The field of application of road transport in the delivery of drinking water and wastewater disposal

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Abstract. Due to the uneven distribution of water resources across the territory of Russia, many settlements and even cities do not have their own sources of water supply and reservoirs, where treated wastewater could be discharged. Group and regional water supply and sanitation systems are being designed, built and developed to solve this problem. The length of such systems is hundreds and even thousands of kilometers. The construction and operation of such structures requires significant annual financial investments. Therefore, the choice of routes, the composition of structures, and especially the methods of transporting water and wastewater, justifying the location of water intakes and treatment facilities are relevant and require special attention and a feasibility study of design options. Based on the method of redundant design schemes, the paper proposes an integrated approach to optimize structures and methods of supplying water to consumers, transporting wastewater to treatment facilities by pipeline and road transport.

1. Introduction
With an abundance of water resources in the Russian Federation, most small settlements, cities and villages do not have centralized water supply systems, and even more so, drainage and wastewater treatment systems. Although the state allocates a sufficient amount of funds annually to solve these problems. For more than a dozen years now, the Federal Target Programs “Clean Water”, “Water of Russia”, “Provision of the Russian Population with Drinking Water”, etc. have been developed and implemented. However, this problem has not yet been resolved. There are many reasons for this, including insufficient funding, the lack of a unified state policy in this area, poor methodological, scientific and technical support, etc. At the same time, one of the most important and unsolved problems is the rational distribution of allocated funds for the reconstruction and renovation of existing water supply and sanitation systems and the construction of new ones. As the practice of designing engineering systems for various technological purposes has shown, the greatest economic effect is achieved when solving circuit-structural and circuit-parametric optimization problems. With regard to water supply systems, these tasks include:

Substantiating the location of water supply sources, the composition and parameters of water intake structures (surface, underground, combined)
Substantiating the location of water treatment facilities, the degree of purification, technology and composition of facilities
Optimizing the route and parameters of pipelines, locations, heads and capacity of pumping stations
Substantiating the type of water transportation to consumers (pipeline, road, rail, water transport)
Substantiating the degree of thermal insulation of pipelines and their depth in the ground, as well as in the form of an alternative option for heating water and wastewater (for the regions of the far north and permafrost)

For drainage systems:
Substantiating the location, performance and composition of sewage treatment facilities, including places where treated wastewater is discharged into natural and artificial reservoirs
Optimizing the route and parameters of pressure pipelines, slopes of gravity collectors, locations, heads and capacity of pumping stations, parameters of connecting structures
Substantiating the type of transportation of source and treated waste water from consumers (pipeline, road, rail, water transport) to treatment facilities
Complex optimization of water supply and sewerage systems, including all the tasks listed

The task of choosing the type of transportation of drinking water, source and treated wastewater deserves special attention. The expediency of a particular type of transport depends on many factors and a specific situation. It should be noted that road transport is already being used to provide water and remove wastewater from individual consumers from detached houses that are not connected to centralized water supply and sanitation systems. For centralized water supply and sewerage systems in cities and large populated areas, pipeline transport is undoubtedly the most successful and economical option. Water transport is often used to collect and deliver sub-shale waters from ships and motor vessels, domestic wastewater from protected areas to the treatment facilities. Special tanks are used for areas where there are no roads, but there is railway transport. Air transport is sometimes used for firefighting and transportation of bottled water. In general, the type of transport is chosen on an intuitive basis without any feasibility studies. At the same time, the question arises: at what capacity and need for water and wastewater disposal is it economically profitable to use a certain type of transport and what will be the distances? Such dependences can be obtained based on processing the cost indicators of the corresponding types of transport.

2. Methods
The generally accepted criterion for optimization and comparison of options is the reduced (to one year) costs for the construction and operation of a hot water supply system, which are determined as follows:

$$C_{\text{red}} = K \cdot E + O_c,$$

where $C_{\text{red}}$ is reduced costs, thousand rubles/year; $K$ is capital investment in the network, thousand rubles; $E$ is the coefficient of efficiency of capital investments, which in a market economy is identified with bank interest; $O_c$ is annual operating costs (thousand rubles/year) calculated based on recommendations for the regulation of labor of workers in the water supply and sewerage sector (Order of the State Construction Committee of the Russian Federation of June 15, 2020 No. 316/pr) and are determined according to [2,3,4]. The most effective optimization criterion is the life cycle costs [3], which, taking into account the system life cycle ($T$, in years), can be obtained by transforming (1)

$$\text{LCC} = K \cdot \frac{T}{t_p} + T \cdot (O_c),$$

where $t_p$ is the amortization life of the system. For example, with a life cycle of 50 years and a service life of a car of 8 years, it will have to be updated 6.26 times. The same applies to other elements of a complex system.

To concretize the one-time (capital) costs, we will use the information given in the consolidated standards for construction prices (NCS 81-02-14-2020). For external water supply networks 1 km long consisting of polyethylene pipes, when developing dry soil to a depth of 3 m (which is typical for the Irkutsk Region), it is not difficult to obtain the following dependence of capital investments on the diameter of the pipeline:

$$K = (50246 \cdot d^2 - 10277 \cdot d + 5363.6) \cdot L$$

$$d = \frac{4x}{\pi y}$$
where \( v \) is the velocity in m/s, \( x \) is the water flow rate in the pipeline section of the network, in m\(^3\)/s. Taking into account (4), formula (3) will take the following form:

\[
K = (63812.42 \cdot x \cdot v^{-1} - 11602.73 \cdot x^{0.5} \cdot v^{0.5} + 5363.6) \cdot L
\]  
(5)

Operating costs include the annual costs of electricity \( C_{el} \) (thousand rubles/year):

\[
C_{el} = 108 \cdot z_{el} \cdot H \cdot x
\]  
(6)

where \( z_{el} \) is the cost of 1 kWh, \( H \) is the head developed by the pumping station, in mm H2O.

The calculation of electricity costs requires separate consideration. In the theory of hydraulic circuits [5], the energy conservation law for an arbitrary hydraulic circuit is formulated as follows: “All the energy brought in, minus the energy for pouring out water, is spent on overcoming friction forces”:

\[
\sum_{i=1}^{J_1} Q_j \cdot H_j - \sum_{j=1}^{J_2} Q_j \cdot P_j = \sum_{i=1}^{N} h_i \cdot x_i
\]  
(7)

where \( J_1 \) is a set of nodes of pumping stations, \( J_2 \) is a set of nodes for water consumption, \( H_j \) is piezometric heads of pumping stations, \( P_j \) is piezometric heads of water at consumers, in meters, \( h_i \) is head losses along sections of the water supply network, \( Q \) is water consumption at consumer \( j \).

Therefore, the annual electricity costs for the water supply system can be represented as the sum of electricity costs for each section of the network:

\[
C_{el} = 108 \cdot z_{el} \cdot O_i \cdot L_i = h_i \cdot x_i
\]  

To simplify the presentation and calculation of head losses along the length of the pipeline, we use the formula of F.A. Shevelev for plastic pipes [6]:

\[
S_i = 0.001052 \cdot \frac{x_i^{1.774}}{d_i^{1.774}} \quad h_i = 1.1 \cdot S_i \cdot L_i.
\]

Where \( S \) is the hydraulic slope, \( L_i \) is the length of the network section, in m.

\[
h_i \cdot x_i = 0.0011572 \cdot L_i \cdot \frac{x_i^{1.774}}{d_i^{1.774}}
\]

or taking into account (4):

\[
h_i \cdot x_i = 0.000649 \cdot L_i \cdot x_i^{0.387} \cdot v_i^{2.387}.
\]

It is not difficult to reduce the costs of electricity to a section of the pipeline network 1 km long and express them as a function of the flow rate and velocity of water movement:

\[
C_{el} = 108 \cdot z_{el} \cdot \left(0.000649 \cdot L_i \cdot 1000 \cdot x_i^{0.387} \cdot v_i^{2.387} + p_i \cdot x_i \right)
\]  
(8)

\( L \) is length in km, \( P_j \) is piezometric heads of water at consumers (for example, 10 mm H2O).

The costs of operating water supply systems according to [7,8] are expressed as deductions from capital investments:

At constant operating costs, the life cycle costs for water systems can be recorded as follows:

\[
LCC = K + T \cdot (0.11 \cdot K + C_{el})
\]  
(9)

As a result, we obtained the life cycle costs as a function of the flow rate and velocity of the transported water, the length of the pipeline and the specific electricity costs. SP 31.13330.2012 and a number of guidelines recommend the velocity of water movement in the range of 1.5 - 3 m/s. However, in each case, the economic velocity can be determined by calculation. For this, it is necessary to take the partial derivative of the reduced costs and life cycle costs in terms of velocity and equate to zero. Next, solve the resulting equation for the velocity.

To select the economic velocities, we will carry out numerical experiments in relation to life cycle costs, varying unit values of electricity costs and the length of pipelines. The unit cost of electricity will vary from the lowest for the Irkutsk Region - 1.11, to the maximum for Chukotka - 8.5 rubles per kWh. The results of numerical experiments are presented in Table 1, from which it follows that the tariff for electricity and the volume of pumped water have a significant impact on the economic velocity values. The length of the networks technically does not affect the velocity of water movement. The criterion of the life cycle costs reduces the economic velocity by 25%.

**Table 1.** Estimation of the economic velocities of water movement along pressure pipelines.
Calculations for 1 km, 10 km, 50 km, 100 km showed that the distance does not affect the economic velocity of water movement. The velocity increases with increasing volumes of transported water. These dependences are as follows:

\[ V_{\text{econ}} = a \cdot x^b, \quad (10) \]

Where the coefficients \( a \) and \( b \) are presented in Table 2.

| Electricity cost, rubles per kWh, \( Z_{el} \) | Coefficient a \( a \) | Coefficient b \( b \) |
|------------------------------------------|-----------------|-----------------|
| 1                                        | 2.9839          | 0.2147          |
| 2                                        | 2.4566          | 0.2139          |
| 3                                        | 2.1653          | 0.2144          |
| 4                                        | 1.9998          | 0.2121          |
| 5                                        | 1.8798          | 0.1999          |
| 6                                        | 1.7818          | 0.2015          |
| 7                                        | 1.7276          | 0.1972          |
| 8                                        | 1.6389          | 0.2111          |
| 9                                        | 1.5878          | 0.1988          |
| 10                                       | 1.5336          | 0.1928          |

Substituting (10) into expressions (5) and (8) for the cost of electricity of 1 ruble per kWh, we obtain capital investments and electricity costs as a function of water consumption:

\[
K = (21377.2 \cdot x^{0.7853} - 67168.2 \cdot x^{0.393} + 5363.6) \cdot L \quad (11)
\]

\[
C_{el} = 108 \cdot Z_{el} \cdot (8.82173 \cdot L_{i} \cdot x^{0.8995} + p_{i} \cdot x_{i}). \quad (12)
\]

Similar dependences were obtained for pressure sewerage:

\[
K = (12639.6 \cdot x^{0.7956} - 32826.658 \cdot x^{0.3978} + 5363.6) \cdot L \quad (13)
\]

\[
C_{el} = 108 \cdot Z_{el} \cdot (5.2797 \cdot L_{i} \cdot x^{0.8749} + p_{i} \cdot x_{i}) \quad (14)
\]

3. Road transport

Based on [9,10], in the work, we carried out similar studies and determined the dependences of the life cycle costs of road transport for the transportation of drinking and waste water at various distances. The following linear dependences were obtained:

\[
LCC = a \cdot x + b \quad (15)
\]

Where the life cycle costs are in thousand rubles, \( x \) is the flow rate in m3/s. The coefficients \( a \) and \( b \) are presented in Table 3.
Table 3. Approximation coefficients.

| Tank capacity, m³ | Distance, km | a   | b   | a   | b   | a   | b   |
|-------------------|--------------|-----|-----|-----|-----|-----|-----|
|                   | 10           | 50  | 100 | 150 |
| 8                 | 1E+09        | 857312 | 2E+09 | 442471 | 5E+09 | 419506 | 6E+09 | 456298 |
| 15                | 4E+08        | 350756 | 1E+09 | 276135 | 3E+09 | 380248 | 3E+09 | 411175 |
| 18                | 3E+08        | 334077 | 1E+09 | 303067 | 2E+09 | 364648 | 2E+09 | 393836 |
| 20                | 3E+08        | 239939 | 9E+08 | 324568 | 2E+09 | 178758 | 2E+09 | 185690 |

4. Determining optimal areas for the use of various types of water and waste transport

For this purpose, based on the obtained dependences (9), (11), (12), (15), for different distances, we will construct dependence diagrams of the life cycle costs for pipeline and road transport with tank capacities of 20 m³. These diagrams are shown in Figure 1.

![Figure 1. Determining the area of use of various types of water transport.](image)

As you can see from the figure, the trend lines for the life cycle costs for pipelines and road transport have intersection points. These points are presented in Table 4.

Table 4. Areas of application of road transport.

| Route length, L, km | Intersection points of diagrams for road and pipeline transport at consumption |
|--------------------|--------------------------------------------------------------------------------|
| 10                 | 0.0031 m³/s (267.84 m³/day)                                                    |
| 50                 | 0.0044 m³/s (380.16 m³/day)                                                    |
| 100                | 0.0043 m³/s (371.52 m³/day)                                                    |
| 150                | 0.0052 m³/s (449.28 m³/day)                                                    |

Consequently, for the Irkutsk Region (the cost of electricity is 1.11 rubles/kWh) for water flow rates up to 450 m³/day, it is efficient to use road transport. For other regions, the application area of road transport is expanding significantly.

Thus, the obtained dependences make it possible to determine the cost-optimal application areas of road transport for water and wastewater. At the same time, combined systems can be effective for various regions of supplying the population with drinking water and wastewater disposal, consisting of pipeline, road, water and railway sections of transport. Obviously, in this formulation, circuit-structural problems acquire a new meaning, and the solutions obtained will differ from pipeline or road transport.
Therefore, it is proposed to consider and optimize the water supply and wastewater disposal systems of a group of settlements in the study area as a whole.

The rationale for a joint solution is common corridors for laying pipelines, common roads for transporting water and wastewater, and other mutually beneficial situations. Moreover, the following options are possible:

- Group water supply from a surface or underground source of drinking water to reservoirs of settlements
- Group water supply from a surface or underground source of drinking water to each house in settlements
- Delivery of water by road from a surface or underground source of drinking water to reservoirs of settlements
- Delivery of water by road from a surface or underground source of drinking water to each consumer in settlements

If the water in the sources does not correspond to GOST “Drinking Water”, then it is necessary to install water treatment facilities. In this case, there may be the following options:

- Treatment facilities are arranged at each source of water, which is then delivered by pipeline or road transport to settlements
- Process water is delivered by road or pipeline transport to settlements, where for the purposes of drinking water supply, it is purified to the required standards. In this case, part of the process water without purification can be used for agricultural and industrial needs.

If there are underground sources of drinking or process water in settlements, alternative options may be their purification and delivery by road or pipeline transport to each consumer within the settlement, as well as to other settlements.

The following options are possible for drainage systems:

- A centralized system of wastewater disposal from all villages to centralized WWTP is organized, followed by discharge into a flowing reservoir (while wastewater can be delivered to treatment facilities by pipeline and road transport)
- A centralized wastewater disposal and treatment system is organized in each settlement. Wastewater of each consumer can be delivered to WWTP by pipeline and road transport
- Treated wastewater in each village is discharged into a flowing water body (if there is one), or into specially equipped storage, filtration and evaporation ponds, or delivered to a storage pond shared for all villages or a specially organized discharge into a flowing water body (river)
- There can be combinations of the listed options for wastewater disposal and treatment

The listed options can be represented as a redundant graph in which it is required to reject inefficient nodes and links. For this, an approach is proposed based on a purposeful enumeration of redundant scheme tree options using the coordinate-wise minimization method with respect to contour variables [11-15] and the method of finding the maximum flow of minimum cost [16,17]. Figure 2a shows a redundant circuit in the form of a transport network. Nodes from 1 to 9 represent settlements, node S is fictitious and simulates the total water demand of settlements, branches from this node to settlements simulate possible local water sources - underground water intakes with water treatment facilities. A possible transport network is shown in dark color - pipelines, dashed lines - possible road traffic routes. Node t simulates the total discharge of treated wastewater from each settlement (wastewater treatment is performed in each settlement). Red dashed lines represent the discharge of wastewater into the wastewater system. Node 20 simulates a possible centralized wastewater treatment plant.
The most effective method for finding an optimal solution based on a transport scheme is the method described in [18-19]. In our work, based on the developed software package Trace-BK [20], we carried out optimization calculations and obtained the results presented in Figure 2 b. According to these results, it is economically viable to arrange surface water intake with water treatment facilities. To transport water to consumers 11 and 14 by pipeline transport, then to deliver water by road to consumers 12, 15,16,17,18,19. It is beneficial for consumer 13 to have their own underground water intake. To deliver wastewater from consumers 16,15 to consumer 14 by road transport. To deliver wastewater from consumers 11,14,17 to WWTP by pipeline transport. Consumers 12 and 13 will have their own treatment facilities.

5. Conclusion and Discussion
The results obtained from the calculation showed the advantage of combined schemes for transporting water and wastewater over solving individual problems of organizing water supply and wastewater disposal in the studied settlements. The final values of the total reduced costs turned out to be 25% less than the sum of costs for individual solutions.

Thus, the implementation of this approach makes it possible to substantiate newly designed, reconstructed and developing systems of water supply and wastewater disposal in urbanized areas at the lowest cost for the entire life cycle of the system.

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