Analysis of intermittent supply systems in water scarcity conditions and evaluation of the resource distribution equity indices

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Abstract

Generally, urban water distribution shortage situations are solved by introducing discontinuous service and rationing the available water resources. This approach is widely adopted, not only in developing countries but also in developed ones, for solving short term scarcity conditions which can be caused by unpredicted drought periods. Intermittent distribution has the advantage of requiring small financial efforts but it leads to network operating conditions that are very far from the usual design ones. With the aim to analyse and describe the water supply network behaviour in intermittent conditions, a network hydraulic model has been set up in which both user and manager dependent regulation structures have been schematised (pumps, private reservoirs, etc.). The analysis allowed evaluating network performance introducing several control strategies so suggesting operational plans for reducing the impact of water scarcity events on population and improving resources distribution equity. The presented model has been applied to the water distribution network of Palermo (Italy).
Keywords: distribution network performance, water scarcity conditions, intermittent distribution.

1 Introduction

The urban development and the population growth have several consequences connected with design and management of water distribution systems. The contemporary increase in water consumption and reduced availability of water resources produce unbalances between water demand and offer, so leading to

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water shortage scenarios. This happens even in those situations where water resources procurement was not historically an issue.

Water shortage situations are commonly solved by using discontinuous water distribution and rationing the available water resources. This approach is widely adopted not only in developing countries [1–4] but also in developed ones for solving short-term scarcity conditions, which can be caused by drought periods [5].

Intermittent distribution is quite frequent in Mediterranean countries as well. In this area, the lack of natural resources management and network maintenance plans, explicitly considering the possibility of scarcity scenarios, produces unexpected water shortage situations that can be handled only by mean of emergency interventions. Intermittent water distribution has the advantage of requiring small financial efforts but it leads to network operating conditions that are very far from the usual design ones. The network is subjected to cyclical filling and emptying periods and users need to collect water during distribution periods for covering their needs when supply service is not available.

In intermittent distribution, the users try to compensate water service intermittency by searching new local resources, when available (as an example by perforating private wells), or, more commonly, by building private reservoirs, used for collecting water during serviced periods and distributing it when public water service is not available. During intermittent distribution periods, the public network is greatly influenced by the presence of such reservoirs that are usually filled in a very short period after the reactivation of water service, leading to very high peak flows and, consequently, inequity in water resources allocation among population. Moreover, those local reservoirs are often over-designed in order to take into account higher water consumption and possible leakages. In these cases, the intermittent distribution is useful to limit water losses due to pressurization more than to limit water consumption by users.

Intermittent distribution systems are affected by several problems connected with inconsistence between design and operational conditions. In the design phase, in fact, it is supposed continuous operational conditions and sufficient water resources to match the volumes required by the users and the available ones. When a continuous system is managed as an intermittent one, pressure and flow distributions are inadequate and not homogenous.

Intermittency generates inequitable water distribution due to pressure dependent flow conditions, with obvious disadvantages for consumers located faraway from the supplying nodes or at higher elevation in the network. In distribution systems designed for continuous water supply, the consumers exposed to intermittent supply conditions are likely to collect as much water as possible in their reservoirs whenever the service resumes [6]. In this condition, consumer reservoirs are filled once the supply has been restored and this contemporary use of water service generates larger peak flows than predicted in the network design process, increasing the pressure losses in the network. Consequently, disadvantaged consumers will always collect less water than those nearer to the source. Intermittent distribution can also have a large impact on

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water quality allowing for the introduction of soil in the pipes when they are empty [7].

For these reasons, it is absolutely necessary designing and managing water distribution systems according to their operational conditions in order to improve system performances and to deliver equitably the available water resource. Intermittent distribution networks, therefore, have to be designed in a particular way, absolutely different to those applied to systems delivering water 24-hours per day [8].

In order to efficiently analyze urban distribution networks in scarcity conditions, it can be helpful to evaluate how water scarcity and intermittent service affect water consumption. The study proposes a methodology for identifying those users that are more disadvantaged by the intermittent distribution condition providing a useful tool to be used when managing a network in such a delicate operational condition. The identification of disadvantaged users is carried out by the mean of network performance indicators specifically defined for intermittent distribution and described in the next paragraph. In the study, a real distribution network has been analysed proposing some indices for assessing the equity of water service in intermittent distribution conditions.

2 Intermittent distribution network mathematical model

The primary objective of a water distribution system is to provide water at a sufficient pressure and quantity to all its users. In traditional demand-driven analysis, the network solution is achieved by assigning the assumed demands for all nodes and computing the nodal pressure heads and link flows from the equations of mass balance and pipe friction headloss [9]. For networks operating under intermittent conditions, a demand-driven analysis can yield nodal pressures that are lower than the minimum required service level or which even become negative. In the real network, the design demands would not be met. Although this is a well-known problem that has been tackled by many researchers [10–16], it is still sometimes ignored. Since the 1980s, researchers have proposed various methods to compute actual water consumptions, node pressures and flows in networks operating in conditions different from design ones (such as intermittent systems). Most of the proposed methods involve an assumption on the relationship between pressure and outflow at the demand nodes. These methods are generally termed head-driven analyses.

Bhave [10], who firstly acknowledged demand driven analysis does not behave well when node heads are lower than required service standard ones, proposed the following pressure-consumption relationship:

$$\text{If } H_j^{avl} < H_j^{\min}, \quad q_j^{avl} = 0 \tag{1a}$$

$$\text{If } H_j^{avl} \geq H_j^{\min}, \quad q_j^{avl} = q_j^{req} \tag{1b}$$

where q_j^{avl} is the actual outflow at node j, q_j^{req} is the required outflow at that node (water demand), H_j^{avl} is the available head and $H_j^{\min}$ is the minimum head required to have outflow at the node.

Germanopoulos [11] suggested the use of an empirical pressure-consumption relationship to predict the outflows at various nodal head:

$$\text{If } H_j^{avl} \le H_j^{\min}, \quad q_j^{avl} = 0 \tag{2a}$$

$$\text{If } H_j^{avl} > H_j^{\min}, \quad q_j^{avl} = q_j^{req}\left\{1 - 10^{-c_j\left[\left(H_j^{avl} - H_j^{\min}\right)/\left(H_j^{des} - H_j^{\min}\right)\right]}\right\} \tag{2b}$$

where H_j^{des} is the head required to satisfy the water demand, q_j^{req}, at the node j and c_j is a calibration parameter ranging from 1 to 5.

Then, Wagner *et al.* [12] proposed the use of a parabolic curve to represent the pressure-consumption relationship at a demand node for head between $H_j^{\min}$ and H_j^{des}:

$$\text{If } H_j^{avl} \le H_j^{\min}, \quad q_j^{avl} = 0 \tag{3a}$$

$$\text{If } H_j^{\min} < H_j^{avl} < H_j^{des}, \quad q_j^{avl} = q_j^{req}\left(\frac{H_j^{avl} - H_j^{\min}}{H_j^{des} - H_j^{\min}}\right)^{\frac{1}{n}} \tag{3b}$$

$$\text{If } H_j^{avl} \ge H_j^{des}, \quad q_j^{avl} = q_j^{req} \tag{3c}$$

where *n* is a calibration parameter ranging from 2 to 1.

Reddy and Elango [13] introduced a method completely different from the others previously referred to. The authors suggested a pressure-consumption function without above boundary as the following equations show:

$$\text{If } H_j \le H_j^{\min}, \quad q_j^{avl} = 0 \tag{4a}$$

$$\text{If } H_j \ge H_j^{\min}, \quad q_j^{avl} = S_j\left(H_j - H_j^{\min}\right)^p \tag{4b}$$

taking the value of the coefficient S_j from the following condition:

$$\text{If } H_j = H_j^{des}, \quad q_j^{avl} = q_j^{req} \tag{5}$$

and being *p* a coefficient ranging from 0.5 to 1.

This method has been introduced to evaluate the node consumptions in water distribution networks operating in intermittent conditions. In this case, all the users are endowed with private reservoirs and the node outflow is the maximum taken by the network, only related to the available nodal head. The outflow stops when the reservoir is just completely full.

Where water distribution is periodically provided on intermittent basis, the users often provide private reservoirs with pumps to collect as much water as possible even if nodal pressure is lower than minimum required having outflow at the node. In such situations, the method proposed by Reddy and Elango [13] has to be modified to take into account the pressure-consumption relationship in the range of node head lower than the minimum value. In order to do this, eqn. (6) has been defined setting $H_j^{\min}$ equal to zero in eqn. (4b):

$$q_j^{avl} = k \cdot H_j^{\ p} \tag{6}$$

where k and p are calibration coefficients.

This algorithm has been readily implemented into an existing hydraulic network solver, EPANET 2 [17]. Furthermore, a private reservoir under the roof and a pump have been associated with each node (fig. 1) thus providing a complete model for analysing intermittent distribution networks.

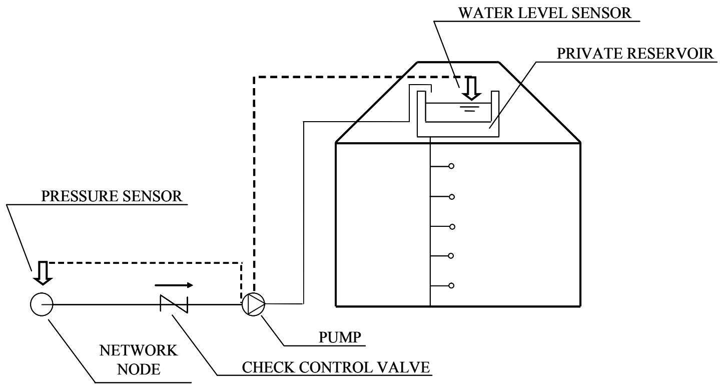

Figure 1: Distribution node numerical scheme.

The reservoir has been designed according to nodal daily water demand and a pump has been chosen being able to fill the reservoir in 4 or 5 hours. The pump is turned on if the reservoir is empty and turned off if the reservoir is full or the pressure on the network is negative.

In order to evaluate the equity in the distribution during intermittent operational conditions, two performance indices have been proposed in the present study:

1. the ratio between the water volume supplied to the users in a service cycle (if the service is intermittent on daily basis, the service cycle is correspondent to two days) and the user demand:

$$EQ1 = \frac{V_{\text{int}}}{D} \tag{7}$$

   where V_{int} is the water volume supplied to the users in a service cycle and D is the user water demand in the same period;

2. the ratio between the water flow discharged to the user during a service day in intermittent and continuous distribution conditions:

$$EQ2 = \frac{Q_{\text{int},i}}{Q_{cont,i}} \tag{8}$$

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where $Q_{int,i}$ is the water volume supplied to the users in a service cycle and $Q_{cont,i}$ is the user water demand in the same period.

The index *EQ1* represents the ratio between supplied and required water volumes in intermittent distribution and it is able to identify the users that will obtain less water than their needs and the advantaged users that will have available volumes even higher than their needs. But even if globally in a service cycle water volumes distributed at the users do not greatly differs among them, wide differences may be possible during the distribution period because advantaged users can fill their reservoirs much faster than disadvantaged ones. This aspect can create difficulties in water supply of disadvantaged users and it can modify the users' perception of the water service reliability. For this reason, the index *EQ2* can be useful for analysing the behaviour of the network in different operational periods (at the start or at the end of the distribution service after a 24-hours stop).

3 The adopted case study

To provide a more effective description of the proposed methodology, an analysis has been conducted on one of the 17 distribution networks of Palermo city (Sicily). This network has been chosen because it is recently built and it is precisely known all its geometric characteristics, the number and the distribution of user connections, the water volumes delivered and measured, and pressure and flow values in a few important nodes.

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. 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. The network is about 40 km long and users' elevation ranges between 47 m and 3 m above the sea level. Fig. 2 shows the distribution network adopted in the present study.

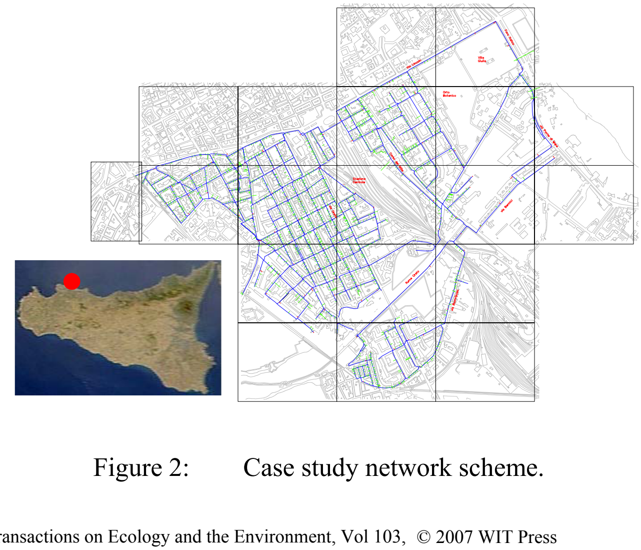

Figure 2: Case study network scheme.

However, because of the great amount of water losses occurring in the pipe connecting the tanks with the network and the recurrent lack of water resources, the water service manager has decided to operate the network on intermittent basis and introduced pressure reduction valves at the network inlets in order to reduce pressures and consequently leakages.

4 Model calibration and network simulation

The network has been simulated by the mean of EPANET2 model in which each supply node has been simulated according to the scheme provided in fig. 1. The model has been calibrated by the mean of a large set given by six months of continuous water flow data at the two network inflow nodes and correspondent pressure and flow data in 6 nodes distributed inside the network. The data has been collected on hourly basis.

The only parameter that has been considered in the calibration process was the pipe roughness and the calibration has been performed by the least square method fitting the simulated pressures and flows in the network internal nodes with the measurements. Fig. 3 shows the calibration results. The relative pipe roughness obtained from the calibration was equal to 0.64 mm.

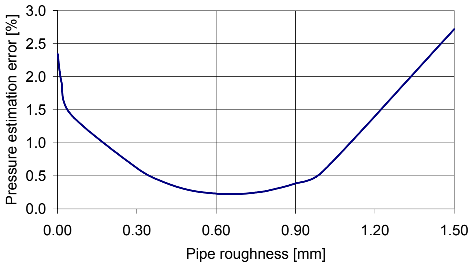

Figure 3: Modelling calibration results.

The model has been firstly run in order to analyse pressures distribution over the network in continuous and in intermittent distribution condition in order to identify the different network behaviour in the two situations. Afterwards a long term analysis has been performed over a service cycle in order to estimate the inequities in water distribution when the network has been subjected to intermittent distribution.

5 Results discussion and possible network management strategies

As discussed above, network diameters are largely overestimated with respect to the real need of population. The design user water demand is, in fact, almost two times of the real population needs. For this reason, in ordinary conditions the network is characterised by low water velocities and correspondently high pressures. The high pressures on the network caused in the past high leakages and, for this reason, pressure reduction valves have been introduced for reducing the problem (fig. 4). As discussed above, the level of leakages did not allowed to maintain continuous distribution (at least in summer period) in the last 5 years and intermittent distribution on daily basis was introduced as a common practice convincing the users to build up local private reservoirs with schemes presented in fig. 1.

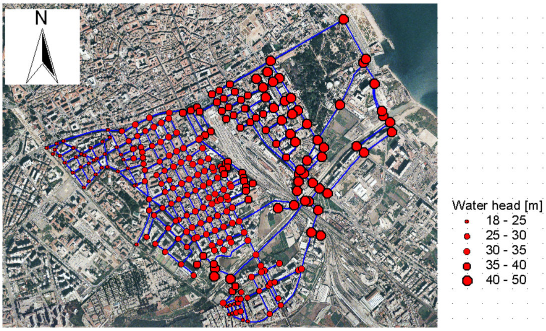

Figure 4: Water head distribution over the network.

The network was analysed by the mean of a long term simulation, with a time step equal to one hour, involving a whole service cycle in intermittent distribution condition. In this simulation, water resources availability is considered equal to the demand (intermittent distribution is adopted only for leakages reduction) so the iniquitous water supply is due to wrong distribution of resources among users. Index *EQ1* has been computed for the whole period and for each network node. The index *EQ2* has been computer for each node and each analysis time step.

The analysis of equity index *EQ1* shows that in intermittent conditions the inequity in water volumes distributed to users are limited within 15% (fig. 5). This number can be considered acceptable because it does not generate a great compression of user water consumption but it has to be stressed that this value has been generated in a condition where water supply would be able to fully satisfy users demand.

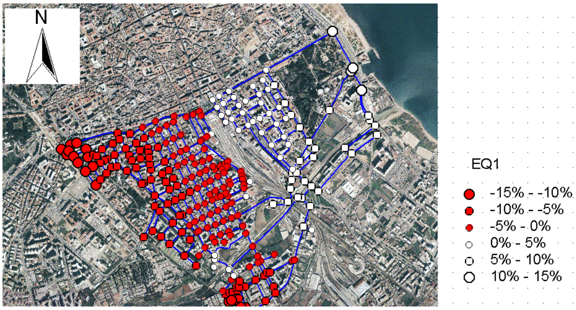

Figure 5: Distribution of EQ1 values over the network.

The analysis of index *EQ2*, on the contrary, has demonstrated that, in the first part of the service day (just after the restart of the water service), the lower nodes drain the most part of the available resources for filling their local reservoirs showing values of *EQ2* near to 250%; in the meantime, at higher elevated nodes, water is still not available and *EQ2* values are near to zero (fig. 6(a)). When lower reservoirs are filled (fig. 6b), water resources are available for elevated nodes that show high values of *EQ2* while lower nodes (where reservoirs are filled) show low *EQ2* values. *EQ2* is highly variable and it demonstrates that the network subjected to intermittent distribution will work in conditions that are quite far from the design ones and also from the operating conditions that take part in continuous distribution.

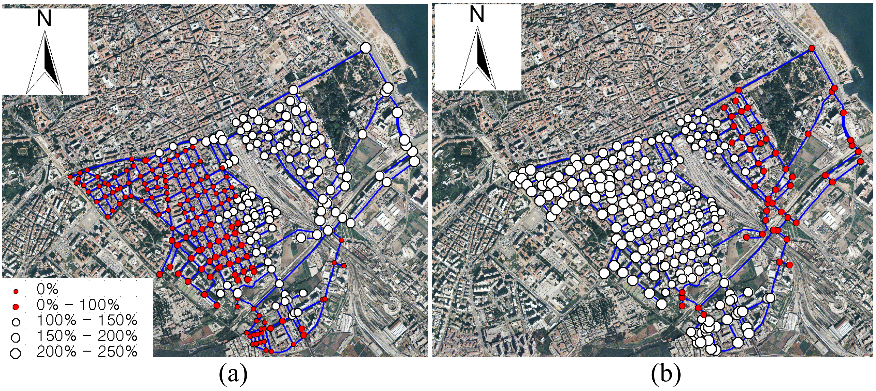

Figure 6: EQ2 values at the beginning (a) and at the end (b) of the service period.

6 Conclusions

The present study proposed a methodology for analysing a distribution network under intermittent distribution condition. The methodology has defined two performance indicators able to identify inequality in water supply both considering long term effect with user consumption compression and short term during the service cycle with large variations in network hydraulic behaviour.

The application of the methodology to a real case study has shown that intermittent distribution can greatly affect both water availability for the users and the behaviour of the network. In the case study, even if water supply would be sufficient for fulfilling user demand, intermittent distribution will create inequalities among users by reducing water supply to high elevated nodes and increasing supply to lower nodes. The effect on the short term behaviour of the network is much higher with differences higher than 200% in the ordinary continuous distribution condition.

The intermittent distribution has thus a great impact on users and networks. Users change their water supply patterns with higher peaks (connected with the filling of local reservoirs) and large periods with very low discharges and they can also receive higher or lower water volumes depending on their elevation and position in the network. Intermittent distribution changes radically the behaviour of the network with parts of it that are interested by flows that are much higher than the design ones and parts that are interested by almost null discharges.

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