Justification of the parameters of developing water supply and sanitation systems based on their electronic models

E S Melekhov¹ and R V Chupin²

¹Irkutsk National Research Technical University, 664074, Irkutsk, Lermontov st., 83, Russia
²VORTEX Limited Liability Company, 664039, Irkutsk, Lermontov st., 297, Russia

E-mail: melechov@istu.irk.ru

Abstract. Most of the water supply and sanitation systems of modern cities and populated areas of the Russian Federation are characterized by significant physical depreciation, which is estimated at 60%. Significant moral depreciation, since some structures and pipelines are almost a hundred years old or more. At the same time, the replacement of old equipment is carried out annually at a rate of 2%. Such unsatisfactory rates of renovation are due to the lack of adequate funding and their irrational allocation to the construction of new ones, reconstruction and development of existing pipelines and structures. Obviously, to solve this problem, new and integrated approaches, new technologies for the design, construction and operation of water supply and sanitation systems are needed. One of such approaches is proposed in the work, based on digital technologies using electronic models of water supply and sanitation systems, on the basis of which methods for modeling operating modes and optimization methods for design solutions for the development of networks and structures have been developed. The results of applying the proposed technology on the example of water supply and sanitation in the city of Nizhneudinsk, Irkutsk region.

1. Introduction

Most of the water supply and sanitation systems in Russia currently do not fully comply with modern technological, environmental and sanitary-hygienic requirements, which are set out in the relevant state standards, technological regulations and standards. The reason for this was the lingering nature of the transition of communal systems to market relations.

The rapid scientific and technological progress brought new technologies and materials, so necessary for the construction and reconstruction of wastewater systems. The emergence of geographic information systems, the creation of a global communication and information transfer system, the development of intelligent control systems - all this contributes to the reassessment of the existing technology for designing water supply and sanitation systems and the development of a new methodology for the formation and optimization of their prospects for reconstruction and development schemes.

Despite the large number of works on this issue, modern information technologies are not used enough in the practice of modeling and designing water supply and sanitation systems.

This work proposes a new approach to optimizing the reconstruction and development of water supply and sanitation systems, based on digital technologies for modeling the systems themselves, their operating modes, mathematical methods for optimizing design decisions, taking into account increased
reliability, seismic resistance, operational controllability, risk assessment methods from decisions made, methods for overcoming the uncertainties in the behavior of systems in future periods of its operation. The proposed approach and the above methods [12] are implemented in the environment of the TRACE-VK software package [13], on the basis of which electronic models of water supply and sanitation systems in the cities of the Irkutsk region: Irkutsk, Angarsk, Shelekhov and Shelekhovsky district, Baikalsk, Ust-Ilimsk, have already been developed. Nizhneudinsk and others, developed a program for the integrated development of engineering infrastructure and water supply and sanitation schemes. In this work, using the example of the city of Nizhneudinsk in the Irkutsk region, the possibilities of the proposed approach are demonstrated and recommendations are given for intensifying the work, reconstruction and development of water supply and sanitation systems.

2. Methods

2.1. The method of forming an electronic model of water supply and sanitation. The method is based on a digital representation of the pipeline network, water intakes, water treatment plants, pumping stations, control tanks, sewage treatment plants, pressure and flow regulators. This method is based on the principles of graph theory [1,2], vector-matrix notation and representations [3]. The vertices of the graph are used to simulate manholes, wells for dividing and distributing flows, wells for water withdrawals and wastewater inflows, water intake points from surface and underground water sources, and sewage discharge points. The edges of the graph represent the pipeline sections of the network, the pumps and the characteristics of their impeller, water intake facilities, treatment facilities, pressure and flow regulators. Each vertex has absolute and relative coordinates, geodesic marks, for the tops of subscribers - schedules of wastewater intake and water withdrawals. For visualization of mappings, a specialized graphic editor has been developed for inputting and presenting an electronic model in the form of a geographic information system with N number of layers, such as houses, streets, rivers, ponds, terrain, networks, individual buildings and structures, etc. [4].

2.2. Methods of distributing the flow of water and wastewater in the network. Based on the theory of hydraulic circuits [4], methods for solving linear and nonlinear systems of equations [3], special-purpose algorithms [5]. At the same time, on the basis of the electronic model, the following matrices are formed: the adjacency of sections (edges of the graph) and network nodes (vertices of the graph); adjacencies of sections and network contours, cyclic schemes [6]. Based on these matrices, the conditions of material and energy balance are formed separately for the water supply and wastewater system in the form of the first and second laws of Kirchhoff [4]. The linear and nonlinear equations are solved by the method of I. Newton [3]. For water supply systems in automatic mode, in the presence of several water sources, regulating tanks, an expanded graph is constructed by introducing a dummy node with atmospheric pressure, from which dummy arcs are formed that are closed with the water source nodes. Effective pressures equal to the geodetic marks of the water sources and the regulating capacities are attributed to these arcs. On the basis of the network graph expanded in this way, matrices are formed, and an expanded system of nonlinear equations is constructed and solved. The result will be a load distribution between the water sources and the regulating tanks. For the calculation of drainage systems, a new technique is proposed, based on the construction of cyclic circuits with the allocation of passive, active and dummy branches. Passive sections of the arc model the reservoir and wells of the network. All wells are closed with dummy branches on a common node with atmospheric pressure. Fictitious sections simulate the flow of wastewater into the sewage system and the discharge of wastewater into the WWTP collection tank. Each fictitious branch is assigned acting pressure equal to the geodetic marks of the top of the wells. On the basis of the graph expanded in this way, matrices are constructed, a system of nonlinear equations is formed and solved. As a result, if all the fictitious branches are directed to the nodes - wells, and the costs on the passive branches are less than the costs for their full cross section, then the network will establish a gravity flow mode. If on some sections of the network the flow rate will be greater than or equal to the flow rate for their full cross-section, then the pressure-pressure-free
mode will be established in the network. If some fictitious branches will be directed from the wells to a common node with atmospheric pressure, then the mode of effluent exit to the earth’s surface will be established in an amount equal to the flow rate of this fictitious branch.

2. Methods for detecting blockages and sunken valves. Such a task usually arises at the network calibration level, i.e., checking the mathematical model of the network for its adequacy to real parameters. This problem is solved as follows: hydraulic calculation of the water supply network is performed. Free pressures in the nodes of the circuit are determined and compared with the actual measured values. For example, in Figure 1, the calculated piezometer is shown in red, and the actual one is shown in blue. If the calculation model is adequate to the real network, then the red and blue piezometers coincide. In this example, in the second section, the actual piezometer "breaks"; in this section, greater than the calculated pressure losses occurred. Consequently, the section has blockages, or the actual diameter is less than the calculated one, or has valves with sunken working bodies. The second section in terms of pressure losses coincides with the calculated one, therefore there are no blockages. The third section also has a "scraping" and, accordingly, blockages, etc. The described procedure automatically issues such suspicious network sections.

2.4. Methods for optimizing design decisions. The problem is solved on a previously constructed redundant scheme. For example, the designers, taking into account possible development, surveys, terrain, etc., outlined two options for tracing the drainage system, which are presented in Figure 2a, b. These two options can be replaced with a single graph, shown in Figure 2c, for which it is already possible to count 8 options for tracing the water supply and sanitation system. As part of urban development, you can build a graph that will contain many possible options.
At the same time, possible ways of their reconstruction (parallel laying, relocation, laying of a new collector, arrangement of pumping stations, etc.) can be indicated on various sections of the network, and the location of new water intake facilities, treatment facilities with various water treatment technologies can be outlined in separate nodes and wastewater. The task will be to reject inefficient (according to a given cost criterion) sections and nodes of the excess scheme of the water supply and sanitation system. In the TRACE-VK software package, several optimization methods have been proposed and implemented. The first is a modified method for finding the maximum flow of minimum cost [6-8]. To implement this method, a transport network is constructed on the basis of the redundant circuit [8-10], which consists of a stream entry node and a stream exit node and a redundant network scheme. For drainage systems, the transport scheme is formed as follows. The flow inlet node is closed by arcs with all subscribers from which waste water enters the drainage system. These arcs are assigned the maximum throughput equal to the estimated performance of the subscribers. All nodes - possible sewage treatment plants are closed by arcs to a common outlet outlet. Each arc is assigned the maximum throughput equal to the maximum productivity of the treatment plant and the cost of a unit flow equal to the cost of cleaning one cubic meter of waste fluid. For network sections simulating existing network sections, two-sided flow restrictions are imposed, lower ones based on non-silting flow rates, and upper ones based on the inadmissibility of the work of gravity collectors in pressure mode. For sections of the network simulating the laying of new pipelines and structures, the cost of a flow unit is assigned. For water supply systems, the inlet of flows is connected to nodes that are possible sources of water supply (surface and underground), and the outlet of flows is closed by arcs with all subscribers. The flows of these arcs are subject to restrictions equal to the estimated loads of subscribers. Taking into account the constructed transport network, using the modified search algorithm for the maximum flow of minimum cost, the structure of structures, the route of pipelines, ways of laying new and reconstruction of existing sections of the network are determined. The type of transport is determined - pipeline, or automobile.

In detailed design, when local conditions, soils, intersections with other communications are already defined, the task of specifying the parameters of the designed water supply and sanitation systems arises. To solve this problem, a method has been proposed that implements a multi-step process of targeted sorting of possible slopes and diameters of pipelines (from among the standard series), pressure of pumping stations and parameters of mating structures. The multi-step process is carried out according to the dynamic programming scheme and starts from the subscriber units to which water is supplied and from which the wastewater enters the wastewater system to the nodes - water intakes and wastewater intake units at the WWTP. From the set of variants of piezometric surfaces of pipelines constructed in this way, the best of them is selected by the criterion of reduced costs. Figure 3a shows the multi-step process of forming the piezometric surface of five pipelines, where the solid bold line indicates the best option for the given costs. This option corresponds to the optimal profile shown in Figure 3b.

**Figure 3.** Optimization of sewage network parameters

Optimization Criteria. The generally accepted criterion is the present discounted costs and life cycle costs. Studies have shown that if the problem of the long-term development of water supply and sanitation systems is being addressed, then the life cycle cost criterion provides a solution with minimal operating costs, and for short-term projects, the presented costs give a solution with minimal one-time costs (capital investments).
2.5. Methods of dealing with the uncertainty of promising water consumption
Currently, in almost all cities of the Russian Federation there is a significant decrease in specific water consumption and sanitation. For example, for the city of Irkutsk over the past 17 years, it has decreased from 300 to 191 l / person per day. It is possible that by the end of the implementation of the approved water supply and sanitation scheme (by 2035), it will either decrease and reach the limit of 100 l / person per day, or it will return to its previous values.

Figure 4 shows the possible intervals and trajectories of changes in the values of specific water consumption at the stages of development of the wastewater system. For the first phase of construction, the possible range of specific loads will be (130-220 l / person per day), for the second (110-250 l / person per day), for the third (100-300 l / person per day). The TRACE-VK software package implements an approach based on the use of the theory of fuzzy sets and decision theory [11-12]. Moreover, for each construction phase, the intervals of possible loads are divided into n values. As a result, taking into account the membership function (preference), n variants of development of the water supply and sanitation system are formed. For each option, justification (optimization) of the parameters of the water supply and sanitation system is carried out immediately for all (in this case, three) construction phases. Moreover, the option for which the estimated investment in the construction of the first stage exceeds the possible funds generated in the investment programs is excluded from consideration. For each of the investigated options for the development of a drainage system, financial risks are assessed. For this, a risk matrix is built. In this matrix in the first row and first column presents the values of the estimated estimated costs. On the diagonal are located “zero” values of costs - risks, which means that the accepted value of costs coincides with those that will be after the implementation of the project (100% match option). The values to the right of the diagonal indicate the risk values from the fact that the actual value of the wastewater discharge after the project will be greater than their values assigned in the project. Consequently, additional reconstruction and costs — financial risks — will be required. To the left of the diagonal in the matrix will be the risk values associated with overstating the parameters and, consequently, with excessive investment. The last column of the “risk matrix” gives the maximum risks for each option for making an estimated expense. The last element of this column corresponds to the minimum value of the maximum risks.

3. Results and discussion
We illustrate the work of the proposed complex of models and methods on the example of water supply and sanitation in Nizhneudinsk, Irkutsk region. The city of Nizhneudinsk, with a population of 34 thousand people, is located along the Trans-Siberian Railway on the right and left banks of the Uda
River. In the summer of 2109, due to flooding, the city was partially flooded. At the same time, sand and silt got into the city’s pipeline water supply system, which affected the water quality and hydraulic parameters of the system.

**Figure 5.** Hydraulic model of the water supply and sanitation system in Nizhneudinsk

**Figure 6.** Pressure map for water supply and filling map for water disposal
Figure 7. Modeling of promising city development

Figure 5 shows the hydraulic models of the city's water supply and sanitation systems. Figure 6 shows calibrated models in the form of calculated and actual pressure maps for water supply and filling maps in gravity collectors. During the calibration, it was shown that the sand that got into the pipelines shifted to the entrances to the buildings and the dead ends of the network. Some sewer collectors were completely clogged with sludge from the flood. Figure 7 shows illustrations for optimizing the connection of a new residential community to existing water supply and sanitation networks.

4. Conclusions

A set of models and methods is proposed for assessing the health, optimization and reconstruction of developing water supply and sanitation systems. These models and methods are implemented in the TRACE-VK software complex, the use of which in the practice of operation and design of water supply and sanitation systems has shown its economic efficiency and efficiency in substantiating design decisions.

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