Survey of the Water Distribution Network Operation Using a Hydraulic Electronic Model

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Key words: System, water distribution network, pipelines, simulation, information, calibration.

Abstract: The integrity and safety of public water supply are among the main requirements for these systems - the most important component of public health and one of the main priorities of the federal social policy (Primin, Gromov, 2021; Primin, Pupyrev, 2012). The development of water industry and engineering infrastructure in Russian cities must be carried out in accordance with the projects of the water supply and wastewater disposal schemes. The water distribution network is one of the most cost-expensive and at the same time vulnerable elements of the municipal water supply system. The significant amount of statistical and operational information, complex configuration and structure of the municipal water supply systems, uncertainty of water demand required the use of information technologies to study the functioning of the municipal water distribution network. The paper describes the implementation of the project based on the use of a hydraulic electronic model of a water distribution network

1 INTRODUCTION

Estimation of the condition, water supply continuity, development of engineering and technical solutions aimed at developing and upgrading the system, assessment of the required capital investments are the main objectives while examining the efficiency of the water distribution network of a public water supply system (Chupin, Melekhov, 2020; Hayworth, 2009).

Currently, more than 18 billion cubic meters of water are supplied annually to the water networks in the Russian Federation; however, 30.5 million people, or 22% of the population, are not provided with public water supply services so far. There is no public water supply in 12% of cities and 68% of rural settlements. Water losses in the water distribution networks average 19% of the total volume supplied. The condition of water-transportation conduits is worrying. In terms of the length of underground pipelines, Russia ranks second in the world, and in terms of deterioration of pipes, Russia is among the leaders; hence resulting in a high failure rate of pipelines, losses of drinking water and wastewater leaks (Primin, Pupyrev, 2012). According to the data of the RF Ministry of Construction the vast majority of water and wastewater pipelines in the Russian cities (more than 60%) today have been worn out and need to be reconstructed.

This situation causes serious harm to the life and health of the Russian citizens, damage to the environment and the state's economy; and entails an increase in water tariffs.

As regards the organizational policies, currently, with the development of the economy, market consolidation, and improvement of the regulatory framework in terms of design and construction of water supply systems in Russian cities, a real opportunity has emerged for a large-scale

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reconstruction of public water supply systems in Russia.

This is one of the main targets of the Federal Project “Clean Water” developed within the framework of the national project “Ecology” in accordance with Decree of the President of the Russian Federation dated May 7, 2018 No. 204 “On the national objectives and strategic missions of the development of the Russian Federation for the period up to 2024."

In operating practice, the general requirements to the technical inspection of public water supply systems are given in Article 37 of the Federal Law of the Russian Federation dated December 7, 2011 No. 416-FL “On Water Supply and Wastewater Disposal” and determined by Order of the Ministry of Construction of the Russian Federation dated August 5, 2014 No. 437 “On approval of the Requirements to the technical inspection of public hot water supply, cold water supply and (or) wastewater disposal systems.”

However, the analysis of these documents showed the lack of recommendations during the survey for the use of advanced information technologies, software products for estimating the operation and condition of the water distribution network, obtaining and using the initial data needed for the development and upgrade of water supply systems of the cities and communities in Russia, and plans of action to improve the reliability of water supply in accordance with the established requirements, based on their technical condition and actual operating conditions.

The research carried out in NRU MSUCE proved the efficiency of using hydraulic electronic models in the furtherance of these goals (Gromov, 2018).

2 SURVEY METHOD

The electronic model of a water supply system is an information system consisting of databases, technical support and software designed for the storage, monitoring and updating the information on the engineering and technical condition of public water supply systems; implementing the mechanism of the supervisory control in the system, and carrying out hydraulic calculations. Herewith, the electronic model of a water supply system is an integral part of the water supply scheme being, at the same time, a powerful tool for estimating, as part of a technical survey, the measures on upgrading the system, such as: searching for and eliminating latent water losses, optimizing the water distribution network, identifying emergency areas, selecting the locations for installing dictating points and pressure regulators.

The electronic model of a water distribution network consists of two parts: a database and software. The database contains the information that describes the operational characteristics of the water distribution network, such as: the diameter, material of the pipelines, diameter of the valves, water abstraction amount, characteristics of the pumping equipment, and much more. The topographic framework of the hydraulic electronic model of the water supply is the Master Plan of the city and water pipeline routing in the format of the geographic information system (GIS) (Gromov, 2018).

The electronic model software package provides for solving continuity and energy balance equations in order to determine pressure losses in the water distribution network and allocation of costs. Continuity equations ensure compliance with the mass conservation law. Energy equations ensure compliance with the energy conservation law with account of the pressure losses along the length of pipelines and local pressure losses. The global energy balance round each closed loop in the system must be equal to zero.

The requirements to the software of the electronic model of the municipal water supply system in Russia are regulated by the Decree of the RF Government of September 5, 2013 No. 782 “On the water supply and wastewater disposal schemes.” In accordance with it, the software of the hydraulic electronic model shall provide for the storage and possible update of the following information on the water supply and distribution system:

-graphic display of the water supply facilities with reference to the topographic basis of the municipal unit;

- description of the main facilities of the water supply systems;

- description of the actual characteristics of the operating modes of the water supply system and its separate elements;

-simulation of all types of switches over carried out in the network;

- measurement of the water consumption and calculation of pressure losses in the sections of the water distribution network;

-calculation of changes in the characteristics of the water supply facilities in order to simulate various scheme options;

-estimation of the implementation of scenarios for the perspective development of the water supply system in terms of ensuring water supply modes.

Currently, various software packages can be used for the practical implementation of the hydraulic electronic models (Bentley, MIKE URBAN, ZuLu, ISIGR, Citi Com, etc.. In the Russian Federation, domestic software products are most popular, this is largely due to the low price compared to the considered software packages and a sufficient set of functions.

One of the main software products developed by Polyterm Russian company is ZuluHydro computer-aided calculation package for the survey and analysis of water supply networks in large cities.

ZuLuHydro software package provides for completing the following tasks: conducting a scheduled annual analysis of the condition and operation efficiency of the network; identifying overloaded sections of the network and equipment that limit the conveying capacity; performing hydraulic calculations and analysis of the possible consequences of the scheduled switches over in the water mains; revealing the areas with increased hydraulic resistance and latent leaks by comparing the calculation results with the data of the manometric survey of the network; simulating emergency situations in the network and justifying the measures to minimize the consequences of the failures; simulating the consequences of major water abstractions associated with big leaks in case their urgent localization is not possible; looking up for the gate valves to isolate the failed section of the water distribution network; estimating the hydraulic pattern of the consumer activities and the impact of cutoffs in the water distribution network.

It should be noted that ZuLuHydro software package provides for developing independently plugs-in while installing ZuluNetTools and ZuluXTools components. Besides, this software product has a reference book and a support system in Russian.

An analysis of the ZuLuHydro capabilities shows that this package does not provide for estimating the convergence of the model with respect to the operation of a real water supply system.

Since 1990 **Potok** data processing center has been developing and implementing information systems for the utility operators. One of the products of this company is IGS package. The developer of the software product presents the following characteristics:

-Hydraulic calculations of water distribution networks of arbitrary complexity with an unlimited number of sources and pumping stations operating for the common network, situational simulation and analysis of the water supply modes.

-Simulation of switches over and their arbitrary combinations.

-Optimization of operating modes for pumping stations; drawing up hourly process flow diagrams and schedules of clean water tanks filling.

- Simulation of emergency situations, drawing up recommendations for the localization of failures with the generation of comprehensive reports on the zone of emergency shutdown.

-Simulation of water consumption objects and networks of perspective development, drawing up technical specifications for the connection of consumers.

-Building piezometric graphs including comparative ones for different day hours and water consumption patterns.

-Keeping and analyzing the logs of the network failure rates.

-Keeping switch over logs and retrospective analysis of the modes according to the log data.

-Keeping the logs of applications for scheduled and emergency repairs and rehabilitation works; logs of the vehicles and machinery use; drawing up work orders for the maneuver brigades.

- Analysis of the performance indicators of the water supply system.

- Drawing up preventive maintenance schedules.

-Full capacity of the GIS geographic information system and certification of networks and equipment for the water supply system.

The characteristics of CityCom-GroGraf software fully meet the requirements set by the Decree of the RF Government No. 782 of September 5, 2013; however, this software does not provide for estimating the model convergence, and lacks the functions of automatic model calibration.

ISIGR software package was developed by the Institute of Energy Systems named after L.A. Melent'ev of the Siberian Branch of the Russian Academy of Sciences. A distinctive feature of ISIGR software package is that it is implemented as an Internet system that provides for the connection to make hydraulic calculations from anywhere in the world provided a computer and Internet are available.

The functionality and capabilities of the domestic products are lower compared to Bentley WaterGEMS and Mike Urban software packages based on EPANET standard. Nevertheless, it can be said with full confidence that the presented domestic software packages are capable of completing the main tasks of the hydraulic survey of the municipal water distribution network while providing for a large amount of reporting information.

In terms of the cost-benefit analysis, energy and water quality calculations, the Russian software packages are somewhat retarded compared to Bentley WaterGEMS and Mike Urban software. Therefore, while choosing a software product for developing an electronic model, one must be sure that either now or in future the operator of the water distribution network will not face the tasks that the Russian software packages cannot complete. A significant disadvantage of the Russian software packages is that they do not provide for a complete design solution in terms of the system energy efficiency and water quality. It should be noted that the Russian software packages are not based on a common standard; thus, it is not inconceivable that certain problems can arise while transferring the data from one software package to another.

Building a hydraulic electronic model involves the following steps:

1. Building a design scheme of the model.
2. Developing the balance characteristics of the model.
3. Carrying out preliminary calculations of the system.
4. Calibrating the hydraulic model.

Building a design scheme consists in choosing the type of the design scheme (scaled-up or detailed); it is based on a geophysical basis on a scale of M 1:500. To link the water supply network diagram to the local plan, one has to use the functions of modern software systems and load additionally topographic tablets, geophysical basis or other necessary graphic information in the format of ca geographic information system (GIS) into the program.

Developing the balance characteristics of the model consists in the development of a balance scheme in accordance with the adopted type of the design scheme. During this stage, an analysis of the balances of the water consumption in the city is carried out. This stage provides for indicating certain consumption values for each consumer included in the model.

Carrying out preliminary calculations of the system consists in correcting errors and inaccuracies in the electronic model. The purpose of this stage is launching hydraulic calculation in the software package.

Calibration of the hydraulic model consists in making various changes to the model in order to accurately match the model to the operation of the system based on a series of measurements in the network.

To build a hydraulic model the following information is required:

1. Characteristics of the elements of the water distribution network (pipelines, pumping units, tanks, control valves).
2. Water consumption of consumers assigned to the corresponding network nodes.
3. Topographic information (geodesic marks in the network nodes, coordinates).
4. Information about the system control (for example, pump operating mode).

It is recommended to use design schemes of two types: detailed and scaled-up. A detailed design scheme of the network includes all the elements (pipeline routing, information on the system consumer flow rates, schemes of pumping stations, central heating stations, etc.).

Figure 1 shows an example of a part of the detailed hydraulic electronic model of a city in GIS format.

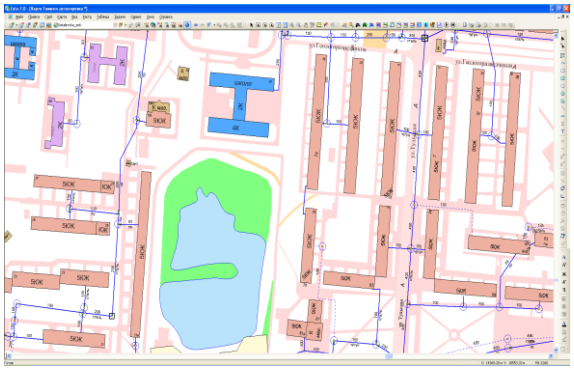

Figure 1: Example of a part of the detailed hydraulic electronic model.

In case a water utility operator does not have a developed water supply model while conducting a survey of the water distribution network, the decision to build a scaled-up network model as a first stage of the detailed model implementation is made.

The scaled-up model provides for analyzing the operation of the major water mains and pumping stations, as well as estimating possible passing of the required flow while connecting large water consumers. Once the design scheme of the selected type has been built, the flow characteristic of the model is determined that is based on the analysis of the operational data and actual supply of the booster pumping stations. Based on the analysis, the maximum day and maximum hour of water delivery is determined. Next, a balance diagram of the system is made that includes zones, as well as subzones of the water supply system.

Based on the balance scheme, either the hydraulic calculation of the water distribution network can be

performed for the estimated hour; or 24-hour system simulation can be executed.

Choosing the type of the design scheme of the electronic model should be based on the simulation objectives, amount of available initial data, as well as on the time required for the implementation of the model.

3 SURVEY RESULTS

Fundamentally, all the software packages for the hydraulic calculation of the water distribution network have been designed to solve a system of equations that satisfy Kirchhoff's I and II laws.

In the process of mathematical simulation of water supply systems, the design network scheme is presented in the form of an oriented graph where elements of the water distribution network such as pipelines are usually presented in the form of edges (branches) with account of the water flow direction. The key elements of the hydraulic electronic model are system consumers, pumping equipment, hydrants, etc.

Herewith, the hydraulic calculation methods require an unambiguous specification of initial data, which in turn is characterized by significant uncertainty. It should be noted here that while calculating the designed network, the resistances of its elements, i.e. pipeline sections, are known and can be taken from reference books (11).

Studies in real networks have shown that while calculating an existing network, the resistance of sections may differ from the tabular values. In this regard, it should be noted that about 70% of pipelines in Russia are made of steel. Without adequate protection steel pipelines are most vulnerable to the internal and external corrosion. In turn, the internal corrosion is the main reason for changes in the hydraulic resistance of steel pipelines.

Studies have shown that a fairly large number of factors can influence the discrepancy between the electronic model of the system and the actual data on the network operation:

- incorrectly entered network topology;
- incorrect display of the boundaries of water supply zones in the model;
- adopted simplifications and assumptions in the development of the model;
- errors while entering the information on the system structures (for example: ground elevations, lengths and diameters of the pipelines, characteristics of control valving);
- incorrectly entered level in the regulating tanks;
- indication of incorrect data on the operation of pressure regulators;
- indication of incorrect operating characteristics of pumping units;
- changes in the hydraulic characteristics of the network elements with time (increase in the pipeline resistance, changes in the *Q-H* characteristics of the pumps, changes in the amount of water abstraction);
- incorrect distribution of water flows in the system in relation to the actual water consumption;
- errors in elevation marks while allowing for the data of the pressure sensors;
- latent leaks in the network.

The main objective of calibrating an electronic model of a water distribution network is to ensure the model keeping the measured characteristics of a real water supply system (Vassiljev, 2009). From a mathematical standpoint, the process of a hydraulic model calibration consists in minimizing target *E* function:

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$$E = \sum_{j=1}^{P} w_h \, (h_j^m - h_j)^2 + \sum_{i=1}^{Q} w_q \, (q_i^m - q_i)^2 \quad (1)$$

where P and Q are the measurable values of pressure and flow rate; h_i^m - measurable head in assembly j; h_j - design head in an assembly j; q_i^m- measurable flow rate in pipe i; q_i - design flow rate in pipe I; w_h and w_q are dimensional weighting factors for the pressure and flow measurements, respectively.

In fact, *E* function is the sum of the quadratic differences between the actual network operation data and simulated flow and free head data. Therefore, this function reflects the convergence of the model with the operation of a real network. Accordingly, the objective of the calibration is to minimize this function. As part of the development of a method for calibrating an electronic model of a water distribution network, macro- and micro-calibration is proposed. Macro-calibration focuses on the convergence of the entire water supply network model. In this case, the material of the pipeline is taken into account while estimating the roughness value of a particular pipeline in accordance with the following equation:

$$\varepsilon_i = \varepsilon_{max} - (\varepsilon_{max} - \varepsilon_{min}) \left[{(age_{max} - age_i)} \Big/ {(age_{max} - age_{min})} \right]^b, \quad (2)$$

where ε_i – roughness of pipe i, mm; ε_{max} и ε_{min} – maximum and minimum roughness values

corresponding to age_{max} and age_{min} – maximum and minimum time for pipeline laying. The degree *b* in equation (2) provides for accounting additionally for the power dependence of the distribution of equivalent roughness relative to the pipeline laying time. The value of the degree *b* is refined during the model calibration process.

4 DISCUSSION OF THE RESULTS

The analysis of Russian software products showed the lack of the algorithm-driven calibration function. In this regard, an algorithm for automatic calibration of the electronic model for "Zulu" Russian software was developed based on the genetic algorithm (Primin, Gromov, 2018).

The calibration algorithm is implemented in Visual Basic for Application (VBA) language using Excel spreadsheets and ActiveX library of ZuLuNetTools components.

The structure of the algorithm action includes:

1. Acquiring from the electronic model database the data on the material and year of the pipeline construction.

2. Based on the values of the specified range of roughness as a result of calculation using formula (2), the algorithm determines the values of the equivalent roughness of each pipeline.

3. The equivalent roughness values obtained as a result of the calculation are exported to the electronic model database, whereafter a hydraulic calculation of the network is carried out.

4. After performing the hydraulic calculation, the macro calibration algorithm calculates the value of the function *E* using formula (1). Based on the obtained values, a surface is formed that reflects the dependence of the objective function *E* on the maximum values of the roughness of pipelines made of various materials. Next, the minimum value of the function *E* and the corresponding maximum values of the equivalent roughness of steel and cast iron pipelines are selected.

The developed calibration algorithm was evaluated while building a real electronic model of the water distribution network of one of the Russian cities (Primin, Gromov, Stepanov, Kozlova, 2018).

5 CONCLUSIONS

1. One of the important steps in the use of information technology in the survey of the operation of a water distribution network is the use of hydraulic electronic models.

2. Electronic models are tools for evaluating the current state of the water supply system, and allow modeling its prospective development.

3. Based on the experience of implementing electronic models in a number of Russian cities, a technique for building electronic models, and algorithms applicable to the Russian software "ZuLuHydro" and needed for building and calibrating models were developed.

4. So that the electronic model corresponded to the real characteristics of the system, carrying out a calibration stage is required. From a mathematical standpoint, calibration involves minimizing the function that reflects the quadratic difference between the measured characteristics of the system and the values obtained as a result of the simulation.

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