Short Communication

A Hydraulic Model as a Useful Tool in the Operation of a Water-Pipe Network

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Abstract

Our paper presents a model of the water-pipe network for the Kawie Góry supply zone. The zone under analysis is part of the network operated by the PWiK (Water-Pipe and Sewage Company) in Czestochowa. The model was made in the Epanet program using numerical and operational data.

The water-pipe network under examination supplies water to a family housing estate and is fed from a field water-supply reservoir. The total population of the area is approx. 1,500 people, the length of the water-pipe network is 11,704 running meters, and the pipe diameter range is ♮ 100-150 mm. The pipes are made of grey cast-iron, PE, and PVC. Based on the selected measurement points, calibration of the model was performed. Within the validation of the model, sensitivity analysis was made.

Then, a series of simulations were performed to illustrate the network operation for variable water supply and demand conditions. Multi-period analysis was employed for modeling. The developed model made it possible to determine the magnitude of pressure in the network points, and flows in particular sections for operational parameters under consideration. The prepared model can also provide a base for alternative network management variants, for example in the case of failure or increased water demand and enable the forecasting of possible water shortage locations. In the event of the development of the network, in turn, it will enable the optimal design of new lines.

Keywords: water-pipe network, hydraulic model, model calibration and validation

Introduction

A water-pipe network constitutes one of the key elements of the water supply system and, at the same time, is usually the most expensive part of this system. Its purpose is to supply water in the required quantity and of proper quality under correct pressure and at a time convenient for every user. The prerequisite for meeting the above conditions is the proper design and execution of the new, as well as the operation of the existing network. At the same time, the correct operation and control of operation of the water line has a key influence on the water distribution costs, and thus on the final water price. A versatile tool that can be used both at the stage of designing a new network and during the operation of an existing one is the hydraulic model. The use of computers and available software programs offers virtually unlimited possibilities for solving water distribution-related problems, which would have not been possible to achieve using traditional methods (e.g. the capability to simulate the quality of water in the grid). Computer simulation of network operation facilitates the making of important decisions about ongoing tasks in a water supply company. Among those distinguished by high functionality are especially dynamic models that accurately reflect the network operation under variable water withdrawal conditions.

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Modeling involves the development of a mathematical model (using e.g. numerical methods) that will render the course of a given process as faithfully as possible. In the case of water-pipe networks, the point is that the behavior of water in the lines be reproduced in the most faithful manner, while considering parameters such as: water withdrawals, pressure and its losses, flows, velocities, water quality, etc. Taking measurements including the above quantities over the entire operated network is essentially impossible due to both the cost and duration of such analyses. The development and calibration of a model is more effective and provides the capability to simulate the operation of such a network [1, 2]. At the same time, the analysis of the network records made within modeling facilitates checking the input data describing the network for correctness. At the same time, relating the data obtained from modelling to the spatial information system (GIS) makes it better depicted [3].

The numerical analysis of the network also facilitates its assessment in terms of operation. The available programs enable the simulation of network operation after a specific time; it is then possible to cover the network points indicated by the model by special supervision. Modeling is helpful when planning overhauls or flushing individual water line sections. In turn, analysis of the behavior of the network during failures in its vulnerable sections makes it possible to make sure that the system equilibrium will not be disrupted and that water supply to the users will not be compromised. In that case, the model will allow alternative failure mitigation solutions to be tested [4, 5].

Modeling is especially important in the case of redevelopment or extension of an existing network. It is then possible to analyze different variants of proposed solutions and to select the most advantageous one in an expeditious manner. We are able to determine the effects of loading down the existing system and to capture any errors that occurred while designing new sections. The model will enable us to avoid oversizing a network or designing a network of too small a capacity against the demand. Therefor, it will bring about measurable savings at the construction stage, as it will enable the selection of the most economical variant and will eliminate any errors that might otherwise show up only at the execution or operation stages [6, 7].

Analyses and simulation computations could be conducted both for already existing or modernized networks and in the design of new networks. The use of numerical methods for modelling and simulation of water-pipe networks is of paramount importance for the optimization of operation of these networks. The growth and increasingly wide application of numerical methods stems chiefly from the need for the assessment, as well as proposing better solutions of the functioning of the water distribution subsystem under operational conditions. Available specialized programs such as Epanet, Piccolo, Mike Urban, Geosecma, or Woda, make use of hydraulic analysis algorithms that allow a network of any size and complexity to be analyzed. They enable local pressure losses on bends and reducers to be allowed for and provide the capability to model either the constant or variable speed of pump operation. A very great interest and increasingly common use of numerical methods for the computation of water-pipe networks is observed both at home and abroad [8, 9].

Purpose and Scope of the Study

The purpose of the study was to make a dynamic hydraulic model of a selected zone of the water-pipe network based on variable time standards, which was to be subsequently used for the analysis of network operation.

The scope of the work encompassed the following:

- collecting input data for the model
- entering the data in the program and making the model
- testing the sensitivity of the model
- calibrating the model based on field measurements
- carrying out a series of network operation simulations for variable water supply and demand conditions.

Input Data for the Model

The Kawie Góry supply area is situated within the area of the water-pipe network operated by the Czestochowa District Water-Pipe and Sewage Company (Przedsiębiorstwo Wodociągów i Kanalizacji Okręgu Częstochowskiego S.A.) with its ofice at 14/20 Jaskrowska St. in Czestochowa. The company supplies an area of about 1,000 km^2 with water and has the second longest network in Poland. The total length of the whole network is more than 2,200 km.

The Kawie Góry water-pipe zone under examination includes a family housing estate that borders the Północ and Rząsawa quarters of Czestochowa. The housing estate has a separated supply zone: water is supplied to the whole zone via a pumping station from the Kawie Góry field water-supply reservoirs of a total capacity of 10,000 m^3. The total length of the network in the examined area is 11.7 km, the number of water service lines is 368, and the number of users supplied by the water-pipe network is 1,472 people. The buildings in the zone under consideration are connected to the urban sewage system, while hot utility water is prepared locally. The zone area has no developed services; essentially, there are no industrial plants or public facilities here. The main users of water are households; in addition, some water is used by a car showroom or for watering greenery in an allotment garden.

Data for the water-pipe network, such as the arrangement of pipes, diameters, material, utilities, land ordinates, and the area supply method were obtained from the grind operator. Based on data from 2010-11, the average and maximum water demands in the examined area were calculated while considering the specificity of particular users. The withdrawal variation coefficients also were determined. Characteristic water demand quantities were as follows:

q_{dav} = 95-103 l/Person×day

N_{dmax} = 3.5 for the year 2010 and 1.9 for the year 2011

N_{hmax} = 2.7 for the year 2010 and 1.8 for the year 2011

The Hydraulic Model, Testing and Calibration of the Model

The hydraulic model was made within the Epanet 2 program. This is a software program designed for simulating water distribution systems, developed by the United States Environmental Protection Agency in 1994. The program is free of charge, and many chargeable applications for mathematical simulation of hydraulic systems make use of the Epanet's algorithms. In order to simplify the arduous Cross computational procedure, the so-called gradient algorithm-hybrid, or a hybrid node-loop iteration method (gradient method) was employed [10]. The multi-period analysis was used for modeling. The basic pattern of water demand distribution is based on the water consumption measurements during the calibration day. The developed grid model consists of 123 nodes interconnected with 130 pipe sections. The diameter range is ϕ 100-150 mm. The pipe material is cast iron, PE, and PVC. A schematic of the network structure is shown in Fig. 1. The developed model is characterized by a high degree of detail.

As per today, there are no guidelines in Poland that would specify the conformance criteria to be met when calibrating hydraulic models. Such prescriptions have been developed, however, in the UK and the USA. Accordingly, it is assumed in the UK that 100% of the pressure values from measurement data shall be contained within ±2.0 m of the water column (WC). In the USA, in turn, the permissible pressure deviation values shall be contained within ±1.4 m WC for 90% of measurements [11].

The created model was subjected to calibration based on select measurement points. Because of the degree of detail of the model, the required number of points should be 2% of nodes at the minimum [11]. During field tests, pressure measurements were taken at 4 nodes on the network and at the exit from the pumping station (4% of nodes). The measurement points were selected using the computational algorithm developed by R. Straubel and B. Holznagel [12]. For the calibration of the model, fire hydrant flow tests also were used, which were conducted according to [13].

During calibration, by varying the parameter values in the preset ranges and making simulation computations of the model, the pressures and flow in the network lines and nodes were calculated, which were then compared with the flow and pressures measured at the measurement points. As a result of this comparison, the mean absolute deviation

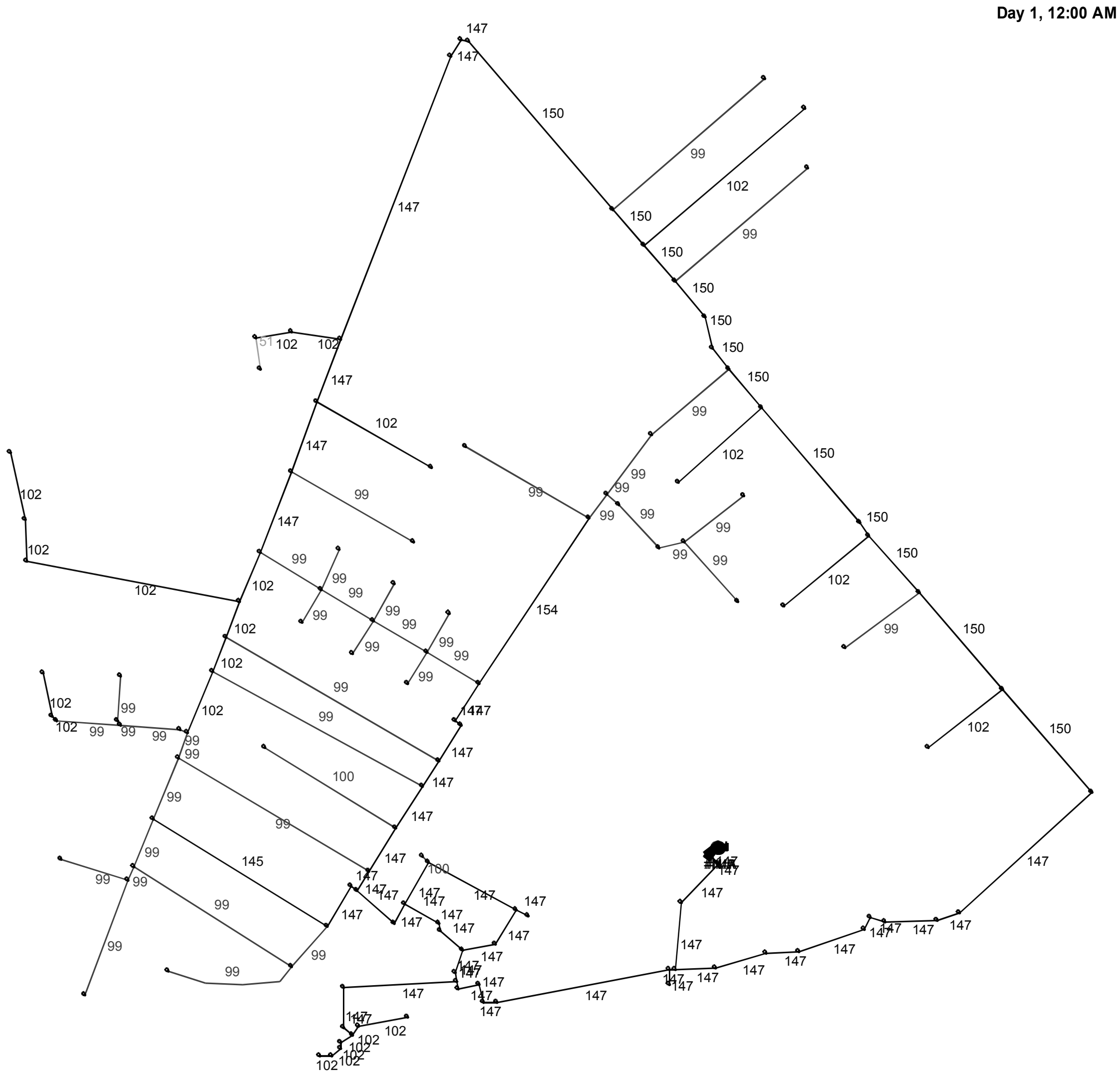

Fig. 1. Schematic of the water-pipe network. Pipe diameters.

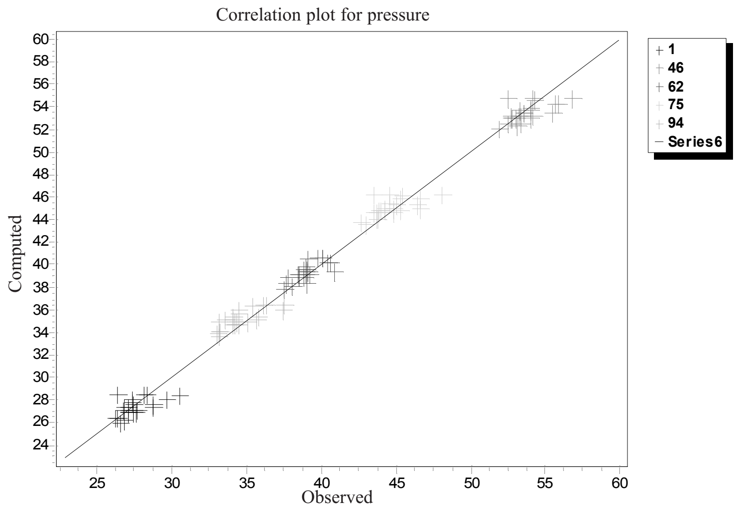

Fig. 2. The correlation between the compared values for the observed nodes for the pressure parameter.

between all pressure value pairs were determined. The difference between the observed and simulated values did not exceed 0.009 MPa (0.9 WC) for all nodes, and the mean square error ranged from 0.66 to 1.05. This is indicative of good reproduction of the actual conditions prevailing in the simulated network. The value of the coefficient of correlation between the mean observed and simulated values was 0.999; so the correlation should be described as practically full. Fig. 2 shows the scatter of observed and simulated values for all measurements at the examined nodes.

In turn, within the validation of the model, a sensitivity analysis was made. In the first place, subject to changes were the values of the roughness coefficients of the lines. Then, the operation of the model at an enhanced water

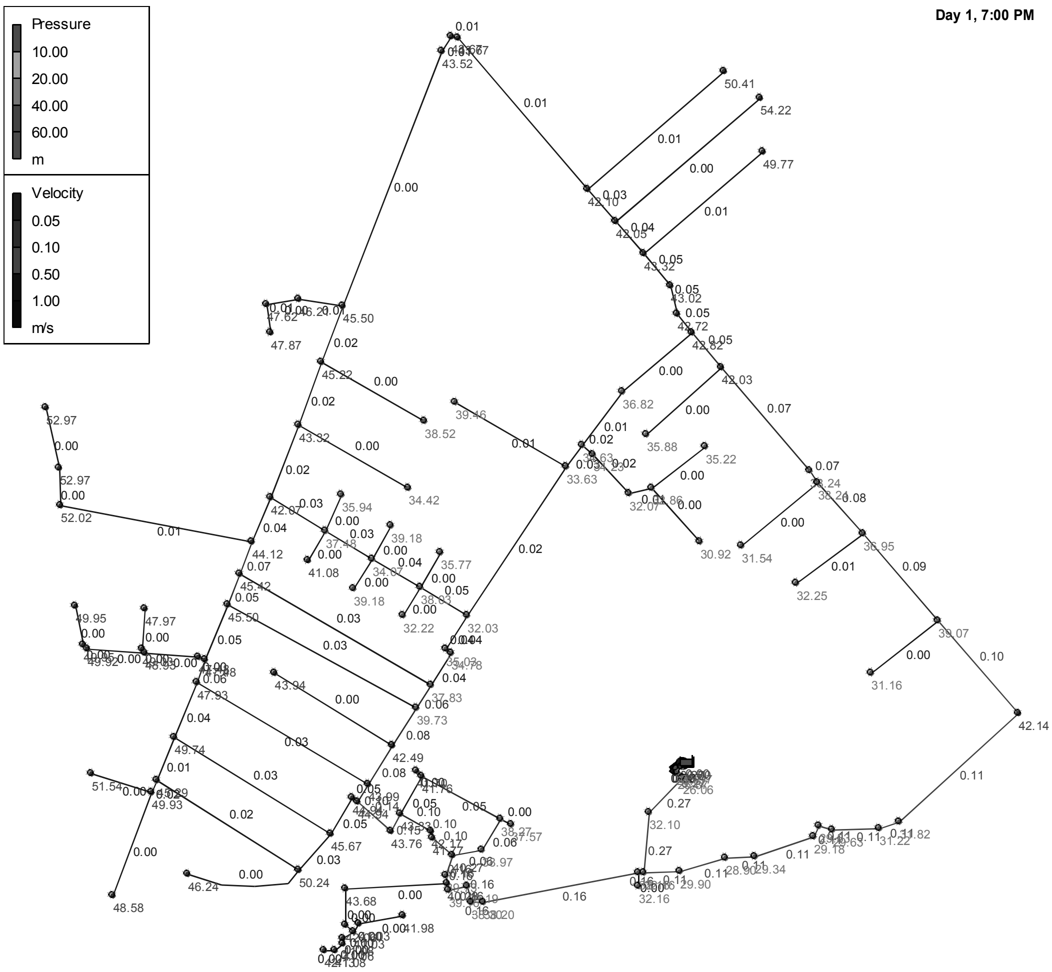

Fig. 3. The distribution of pressure and flow velocity at the time of maximum water demand.

demand was analyzed. On the basis of the performed calibration and validation it was accepted that the developed model was correct and provides a reliable reflection of the water-pipe network under study.

Simulation of Water-Pipe Network Operation

Using the calibrated water-pipe network model, a series of simulations were carried out to demonstrate the operation of the network for variable water supply and demand conditions. The following network operation variants were examined: the standard water demand conditions, activated fire-fighting water flow in selected hydrants, a 24-hour-period with increased water demand, and cut-off water flow on select sections with the standard water demand. The obtained results made it possible, among other things, to plan overhauls on select network sections, to select lines requiring flushing to prevent any deposits from building up, or to make sure that the planned cut-off of flow in one of the main lines will not cause any disruptions in water supply to the users. The three selected network operation statuses are shown below.

Fig. 3 shows the simulated magnitudes of pressure at individual points and water flow velocity for the lines at the time of the highest water demand. It was observed that at all network points the pressure magnitude varied in the range of 29-54 m WC, and the water flow velocities were very low. Analyzing the variability of the demand was found that pressure fluctuations in the most remotely located points didn't exceed 2.8 m WC at the standard water demand conditions (the difference between the pressure in the hours of the smallest and largest demand).

Fig. 4 represents the distribution of pressure and flow velocity in the case of cutting off the flow on the selected section (e.g. because of repair work) for the time of the maximum water demand. Some increase in flow velocity in particular sections can be noticed; however, these are still values below the minimum velocity recommended for water-pipe networks, i.e. 0.5 m/s. It was found that, in spite of the zone being supplied from a single direction only, the magnitude of pressure in the points allowed uninterrupted water uptake by the users.

Fig. 5 shows in turn the distribution of the pressure and flow velocity of water for the time of the maximum water

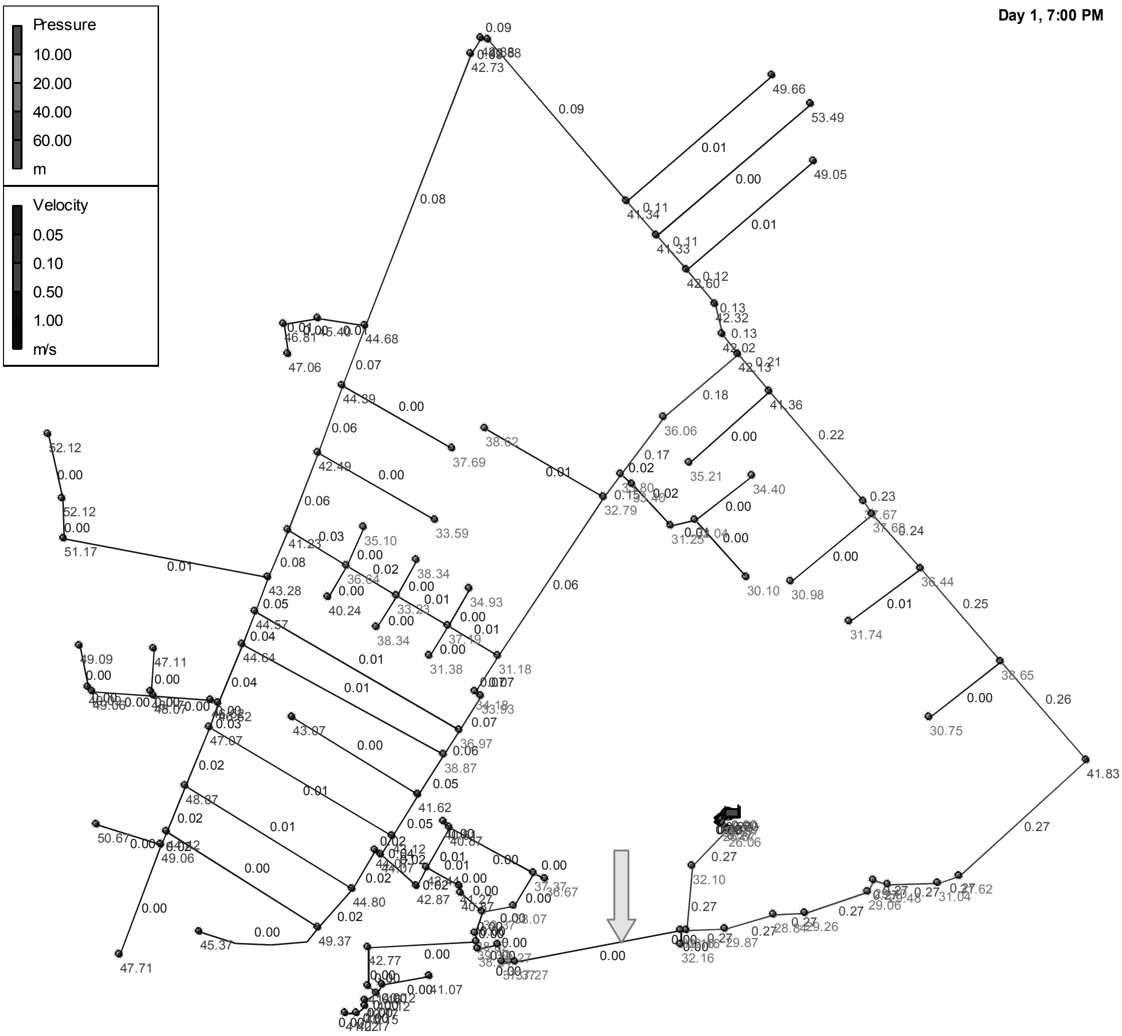

Fig. 4. The distribution of pressure magnitude and flow velocity for the time of the maximum water demand; the flow cut-off in selected section (grey arrow).

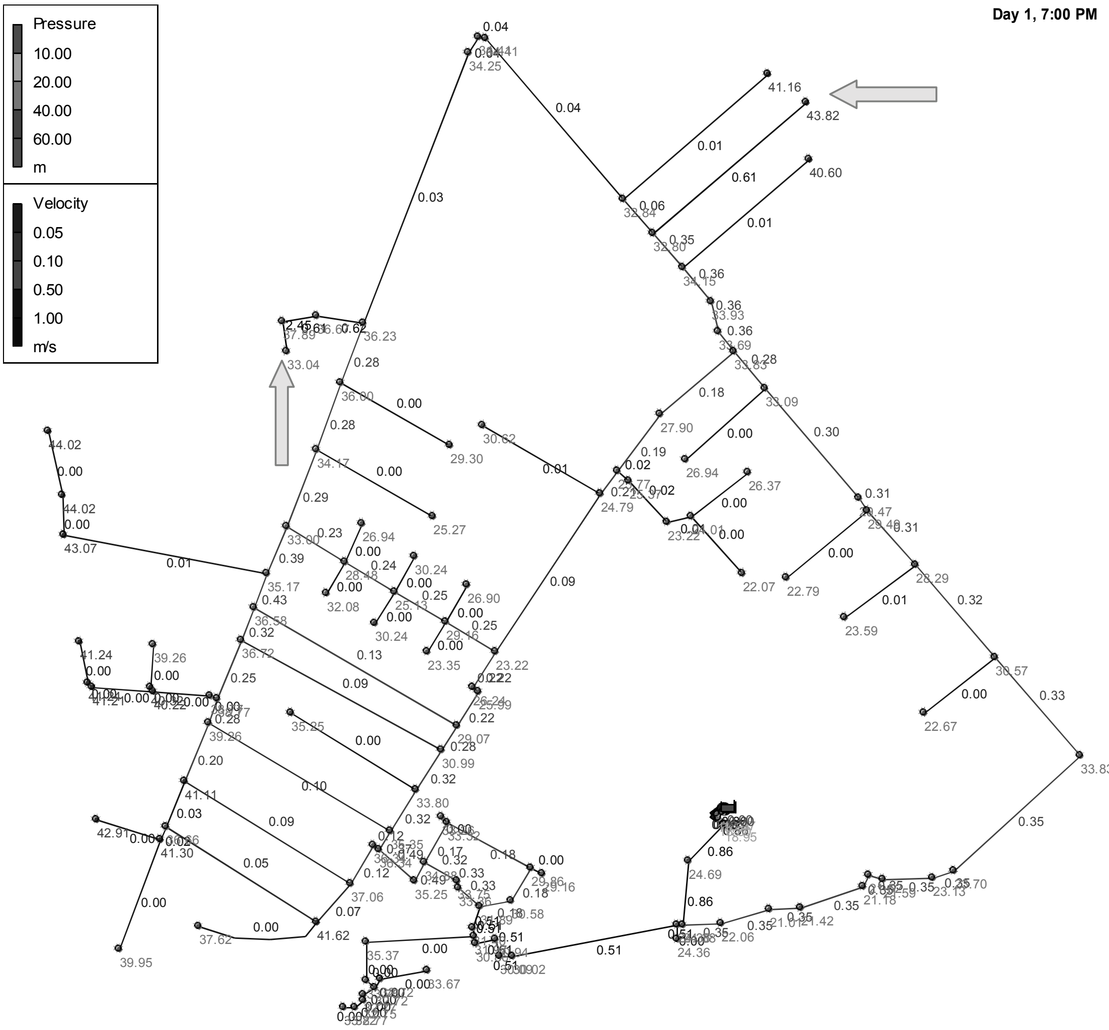

Fig. 5. The distribution of pressure magnitude and flow velocity for the time of the maximum water demand, with the fire-fighting water flow additionally activated (grey arrows).

demand with the fire-fighting water flow activated. The flow was simulated at the times of the maximum water demand from 18.00 to 20.00 hours in two select points. An increase in flow velocity can be observed, especially in the lines located between the activated hydrants and the pumping station. At the same time, the observed drop in water pressure in the points will not adversely affect the water supply to the users. This indicates the possibility of using hydrants for flushing the network.

At the next stage, the model will be used for establishing the possibility of extending the network by including new supply areas to the zone being served. After expanding the created model by adding new line sections, the operation conditions for the new network will be defined. In the future, the developed hydraulic model is planned to be used for predicting the variations in the quality of water in the water-pipe network.

Conclusions

The properly made and calibrated model can bring about substantial savings due to the elimination of wrong capital investments, by providing the capability to test various solutions, as well as to compare the effects of each of them. It also enables the design of solutions concerning periodically shutting down select water-pipe sections for the duration of repairs or making new capital investments (e.g. extending the network) in a manner that causes the least possible nuisance to the users. From the performed analysis with the use of computer modeling, simulation results were obtained, based on which of the following concluding remarks regarding the network concerned have been formulated:

1. The analysis of the distribution of velocity, made on the existing water-pipe network model, has shown that in the majority of lines the velocity values are lower than the recommended value of 0.5 m/s. In a large number of lines, even at the time of the maximum water demand, conditions prevail, which cause stagnation of the water – the velocity is lower than 0.1 m/s.
2. Using fire hydrants for flushing the network allows the flow velocity to be periodically increased, while not adversely affecting the supply of water to the users.
3. The developed hydraulic model provides a useful tool in the operation of the water-pipe network. It enables, for instance, the operation of the network to be analyzed

at increased water withdrawals or during planned overhauls. For example, it has been verified that cutting off the flow on a select network section will not adversely affect network operation; despite some decrease in water-pipe pressure, the water will reach all the users in the required quantity and under the proper pressure.

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