Water losses analysis based on FEFLOW FEM simulation and EPANET hydraulic modelling

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Abstract. Water losses occur in every water distribution system (WDS) and are one of the most onerous problems for water distribution network’s exploiters. Water losses can cause not only financial and operating costs but also negative ecological and social issues. Therefore, there is a great need to individually assess the water losses level in every WDS. The aim of this paper is to analyse water losses in a selected water supply system group, serving approx. 5 000 inhabitants. The water losses analysis was performed on the basis of Finite Element Method simulation in FEFLOW v.5.3 software and numerical hydraulic modelling in EPANET software. The water outflow from a distribution pipeline was simulated for variable conditions: different pipe diameters and dynamic time-varying pressure values. The obtained results enabled to present differences in approaches to including water losses level into WDS models.

1. Introduction
The main goal of every water supply distribution system (WDS) is to deliver water to all customers in an unlimited amount and at any time. In a theoretically ideal situation, a total volume of water pumped into the water supply network (System Input Volume SIV) equals the total volume of water demanded by customers. However, as water losses occur in every WDS and often are one of the most onerous problems for network’s operators, such theoretically ideal situation does not exist in complex or semi-complex water systems. Real water losses through leaking pipes are phenomena of a random and unpredictable character, which cause not only financial and operating costs but also can have negative ecological and social effects. Therefore, there is a great need to individually assess the water losses level in each WDS.

The water losses analysis can be performed on the basis of total volumes of water produced, imputed and sold, most often in accordance to IWA (International Water Association) methodology [1,2]. This widely used analysis method allows to define the approximate level of real water losses in a water supply system. However, as the water supply companies introduce the digital models of their WDSs more, there is a need to include water losses in hydraulic modelling. Most often, the process of WDS model creation includes two steps in defining the amount of water demanded by customers. First of them, is the amount of water actually demanded in accordance to billing meter system. The second is the calculation of water losses level in separate DMAs (District Meter Areas) and further multiplying base demands by water losses coefficients estimated on the basis of water flow analysis [3,4]. Such approach can lead to inexact assessment of hydraulic conditions due to the fact that customers’ demands are calculated as Demand Driven Analysis (DDA) (pressure independently),
while the amount of water leaking from a pipe depends on the pressure and therefore should be calculated as Pressure Driven Demand (PDD) [5].

The aim of this paper is to analyse water losses in a selected water supply system group in accordance to IWA methodology, to compare them with FEM calculations results in FEFLOW software and finally, to include real water losses in hydraulic modelling in EPANET, in order to present differences in approaches to including water losses level into WDS models.

2. Materials and methods

2.1. Water system characteristics

The water losses analysis was performed for an exemplary water supply system group located in Lublin Voivodship, Poland. The water supply system consists of three different zones with three individual underground intakes. The total length of water pipes is equal to 94.23 km (including 1 651 household connections the total length is 171.77 km). The material structure of WDS is homogenous, nearly all pipes are plastic (93.66% PVC, 5.65% PE, 0.69% steel), with diameters DN/OD: 90, 110, 125, 160 and two steel pipes DN 150 and DN 250. In 2015, the WDS served approx. 5500 inhabitants in 3 different settlement units (100% water supply coverage) with average operating pressure 0.38 MPa.

In recent years, one of the main issues hindering the proper operation of the analysed WDS was the significant level of water losses. Due to that fact, the water losses reduction strategy was implemented in 2010 and resulted in noticeable improvement. In 2015, the calculated Water Network Intensity Indicator WNII for the whole network was 7.50 m³/(day-km) [6], while the average water production in 2010÷2015 years was 245 266 m³/year, with average water sale 198 563 m³/year. The average water consumption for own company purposes was 3 125.8 m³/year. In accordance to [7], in 2015 the national average water demand for an individual consumer in Poland was 94 dm³/day, while in the analysed system that value was significantly bigger (115.26 dm³/day), which may suggest a noticeable influence of water losses. Detailed information and geometrical structure of WDS is presented in figure 1.

![Figure 1. Geometrical structure and detailed information about the analysed WDS [5].](image-url)
The analysed WDS can be divided into three different pressure zones of low (0.27÷0.33 MPa), medium (0.29÷0.39 MPa) and high (0.39÷0.43 MPa) pressure. The representative nodes of each pressure zone are presented in figure 1 (blue node – represents low pressure zone, orange – medium pressure zone, red – high pressure zone). In each zone pipes of all possible diameters (DN/OD 90, 110, 125, 160) do exist.

2.2. IWA water balance
As a reference basis for numerical modelling in FEFLOW software, the water balance calculations over the period 2010÷2015 were used. The water balance was calculated in accordance to the IWA methodology. The details about IWA water balance for analysed water supply system are presented in paper [5]. In table 1 only selected components of water balance are presented.

| Parameter                  | Unit          | 2010      | 2011      | 2012      | 2013      | 2014      | 2015      |
|----------------------------|---------------|-----------|-----------|-----------|-----------|-----------|-----------|
| System Input Volume (SIV)  | m³/year       | 251 156   | 245 486   | 259 532   | 232 733   | 237 061   | 258 000   |
| Water Losses (WL)          | m³/year       | 67 296.0  | 50 745.0  | 53 807.0  | 33 153.0  | 27 804.0  | 24 533.0  |
| Real Losses (RL)           | m³/year       | 57 249.8  | 40 925.6  | 47 318.7  | 27 334.7  | 21 877.5  | 18 083.0  |
| Non-Revenue Water (NRW)    | m³/year       | 77 046.0  | 60 495.0  | 63 557.0  | 35 153.0  | 29 804.0  | 26 533.0  |

2.3. FEFLOW modelling methodology
The aim of the numerical simulations of water losses in the analysed WDS was to determine the possible amount of water lost through a single pipe break and later to compare it with the water losses calculated by the IWA water balance. Numerical simulations were performed in FEFLOW v.5.3 software, using the finite element method analysis (FEM). The application can solve the groundwater flow equation of both unsaturated and saturated media and can be successfully used for modelling of natural water flow in porous media of different kind and outflows from damaged pipes [8-11]. Numerical simulations of water outflow from damaged pipes were performed for 9 different variants: three diameters (DN/OD: 90, 125, 160) in three zones (low, medium and high pressure). In all cases, the conditions of the simulation were analogical – water was leaking through the one tenth of the circumference of the pipe. The 2-dimentional soil profile used in simulation consisted of two parts: the excavation (2,0 m × 0,7 m) and natural ground surrounding the excavation (20 m × 5 m). The pipes were located in the bottom of excavations on a sand base layer. Soil profiles were further automatically meshed with triangle polygon mesh. The soil model was implemented with two kinds of boundary conditions: the first type (Neumann boundary condition), reflecting the impermeable and evaporation layers, and the second type (Dirichlet boundary condition), reflecting the leaking part of the pipe. For each pressure zone variant, the time-varying pressure values over the 24-hours simulation were given as a boundary pressure condition. The flow in unsaturated media was calculated in accordance to standard Richards equation, with the automatic time step control via aggressive target-based strategies (backward Euler scheme) [12]. The graph of pressure varying in representative nodes of each zone is presented in figure 2. The scheme of cross section of soil profile with water pipe is presented in figure 3. The Mualem model parameters of used soils are given in table 2.

Figure 2. Pressure values in representative nodes of high, medium and low pressure zone.
Figure 3. Scheme of the cross section of soil profile with the water pipe (1 – inner pipe diameter, 2 – sand, 3 – natural ground in and around the excavation; dimensions in cm).

Table 2. Hydraulic parameters of soils used in the simulation in accordance to Mualem model ($\theta$ – volumetric water content ($\text{m}^3/\text{m}^3$); $K_s$ – saturated hydraulic conductivity coefficient ($\text{m/s}$); $P$ – porosity; $\alpha$, $n$ – fitting parameters).

| Soil                    | $\theta$ | $K_s$ | $P$ | $\alpha$ | $n$ |
|------------------------|----------|-------|-----|----------|-----|
| in the excavation      | 0.177    | 3.34  | 36.12 | 1.662    | 1.334 |
| around the excavation  | 0.146    | 1.40  | 26.56 | 2.170    | 2.133 |

2.4. EPANET modelling methodology

EPANET is a popular water system modelling software application developed by the United States Environmental Protection Agency (EPA U.S.) for performing hydraulic and water-quality extended-period simulations (EPS) of pressurized water supply networks [13]. Hydraulic modelling, using EPANET or any other modelling software, can be a comprehensive tool supporting both the designing and operating of WDS [14-16]. In this paper, on the basis of numerical simulations in FEFLOW software, the modelling in EPANET software (v. 2.00.12) was used to present different approaches to including real water losses in hydraulic modelling.

The numerical model of analysed WDS includes 1387 junctions and 1394 pipes, three reservoirs representing three water intakes, four pumps and one tank. The model has a general character – includes only distribution pipes without household connections. The Darcy-Weisbach head loss formula was used in calculations. The total duration of simulation was 24 hours, with one hour hydraulic calculation time step. Three different stepwise demand patterns were included in a model: general (common for all customers) and two specific ones for a school and a breeding farm. The minimum demand hour for the whole WDS: 03:00, maximum demand hour: 19:00.

The real water losses occurring in the analysed WDS were included in a hydraulic model in two ways. First, base demands in all nodes were multiplied by calculated factor. In this way, all nodes generated the increased demand. The second approach included determination of the emitter coefficient for selected nodes, which caused the additional pressure dependent demand equalled to calculated leakages from pipes. Emitters are model devices that can simulate the outflow through an orifice or nozzle discharging to the atmosphere. Most often, emitters are used to model sprinkler systems and irrigation networks, but they can also be successfully used to simulate the pipe leakages or fire flows at hydrants [17]. In EPANET software, emitters are not separate network components but are treated as a property of a junction. The emitter flow rate varies as a function of pressure available at the associated node, according to the formula (1) [18-19]. In this paper, the pressure exponent was assumed as 0.5 and leakage volume was determined by fitting the discharge coefficient C.
\[ q = C \cdot p^\gamma \]  

where:
- \( q \) – flow rate (dm\(^3\)/s),
- \( C \) – discharge coefficient (dm\(^3\)/s/m\(^\gamma\)),
- \( p \) – pressure (m H\(_2\)O),
- \( \gamma \) – pressure exponent (-).

3. Results

The results of possible amount of water lost through a single pipe break (calculated in FEFLOW software) in different pressure zones in the analysed WDS are presented in table 3. According to the IWA water balance, in 2015, the total volume of water pumped into the system (SIV) equalled 258.00 m\(^3\), which gives an average daily demand of 706.85 m\(^3\)/d. In the same year, real water losses (RL) equalled 18.083 m\(^3\), which gives an average 49.54 m\(^3\) of water lost each day. Such amount can be generated by approx. three leaking DN 90 water pipes in low pressure zone or approx. two leaking DN 160 water pipes in high pressure zone. On the other hand, these real water losses can be generated by leaking household connections. As was examined in paper [20], a single leaking household connection can cause over 7 m\(^3\) of water lost per day. Therefore, the daily real water loss in the analysed system can be as well generated by seven leaking household connection (assuming similar diameter and pressure in a pipe).

| Pressure zone    | Volume of lost water (m\(^3\)/d) |
|------------------|-----------------------------------|
|                  | DN 90    | DN 125   | DN 160   | Average |
| Low pressure     | 17.82    | 18.85    | 19.00    | 18.59   |
| Medium pressure  | 21.85    | 22.18    | 23.16    | 23.40   |
| High pressure    | 24.18    | 24.56    | 25.73    | 24.83   |

The total base demand in all nodes in EPANET hydraulic model based on billing records equalled 567.92 m\(^3\)/d. In comparison with System Input Volume (SIV), that total daily amount of water equalled 706.85 m\(^3\)/d, which states that water losses in a system equals 19.65%. In order to include water losses in hydraulic conditions, all base demands were multiplied by 1.245 factor. The graph representing flow velocity in pipes at the maximum demand hour (19:00) in a model with equally distributed water losses for all nodes is presented in figure 4A. The flow velocity values in pies are relatively small (below 0.4 m/s) which is a typical situation for nearly all water supply networks in Poland. The graph representing flow velocity in pipes at maximum demand hour (19:00) in a model with water losses simulated as PDD outflows in two selected nodes (marked as green stars in upper right corner) in medium pressure zone is presented in figure 4B. The total additional outflow from two selected nodes equalled the average water loss in a system (nearly 50 m\(^3\)/d) and caused the flow velocity values increase (over 0.5 m/s) in the north part of the network. In the other part of a WDS, the hydraulic conditions (flow velocity) were similar to the model with equally distributed water losses.

4. Conclusions

Water losses analysis conducted on the basis of the IWA balance does not only give a comprehensive view of the losses’ nature – neither leakages location nor amount of water lost through different pipes are identified this way. As revealed by the FEFLOW software analysis, daily amount of water losses (in this case 50 m\(^3\)/d) can be generated by two or three damaged pipes or a small number of household connections, further impeding to locate a leakage in reality. The assumption that water losses should be equally distributed in a DMA can lead to covering actual locations of leakages and can suggest the mistaken impression that a network operates properly. The analysis conducted in EPANET software proved that the hydraulic model reaction to leakages locations specified in nodes can be a tool supporting the process of leakages locating.
Figure 4. Comparison of flow velocity in pipes at maximum demand hour (19:00) between two approaches (4A: equally distributed water losses for all nodes, 4B: water losses simulated as PDD outflows in two selected nodes) of including water losses in hydraulic WDS model.

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