IMPLEMENTATION OF PRESSURE REDUCTION VALVES IN A DYNAMIC WATER DISTRIBUTION SYSTEM NUMERICAL MODEL

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The analysis of water distribution networks has to take into account the variability of users water demand and the variability of network boundary conditions. In complex systems, e.g. those characterized by the presence of local private tanks and intermittent distribution, this variability suggests the use of dynamic models that are able to evaluate the rapid variability of pressures and flows in the network. The dynamic behavior of the network also affects the performance of valves that are used for controlling the network. Pressure Reduction Valves (PRV) are used for controlling pressure in the network and for avoiding excessive pressure in the periods of low demand and reduce leakages. When network is characterized by highly variable demands, the PRV outlet pressure can be seen to fluctuate significantly with minor demand changes in the network. The related transient phenomena propagate through the network and may result in water quality problems, unequal distribution of resources among users, and premature wear of the pipe infrastructure. A model was developed in previous studies and demonstrated to provide reliable results in the analysis the behavior of intermittent networks. The model is able to simulate the initial filling of the network and the dynamic behavior of the network. The model was applied to a district of Palermo network (Italy) characterized by intermittent distribution and the presence of PRVs. The district was monitored and pressure as well as flow data were available for model calibration.

INTRODUCTION

The distribution of water resources can be made through two different delivery methods: continuous or intermittent distribution. Continuous distribution ensures better management of water network because the water demand depends only on user requests and the service quality can be better guaranteed. In water scarcity condition, intermittent system allows the management authority to program duration of distribution with scheduled insulation of parts of network, rationing the available water volume.

This approach, broadly adopted not only in developing countries (Hardov *et al.* [1], Vairavamoorthy *et al.* [2]) but also in developed ones (Cubillo, [3]), has certain advantages,

such as the requirement of little financial commitment and the reduction of background water losses (Criminisi *et al.* [4]).

Discontinuous distribution, however, presents several critical aspects, such as users inequality in access to water resources and the presence of transient filling and emptying phenomena affecting the mechanical stability of the pipes and the durability of the network. Another complex aspect is determined by the presence of numerous tanks, often oversized, installed by private users in an attempt to reduce their vulnerability to water shortage (Arregui *et al.* [5] – Cobacho *et al.* [6]). In this condition, the tanks are filled up once the supply has been restored causing larger peaks flows than predicted in the network design process, increasing the pressure losses.

This configuration of the system does not allow easy analysis of the distribution network by means of common steady state models, because the filling of private tanks creates continuous change in the hydraulic network behavior. To follow this constant change in network configuration dynamic and pressure driven models are needed., Considering this aim, Giustolisi [7] presented an extension of the pressure-driven analysis using a global gradient algorithm (Todini, [8]; Giustolisi *et al.*, [9],[10]) permitting the effective introduction of the lumped nodal demand while preserving the energy balance by means of a pipe hydraulic resistance correction. The model allowed the simulation of private tanks but appliances for the regulation and control of network pressures could not be modeled. A model for analysis and control of pressure reducing valve (PRV) was implemented by Prescott and Ulanicki [11], using the dynamic formulations and experimental analysis but the model was not integrated with a dynamic network modeling approach.

In the present paper, the analysis of network during the filling process is made with a dynamic model, assuming that the air pressure inside the network is always equal to the atmospheric one and that the water column can not be fragmented. A demand model based on the node pressure-consumption law defining flow draw from the network and filling the tank has been integrated to the network model (De Marchis *et al.* [12], [13]). PRVs were simulated by means of the dynamic approach proposed in Prescott and Ulanicki [11] obtaining a fully dynamic model. The model was previously calibrated and applied to the implementation of Pressure Management Areas (PMA) in one of the distribution networks of Palermo (Italy).

MATERIALS AND METHODS

In the present paragraph the numerical model and the case study are presented. The model description is divided in two parts: the discussion of the network hydrodynamic model that was previously presented in (De Marchis *et al.* [12]) and the detailed description of the PRV valve that was implemented and integrated in the present study.

The network model

In water distribution networks, pipe may be filled by the start node or by the final node, with the result that two wave-fronts may be progressing within the same pipe in the opposite direction.

The resulting collision overpressure propagates through the network with remarkable rapidity. Because of the complexity of the system, determined by the various possible

filling conditions that may occur, it is necessary to make some simplifying assumptions. Based on the study by Liou and Hunt [14], it is assumed that the air pressure at the water front is always atmospheric and the wave-fronts are always perpendicular to the pipe axis and coincident with the cross sections.

In this paper, the solution of hydraulic equations has been carried out by means of the Method of Characteristics (MOC), starting from the condition of empty network.

In order to study the transient flow in water distribution network, the MOC are combined with the proper boundary conditions. A constant water head is imposed to all the reservoirs feeding the network, thus water levels remain constant during the filling process. Coherently with the assumption of atmospheric air pressure in the pipelines network, the water head at the front face of partially filled pipes is equal to zero. Further details on the model can be found De Marchis *et al.* [12].

The valve model

The dynamic analysis of Pressure Reduction Valves (PRV) follows the formulation and experimental analysis provided by Prescott and Ulanicki [11], in which the derivative of the opening of the valve χ_m is proportional to the difference between a given set point h_{set}, and the current outlet pressure h_{out}. The PRVs are located at some nodes of the network. Assuming an initial value of $\chi_m = \chi_{m0}$ is calculated the valve capacity Cv using the following equation:

$$Cv = 0.021 - 0.0296e^{-51.1x_{m0}} + 0.0109e^{-261x_{m0}} - 0.0032e^{-683.2x_{m0}} + 0.0009e^{-399.5x_{m0}} \tag{1}$$

So, knowing the incoming flow (q_m) and the inlet head (h_{in}) of PRV, one can determine the PRV outlet head (h_{out}) with the equation:

$$h_{out} = \frac{h_{in} - q_m^2}{[Cv(x_{m0})]^2} \tag{2}$$

The equation (2) relates the flow through the PRV to the head loss across it and the opening. The valve opening is controlled by the pilot circuit allowing a flow q_3 to fill the valve control space determining the opening and the closure of the valve.

The inflow to the control space of PRV is dependent on the difference between the outlet head and the valve setting. The valve is characterized by two parameters α_{open} and α_{close}, equal to $1.1 \cdot 10^{-6}$ m^2/s and $10 \cdot 10^{-6}$ m^2/s respectively, determining the opening and closing celerity and, at the same time, the sensitivity and reactivity of the valve to pressure fluctuation.

The inflow q_3 to the control space is calculated as follows:

$$q_3 = \begin{cases} \alpha_{open}(h_{set} - h_{out}) & \text{if } \dot{x}_m \geq 0 \\ \alpha_{close}(h_{set} - h_{out}) & \text{if } \dot{x}_m < 0 \end{cases} \tag{3}$$

where $\dot{x}_m = \dfrac{dx}{dt}$.

Another function of valve opening (χ_m) is the cross sectional area A_{cs} of the control space, that is determined using the equation:

$$A_{cs} = \frac{1}{3700(0.02732 - x_{m0})} \tag{4}$$

Calculating q_3 with the equations (3), a new value χ_m can be estimated representing the adaptation of valve opening to seek the required set point h_{set}:

$$x_m = \frac{q_3}{A_{cs}(x_{m0})} \Delta t + x_{m0}$$

(5)

The system of equations (1) – (5) requires an iterative resolution because inflow q_3 is depending on h_{out} by means of eq. (3) that is dependent on valve opening condition χ_m again dependent on q_3 according to eq. (5). The system has to be solved making an initial hypothesis on valve opening χ_{m0} and then solving the equations in order until a new value of χ_m is obtained in eq. (5). The iterations are continued until the difference between $q_{3,i}$ (with i the i-esima iteration) and $q_{3,i-1}$ is less of an established tolerance that was assumed equal to 0.1% in the present study.

The case study

The model has been applied on one of the 17 distribution networks of Palermo city (Sicily). The network is fed by two tanks at different levels, that can store up about 40.000 m^3 per day, and supply around 35.000 inhabitants (8700 users). It has been designed to deliver about 400 l/capita/d but the actual mean consumption is about 260 l/capita/d. Pipes are made of polyethylene and their diameters ranging from 110 to 225 mm (Figure 1). Additional details on the analysed network can be found in De Marchis et al. [13].
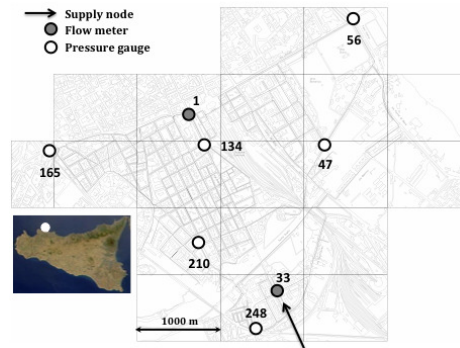

Figure 1. Case study network scheme

The system is monitored by six pressure cells and two electromagnetic flow meters (Figure 1). Data have been provided on hourly basis almost continuously since 2001, and the network hydraulic model calibration is constantly updated when new data become available (Criminisi et al., [4]). The pressure data used for model calibration have a time resolution of five minutes and were taken from the period between June and October 2002, during which the network was managed by intermittent supply on a daily basis. The pressure time series were available at each of the six pressure gauges and used to represent the filling and the emptying processes. For the same period, flow data entering the network were available with the same temporal resolution.

The current configuration of the network is characterised by significant iniquity in the distribution of water resources during intermittent supply. As demonstrated in De Marchis *et al.* [13], the users in the lower part of the network can access to water resources soon after the beginning of service period and they are able to fill up their tanks that were emptied in the period of service unavailability. At the same time, the users in the upper part

of the network have to wait the advantaged users to collect water resources and pressure over the network to raise in order to begin filling their tanks.

As discussed in the introduction, the definition of PMA can help in the reduction of inequalities among advantaged and disadvantaged users. In the present study, two configurations were considered dividing the district in two and four PMAs. In the Scenario A, the network was divided in two approximately equal parts (Figure 3a). In the Scenario B, the network was divided in four PMAs increasing the number of valves to be introduced in the system and the number of closed pipes (Figure 3b)
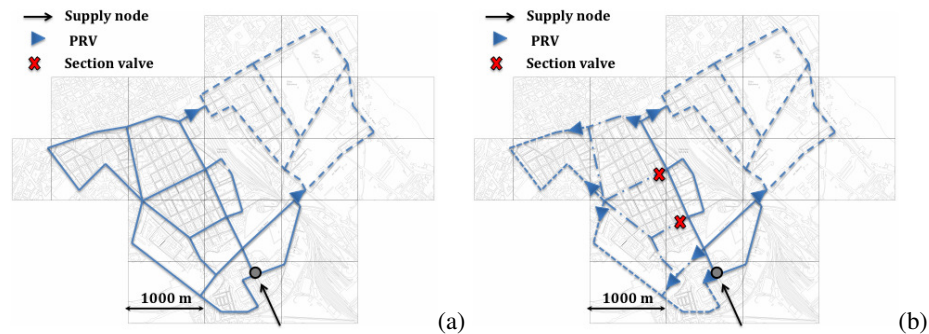

Figure 3. Position of the PRVs and closed pipes on network mains: Scenario A (a) and Scenario B (b).

ANALYSIS OF RESULTS

The presented model was used to analyse and compare different configurations of PMAs in order to reduce inequalities among user accessing and collecting water resources considering the relevant role of private tanks.

In the analysis of results, the Scenario 0 (i.e. the current situation with one network district with no pressure control) was compared with the two proposed PMA Scenarios. The effectiveness of district definition was evaluated by means of pressure levels on the network and by means of the water volume supplied to the users in different moments of the service day. In all the scenarios, the simulation starts with the reactivation of service during intermittent distribution on daily basis. Because of user water consumption in the day before, at the beginning of the simulation, all the private tanks are almost empty and their supply valves are fully open. The comparison between scenarios was carried out after three hours from the service re-activation (when some users have yet collected 100% of their daily demand) and after five hours.

Figure 4 shows pressure levels on the network after 3 hours in the three selected scenarios, the separation between the different PMAs is clear and the average pressure on the network progressively decreases by implementing 2 and 4 different districts: in Scenario 0, the average pressure head is 22.1 m, decreasing to 21.4 m in Scenario A and 20,7 m in Scenario B. More interestingly, the standard deviation drops from 6.5 m in Scenario 0 to 5.4 m and 4.6 m, respectively in Scenario A and Scenario B. This fact confirms a more uniform distribution of pressures over the network and, considering that the most part of the uses are head driven because of private tanks, a more uniform distribution of resources.
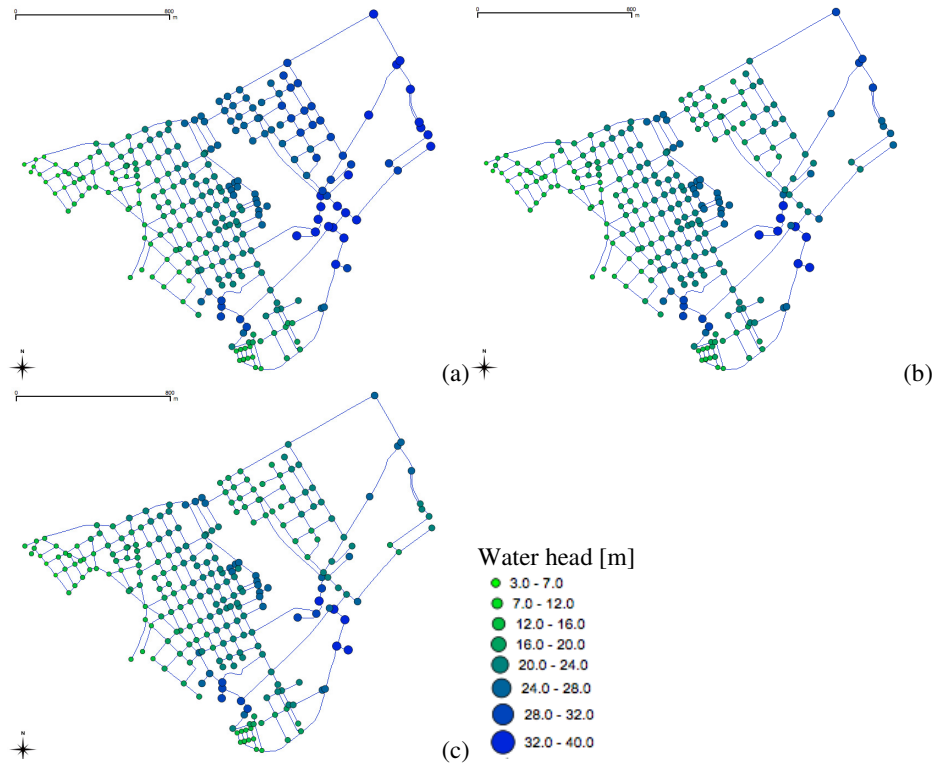
Figure 4. Pressure levels on the network after 3 hours: (a) Scenario 0; (b) Scenario A; (c) Scenario B.

This consideration is confirmed by looking at supplied water volumes after 3 hours (Figure 5) and after 5 hours. The percentage of users able to collect the totality of their daily demand after 3 hours drops from 14% to 10% and 4% in Scenarios A and B. After 5 hours in Scenario 0, one fourth of the users have collected all their daily demand while only the 20% and the 13% have completed their supply in the two PMA Scenarios. The implementation of PMAs has a more relevant impact on users unable to supply: after three hours, 45% of users are unable to be supplied in the Scenario 0 and this number is reduced to 38% and 29% in Scenario A and B, respectively; after five hours, the number of non supplied users is still high (39%) while it is reduced to 29% and 18% in the two PMA scenarios.
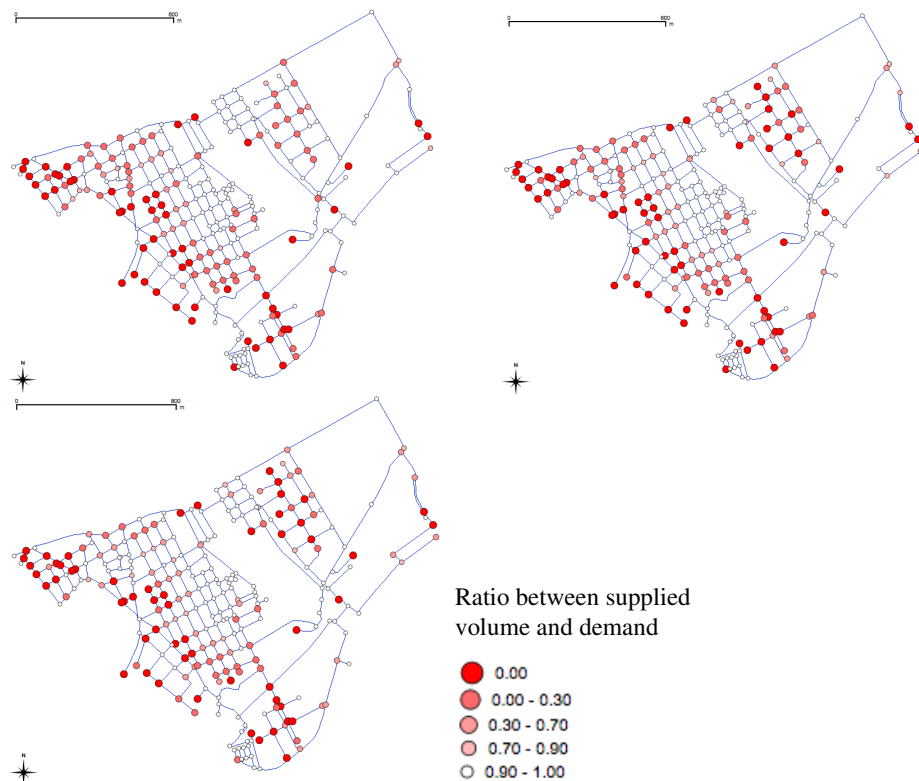
Figure 5. Volume supplied to the users after 3 hours: (a) Scenario 0; (b) Scenario A; (c) Scenario B.

CONCLUSIONS

In the study, a dynamic mathematical model for intermittent networks was integrated with a PRV model in order to simulate management actions for reducing inequalities between users in their access to water resources. The model demonstrated to be robust and to correctly represent the application of several valves in the network. From a practical perspective, the creation of PMAs has a relevant impact on intermittent networks helping the reduction of inequalities between users accessing and collecting water resources. The presence of private tanks helps advantage users to collect as much water as possible in a few hours after the restoration of service; at the same time, several users are unable to collect water because pressure on the network is too low. The introduction of PMAs mitigates such problem by reducing the differences of pressure between different points of the network. The introduction of the valves reduces the differences between collected water by users in the first part of the service day even if inequalities still remain. The analysis demonstrated that PMAs can help to have equal distribution of water resources during intermittent service but further analyses are needed to implement an optimal distribution of valves in order to reduce the different distribution of water supply between users.

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