The use of a hydraulic electronic model to assess the functioning of the water supply network

Grigorii Gromov [*], and *Oleg* Primin

National Research Moscow State University of Civil Engineering, Moscow, Russia

Abstract. Reliability and safety of centralized water supply are fundamental requirements for these systems — the most important component of public health and one of the key priorities of the state's social policy. The development of water management and engineering infrastructure in Russian cities should be carried out under the draft schemes of water supply and sanitation. The water supply network is one of the most expensive and vulnerable elements of the city's water supply system. A significant amount of statistical and operational information, the complex configuration and structure of urban water supply systems, and the uncertainty of water demand required the use of information technologies to survey the functioning of the city's water supply network. The article presents their implementation based on the use of a hydraulic electronic model of a water supply network.

1 Introduction

The main task of the survey of the efficiency of the functioning of the water supply network of the centralized water supply system is to assess its condition and the continuity of water supply, to determine the engineering and technical solutions aimed at the development and modernization of the system, as well as the required capital investments [3,4].

Over 18 billion cubic meters of water are supplied to the network in the Russian Federation annually, but 30.5 million people - 22% of the population - do not have a centralized water supply. There is no centralized water supply in 12% of cities and 68% of rural settlements. Water losses in the water supply networks represent on average 19% of the total supply. The state of water supply networks is a cause for concern. Russia has the world's second-longest underground pipelines and one of the highest levels of dilapidation. This leads to a high pipeline failure rate, drinking water losses, and sewage leaks [2]. According to the Ministry of Construction of Russia, the vast majority of pipelines of water supply and sewerage networks in Russian cities (over 60%) have significant physical deterioration and need reconstruction.

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

[*] Corresponding author: gromovgn@mgsu.ru

With the development of the economy, the strengthening of market mechanisms, and the improvement of the regulatory framework for the design and construction of water supply systems, there is a proper opportunity for the large-scale reconstruction of Russia's centralized water supply systems.

This is one of the main objectives of the federal project "Clean Water" as part of the national project "Ecology" under the Presidential Decree of May 7, 2018 № 204 "On the national goals and strategic objectives of the development of the Russian Federation for the period up to 2024".

The analysis of the available regulatory documents of the Russian water sector showed the lack of recommendations on the use of modern information technologies, and software products to assess the functioning and reliability of the water supply network, getting and using baseline data for the development and reconstruction of water supply systems of Russian cities and settlements, action plans to bring water supply reliability in line with established requirements, based on their technical condition and actual operating conditions.

Researchers of the Moscow State University of Civil Engineering have shown the efficiency of the application of hydraulic electronic models for the decision of these problems [5].

2 Research methodology

The hydraulic electronic model of water supply systems is an information system, including databases, software, and hardware, designed to store, monitor and update information on the technical and economic condition of centralized water supply systems, implement the mechanism of operational and dispatch control in the system, and conduct hydraulic calculations. The electronic model of the water supply system is a part of the water supply scheme and a powerful tool for the evaluation of measures to upgrade the system, such as search and elimination of hidden water losses, optimization of the water supply network, identification of emergency sections, selection of dictation points and pressure regulators.

The electronic water network model comprises a database and software. The database includes operational characteristics of the water supply network: diameter, pipe material, the diameter of shut-off and control valves, size of withdrawals, characteristics of pumping equipment, and more. The topographic basis of the hydraulic electronic water supply model is the city's master plan and the tracing of the water pipes and network in Geographic Information System (GIS) format [5].

The e-model software solves the continuity and energy balance equations to determine head losses in the water distribution network and flow distribution. Continuity equations ensure compliance with the law of conservation of mass. The energy equations ensure compliance with the law of conservation of energy, considering the pressure losses of pipelines along the length and local pressure losses. The overall energy balance around each closed loop in the system must be zero.

The software of the hydraulic electronic model must ensure the storage and possibility of updating the following information about the water supply and distribution system:
- a graphic representation of the water supply system facilities regarding the municipality's topographical base;
- a description of the major facilities of the water supply system;
- description of the characteristics of the operation modes of the water supply system and its elements;
- modeling of many switching operations carried out in the network;
- determination of water discharge and calculation of head losses in the water supply network sections;

- calculation of changes in the characteristics of water supply system facilities to simulate different scheme options;
- assessment of implementing scenarios of prospective development of the water supply system to ensure water supply regimes.

For practical implementation of hydraulic electronic models, we can use various software packages (Bentley, MIKE URBAN, ZuLu, ISIGR, Citi Com, etc.). [6, 7, 8, 9, 10]. Domestic software products are the most popular in the Russian Federation because of their low price and sufficient set of functions.

The automated calculation complex ZuluHydro is one of the major software products of the Russian company "Polyterm", it investigates and analyzes outdoor water supply networks of large cities [6].

The ZuLu Hydro software package allows to solve the following tasks: to carry out planned annual analysis of network condition and efficiency of its operation; to identify overloaded network sections and equipment limiting throughput capacity; to perform hydraulic calculation and analysis of consequences of planned switching on the major network; identify areas with increased hydraulic resistance and hidden leaks based on a comparison of the calculation results with the data of the manometric survey of the network; simulate emergencies on the network and justify measures to minimize the consequences of these accidents; to simulate the consequences of large water withdrawals associated with large leaks when their urgent localization is impossible; search for valves that turn off (isolate) the emergency section of the water supply network; evaluate the impact of shutdowns on the water supply network and the hydraulic mode of operation of consumers.

The ZuLu Hydro software package allows you to develop your add-ons when you install the ZuluNetTools and ZuluXTools components. The software has a Russified manual and support system in Russian.

The analysis of ZuLuHydro possibilities shows that this complex lacks the possibility of assessment of model convergence about the operation of real water supply system.

Since 1990, "Potok" IVC company has been engaged in the development and implementation of information systems for enterprises, which operate engineering communication systems. One product of this company is a complex information geographic system [7]. The developer of the software product presents the following characteristics:
- Hydraulic calculations of water supply networks of arbitrary complexity with an unlimited number of sources and pumping stations operating on a common network, situation modeling, and analysis of water supply regimes.
- Modeling of switching operations and arbitrary combinations thereof.
- Optimisation of pumping stations' operation modes, generation of hourly operation charts and schedules for filling the clear water reservoirs.
- Simulation of emergencies, and formation of recommendations for the localization of accidents with the generation of comprehensive reports on the emergency shutdown area.
- Modeling of water consumption facilities and networks of prospective development, generation of technical conditions for connection of consumers.
- Construction of piezometric diagrams, including comparative diagrams for different hours of the day and water consumption modes.
- Maintaining and analyzing logs of network faults.
- Maintaining logs of switching and retrospective analysis of modes based on the logs.
- Maintenance of dispatch logs of applications for scheduled and emergency repair and recovery works, logs of machines and mechanisms usage, and formation of orders for line crews.
- Analysis of the technical and economic performance of the water supply system.
- Preparation of schedules of preventive maintenance.
- Full GIS functionality and certification of water supply system networks and equipment.

The software "CityCom-GroGraf" meets the RF Government Decree No. 782 of 5 September 2013, but cannot assess model convergence, nor does it have automatic model calibration functions.

L.A. Melentyev Institute of Energy Systems. L.A. Melentyev Institute of Energy Systems, Siberian Branch of the Russian Academy of Sciences has developed the software package ISIGR [8]. The distinctive feature of software complex ISIGR is the realization as an internet system that allows us to connect and make hydraulic calculations from any point of the world in the presence of a computer and internet connection.

The functionality and capabilities of the domestic products are lower than those of Bentley WaterGEMS and Mike Urban's EPANET-based software packages [10, 9]. The presented domestic software complexes can solve the major tasks of hydraulic study of the city water supply network with a large amount of reporting information.

Russian software packages are behind Bentley WaterGEMS and Mike Urban in terms of technical and economic calculation, energy calculation, and water quality calculation. Therefore, when selecting a software product for e-model development, you should be sure that the water utility company will not face any problems that the Russian software cannot solve. A significant disadvantage of Russian software packages is their inability to provide a complete design solution in terms of system energy efficiency and water quality. The Russian software packages do not have a common standard and therefore do not exclude potential problems in data transfer.

The construction of a hydraulic electronic model involves the following steps:

- Development of the model design scheme.
- Development of the balance characteristic of the model.
- Carrying out preliminary calculations of the system.
- Calibration of the hydraulic model.

The development of the design scheme comprises selecting the type of design scheme (enlarged or detailed) on a geo database on a scale of M 1:500. To link the water supply network scheme to the ground plan, we need to use the functions of modern software and upload to the program topographic maps, geo database or other necessary graphic information in the format of a geographic information system (GIS).

The development of the model's balance sheet is to develop a balance sheet according to the type of calculation scheme adopted. The analysis of water consumption balances in the city takes place at this stage. The outcome shows the flow rate for each consumer in the model.

The pre-calculation of the system comprises correcting errors and inaccuracies in the electronic model. This step runs the hydraulic calculation in the software.

Calibrating the hydraulic model comprises making various modifications to the model in order to match the model to the system operation based on a series of measurements on the network.

The construction of a hydraulic model includes the following information:

- Characteristics of the water network elements (piping, pumping units, reservoirs, control valves).
- Consumers' water flow rates assigned to the corresponding nodes in the network.
- Topographical information (geodetic marks at the network nodes, coordinates).
- System control information (e.g. pump operating mode).

We recommend the use of two types of design diagrams: detailed and aggregated. A detailed network design includes all elements of the network (pipe routing, consumer flow rate information, pumping stations, district heating substations, etc.). Figure 1 shows an example of a part of the detailed hydraulic electronic model of a city in GIS format.

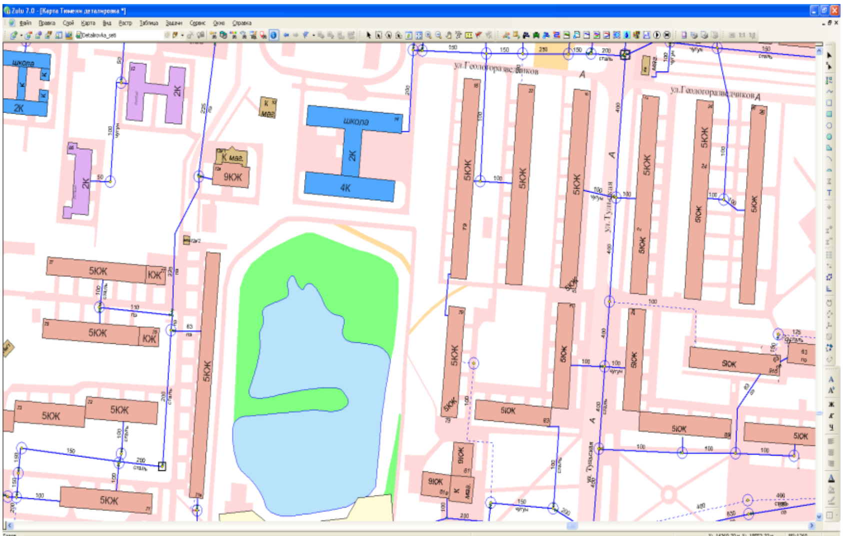

Fig. 1. Part of a detailed hydraulic electronic city model in GIS format.

When investigating the operation of a water supply network, if the water operator does not have a water supply system model, it is in most cases built an enlarged network model as the first step in implementing a detailed model.

The enlarged model allows the analysis of the major networks and pumping stations to be carried out and the possibility of passing the required flow rate when connecting large water consumers to the network is to be assessed. After selecting the type and constructing the calculation scheme, we determine the flow rate characteristic of the model based on the analysis of operational data, and the actual supply of the second lift pumping stations. Based on the analysis, we determine the maximum day and maximum hours of water supply. Then, the balance scheme of the system, which includes zones and sub-zones of the water supply system.

We can perform a hydraulic calculation of the water supply network based on a balancing diagram for a design hour or a 24-hour simulation of the system.

The choice of the type of electronic model design scheme should be based on the purpose of the simulation, the amount of input data, and the required time frame for implementing the model.

3 Research results

All software packages for hydraulic calculation of a water supply network have the purpose of solving a system of equations satisfying Kirchhoff's I and II laws.

The calculation scheme of the network in the mathematical modeling of water supply systems is an oriented graph, where elements of the water supply network are usually as edges (branches), as pipelines (considering the direction of water flow). Nodal elements of the hydraulic electronic model are consumers of the system, pumping equipment, hydrants, etc.

Hydraulic calculation methods require unambiguous input data. With a projected network, the data on resistance of its elements, i.e. pipeline sections, is known and can be accepted according to references [11].

Investigations on real networks have shown that the resistances of sections may differ from the table values. We note that about 70% of the pipelines in Russia are steel. Steel pipelines without adequate protection are the most vulnerable to internal and external corrosion. Internal corrosion is the major cause of changes in the hydraulic resistance of steel pipelines.

Studies have shown that many factors influence the discrepancy between the electronic model of the system and the actual network operation data:
- incorrectly recorded network topology;
- incorrect representation of water supply zone boundaries in the model;
- simplifications and assumptions made during model development;
- errors in entering information on system objects (e.g. ground elevations, lengths and diameters of pipelines, characteristics of control valves);
- incorrect entry of the level in the control tanks;
- incorrect information about the operation of pressure regulators;
- incorrect operating characteristics of pump units;
- changes in the hydraulic characteristics of the network elements over time (increase of pipeline resistance, changes in Q-H characteristics of pump operation, changes in water withdrawal values);
- incorrect distribution of water discharge in the system about actual water consumption;
- errors in elevation when considering data from pressure sensors;
-concealed leaks in the network.

The main purpose of calibrating an electronic water network model is for the model to follow the measured characteristics of a proper water system [12]. From a mathematical point of view, calibrating a hydraulic model comprises minimizing the target function *E*:

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

where *P* and *Q* are the measured values of pressure and flow; h_i^m- s the measured head at node *j;* h_j – the calculated head at node *j;* q_i^m- the measured flow in *i* pipe; q_i- the calculated flow in *i* pipe. w_h and w_q — dimensional weighting factors for pressure and flow measurement values.

The function *E* is the sum of the quadratic differences between the actual network operation and the flow and head simulation data. The function reflects the convergence of the model to the real network operation. The calibration task is to minimize this function. As part of the development of the electronic network model calibration methodology, we propose the use of macro- and micro-calibration. Macro calibration is focused on the convergence of the whole water network model. We take the pipeline material into account when estimating the roughness value of a particular pipeline according to the following equation:

$$\mathrm{E_i} = \varepsilon_{\max} - (\varepsilon_{\max} - \varepsilon_{\min}) \left[{(\mathrm{age_{max}} - \mathrm{age_i})} \big/ {(\mathrm{age_{max}} - \mathrm{age_{min}})} \right]^{\mathrm{b}} \tag{2}$$

where ε_i - the roughness of *i* pipe, mm; ε_{max} and ε_{min} - maximum and minimum roughness values, which correspond to age_{max} and age_{min} - maximum and minimum pipeline laying period". The degree *b* in equation (2) additionally allows to take into account the power dependence of the distribution of equivalent roughness about the pipe-laying period. The value of the degree *b* is refined during the model calibration process.

4 Discussion of results

Analysis of Russian software products showed a lack of algorithmic calibration functions. The algorithm of automatic calibration of the electronic model for Russian software "ZuLu Hydro" is developed based on a genetic algorithm [13].

The calibration algorithm is written in Visual Basic for Application (VBA) language using Excel tables and "ZuLuNetTools" ActiveX component library.

The work structure of the algorithm includes:

- Getting pipeline material and year of installation data from the electronic model database.
- Based on the values of the specified roughness range, the equivalent roughness values of each pipeline are determined by the algorithm using formula (2).
- The resulting equivalent roughness values are exported to the electronic model database, after which the hydraulic calculation of the network is carried out.
- After the hydraulic calculation has been performed by the macro calibration algorithm, the value of the E function is calculated using the formula (1). Based on the values got, a surface is formed that reflects the dependence of the target function E on the maximum roughness values of pipelines made of different materials. Then the minimum value of the function E and its corresponding maximum values of equivalent roughness of steel and cast-iron pipelines are selected.

The construction and calibration algorithm has been tested during a performance survey using a real electronic model of the water supply network of one of the Russian cities [14].

5 Conclusions

Using hydraulic electronic models is one of the important steps in using information technology in assessing the functioning of the water supply network.

Electronic models are a tool for assessing the current state of the water supply system and also allow modeling prospective development.

Some Russian cities have developed techniques for building electronic models, algorithms applicable to the Russian software "Zuu Hydro" required to build and calibrate the models.

The calibration step is necessary for the electronic model to match the actual performance of the system. Calibration from a mathematical point of view consists in minimizing a function that reflects the quadratic difference between the measured system characteristics and the values got from the simulation.

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