Calibration of water supply electronic models (by example of water supply network of city of Salavat)

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Abstract. In accordance to the Russian Federation legislation acts, it is necessary to develop a hydraulic model as a part of city’s water supply scheme (document). It is necessary to calibrate a hydraulic model to get reliable results as a result of modelling. The analysis of Russian software reveals the lack of the auto-calibration function. The goal of this article is to describe the algorithm of hydraulic model calibration by the example of the water supply network of the Salavat city (Russian Federation, the Republic of Bashkortostan). The algorithm uses information about the material and age of pipes. The algorithm is developed on the basis of VBA language applying Excel tables. The developed algorithm is applicable to the most popular Russian software.

1. Introduction

According to the information of the Federal Government Statistical Service, in most Russian cities the average specific water consumption for drinking and household needs amounts to some 220 – 240 l per capita per day [1], considerably exceeding the corresponding value for most West-European countries. Some reduction in water consumption, specific for Russia in recent years, resulted in reduced water consumption from the water supply system and increased operating costs of Vodokanals (Russian Water Supply & Wastewater Disposal Administrations), because of the necessity to carry out some additional operations improving the sanitary safety of water (quality control, washing out, etc.).

Despite the stable dynamics of water consumption reduction in Russia, the average percentage of leakages and unaccounted water consumption of the total volume of water, supplied to the network, amounts to some 20 – 30 percent [1]. In this connection, it should be noted that the leakage value is directly proportional to the current condition of the relevant water supply system and the quality of its operation. Water losses result not only in operating costs growth and deteriorated operating results of the system, moreover they are among the results of degraded quality of rendered services.

It should also be mentioned that the depreciation of the facilities and equipment of Russian water-sector enterprises amounts to 54 percent [2]. The percentage of steel pipelines operated in the Russian Federation is 70 percent. At present most of Russian water pipes are considerably physically depreciated and need reconstruction [3].
All these factors should be taken into account for working out the schemes for the development, reconstruction and operation of Russian urban water supply systems. According to the existing Russian Regulations for the Development and Approval of Water Supply and Wastewater Disposal Plans [4,5], these plans must comprise the electronic model of the centralized water supply and wastewater disposal systems of a city. The objective assessment of the impact of measures aimed at improved operation of a water supply system requires computer-based simulation based on the application of an adequate electronic model. The validity of an electronic model with respect to the current operating results of a water supply system is provided through its calibration.

In this respect it should be mentioned that the electronic model of a water supply system is an instrument for analyzing the operation of this system, apart from that, the model makes it possible to model some future measures aimed at its further development.

It is also worth mentioning that in accordance with the Regulations for the Development and Approval of Water Supply and Wastewater Disposal Plans [5], the requirements for the development of electronic models are standardized. Nevertheless, these requirements are related to the model content and the software. They do not comprise any explanations concerning the methodology and the degree of the detailed elaboration of models; there are also no any requirements for the convergence of electronic models and the actual operating results of relevant systems. The instrument that solves this task is the calibration of the electronic models of water supply systems.

2. Approaching the calibration of the electronic models of water supply systems

The analysis of available data [6] reveals that the approaches to the calibration of electronic models may be subdivided into the following three categories

1. Iterative models (trial-and-error method);
2. Expanded calibration models;
3. Implicit calibration models.

The calibration of iterative models requires “manual” correction of initial data to be performed at every stage. As a result of great time expenditures required for model calibration, this method is based on network simplification.

Expanded calibration models are based on solving some extended set of equations of mass and energy balance. “Mathematical Flow-Meter” [7] may be an example of this approach.

Implicit calibration models are based on solving the optimization problem of weighted-least-squares type aimed at its minimization. The article [8] comprises the equation of such a function (E):

\[ E = \sum_{i=1}^{P} w_p (h_{i,m} - h_i)^2 + \sum_{j=1}^{Q} w_q (q_{i,m} - q_i)^2 \]  

where P and Q are the values of pressure and flow-rate correspondingly measured, \( h_{i,m} \) - measured pressure in the i unit, \( h_i \) - design pressure in the i unit, \( q_{i,m} \) - measured flow-rate in the i pipe, \( q_i \) - design flow-rate in the i pipe, while \( w_p \) and \( w_q \) - the weight factors for the pressure and flow-rate correspondingly.

The world-wide famous software products, such as Mike Urban [9] and Bentley [10], apply implicit (optimization) calibration models. The operating manual of Mike Urban software comprises the description of a calibration module [11] based on the application of a complex genetic algorithm. For its operation many parallel computations are needed. The architecture of a complex genetic algorithm is contained in the operating manual for the application of Darwin Calibration [12] of Bentley software.

Regardless a high productivity of complex genetic algorithms, when a large number of unknowns is preset, the work time for detailed electronic models is high enough. Therefore, the Mike Urban Operating Manual [11] and [13] propose to group the pipelines preliminary, according to their roughness or some other characteristics. Also, in order to coordinate such factors as pipe material, year of laying and roughness, the authors of works [14] and [15] offered the following formula:
\[ e_i = e_{\text{max}} - \left( e_{\text{max}} - e_{\text{min}} \right) \left[ \left( t_{\text{max}} - t_i \right) / \left( t_{\text{max}} - t_{\text{min}} \right) \right]^b \]  

where: \( e_i \) - roughness for the \( i \) pipe, mm; \( e_{\text{min}} \) and \( e_{\text{max}} \) - minimal and maximal roughness values, which correspond to the minimal and maximal pipe ages, mm; \( t_{\text{min}} \) and \( t_{\text{max}} \) - minimal and maximal ages of the pipelines in a group, year.

Summing up the discussion of different approaches to the calibration of electronic models of water supply systems, it should be mentioned that at present Russian software products are most popular for the development of water supply and wastewater disposal systems in Russia, since their prices are lower than the prices of foreign software (Mike Urban, Bentley). Nevertheless, the analysis of Russian software ("ZuLu" [16], "CityCom-GidroGraf" [17], "ISIGR" [18]), reveals a lack of any auto-calibration functions. That is why the calibration of electronic models developed on the basis of Russian software requires the establishment of additional sub-programs.

This article represents the algorithm for the calibration of the electronic model of a water supply system for the Russian software "ZuLu". The operation of the algorithm is validated by the example of the calibration of a detailed model of the water supply system of the city of Salavat (the Republic of Bashkortostan, the Russian Federation).

3. Analyzing and correcting the data of the electronic model of a water supply system

Salavat is rather a small city having the population of 165 thousand people. It is located between two large cities – Ufa and Orenburg.

The water source of Salavat is a deep-well water intake. The pumping equipment of the city pumps the well water through the 3 water conduits of 3.4 km length each to the reservoir of the 2nd stage pumping station and there from to the municipal network of the city. The local Vodokanal owns a number of wells, 85 km of water conduits of 700 – 1000 mm diameter, 2nd stage and 3rd stage pumping stations, a chlorination plant and clear-water reservoirs of 40 thousand m³ total capacity. The total length of the networks amounts to 321 km.

In accordance with the [5], an electronic model based on "ZuLu" software system was made for the development of the water supply system of the city of Salavat. The analysis of the electronic model submitted by Salavat Vodokanal MUE revealed a considerable divergence between the model and the actual operation of the network. In particular, the following basic problems were revealed: incorrect network routing and incorrect detailing of the basic water supply facilities, as well as incorrect basing of the initial data on the elements of the network; apart from that, the electronic model was not calibrated.

Having analyzed the electronic model of the Salavat water supply system, MosvodokanalNIiproject JSC formulated the following basic goals of further work:

1. To update the existing routing of the electronic model of the water supply system and to coordinate it with the general design water supply system of the city;
2. To update the databases of the electronic model with the latest information;
3. To calibrate the electronic model on the basis of actual measurements of the flow-rate and hydraulic head.

Firstly, the correctness of the network routing displayed by the electronic model was analyzed through its comparison with the routing performed by Salavat Vodokanal MUE in the GIS "InGeo" software system. The analysis revealed considerable position differences between the existing network routing and the electronic model of the water supply system; in connection with this, a relevant correction was made.

The next stage of work revealed some differences in the ground elevation marks entered into the database of "ZuLu" software. A terrain model was developed in order to solve this problem. This terrain model was based on the data of the initial network routing "InGeo" GIS). The terrain model was made using the standard functions of "ZuLu" software.
4. The calibration of the electronic model of the water supply system of the city of Salavat

To calibrate the electronic model of the existing condition of the water supply network of the city of Salavat, the hydraulic calculation was made for a typical water consumption day. With this end in view, on the basis of available operational data, a daily water supply pattern was analyzed and the peak water consumption hour was determined. Based on the assumed calculation hour, there was developed a water-balance diagram which implied the subdivision of the water supply system of the city of Salavat into various groups of consumers based on their consumption rate.

In the electronic model, the water consumption rate of water users was corrected through increasing the consumption rates of various groups of water consumers. Also, for the calibration of the electronic model, the free-head measurements were made. These measurements were performed for the water supply network of the city of Salavat for the assumed calculation hour (36 measurement points). These measurements were made by Salavat Vodokanal MUE using the DM02-100-2-M pressure gauges. The on-site measurements thus obtained were bound to relevant wells in the electronic model of water supply. Also the calibration of the electronic model took into account the actual situation in the water supply system of the city: information concerning the process of pressure reduction, information regarding the cases of water conduit cut-off and data on the operation of pressure controllers.

The goal of the calibration of the electronic model of the water supply system of the city of Salavat was to adhere to the actual free-heads in the node points of the calculation model, in accordance with the assumed calculation, as well as to adhere to the water consumption from the water supply sources, according to assumed calculation hours.

In fact, the E function (1) is the sum of quadratic differences between the actual data on the network operation and modeling data on the flow-rate and free-head values. Therefore, this function reflects the convergence of the model with the operation of the actual network. Correspondingly, the aim of calibration is to minimize this function.

For the calibration of the electronic model, the weight factors \( w_h \) and \( w_q \) in formula 1 were assumed to be equal to 1. During the calibration process, the model was corrected through the changes in the equivalent roughness of pipelines. Equivalent uneven-grained roughness is the roughness height that produces the resistance that is equal to the actual resistance of the pipeline being tested [19].

It is also possible to correct the model through making the changes in the parameter of “pipe encrustation”. This encrustation is the result of physical, chemical and biological processes. Nevertheless, during the calibration of the water supply electronic model of the city of Salavat, there were no changes in this parameter in connection with the following factors:

1. "ZuLu" software system takes into account the “encrustation of pipes” as a homogenous reduction of their diameters, while actually “pipe encrustation” may be non-uniform.
2. The parameter of “pipe encrustation” has a considerable impact on pipe resistance variations compared to roughness changes and consequently, it provides a greater change in the E function.

The initial data on the routing of the water supply network (developed by "Salavat Vodokanal" MUE in the "InGeo" GIS software system) were used to take into account pipe age and material.

Equation (2) was used to assess the roughness value of a specific pipeline. For this purpose, the coefficient was assumed to be equal to 1. It should be mentioned that during the process of electronic model calibration, the roughness of polyethylene pipes was assumed to be independent of the pipe age and to amount to 0.03 mm. Also, as a limitation, the calibration of the model was made only for the pipeline sections which diameter exceeded 100 mm, because for large roughness values assumed for small-diameter pipes, some software errors occurred during the hydraulic calculations. In accordance with the hydraulic reference manual, the following minimal roughness values, corresponding to the minimal age, were assumed for steel and cast-iron pipes [20]:

- Steel water pipes, in operation currently: 1.20 - 1.50.
- Cast-iron pipes that had been in operation: 1.0 -1.5.

The calibration of the electronic model was carried out through the variation of the maximal roughness values for steel and cast-iron pipes that correspond to the maximal pipe age. The calibration
process required numerous hydraulic calculations. 256 hydraulic calculations were made in order to construct the surface shown in Figure 1. In order to automate this process, a VBA language-based algorithm was used applying Excel tables and ActiveX library of "ZuLuNetTools" components.

The algorithm is applicable to "ZuLu" software. To provide the operation of the algorithm, it is necessary to establish some additional fields in the database whereto the information concerning pipe age and material is entered for various pipeline sections. The range of maximal roughness values corresponding to the maximal pipe age is also preset as initial data. The structure of algorithm operation comprises the following:

1. Uploading the data on pipe material and year of laying from the "ZuLu" software system;
2. Using the values of specified range, the roughness values for every pipeline are calculated on the basis of equation (2);
3. The roughness values are exported into the "ZuLu" database and a hydraulic calculation is made;
4. Using equation 1, the value of F function is assessed for the specified value of maximal roughness. Calculation results shown in Table 1 are formed on the basis of obtained values.

On the basis of obtained surface, the user may select the optimal interrelation between the maximal roughness values and the convergence of the model.

Table 1. The values of the function E for various maximum values of roughness (tabular form).

| Roughness of steel pipelines, mm | 45 | 44 | 43 | 42 | 41 | 40 |
|---------------------------------|----|----|----|----|----|----|
| 254.87                          | 254.85 | 254.79 | 254.72 | 254.70 | 254.63 | 254.59 | 254.57 | 254.52 | 254.47 | 254.42 |
| 244.02                          | 243.95 | 243.86 | 243.81 | 243.69 | 243.63 | 243.60 | 243.55 | 243.50 | 243.48 | 243.40 |
| 235.71                          | 235.62 | 235.55 | 235.43 | 235.39 | 235.31 | 235.27 | 235.18 | 235.10 | 235.03 | 234.95 |
| 228.97                          | 228.90 | 228.80 | 228.75 | 228.65 | 228.58 | 228.46 | 228.39 | 228.33 | 228.20 | 228.15 |
| 225.14                          | 225.05 | 224.95 | 224.84 | 224.73 | 224.65 | 224.57 | 224.48 | 224.34 | 224.25 | 224.12 |
| 223.16                          | 223.05 | 222.92 | 222.79 | 222.70 | 222.56 | 222.42 | 222.36 | 222.30 | 222.14 | 222.10 |
| 238.83                          | 223.89 | 223.69 | 223.55 | 223.43 | 223.28 | 223.17 | 223.03 | 222.94 | 222.78 | 222.67 | 222.54 |
| 227.00                          | 226.68 | 226.41 | 226.26 | 226.10 | 225.99 | 225.81 | 225.72 | 225.55 |

Roughness of cast iron pipelines, mm

The minimal value of E function was 222.10 and for the maximal roughness value of steel pipes – 40 mm; cast-iron pipes – 50 mm. For the assessment of an electronic model calibration results one should take into account the obtained average roughness values of pipelines (steel pipes – 13.58 mm; cast-iron pipes – 14.63 mm). The results for the free-head convergence are given in Table 2. The results of convergence for the flow-rates of the sources are given in Table 3.

The average absolute free-head difference between the electronic model and the actual operation of the network was 4.03 percent.

The difference of free-head values between the electronic model and the actual operation of the network was within the range of 0.06 m – 4.5 m at 32 measurement points. The free-head difference within the range of 4.5 m – 7.72 m was observed at 4 points of the network; it is necessary to study these points in the future in order to detect some additional resistances.

The average absolute free-head difference between the design measurements and actual measurements was 3.99 percent. The average absolute flow-rate difference between the electronic model and the actual operation of the network amounted to 1.21 percent.
Table 2. The results for the free-head convergence between the model and water supply network.

| Point № | Free head fact, m | Free head calc, m | Δ, м | Δ^2, м^2 |
|---------|------------------|------------------|------|----------|
| 1       | 46.00            | 45.05            | -0.95| 0.90     |
| 2       | 45.00            | 45.03            | 1.03 | 1.06     |
| 3       | 45.00            | 46.88            | -0.12| 0.01     |
| 4       | 44.00            | 45.96            | 1.96 | 3.83     |
| 5       | 50.00            | 47.71            | -2.29| 5.23     |
| 6       | 47.00            | 47.07            | 0.07 | 0.01     |
| 7       | 46.00            | 46.85            | 0.85 | 0.72     |
| 8       | 44.00            | 45.90            | 1.90 | 3.63     |
| 9       | 45.00            | 46.95            | 1.95 | 3.79     |
| 10      | 40.00            | 42.42            | 2.42 | 5.87     |
| 11      | 51.00            | 50.39            | -0.61| 0.37     |
| 12      | 48.00            | 48.70            | 0.70 | 0.49     |
| 13      | 56.00            | 51.33            | -4.67| 21.77    |
| 14      | 44.00            | 50.97            | 6.97 | 48.51    |
| 15      | 48.00            | 52.06            | 4.06 | 16.49    |
| 16      | 51.00            | 50.70            | -0.31| 0.09     |
| 17      | 50.00            | 47.56            | -2.44| 5.94     |
| 18      | 43.00            | 46.84            | 3.84 | 14.75    |
| 19      | 41.00            | 44.69            | 3.69 | 13.62    |
| 20      | 43.00            | 42.11            | -0.89| 0.80     |
| 21      | 43.00            | 44.15            | 1.15 | 1.31     |
| 22      | 45.00            | 49.93            | 4.93 | 24.30    |
| 23      | 43.00            | 42.64            | -0.36| 0.13     |
| 24      | 48.00            | 48.04            | 0.03 | 0.00     |
| 25      | 47.00            | 48.75            | 1.75 | 3.07     |
| 26      | 44.00            | 45.50            | 1.50 | 2.24     |
| 27      | 44.00            | 44.19            | 0.19 | 0.03     |
| 28      | 43.00            | 43.93            | 0.93 | 0.87     |
| 29      | 43.00            | 44.72            | 1.72 | 2.96     |
| 30      | 53.00            | 52.44            | -0.56| 0.32     |
| 31      | 53.00            | 53.30            | 0.30 | 0.09     |
| 32      | 51.00            | 52.23            | 1.23 | 1.51     |
| 33      | 43.00            | 42.72            | -0.28| 0.08     |
| 34      | 46.00            | 47.56            | 1.56 | 2.43     |
| 35      | 47.00            | 49.22            | 2.22 | 4.93     |
| 36      | 44.00            | 49.04            | 5.04 | 25.44    |

Σ ∑ 217.60

Table 3. The results of the electronic model (the city of Salavat) convergence for the flow-rates of the sources.

| Source name                | Actual flow-rate, l/s | Model flow-rate, l/s | Δ, l/s | Δ^2, м^2 |
|----------------------------|-----------------------|----------------------|--------|----------|
| Reservoirs                 | 145.00                | 146.50               | +1.50  | 2.25     |
| 2nd stage pumping stations | 777.00                | 775.50               | -1.50  | 2.25     |
5. Conclusions
The existing standard requirements for the development of electronic models of water supply systems do not regulate the degree of convergence of the model and the actual operation of the network. The analysis of Russian software also reveals that electronic models lack the function of auto-calibration.

This article describes the electronic model calibration algorithm based on the linear law of pipe roughness variation, depending on its in-service time. The algorithm is developed on the basis of VBA language applying Excel tables and ActiveX library of "ZuLuNetTools" components; it is applicable to "ZuLu" software.

The operation of the algorithm was validated using the electronic model of the water supply system of the city of Salavat. The average absolute free-head difference between the calculation measurements and actual measurements was 3.99 percent. The average absolute difference for the flow-rates of sources was 1.21 percent.

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