Comprehensive optimization of water supply and sanitation systems

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Annotation. Because of the uneven distribution of water resources across the territory of our country, many localities and even cities do not have their own sources of water supply and reservoirs where it would be possible to discharge treated wastewater. To solve this problem, group and district water supply and sanitation systems are being designed, built and developed. The length of such systems is hundreds or even thousands of kilometers, and they include many pumping stations, regulating tanks, storage ponds, local and centralized treatment facilities. Significant financial investments are required annually for the construction and operation of such structures [1-6]. Therefore, the choice of routes, structure of structures, ways of transporting water and waste water, justification of the location of water intakes, treatment facilities are relevant and require special attention and technical and economic analysis of design options. The paper proposes a comprehensive approach to optimizing the structure of structures and methods for supplying water to consumers and transporting waste water to treatment facilities on the basis of the redundant design methods.

1. Introduction
The following types of transport can be attributed to the methods of water supply and drainage: pipeline, road, rail, water and even air.

Road transport is the leading one in the Russian Federation. It accounts for 68% of the total cargo transported. The second place is taken by pipeline transport, slightly ahead of railway transport.

In housing and communal services (HCS), pipeline transport is dominant, with the help of which heat, water, and gas are supplied to residents, and sewage and storm water are diverted. The length of this type of transport in HCS is: water pipelines- 523 ths. km; sewerage-163 ths. km; heat networks-183 ths. km.

Road transport in housing and communal services is used to provide water and remove waste water from individual consumers in the private sector who are not connected to centralized water supply, sanitation, heat and gas supply systems.
Railway transport is used to deliver bottled and mineral water. Water transport is used very rarely, mainly in marine areas, as well as for the collection and delivery to treatment facilities of shale water, household waste water from protected and protected areas.

When justifying promising schemes for the development of water supply and sanitation systems in populated and sparsely populated areas, territories with a special status of ecological zones and national parks, the question arises which type of transport to use in order to minimize one-time and operational costs, and not to cause environmental damage to nature.

For localities that do not have their own drinking water supply sources and are located far from each other, water delivery options may be as follows:

1) group water supply from a surface or underground source of drinking water to the reservoirs of localities;
2) delivery of water by road from a surface or underground source of drinking water to each subscriber of localities;
3) delivery of water by road from a surface or underground source of drinking water to each subscriber of localities;
4) if the water sources do not meet the GOST “Drinking water”, then it is necessary to install water treatment facilities. In this case, there may be the following options:
   - treatment facilities are set up at each source of water, which is then delivered to localities by pipeline or road transport;
   - technical water is delivered by road or pipeline transport to localities where it is purified to the required standards for drinking water supply purposes. At the same time part of the process water without treatment can be used for agricultural and industrial needs;
5) if there are underground sources of drinking or technical water in localities, alternative options may be their purification and delivery by road or pipeline transport to each subscriber within the locality, as well as to other localities.

Pic. 1a shows nine localities that require water to be supplied from an open water source—a river. Pic. 1b shows possible options for a centralized water supply system by pipeline (solid lines) and road transport (dashed lines) from a surface water source. Pic. 1c shows the same thing, but with a possible device for an underground source of drinking water located at some distance from populated areas (a rectangle with dots). In pic. 1d the same, but for the case of the need for water treatment facilities.

Pic. 1e shows a redundant diagram in the form of a graph with a single vertex, from which fictitious branches go to possible water sources. These fictitious branches model the economic performance of possible water sources.

In pic. 1f is the same, but with the possible arrangement of water intakes and treatment facilities in each locality. This option includes all possible options 1-6 and their combinations.

Of all the proposed alternatives, it is necessary to find the optimal solution for cost, technical and environmental factors. Pic. 1g shows a possible option, according to which water will be delivered by pipeline to settlements 1, 2, 4. Further from the village settlements of 2 to 3 and 5 of the road transport. In village 8, the underground source of technical water, after its purification, will be used in the village itself, and delivered by road to villages 7 and 9. In the village 6, water from an underground source of technical water will be used only in the village itself after its purification.

When transporting water by road, special requirements are imposed on the containers in which liquids are transported:
- the water must not be heated or cooled to standard values;
- water should not lose its original properties and quality.

2. Methods
To find the optimal variant, we propose an approach based on purposeful search of redundant scheme tree variants using the contour minimization method (coordinate with respect to contour variables).
The essence of this approach is as follows: a redundant scheme is formed, which is obtained by superimposing pre-planned options and can represent a graph of possible routes and locations of various structures.

For example, the graph of the diagram shown in pic. 1b. If there are several possible sources of water, all of them are closed to a common node by fictitious branches that model the cost functions of possible sources (pic. 1e).

We believe that the solution to the problem will be some branched scheme in the form of a tree of a redundant graph. At the same time, the reliability of water supply will be provided by parallel laying of two water pipelines. Taking into account the assumptions made, it is necessary to delete some edges in the redundant graph so that the graph becomes a connected tree of the minimum values of the cost function.

To find such a solution, the following computational process is organized. On the redundant graph, the initial approximation tree is selected, which is taken as the tree of shortest distances (minimum estimated costs). Then, to generate new trees, the tree branches are replaced with chords (edges that are not part of the tree).

To illustrate the computational process, pic. 2.1 shows a redundant diagram in the form of a graph that had 9 vertices, 12 edges, and four fundamental independent contours. For example, a tree is selected as the initial approximation (see pic. 2.2). From an algorithmic point of view it is easy to write this tree as a single array:
Figure 1. Options for transporting water to consumers
Where the second line is the number of the array element, or the number of the final vertex of the arc.
The elements of the array represent the outgoing vertices of the tree, that is, we get to vertex 2 from 1, vertex 3 from 2, 4 from 1, 5 from 2, and so on. As already noted, the choice of the tree uniquely determines the fundamental cycles.

Chorda $x_2 - x_5$ forms a cycle $x_2 - x_5; x_1 - x_2; x_4 - x_5; x_1 - x_4$. 

Chorda $x_3 - x_6$ forms a cycle $x_3 - x_6; x_4 - x_5; x_1 - x_4; x_3 - x_6; x_2 - x_3; x_1 - x_2$. 

Chorda $x_5 - x_8$ forms a cycle $x_5 - x_8; x_4 - x_5; x_7 - x_8; x_4 - x_7$. 

Chorda $x_8 - x_9$ forms a cycle $x_8 - x_9; x_7 - x_8; x_4 - x_7; x_1 - x_4; x_6 - x_9; x_3 - x_6; x_2 - x_3; x_1 - x_2$.

In this case, the direction of the contour traversal will coincide with the direction of the chord.

For subsequent generation of new trees, the first contour is selected. The contour will consist of two chains: $x_2 - x_5; x_1 - x_2$ and $x_4 - x_5; x_1 - x_4$, i.e. the contour will always have the vertex of “exit” 1 and the vertex of “entry” 5.

Therefore, if the chord $x_2 - x_5$ becomes a branch of a tree, that is, a branch $x_4 - x_5$ become a chord (Pic. 2,3). In this case, to form a tree, it is enough to replace 4 with 2 in the $IWAY$ array at position 5 (the original vertex of the chord):

| 0 | 1 | 2 | 1 | 4 | 3 | 4 | 7 | 6 |

Then the $x_1 - x_4$ branch is tried as a chord and the array is corrected again $IWAY$:

| 0 | 1 | 2 | 5 | 2 | 3 | 4 | 7 | 6 |

After viewing all branches of the first contour, the second contour is selected, and all operations for generating new trees are repeated (pic. 2.4, pic. 2.5) Then the third contour is selected and trees are generated (pic. 2.6, pic. 2.7). Then the fourth circuit (see pic.2.8-2.11). Then the first contour is formed again, and all operations are repeated until the trees that have already been built appear. In this case, the best option is remembered. If the best solution is not found after viewing all the contours, the computing process ends.

The drainage options for the localities shown in pic. 1a are as follows:

1) A centralized system of waste water diversion from all settlements to centralized IOWs is organized, followed by discharge into a flowing reservoir. Wastewater at IOW can be delivered by pipeline and road transport.

2) In each locality, a centralized system of wastewater disposal and treatment is organized. Drains on the IOW of each village can be delivered from subscribers by pipeline and road transport.

3) The Treated effluents in each settlement are discharged into a flowing reservoir (if there is one), or into specially equipped storage ponds, filtration and evaporation, or delivered to a common storage pond for all settlements or a specially organized discharge into a flowing reservoir (river).

4) There may also be combinations of the following options for wastewater disposal and treatment.
3. Results and discussions

Pic. 3a shows options for a centralized water disposal system (in the form of a redundant scheme). Wastewater is collected from each locality and transported to IOW by road or pipeline. After cleaning, they are dumped into the reservoir.

*Figure 2.* Illustration of a method for purposefully iterating over variants of redundant schema trees
Pic. 3b shows options for the possible installation of IOW in each locality with the delivery of wastewater from subscribers to these treatment facilities by pipeline and road transport. In this case, the effluents are discharged into evaporation and filtration ponds after treatment.

Pic. 3c shows the final redundant scheme, which has a common flow discharge node from each possible node of the wastewater treatment device.

Pic. 3d shows the best possible option for transporting and treating waste water. According to this option, within localities, the effluents from the subscribers cesspits will be delivered by road to receiving tanks, from which they will be diverted by pipeline to centralized IOWs.

Considering the options for centralized and decentralized water supply and sanitation systems, it is not difficult to understand that they are interconnected and decisions on water disposal systems depend on the accepted water supply options. There are common corridors for laying pipelines, common roads for transporting water and wastewater, and other mutually beneficial situations. Therefore, there is a problem of complex optimization of schemes and systems of water supply and sanitation. To solve this problem, it is proposed to combine two redundant schemes pic. 1e and pic. 3c. As a result, a redundant scheme is formed, as shown in pic. 4a.

It is not difficult to notice that the resulting redundant scheme is nothing more than a transport network [11-13], consisting of a node S of the input of flows and a node t of the output of flows. Branches in the transport network simulate the actual process of flow movement, its transformation (consumption, discharge, cleaning, etc.), and the cost value of structures (the cost per unit of flow). Also, each arc and edge has bandwidth restrictions.

For example, the arc S-1 (see pic. 4a) simulates a surface water intake from a river, a water treatment plant, and has a flow unit cost-the cost of building these structures, assigned to 1 m$^3$ of water taken from the river and treated. It has a capacity limit equal to the maximum possible volume of water taken from the river. Arc S-3 simulates the device of a local underground water source in village 3 with the device of treatment facilities, has the cost per unit of flow, i.e. the cost of all structures is calculated for 1 m$^3$ of water, the flow limit is the maximum possible intake of water from an underground source. Arcs 1-11, 2-12, ... - simulates the use of water by the subscriber and its transformation into waste water. Arc 20-t -simulates wastewater treatment on centralized IOW and discharge of treated wastewater into a reservoir. Arcs 11-t, 12-t-model wastewater treatment in populated areas and discharge it into storage ponds, have specific costs and flow restrictions [10-15].

The most effective method of finding the optimal solution based on the transport scheme is the method described in the works [7-10]. In the work on the basis of the developed software package Track-VK [16] optimization calculations are performed and the results shown in pic. 4b are obtained. It is clear from the calculations that the solutions obtained differ and their total costs are lower than the sum of the costs for the solutions in pic.1zh and pic. 3g.
Figure 3. Options for wastewater transport from subscribers
Figure 4. The diagram of the district water supply and sanitation system is shown

Conclusions
The proposed approach to the complex optimization of the structure of structures and methods for supplying water to consumers and transporting waste water to treatment facilities is based on the method of redundant design schemes. This approach and its implementation in the form of a software package Track-VK allow you to quickly justify the newly designed, reconstructed and developing water supply and sanitation systems in urban areas. On its basis, it is not difficult to form regional programs for the integrated development of engineering infrastructure in cities and localities.
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