Schematic and structural optimization of group water supply systems

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Abstract. Group water supply systems (GWSS) are designed for centralized water supply of settlements located in waterless areas and remote from drinking water sources. GWSS are an object of increased attention, have a great social and environmental significance, require significant capital investments and financial resources for operation, ensuring the required reliability and manageability. Therefore, the issues of optimization of design solutions for the structure and parameters of structures are relevant and require improvement and development of methodological and software solutions to these problems. The paper proposes a method of redundant design schemes and a method of schematic and structural optimization based on a sequential and iterative solution of two problems: for a fixed value of flows in the graph of the redundant scheme, network parameters are optimized (pipeline diameters, heads, and the composition of pumping stations); with fixed network parameters, the problem of the distribution of water flows is solved in the GWSS.

1. Introduction

Group water supply systems (GWSS) are designed for centralized water supply of settlements located in waterless areas and remote from drinking water sources. GWSS are an object of increased attention, have a great social and environmental significance, require significant capital investments and financial resources for operation, ensuring the required reliability and manageability. Therefore, the issues of optimization of design solutions for the structure and parameters of structures are relevant and require improvement and development of methodological and software solutions to these problems. The analysis of existing GWSS indicates that many systems today do not meet the requirements of efficiency, reliability and manageability. The main reasons are insufficiently justified decisions at the design level on the choice of structure of structures, pipeline routes, and their parameters. Increasing reliability by backing up and ringing networks requires additional investment. It is proved that taking into account reliability in the form of parallel laying of pipelines, installation of emergency water storage tanks on the network and in localities leads to an optimal solution of the network structure in the form of a tree for new networks, and in the presence of existing pipelines-in the form of a dominant graph with ringed sections of the network [1-16]. The creation of an extensive network with the strengthening of the graph tree trunk makes it possible to increase the speed of water movement in pipes, reduce the formation of stagnant zones, preserve water quality, and reduce the immediate threat of bacterial and chemical
contamination. In addition to improving water quality, capital costs for the construction of reserve sites are reduced, the probability of accidents is reduced, and so on.

At the same time, we need to develop a method that allows us to optimize the structure of this tree and the ring sections of the network.

2. Methods

Many approaches and methods have been developed to find the optimal network structure in the form of a tree [12-18]. However, all of them are reduced to a purposeful and limited search of variants of trees of the redundant design scheme and do not view the ring graphs of the network. Traditionally, in project practice, this task is solved as follows [17-25]:
- several variants of routes are planned;
- for each option, the parameters of the pipeline, pumping stations and control structures are determined;
- each option is evaluated for reliability, manageability and economic costs of its implementation. The best one is selected. Almost no optimization of design solutions is performed.

At the same time, the task of optimizing the structure and parameters of the GWSS is to find such a pipeline route, places where water intakes, reservoirs, and pumping stations are installed that would correspond to the minimum of the total reduced costs.

From a mathematical point of view, this problem has a multi-extreme character, is difficult to formalize and implement [13]. In most cases, the available approaches and methods for solving this problem are reduced to a step-by-step and iterative procedure for optimizing the route and parameters of transport structures.

This paper proposes to solve this problem in a single iterative process based on the methodology of coordinate minimization. One coordinate is the vector of distribution of expenses in the network, the other is the vector of losses of pressure in pipelines and pump stations, which determines the composition of transportation structures. This is done algorithmically as follows:
- assigned all sorts of connections between the possible sources of consumers (in the General case this can be a complete graph);
- on this graph, the initial flow distribution is assigned (for example, using the proportional flow division method);
- for fixed flow distribution, the optimal diameters and parameters of transport structures are determined and the cost of the option is determined.
- with known diameters and parameters of water pumping stations, the problem of flow distribution in the network is solved (for example, by the method of nodal pressures [1]);
- next, the diameters and parameters of the pumping stations are selected again for the newly obtained water flow values;
- such procedures are performed for new networks until the water flow rate and, accordingly, the pipeline diameters are close to zero in some parts of the network. The number of such sections will be: n−m+1, where n is the number of sections of the redundant scheme, m is the number of nodes.
- as a result, we get a variant of the network in the form of trees. This tree (or network route) will be the solution to the problem. If there are already built sections and structures in the network, then the computing process will end on some solution that will correspond to the graph with the ring sections of the network.

For simplicity and clarity of the proposed approach, we accept the speed of water movement in pipelines equal to 1 m/s. Although this parameter also requires optimization and depends on the cost of electricity in the design area (for example, for the Irkutsk region, the optimal value of water speed in pipelines is 2.7 m/s). With this in mind, the diameter (d) of the pipelines is determined by the following formula:

\[ d = (1 / 30) \sqrt{Q} \]  

where Q is the water flow rate on the pipeline section of the network.

The costs shown 3, taking into account (1) calculated using the following formula:
\[
Z_i = \sum_{j=1}^{n} K_{j,i}(D_j) \cdot L_j \cdot E + \frac{\gamma \cdot 365 \cdot 24 \cdot m \cdot Q_j \cdot H_i}{102 \cdot \eta}
\]

(2)

where \(\gamma\) - specific weight (for water =1), number of hours per year \(365\times 24\), \(H_i\) - head of pumping stations, \(m.V\).

\(Q_j\) - consumption in the node \(l/\text{s}\), \(m\)-unit electricity costs = 1.067 rubles/KWh (for Irkutsk), \(\eta\) - pump efficiency 0.7

\(E=\) the coefficient of comparative efficiency of capital investments is the inverse of the payback period, which is recommended to be determined on the basis of forecast tariffs for utilities; \(K_{j,i}(D_j)\) - specific capital investments, \(\text{RUB/m}\), \(L_j\) - the length of channel, \(m\).

On the basis of (2) level of each iteration, the optimal scheme structure and its parameters are evaluated.

The computational process ends if there is no decrease in the value of the reduced costs during the transition to subsequent iterations.

Thus, the option in which the value of the reduced costs will have the smallest size and will be optimal.

3. Results and discussions

Let's illustrate this approach using the example of a redundant network shown in figure 1, containing 12 nodes and 17 network sections. The source information for network of nodes is shown in table 1, and the source information for network of sections is shown in table 2.

![Figure 1. Redundant (ring) scheme of the group water supply system](image)

**Table 1. Source information for nodes**

| node number | mark in node, m | selection in node Q, l/s | node number | mark in node, m | selection in node Q, l/s |
|-------------|----------------|--------------------------|-------------|----------------|--------------------------|
| 1           | 400            | 30                       | 7           | 400            | 30                       |
The results of iterative calculations to determine the optimal parameters of the group water supply system are summarized in tables 3.1, 3.2, and 3.3.

Table 3.1. The result of the iterative calculation of diameter

| node number | the number of the iteration |
|-------------|----------------------------|
| the beginning of the segment | the end of the segment |
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 2 | 50 | 47 | 47 | 47 | 48 | 49 | 49 | 50 | 51 | 52 | 53 | 53 | 54 | 54 | 54 |
| 2 | 3 | 40 | 37 | 37 | 37 | 38 | 39 | 40 | 41 | 41 | 41 | 41 | 41 | 41 | 40 | 40 |
| 3 | 4 | 25 | 26 | 26 | 26 | 27 | 28 | 30 | 31 | 31 | 31 | 31 | 31 | 30 | 27 | 26 |
| 4 | 5 | 40 | 37 | 37 | 37 | 36 | 35 | 34 | 33 | 31 | 29 | 27 | 26 | 25 | 25 | 25 |
| 5 | 6 | 25 | 22 | 22 | 22 | 22 | 22 | 22 | 23 | 24 | 25 | 27 | 26 | 25 | 25 | 25 |
| 6 | 7 | 20 | 19 | 19 | 19 | 19 | 19 | 19 | 20 | 20 | 20 | 19 | 19 | 19 | 19 | 19 |
| 7 | 8 | 20 | 18 | 18 | 19 | 21 | 22 | 23 | 24 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| 8 | 9 | 25 | 21 | 21 | 21 | 21 | 21 | 19 | 18 | 17 | 15 | 13 | 11 | 91 | 63 | 35 |
| 9 | 10 | 20 | 17 | 17 | 15 | 13 | 11 | 83 | 53 | 28 | 12 | 3 | 0 | 0 | 0 | 0 |
| 10 | 11 | 15 | 12 | 12 | 11 | 95 | 73 | 49 | 27 | 12 | 3 | 0 | 0 | 0 | 0 | 0 |
| 11 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 2. Source information for sites

| node number | the beginning of the segment | the end of the segment | the length of the DL, m | the segment material | node number | the beginning of the segment | the end of the segment | the length of the DL, m | the tube material |
|-------------|-----------------------------|------------------------|-------------------------|----------------------|-------------|-----------------------------|------------------------|---------------------|------------------|
| 1           | 2                           | 1000                   | new                     | 7                    | 8           | 1000                       | new                    | 1000                | new              |
| 2           | 3                           | 1000                   | new                     | 5                    | 9           | 1000                       | new                    | 1000                | new              |
| 3           | 4                           | 1000                   | new                     | 6                    | 10          | 1000                       | new                    | 1000                | new              |
| 4           | 5                           | 1000                   | new                     | 7                    | 11          | 1000                       | new                    | 1000                | new              |
| 5           | 6                           | 1000                   | new                     | 8                    | 12          | 1000                       | new                    | 1000                | new              |
| 6           | 7                           | 1000                   | new                     | 9                    | 10          | 1000                       | new                    | 1000                | new              |

The results of iterative calculations to determine the optimal parameters of the group water supply system are summarized in tables 3.1, 3.2, and 3.3.
The diagram of the group water supply system corresponding to the most optimal structure is shown in figure 2.
Figure 2. Optimal (branched) scheme of the group water supply system

Figure 2, as a result of the above example, shows that the redundant (ring) circuit has become a branched network as a result of optimization. Part of branches (5-6, 6-7, 7-8, 7-11, 9-10, 11-12) it will be rejected, and the remaining cost values will correspond to the optimal distribution of flows in the network.

Conclusions
A new method of optimization of GWSS based on the reduced costs of their construction and operation is proposed. This method is an effective tool for justifying the structure of the network and structures of water supply systems and can be useful for decision-makers to optimize the structure and development of a promising water supply scheme for urban area.

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