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Time-Spatial Analysis of the Functioning of the Water Distribution System in the Mathematical Modeling Process

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ABSTRACT
This paper presents the process of the temporal and spatial functioning of the water distribution system in the mathematical modeling process. The research was carried out on the Bialystok water network model with particular emphasis on the efficiency and energy efficiency of the pumping units located on the analyzed water distribution system (SDW). The calculations and calibration of the model were performed using the ISYDYW software, with particular emphasis on time and spatial distribution. Particular situations were analyzed, especially when the system operated in exceptional conditions, which most often resulted in failure, leading to a shortage of water supply, and thus energy losses of the pumping units. The obtained results allowed demonstrating the auxiliary role of the simulation method in determining and predicting the effects on the existing emergency states. Possible scenarios were prepared for the observed changes, both in the entire network and at the selected points of the pump systems. Assuming the duration of the failure, its consequences were determined and presented in the form of the indicators discussed.

Keywords: mathematical model; pumping station; water distribution system; failure analysis; energy.

INTRODUCTION

The basis for the estimation of the functioning of the water supply network, through the process of computer simulations in normal operation and in emergency situations, was the need to examine the behavior of system elements to the changes in hydraulic parameters, with the assumption that SDW works as a time-varying system. Special attention was paid to the temporal variability of the water movement. Therefore, the time factor was taken into account and selected situations were analyzed, when the operation of the system took place under emergency conditions, which most often result in the poor functioning of the system, and above all, cause a shortage in water supplies, and thus energy drops in pumping units. Research regarding energy produced by pumping stations, and specifically, the reduction of their losses, is an important research problem in water distribution systems. A number of analytical, experimental and computational studies have been carried out. The time of commencement of the failure (event) and its duration are of particular importance for determining the negative consequences of the failure and the effectiveness of any actions aimed at reducing the severity of these events. The ability to map the dynamic nature of the water supply system operation is one of the basic properties that can be obtained with the use of temporal and spatial computer simulation [Sitzenfrei et al., 2013; Studziński, 2014].

The main purpose of the manuscript was the need to examine the water supply network in terms of the failure rate of selected pump units and to analyze the decrease in their efficiency as a result of the changes. The paper presents two representative failures concerning pump systems. The obtained results allowed assessing the quality of operation of the considered model from the point of view of both the user and the operator.

MATERIALS

Characteristics of work and efficiency of a pumping station in a mathematical approach

Characteristics of the capacity and efficiency of the pumping station are one of the bases for estimating the effectiveness of the water distribution system [Trębicka, 2018; Zheng et al., 2015]. Each pumping station located in the model has its own planned work schedule for individual units [Vasan et al., 2011]. The value of water consumption by users varies with time. The dependence of the amount of water intake on the pressure height reflects the impact of its deficiency on the value of water intake. The performance characteristics of the pumping station have a specific range and are valid within the two extreme values of head [Knapik, 2000]. A polynomial in the form of:

$$Q_p = n * (A + h_p * (B + h_p * * (C + h_p * D))) \quad (1)$$

where: Q_p – pumping station capacity, [m^3/s];
h_p – lifting height, [m];
n – number of working (identical) pumping units;
A, B, C, D – coefficients of the polynomial.

Equation (1) describes the shape of the capacity curve with sufficient accuracy and for extreme pressure values it also results in extreme capacity values, where the extreme pressure values must be given for each pump station as limiting the scope of equation (1) [Vicente et al., 2015; Fontana at al., 2012].

In the work, energy efficiency was assessed and analyzed in detail in terms of energy storage necessary to maintain the best possible efficiency of the pumping station. During the entire duration of the simulation, each pumping station pumps a specific amount of water [Knapik, 2020]:

$$W_{pli} = \sum_l \left(Q_{pli} * \Delta T_l\right) \quad (2)$$

at an average head [Knapik 2020]:

$$h_{pmi} = \frac{\sum_l \left(Q_{pli} * h_{pli} * \Delta T_l\right)}{W_{pli}} \quad (3)$$

where: p – designation of the value characterizing the pumping station;
m – mean value;
i – designation of the next pumping station;
l – designation of the value changing for each time step;
h_{pmi} – average pumping height of the i-th pumping station, at nominal pumping height of the i-th pumping station [m];
Q_{pli} – efficiency of the i-th pumping station, [m^3/s];
W_{pli} – pump station capacity [m^3] (% of maximum capacity);
ΔT_l – length of the time step, [s].

It is worth noting that the variability of the conditions prevailing in SDW also makes the efficiency of a pumping station variable, even for the same length of time sections, as a result of the impact of these conditions in accordance with its efficiency curve. Therefore, an important measure of assessing the operating conditions of the pumping station is the amount of electricity used to pump 1 m^3 of water, the average value of the head of the pumping station and the deviation index of the latter value from the nominal value (corresponding to the nominal capacity of the pumping station). For the i-th pumping station, the unit electricity consumption was calculated from the following formula [Knapik, 2020]:

$$E_{pmi} = \frac{\sum \frac{8.8236 * Q_{pli} * h_{pli} * \Delta T_l}{S_{pli}}}{W_{pmi}} \quad (4)$$

where: E_{pmi} – electricity [MJ/m^3];
Q_{pli} – efficiency of the i-th pumping station, [m^3/s];
S_{pli} – pump (pumping station) efficiency coefficient;
W_{pmi} – tank capacity of the i-th pumping station, [m] (% of the maximum capacity);
h_{pli} – nominal pumping height of the i-th pumping station, [m];
ΔT_l – length of the time step, [s].

In order to compare the nominal pump head when the efficiency coefficient reaches the maximum value for each existing pumping station, the Nominal Pressure Height Index of the pumping station was calculated according to the following formula [Knapik, 2020]:

$$WCNP_i = \frac{h_{pmi} * Q_{pni}}{h_{pni} * Q_{pmi}} \quad (5)$$

where: h_{pmi} – average pumping height of the i-th pumping station [m];
h_{pni} – nominal pumping height of the i-th pumping station [m];

Q_{pmi} – average efficiency of the i-th pumping station [m^3/s];
Q_{pni} – efficiency of the i-th pumping station at the nominal pumping head [m^3/s].

The potential of the Pump Station Pressure Height is described by the equation [Knapik, 2020]:

$$PWCP = \frac{\sum_i \sum_l \left(H_{pli} * Q_{pli} * \Delta T_l\right)}{\sum \sum \left(Q_{pli} * \Delta T_l\right)} - \\ -PWPW \tag{6}$$

where: H_{pli} – height of the water table (m above sea level),
Q_{pli} – efficiency of the i-th pumping station, [m^3/s],
ΔT_l – length of the time step, [s],
$PWPW$ – Potential of the height of the location of nodes (m above sea level),
p – designation of the value characterizing the pumping station,
i – designation of the next pumping station,
l – designation of the value changing for each time step.

The formulas listed above allow calculating, with the help of rational numbers, the values of indicators describing the quality of operation of the water distribution subsystem. The obtained results represent average values and contain the static range of their variability.

Mathematical model of the water distribution system and its assumptions

When developing the research model, the following assumptions were made regarding the schematic drawing of the water supply network [Description, 2010]:

- the spatial location of nodes and connections of pipelines was schematized and their parameters have been defined,
- research models of water demand for selected localities were developed, which made it possible to take into account in detail the spatial distribution and specification of the structure of users and the consumption value, along with the hourly schedules applicable to them,
- the spatial location of nodes and connections of pipelines was schematized and their parameters have been defined,
- the resultant consumption values and their time distributions were determined for individual nodes and for the entire SDW [Park et al., 2017; Todini et al., 2000],
- the purpose of water use and the structure of individual user groups were defined, in addition to the applicable schedules of hourly water abstractions,
- a numerical model was developed based on data on the water supply system and the natural operating conditions were mapped on it,
- a review of experimental emergency cases was made, when the SDW conditions are particularly variable and complicated [Walski et al., 2013].
- The introduced assumptions ensure wide access to system monitoring through:
- creating computer databases and managing GIS information and data,
- mapping significant situations in the course of SDW work and improvement of comprehensive SDW management (effective management of SDW and, consequently, reduction of energy costs and operation of the improved system),
- quantitative and qualitative monitoring of the technical and operational system of individual elements of water supply systems in terms of energy and efficiency,
- development of hydraulic SDW models operating in real time with the use of mathematical modeling,
- implementation of simulation flow models (hydraulic models) into operational and design practice [Alperovits et al., 1977; Tabesh et al., 2009].

METHODS

The created mathematical model of the Bialystok water supply network enabled mapping of normal operating conditions, but also allowed simulation of various types of emergency cases when the SDW (water distribution system) conditions are particularly variable and complicated [Alegre et al., 2012; De Marchis, 2016]. By introducing the connection of pressure deficiency and consumption by users, simulation of emergency situations and water supply deficit was also carried out; special attention was paid to the temporary variability of water movement [Praneeth et al., 2018]. The ability to reflect the dynamic nature of the water distribution system is one of the basic properties that can be obtained using temporal and spatial computer simulation [Nazif, et al., 2010].

In the calculations, the assessment of the operation of the water distribution system was based on the size of indicators of fundamental importance. These include the following sizes: WWPW, PWCW, PWCP, WSWC.

The simulation carried out with the use of the ISYDYW program enabled the creation of an extensive database, owing to which the information contained in the database was systematized and, on the basis of both parts, the generation of calculation packages and the calculation of water supply systems were performed. This made it possible to obtain a virtually unlimited number of computational models with varying degrees of accuracy and detail. [Carravetta et al., 2012; Fontana et al., 2012].

Calculations were carried out for any fragment as well as for the whole day divided into stages. The volume of water consumption for each time step is calculated individually for each node, based on the set value of the daily demand for the hourly distribution of water consumption and the reduction factor taking into account the impact of pressure deficiency in relation to its required value [Robles-Velasco et al., 2020, Ramos et al., 2009]. The Bialystok water supply network is supplied by a set of P1 and P2 pumping stations with different pressure values. The SDW schematization carried out indicated the need to build a model with 108 nodes and 158 sections. For the demand model, structural units with housing development and units with industrial function were included. For each of them, the structure of users was determined, i.e. type of building, standard of sanitary equipment, type and variability of industry, as well as hourly timetable was defined accordingly [Romano et al., 2014; Arai et al., 2010].

The created hydraulic and qualitative model of the Bialystok water supply network is now an important source of information about the system in use, and its dynamic model of the water distribution system has proven particularly useful in diagnosing the condition of the system in use and developing the concept of extension or modernization of water supply (Figure 1). The implemented variants became both a study of the failure rate analysis of water supply pipelines and an estimation of energy efficiency [Sinagra et al., 2017].

RESULTS AND DISCUSSION

The research process consisted in carrying out a series of tedious and labor-intensive simulation studies reflecting various types of emergency states of the existing pumping units, aimed at forecasting and preventing unforeseen emergencies. Seven cases simulating the most possible emergency states were considered in the series. The article presents one of the key events that may occur and adversely affect the operation of both the pumps and the entire water distribution system. The SDW diagram with the tested elements is shown in Figure 1.

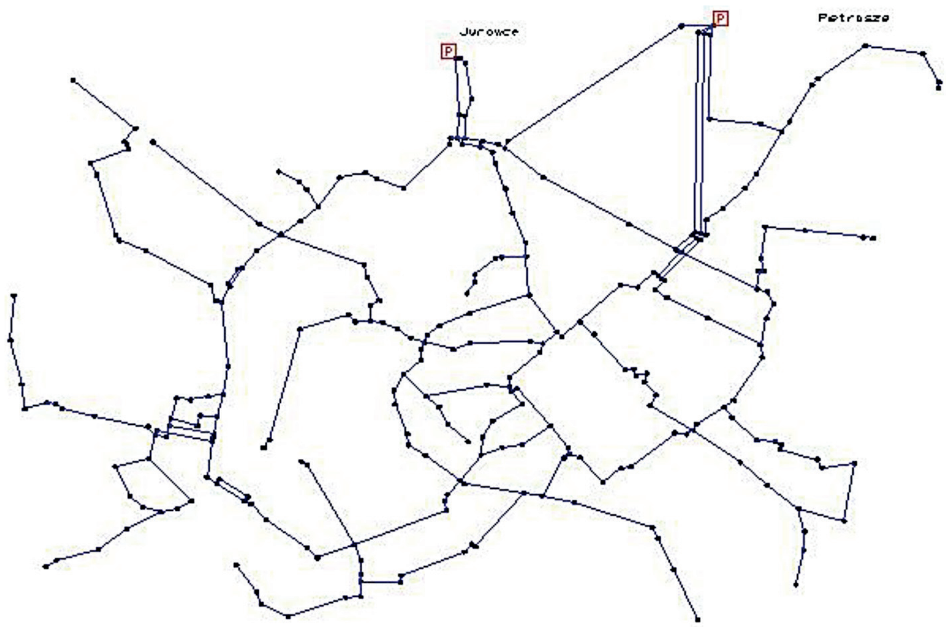

Figure 1. The SDW model with the examined elements

The variant concerned the shutdown of two pumping stations, i.e. Pietrasze (P) and Jurowce (J), from the system for a period of 24 hours. The effect of this was confirmed by the total loss of efficiency of both pumping stations and the resulting high pressure drop on the discharge. Negative WCNP proves that the average pumping pressure of both pumping stations is low compared to the nominal pressures of the given pumps. The calculation results show a clear decrease in the values of the PWCW index (31.7 m) and WWPW (27.19%). Due to the fact that pumping stations are characterized by zero efficiency and negative system discharge pressures, also the PWCP (Pumping Station Pressure Height Potential) has a negative value.

This situation is also noticeable in the value of electric energy E_{pmi}, which disappears at each of the pumping units. The lack of efficiency of both pumping stations makes the average flow velocity for the entire system very low (v_{om}= 0.06 m/s) in WSWC, the low value of which confirms the catastrophic condition of the conditions for water abstraction. This phenomenon is confirmed

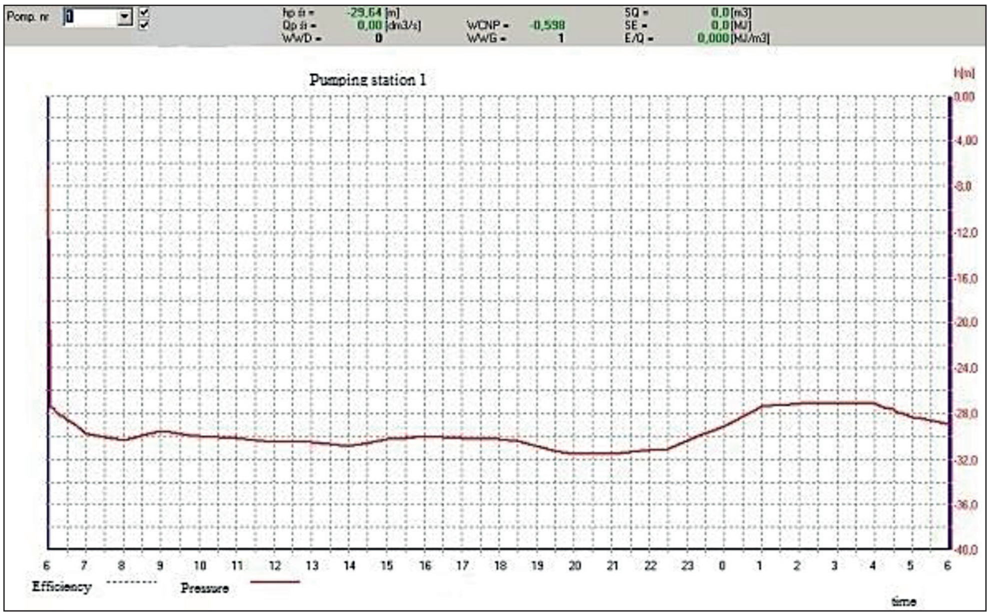

Figure 2. Time course of pump P1 operating parameters in the P pumping station (node_1)

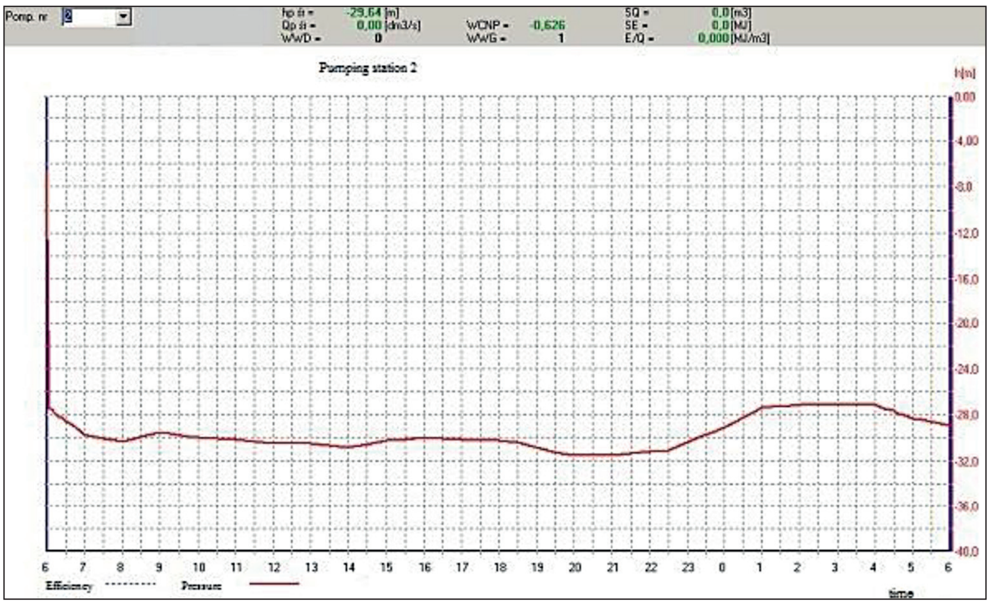

Figure 3. Time course of pump P2 operating parameters in the P pumping station (node_1)

in Figure 1 – Figure 5 in the form of diagrams of pumping station efficiency and WWPW (Figure 6) for the entire system and simulation time.

Indicator of Water Supply Conditions (WWPW) can be calculated by setting the summation indicators (l, k) for: each (l-th) time step, each (k-th) node throughout the simulation time, the entire network and the entire simulation time (as global).

It is worth noting that the WWPW is treated as a measure of the comfort of water intake for the entire SDW. Achieving full comfort may sometimes require expensive technical measures and therefore must be taken into account by explorers. The described case perfectly shows how an unfavorable situation may occur at any time as a result of a decrease in the energy efficiency of the pumping station and cause catastrophic conditions of water intake. It is assumed that a given event occurs when WWPW <75%.

Another important variant was the scenario that assumed the failure of only one pump P1 in the pumping station (node no. 1), and the other two included in the power sources P2 and P3 as well as the pumping station (node no. 23) with the P5 pump fulfilled their role of power supply and cooperated

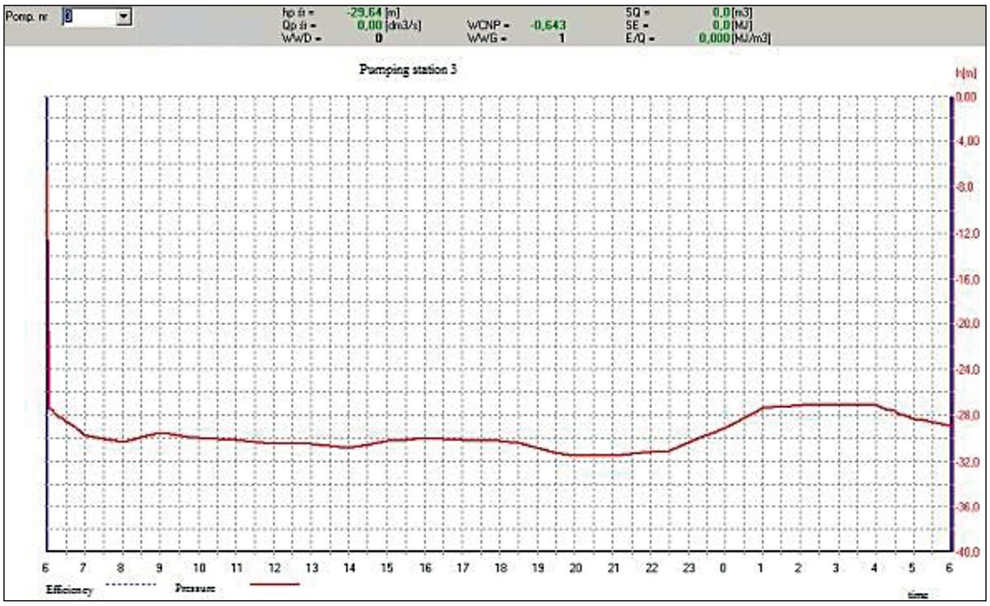

Figure 4. Time course of pump P3 operating parameters in the P pumping station (node_1)

Figure 5. Time course of pump P5 operating parameters in the P pumping station (node_23)

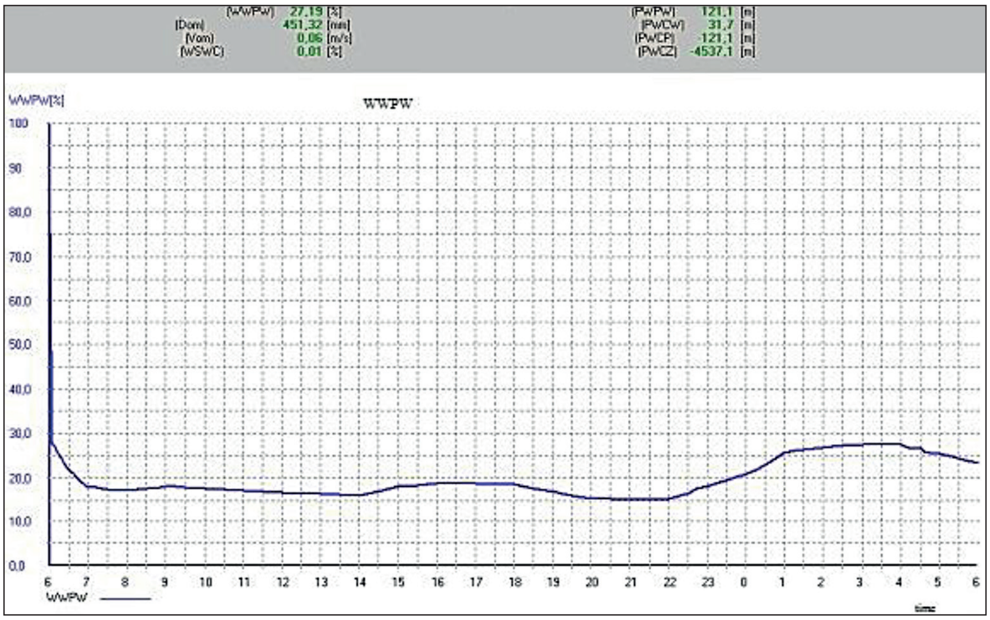

Figure 6. Temporary change of WWPW (Indicator of Water Intake Conditions) indicator

in SDW. The observation and results showed an increase in the level of SDW functioning.

The much better conditions of its operation are evidenced by the higher PWCP (61.5 m H_2O) compared to all the considered variants, as well as the higher PWCW (76.4 m H_2O), which in turn proves the improvement of the efficiency of both pumping stations, especially the greater activity of the pumping units included in the existing pumping stations. On the basis of the obtained results, a decrease in the mean pumping pressure was found at the P station and an increase in the efficiency of active pumps P2 and P3, as well as its complete disappearance when the P1 pump is turned off. The J pumping station, similarly to the pumps at the P station, shows a decrease in the average discharge pressure and a large increase in efficiency. Since the pump efficiency is significantly increased, there are very high costs of electricity consumed and increased unit electricity demand for pumping 1m^3 of water. The WWPW recorded for the case under consideration (99.36%) ensures sufficient comfort of water abstraction with the possibility of slight shortages at maximum water consumption (Figure 11). An illustration of the results is shown in Figures 7–10.

Figure 7. Time course of pump P1 operating parameters in the P pumping station (node_1)

Figure 8. Time course of pump P2 operating parameters in the P pumping station (node_1)

Figure 9. Time course of pump P3 operating parameters in the P pumping station (node_1)

CONCLUSIONS

As a result of simulation studies on the functioning of the water distribution system in terms of the failure rate of selected pump units, their efficiency resulting from the changes was analyzed. The tests were carried out in terms of effectiveness and the degree of use and interaction of individual elements, mainly pump units. The mathematical model made it possible to carry out simulations in terms of checking the required technical and economic assumptions.

The dynamics of the model allowed obtaining a number of data having a significant impact on the functioning of the water distribution system, as a result of the assumed variants of failure of existing pumping stations. In particular, changes in flow rates, water pressure and drops in the efficiency of pumping units, as well as SDW reactions to the modifications introduced, proved to be interesting.

The currently observed systematic decrease in water consumption in urban distribution systems also appeared on the SDW studied, because the flow rates deviated from the

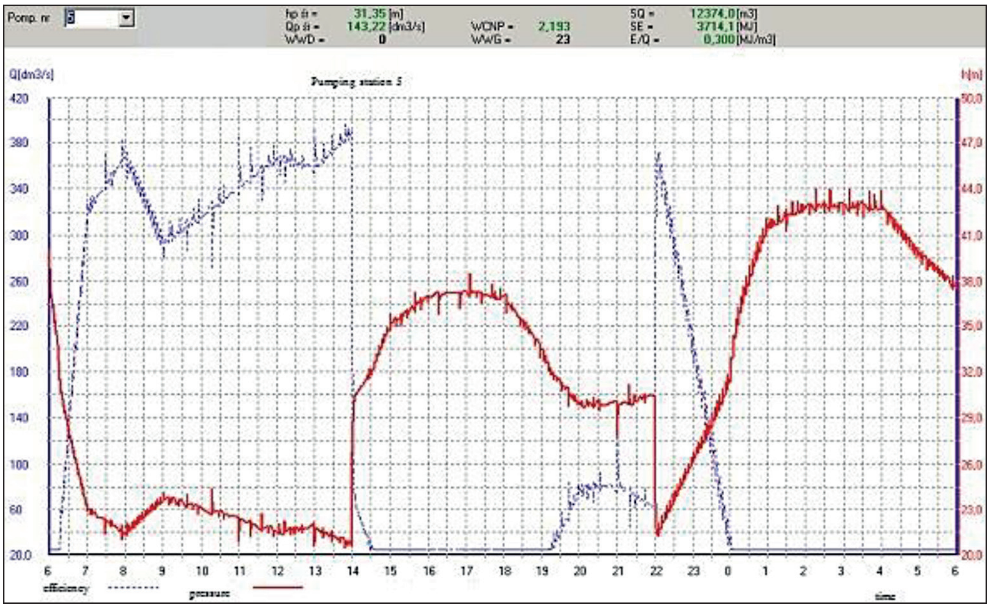

Figure 10. Time course of pump P5 operating parameters in the P pumping station (node_23)

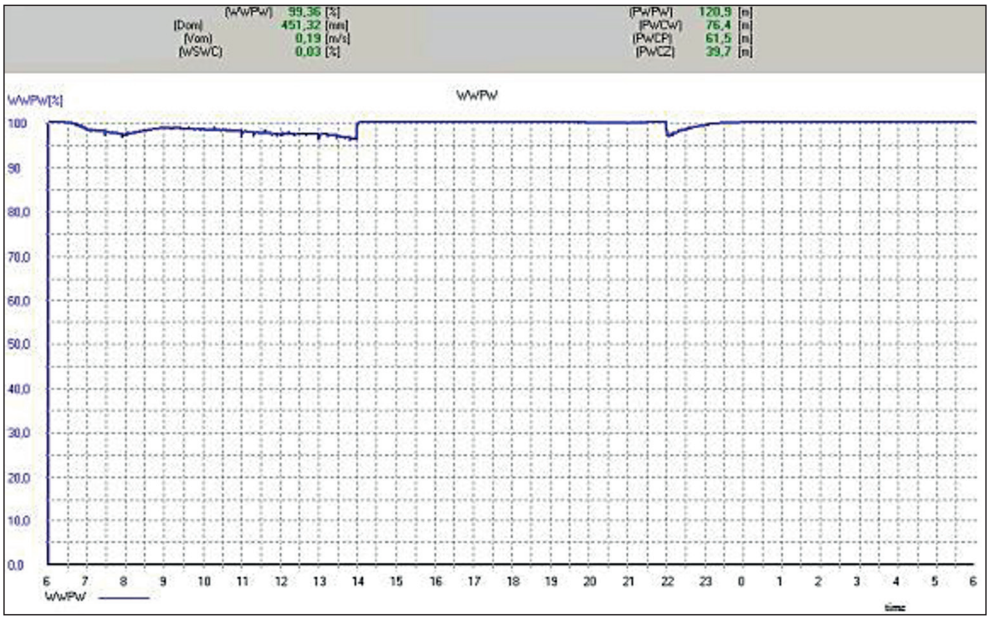

Figure 11. Temporary change of WWPW (Indicator of Water Intake Conditions) indicator

recommended ones depending on the diameter values. Noteworthy is the oscillation of pumping systems, appearing in some situations, which has become disturbing, which in turn will help to eliminate and pay special attention to the resulting effects. The modeling carried out enabled more effective control of pump systems in water distribution systems. This allowed reducing the operating costs of these systems and, above all, reducing the energy losses.

Time-spatial analysis of the functioning of the water distribution system has become a helpful tool for developing a method of inferring the behavior of individual real objects such as pumping stations. It enabled the development of the SDW model based on the assumed scenarios and their observations, which contributes to the efficient management of water resources.

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