (3)$$

where: Bi, Ci are coefficients of linear approximation of life cycle costs (1)-(2) is the cost of a flow unit for road and pipeline transport; A is the matrix of adjacency of nodes and sections of the transport network; q'_{av} is the vector of estimated flow volumes at consumers, L/sec; $\underline{\underline{b}}_i$, $\overline{\overline{b}}_i$ are limits on flows.

As a result of working with this method, we obtained the optimal structure and parameters of LWDS in terms of life cycle costs, as shown in Fig. 2e. The proposed methodology is implemented in the software package [11], on the basis of which the concept of wastewater disposal in the central ecological zone of Lake Baikal was developed [7].

Conclusion

1. The scope of using road transport of wastewater depending on the range and volume of transported wastewater, the cost of electricity and the seismicity of the areas of construction has been defined.

2. Methodology for the formation of design schemes and new methods of optimizing local wastewater disposal systems based on life cycle cost minimization have been developed. The methods make it possible to comprehensively justify the structure of facilities and the route from the pipeline and road sections of the LWDS.

3. Methodology for justifying the structure of local wastewater disposal systems developed and decommissioned in stages has been developed. Economic efficiency of combined wastewater disposal systems in these cases is 45%.

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