Pressure management in water distribution systems: Current status, proposals and future trends

D. J. Vicente[1]; L. Garrote[2]; R. Sánchez[3]; D. Santillán[4]

Abstract

Pressure management (PM) is commonly used in water distribution systems (WDSs). In the last decade, a strategic objective in the field has been the development of new scientific and technical methods for its implementation. However, due to a lack of systematic analysis of the results obtained in practical cases, progress has not always been reflected in practical actions. To address this problem, this paper provides a comprehensive analysis of the most innovative issues related to PM. The methodology proposed is based on a case-study comparison of qualitative concepts that involves published work from 140 sources. The results include a qualitative analysis of four aspects: (1) the objectives yielded by PM; (2) the types of regulation, including advanced control systems through electronic controllers; (3) new methods for designing districts; and (4) the development of optimization models associated with PM. The evolution of the aforementioned four aspects is examined and discussed. Conclusions on the current status of each factor are drawn and proposals for future research outlined.

Subject headings

CEDB subject headings – water distribution systems; leakage; optimization models; valves

[1] Ph.D. Candidate, Technical Univ. of Madrid, Dept. of Civil Engineering: Hydraulics Energy and Environment, C/Profesor Aranguren s/n, 28040 Madrid, Spain. (corresponding author). E-mail: dvicentegonzalez@gmail.com

[2] Professor, Technical Univ. of Madrid, Dept. of Civil Engineering: Hydraulics,Energy and Environment, C/Profesor Aranguren s/n, 28040 Madrid, Spain. E-mail: l.garrote@upm.es

[3] Professor, Technical Univ. of Madrid, Dept. of Agroforestry Engineering, Av/ Complutense, s/n, 28040 Madrid, Spain. E-mail: raul.sanchez@upm.es

[4] Lecturer, Technical Univ. of Madrid, Dept. of Civil Engineering: Hydraulics, Energy and Environment, C/Profesor Aranguren s/n, 28040 Madrid, Spain. E-mail: david.santillan@upm.es

Suggested subject headings: pressure management; DMA; pressure reducing valves; breaks; consumption

1. Introduction

Pressure control in water distribution systems (WDSs) remains a significant concern for water utilities. This process can provide significant benefits for the two main segments of water distribution: water companies and end users. Effective pressure adjustment throughout the day provides sufficiently high pressure that ensures a constant and adequate service to customers while reducing it to an extent that avoids background leakages or breaks at night. In this context, the term pressure management (PM) emerged to refer to this kind of activity. PM may involve a large number of activities with different regulation elements: pump control, tank regulation and pressure reduction by using automatic valves, among others. In particular, the use of pressure regulating valves (PRVs) to reduce excessive pressure at certain times of the day is an increasingly widespread practice used by companies.

It is important to highlight the multiple benefits that can be achieved by PM. The most essential objective is the reduction of background leakage. The importance of pressure control in managing such leakage is apparent from the significant number of published studies. Several researchers and expert practitioners have emphasized the role of PM in reducing leakage (Mutikanga et al. 2013; Wu et al. 2011; Puust et al. 2010; AWWA 2009; Thornton et al. 2008; Fanner et al. 2007; Farley and Trow 2003; Lambert 2002; Farley 2001; UK Water Industry 1994a). PM has also been cited as a key factor required for leakage management by specialized committees from recognized international associations, particularly by the Water Loss Task Force from the International Water Association (IWA) and the Water Loss Reduction Committee from the American Water Works Association (AWWA). However, PM has also allowed water utilities to pursue new benefits beyond classical leakage reduction, such as extending infrastructure life through reduction of new main breaks and saving water through reduction of consumption by users (Fantozzi and Lambert 2010).

In addition, technological and scientific development has led to the emergence of innovative techniques that improve PM processes with PRVs. Certain strategies used for many years have undergone significant evolution. For example, advanced control systems with electronic controllers have evolved from more classical regulation methods such as time-based or flow-based modulation to remote node-based modulation. In addition, the design of district metered areas (DMAs) has experienced several changes, highlighting the emergence of dynamic topologies. Finally, optimization models have provided renewed approaches that are gradually being introduced in practical PM schemes.

To obtain a better understanding of the current status and latest trends related to PM, an exhaustive analysis of specialized literature of a different nature was carried out during the course of this research. First, scientific and academic points of view were considered through peer-reviewed papers, conference articles and reference textbooks. Second, a review of specialized committee reports, technical datasheets and patent documents was undertaken to gain knowledge of the latest equipment and techniques available. Third, and most significantly, special attention was paid to case studies carried out by water utilities. In addition, a number of worldwide expert practitioners were consulted. Finally, Canal de Isabel II Gestión (a water utility company in the Madrid region of Spain) provided scientific and technological advice gained from a large-scale PM program it conducted.

Given this extensive analysis, the purposes of the present work are the following: first, characterization of the current status of PM processes, identification of the distinctive features of various global regions and analysis of the pros and cons of the approach undertook by this programs; second, recognition of the most innovative experiences and latest trends; and third, identification of directions for further work, including research and implementation opportunities.

2. Description of the benefits of PM

This section deals with the relationship between pressure reduction and three of the most common objectives pursued by water companies around the world: leakage reduction, new burst frequency decrease and consumption reduction.

2.1 Leakage reduction

Together with infrastructure replacement, pressure reduction is proven as one of the most effective tools to decrease leakage rates from existing leaks. In this context, the fixed and variable area discharge (FAVAD) principles (May 1994) and the bursts and background estimates (BABE) concept (Lambert 1994) offer significant contributions. Subsequently, several approaches have sought to establish a pressure-leakage relationship, with most being inspired by these concepts. The FAVAD theory models the effect of water flow through an orifice operating at different pressures. Although some equations following FAVAD concepts (Cassa et al. 2010) have been proposed, it is difficult to establish a precise physical relationship between the involved variables. The inherent difficulty of establishing physical models is due to the other parameters involved in the process, including pipe material and orifice geometry (Walski et al. 2006). Experimental studies have determined this relation for specific cases (Guo et al. 2013; Van Zyl and Clayton 2007; Greyvenstein and Van Zyl 2007). Given that widespread implementation of these equations is complex, simpler relationships have been suggested for practical purposes. One of the best known is the N_1 exponent relationship (Thornton 2003; Lambert 2001), which predicts changes in the leak flow rate (L_0 to L_1) as pressure varies (P_0 *to* P_1) following the exponential relationship: $L_0/L_1 = (P_0/P_1)^{N1}$. Based on more than 100 field tests, Thornton and Lambert (2005) found that the N_1 exponent lies within the range [0.5 – 1.5] and occasionally reaches 2.5. Later, Fantozzi and Lambert (2010) suggested values of 0.5 and 1.5 for the N_1 exponent depending on whether the pipes are rigid or flexible, respectively. Other studies have shown that for different pressure values, the exponent N_1 may change for the same leak orifice (Van Zyl 2014; Van Zyl and Cassa 2011).

2.2 New burst frequency decrease

One of the first studies conducted to examine a pressure-burst relationship was carried out in the United Kingdom (Lambert 2002). However, it could not identify a significant relationship due to the method of analysis employed. The IWA Water Loss Task Force recognized that research into pressure-burst relationships needs to be based on analysis of good quality data in individual pressure-managed systems, before and after implementation, with separate predictions for mains pipe repairs and service pipe repairs. This ultimately led to more reliable analysis and prediction methods, firstly with 'quick' methods for areas with high burst frequencies (Fantozzi and Lambert 2010) and then in 2012, for a much wider range of initial burst frequencies (Lambert and Thornton 2012).

One of the proposed methods was the introduction of an exponent similar to N_1. Thus, another parameter, N_2, was proposed to predict new bursts although results were at first less precise (Thornton and Lambert 2005). This predicts changes in new burst occurrences (B_0 to B_1) as pressure varies (P_0 to P_1) following an analogue expression: $B_0/B_1 = (P_0/P_1)^{N2}$. Later, Thornton and Lambert (2007) identified new expressions that showed this relationship depends on the break frequency before PM. If the frequency is relatively high, then a small percentage reduction in pressure may cause a large percentage reduction in new burst frequency. Conversely, if break frequency before PM is relatively low, then any percentage reduction in pressure should have little effect. Finally, Lambert and Thornton (2012) offered more detailed equations through the use of the N_2 exponent by making distinctions between different hydraulic assumptions and pipe materials.

While other approaches have been offered, few physically based methods have been proposed for WDS (Davis et al. 2007), which has led to difficulties in implementation. One reason for this is that deterioration of water distribution pipes is caused by the interaction of several factors of both a static (i.e., pipe material, diameter and length) and dynamic nature (i.e., pipe age and water pressure and temperature) (Wang et al. 2009). Approaches based on data-driven models and statistical techniques have provided more precise results (Martinez-Codina et al. 2015; Shirzad et al. 2014; Xu et al. 2013; Xu et al. 2011; Watson et al. 2004). However, such methods are not as helpful as they could be in establishing pressure-bursts relationships as they are not based on physical laws.

2.3 Consumption reduction

It is important to understand the behavior of water consumption as a function of pressure. Many authors have linked these variables through the FAVAD concept, but this should be used with care. Several approaches that differ with respect to the demand-component disaggregation have been proposed.

There are few references to experimental studies that deal with this topic. The research activities that have been conducted can be classified into two groups according to the nature of the demand: 'outside' consumption elements such as irrigation sprinkler systems (Cullen 2004; Bamezai and Lessick 2003) and indoor, 'in-house' or domestic consumption systems (Bartlett 2004). A new exponent, N_3, which links consumption and pressure, has been proposed by the IWA (Fantozzi and Lambert 2010). This expression is analogous to the one that relates pressure and leakage through N_1 and is based on experimental tests. Different values of N_3 are suggested for outside consumption (0.4-0.5) and indoor consumption (0.02-0.04). A value close to 0.5 for outside elements suggests that in such scenarios, as consumption depends fully on pressure, the FAVAD equation can be applied. Conversely, a value close to zero for domestic consumption may indicate that it is independent from pressure.

Nevertheless, consumption behavior with regard to varying pressure is much more complex. Gomes et al. (2011) presented a model to estimate the benefits of PM in which domestic and non-domestic consumption components were distinguished and divided into pressure-dependent (e.g., irrigation systems, showers and taps) and pressure-independent (e.g., toilet tanks, dishwashers and washing machines, among others). The study considered different parameters for each component based on the values reported for systems in the United Kingdom by the UK Water Industry (1994b). Accordingly, the only domestic consumption components that may be affected by a PM process are those that are pressure-dependent. However, even if this may be correct from a physical point of view, in practice, some approaches suggest that when there is adequate pressure in the system, customer demand varies regardless of pressure. Only when there is insufficient pressure does consumption depend on customer-based demand and the current pressure of the system (Liu et al. 2011; Pathirana 2010). An alternative way to deal with this assumption is focusing on whether the consumption elements are time-based or volume-based (Van Zyl and Clayton 2007). In this sense, the former would be pressure-dependent and the latter would be pressure-independent. Finally, one of the most detailed approaches is that suggested by Giustolisi and Walski (2012), where human-based, volume-based, uncontrolled orifice-based and leakage-based demands were considered.

3. PM methods and emerging trends

Although several factors influence and should be considered when designing a PM scheme, three components were identified as key factors in this research.

3.1 Types of PRV regulation

There are two primary approaches to controlling PRVs; the first involves hydraulic control, with autonomous pilot valves, and the second entails the use of electronic controllers.

3.1.1 Hydraulically-operated controls

Hydraulically-operated controls are the most traditional and remain the most frequently used by water utilities. In particular, the fixed-outlet (FO) pressure profile is the most common. The downstream-pressure setting is maintained as a constant value regardless of varying upstream pressures. To alter the pressure, the valve must be adjusted manually by changing the pressure setting on the pilot. Other downstream-pressure profiles such as proportional discharge and dual set point are available. Hydraulic time-based regulation can be achieved by incorporating two pilot valves set at different pressures (day and night), a solenoid and a basic timing controller. Even flow-based control can be achieved hydraulically through more complex hydro-mechanical circuits (Bermad 2010; C-Valve 2010)

3.1.1 Electronically-operated controls

Over the last two decades, new electronic devices and control algorithms with different levels of sophistication have emerged. The most reported approaches are time-based (TM), flow-based (FM) and remote node-based (RNM) modulation. Some authors have referred to these techniques as advanced pressure control (APC) methods (Fantozzi and Lambert 2010; Charalambous and Kanellopoulou 2010).

(a) TM is the simplest form of APC and involves a local controller with an internal timer device connected to the controlling pilot of the PRV and an open-loop profile. This profile connects downstream pressure and time intervals, enabling pressure to be varied during each period.

(b) FM is a real-time, closed-loop control that enables dynamic local control of pressure according to the demand placed on the system. The usage of a flow meter gauge is compulsory for this type of control. Downstream pressure varies according to a pressure-flow relationship curve that is part of the controller.

(c) RNM uses data from a remote sensor to reduce output pressure while still providing the required pressure at a sensitive point. This point is usually installed at the critical point (CP), which is the node in the regulated area at which the lowest supply pressure occurs during the course of the day.

3.2 Isolated districts with PM purposes: PMAs

The sectorization of WDSs in DMAs is a well-known technique for leakage monitoring introduced in the United Kingdom in the early 1980s (Morrison 2004). It involves dividing the network into areas with defined and permanent boundaries and continuously metering the flow entering and leaving each one. When the water supplied to isolated areas is regulated with a pressure-regulated control, this represents one of the most basic forms of PM. Thus, they have been termed pressure-managed areas (PMAs) by some authors (Yates and MacDonald 2007; Charalambous 2005; Farley 2001).

A number of factors should be taken into account when designing DMAs or PMAs: size (geographical area, length of main pipes, number of connections), topology considerations (number of feeds, areas that cascade into an adjacent district, boundary characteristics), variations in ground level, type of consumption profile (uniform demand, varying profile over time with steady patterns, varying profile over time with stochastic demand) and water quality considerations, among others.

3.3 Optimization models

A considerable amount of research has focused on developing methods for optimizing PM, and the main objective of a large number of studies has been minimization of excess pressure which, in turn, will reduce leakage. Several papers have used mathematical programming techniques to minimize leakage through determining PRV location and setting. There are similarities between models that use the same or a highly similar formulation, with their objective function being either to minimize excessive pressure or minimize leakage. The constraints involved are usually the network-governing equations, mass balance and energy-conservation equations, and the establishment of a minimum pressure for all nodes.

With regard to the optimization methods used, two broad classes can be found: mathematical optimization and meta-heuristic methods. Mathematical optimization approaches use hydraulic equations for problem formulation. A wide range of methods can be used depending on the nature of the variables used in the problem, the constraints imposed and the objective function searched: linear programming (LP), nonlinear programming (NLP), mixed integer linear programming (MILP) and mixed integer nonlinear programming (MINLP).

Meta-heuristic methods such as genetic algorithms (GA) or simulated annealing (SA) are becoming popular in part because the optimization technique is independent of the hydraulic simulator. GAs entail an evolutionary optimization approach that follows the concept of evolution by stochastically developing a number of solution populations using a given fitness or objective function. SA algorithms are based on the concept of annealing and explore the solution space by slowly decreasing the probability of accepting less accurate solutions.

4. Case-study analysis: Selection criteria

Because one of the main objectives of this paper is to reflect the current global reality and latest trends of PM activity, special attention has been paid to the information acquired about and related to practical PM programs. This section presents the main projects found in the literature and describes how information was collected and grouped, with the aim of assisting researchers and practitioners in future work.

Valuable information was extracted from each particular case and summarized in Table 1 as follows: (1) project emplacement (continent, country and city/region), (2) reference of the document that cited the case study (authors and year), (3) whether the PM projects have been implemented in a real WDS or simulated with hydraulic models, (4) the type of control used to regulate PRV and (5) the objectives pursued.

A total of 56 case studies are presented. These projects were selected because they were the most relevant according to: the PM methods used (innovative techniques and alternative solutions), the scope of implementation (large-scale programs, particular considerations of the selected network), and the impact achieved (importance of the results achieved, influence in other projects), among others.

5. Case-study analysis: Critical assessment

The case studies presented in the previous section are discussed in this section. A comprehensive and holistic analysis is made by studying and comparing each project. The most valuable information extracted from specific projects is also linked with documentation of another nature—scientific, theoretical or technical—in order to draw conclusions. The topics discussed, that is to say, the benefits pursued and PM methods, are described in sections two and three. Additionally, a critical evaluation of the geographical areas where PM projects take place is included.

The analysis and discussion are based on the information disseminated in the documents at the time of writing. Hence, all the conclusions should be treated with caution as some of the information may have evolved from the respective period to the present.

5.1 Geographical considerations

To ensure the representative nature of the study, the list of case studies includes examples from five continents. The analysis revealed varying degrees of acceptance and levels of development through the world. For instance, while PM is widely used in Europe, it is less common in the North American context. As every network is unique, the features of each WDS—topology, regulation elements and size, among others—determine the most suitable PM scheme for implementation. Nevertheless, certain commonalities between networks in the same geographical areas exist and should be addressed. A summary of some key points follows.

5.1.1 Europe

In some countries, for example, the United Kingdom, it has been recognized for over 30 years that effective management of pressure is the essential foundation of effective leakage management (Fanner 2007). Hence, the United Kingdom has become one of the main drivers of PM, with a large number of programs in operation. Division of the network into isolated zones for the purpose of managing pressure has been standard practice since the 1980s (Morrison 2004). Some of the newest APM techniques are being introduced by several water utilities that include Affinity Water, Scottish Water, Severn Trent Water, South East Water and Yorkshire Water (i2O Water 2014; Waterworld 2011; Awad et al. 2008). Innovative optimization problems have been developed and tested in specific networks around the country (Wright et al. 2014; Awad et al. 2010). In this context, the Neptune Project (Li et al. 2010; Savic et al. 2008) provided theoretical and practical knowledge related to leakage management and PM. All of these examples highlight the efforts and initiatives carried out in the United Kingdom that are fueling continued development and creating impacts.

Following this trend, many other European countries have carried out projects (shown in Table 1). Some water utilities in Spain are introducing large-scale PM programs as part of their strategic plans (Jiménez 2015, Miguel 2009). For instance, the aforementioned Canal de Isabel II Gestión launched a large-scale PM scheme involving 104 PMAs. The scheme entailed testing all the described techniques for PRV control with the following rates: FO (64%), TM (19%), FM (4%) and RNM (13%).

5.1.2 North America

In North America, the objectives for the design of a DMA are similar to those in Europe (Sturm and Thornton, 2005). However, there are fundamental differences between WDS designs that should be taken into account when considering districts such as PMAs. Some utilities in North America are reticent to employ PM for certain technical and financial reasons (i.e., fire flows, loss of revenue, loss of hydraulic capacity, water quality and reservoirs not filling at night) that need to be addressed prior to implementation of an advanced PM program (Thornton et al. 2008; Fanner 2007). One particular example is that of fire flows in the United States and Canada. National Fire Protection Association (NFPA) regulations require that a system has sufficient hydraulic capacity to maintain pressure and flows for firefighting. In this context, a poorly implemented PM program may cause problems. For instance, the implementation of some types of open-loop pressure controls such as FO or TM should be avoided. An FM alternative may be an advantageous mode of operation in these situations due to its adaptable outflow pressure (Kunkel and Sturm 2011). Another problem found in using a PM scheme in North America is that mains are sized to meet high fire-flow requirements whereas in Europe they are often designed to meet customer demands (Sturm and Thornton, 2005). A consequence of this is lower velocity and hence a lower degree of head loss, reducing the effectiveness of APM techniques (TM, FM and RM).

5.1.3 Australia

One notable, large-scale scheme has been carried out in Australia during last decade. A severe drought, described as the worst on record for southeast Australia (Dijk et al. 2013), affected this region of the country between 2001 and 2009. The so-called Millennium Drought led to a large-scale program of demand management at the national level, with most large utilities implementing PM schemes. The objective was to not only reduce leakage and bursts but also decrease consumption, with the main target a reduction of the amount of water demanded by the system. Some of the Australian cases cited in Table 1 are examples of the scheme (Beaton and Lambert 2013; Bailey 2009; Girard and Stewart 2007; Sydney W. 2005).

5.1.4 Other relevant global cases: developing countries

Many developing countries operate inefficient WDSs, with a high water and revenue losses due to various factors, including poor infrastructure, excessive pressure and illegal water extraction, among others (Babic et al. 2014). While PM may be a widely effective solution to reduce water losses, solutions should be tailored to local circumstances. Several significant large-scale PM schemes can be found in developing countries worldwide. South Africa (Burrows 2014; Shepherd and Poona 2010; Mckenzie et al. 2009; Meyer et al. 2009) and Malaysia (Wyeth et al. 2012; Morrison et al. 2007; Chai 2006) merit a mention due to the significant number of projects conducted in these countries. South Africa has undergone an important transformation since the 1990s, when the first full-scale projects were carried out in Johannesburg (Mckenzie et al. 2000), to the present, where innovative projects are being implemented (Burrows 2014).

5.2 Objectives of PM

From the analysis conducted, it is apparent that leakage reduction remains the most significant objective pursued with PM projects. In almost all the PM schemes shown in Table 1, this objective appears as the principal among all those pursued. In over 46% of cases, this is the sole objective while in the other 54%, it is combined with other objectives. Regarding new burst frequency decrease and consumption reduction, 40% of the programs deal with the former while 29% deal with the latter.

The present research revealed that projects that implement PM programs to reduce bursts are associated with WDS with excessive pressure and poor infrastructure. This is highly common in developing countries such as those shown in Table 1, being South Africa (Burrows 2014; McKenzie et al. 2009; Meyer et al. 2009), the Bahamas (Fanner 2007), Brazil (GIZ 2011) and the Philippines (Eguia et al. 2012) prime examples. Consumption reduction is, from the three objectives analyzed in this paper, the least implemented in practical programs and is usually linked to water scarcity situations. One the most representative programs is the aforementioned case in Australia. The low priority of this objective may be related to the many demand components and the difficulties found when relating pressure and consumption with each other.

5.3 Types of PRV regulation

5.3.1 Fixed outlet and other hydraulically-operated controls

Practical perspective

Hydraulically-operated controls are the most traditional type and, despite the advantages of electronic controllers, remain the most frequently used by water utilities. After consulting expert practitioners and examining reports from case studies, FO was identified as the most common method. A significant percentage of cases shown in Table 1 (almost 70%), and many more not included (as they were of little use in the research), used FO. In the United Kingdom, some of the main water utilities operate in the range of 2,000 DMAs each, and 50-60% are pressure managed. Of these PMAs, more than 80% used FO. Returning to Spain and the case of Canal de Isabel II Gestión, from the 104 PMAs implemented, 63% are also regulated through FO. This trend may extend globally.

Recommendations of use

Some of the principal reasons that FO remains the most common type of control are financial and technological constraints. The cost of this type of control is relatively low, and it is simple to install as it requires only a PRV. This method is an effective low-cost solution in contrast to the little benefit provided by electronically-operated control for districts with low head losses between the PRV and the CP. This may be linked to demand conditions (low demand) or topology features (small areas, oversized mains and insignificant differences in altitude between the highest and lowest nodes, among others) (Fanner 2007; Rogers 2005; Sturm and Thornton 2005). Other scenarios where FO may be effective are where a uniform demand profile occurs over time and where it is necessary to reduce not only the water lost throughout the network but also the water consumed by customers. The latter situation is often associated with water scarcity problems (Babic 2014; Pilipovic 2003).

Other types of hydraulically-operated controls can be highlighted as low-cost alternatives to electronic methods when APM is desired, but a high level efficiency is not required. Thus, these types of controls such as time-based regulation are appealing when financial constraints are present. One problem related to the use of electronic devices (data loggers, electronic controllers and communication systems, among others), specifically in remote locations, is the availability of electricity. In this context, hydraulically-operated methods remain the best option. This has been adapted by Canal de Isabel II Gestión in some of their districts with communication and electric supply problems.

5.3.2 Time-based modulation: TM

Practical perspective

The majority of theoretical documents dealing with types of PM control include TM as one of the most important methods. However, based on the examination of cases that have implemented electronically-operated controls (shown in Table 1), TM has been relatively rarely used in practical programs when compared with FM (35% for TM versus 68% for FM). Some projects comparing the results obtained after the introduction of both TM and FM controllers have found that the second method provides better benefits in terms of leakage reduction (GIZ 2011; Shepherd and Poona 2010). This may be of particular importance in understanding why FM is used more often than TM.

Scientific perspective

Regarding the literature, little research has sought to improve TM controllers. Ulanicki et al. (2000) proposed control strategies and formulated an algorithm for calculating open-loop and 24-hour optimal set profiles. Ulanicki et al. (2008) later developed another methodology to calculate optimal time schedules for PRVs located at DMAs with single- and multi-point entries based on solving a nonlinear programming (NLP) problem. AbdelMeguid (2011) then built upon this work. Advanced evolutionary algorithms such as GAs have also been used to determine optimal time-modulated settings with two switching periods (day and night) (Awad et al. 2010).

Recommendations of use

TM is recommended when APM is desired but cost is an issue. First, time-modulated controllers are often less expensive than other types of controllers. Second, this method does not require other devices such as costly flow meters or communication systems.

Regarding the demand profiles of the regulated district, TM is effective for areas with stable profiles or where the demand pattern is repetitive on a daily/weekly basis. It is also effective in networks with irrelevant head losses. However, in this case, FO is also an effective alternative and a lower-cost solution. Finally, it should be noted that this type of control is not recommended in cases where sudden emergency requirements such as firefighting need to be satisfied. Thus, its use is not widespread in North America.

5.3.3 Flow-based modulation: FM

Practical perspective

Although it may be more expensive than TM, FM provides greater flexibility and allows objectives to be achieved more efficiently. Thus, in recent decades, FM has been the most frequently used APC technique. From the list included in Table 1, 68% of cases installed this type of control. It is used globally and is of particular importance in North America, where special attention is given to firefighting requirements. Almost all the cases found in this region included FM in some or all of the PRVs installed (Yates et al. 2014; Kunkel and Sturm 2011; Lalonde et al. 2008; Sturm and Thornton 2005; Lalonde 2005).

Scientific perspective

Due to the relevance of this type of control, some authors have offered mathematical models to improve or optimize pressure/flow curves implemented by FM controllers. In examining FM control, Prescott and Ulanicki (2008) developed a proportional-integral-derivative controller that depends on system demands. It consists of a hydraulic control loop which, in accordance with the difference between the set point and output pressure, provides a control signal that modifies the PRV opening. Similarly, Li et al. (2010) proposed several control algorithms and assessed the dynamic performance of a PRV with a flow-modulated controller under different, both theoretical and real-life, scenarios. Focusing on the pressure/flow relationship curve, AbdelMeguid (2011) and AbdelMeguid and Ulanicki (2010) used a GA to optimize the outlet pressure of the PRV to minimize background leakage of the system. The decision variables were the coefficients of a second-degree polynomial relationship between the flow and the downstream pressure of the valve.

Recommendations of use

The benefits of FM are widely recognized. The main advantage of this control is its adaptability to the demand profile in real time. This makes it highly suitable when satisfying sudden and unexpected demand such as fire-flow requirements is compulsory. This adaptability is also beneficial in scenarios with varying demand profiles throughout the day. FM can adapt to customer demand at each instant, providing maximum pressure during peak demand periods and minimum values during low demand periods in order to minimize leakage rates and breaks. It should be noted that FM also addresses the effect of significant head losses in systems, ensuring that CPs receive smooth and constant lower pressure.

5.3.4 Remote node-based modulation: RNM

Practical perspective

The use of CP to provide feedback for practical PM schemes has existed since the mid-1990s. Although it is not yet widespread (only 26% of the case studies used this type of control), Table 1 shows an increasing number of PM programs employing RNM over the previous five years (Burrows 2014; 2030 WRG 2013; Wyeth et al. 2012; GIZ 2011; i2O 2011; VAG 2009; Fantozzi et al. 2009).

One of the reasons for this trend in the growing number of manufacturers providing this type of technology (Mejoras energéticas SA 2015; FAST S.p.A. 2014; i2O Water Ltd. 2010; Technolog 2010; HWM Water Ltd. 2010; Bermad 2008). Controllers use the data received from the CP to automatically generate a control profile according to a preset control method. These methods can be based on the actual pressure values at a given moment—real-time transmission (FAST S.p.A. 2014)—or on intermittent measures, which update the control profile through statistical procedures (i2O Water Ltd. 2010; Technolog 2010; HWM Water Ltd. 2010).

Scientific perspective

From a scientific point of view, some authors that have examined RNM have focused on the control algorithm. Nicolini and Zovatto (2009) proposed a closed-loop formulation with feedback from real-time pressure measurements at the CP. More recently, some authors have carried out similar real-time control (RTC) algorithms with the objective of bringing the piezometric head at the CP close to the desired set-point value. Campisano et al. (2012; 2010) first described the results of numerical research and assessed the effectiveness of a RTC algorithm based on the acquisition of the piezometric head at sensitive nodes, identification of the CP for each instant and valve regulation with a standard proportional controller. This algorithm and the one presented by Sanz et al. (2012) are based on correction of pressure at the valve, which is proportional to the error at the controlled point. In addition, Creaco and Franchini (2013) recently proposed a new algorithm based on the head loss induced by the regulation valve.

Recommendations of use

RNM has proven to be one of the most effective options for customers. As the outlet pressure is based on the signal received from the district CP in order to provide minimum pressure at any time, it is highly recommended when this is a main concern. RNM facilitates robust control of pressure at specified CPs, ensuring a minimum service level for customers

Following the aforementioned criteria for FM, its adaptability to real-time hydraulic conditions offers benefits in the case of varying demand profiles and networks with significant head losses. Unlike flow modulation, RNM is useful when it is difficult to calculate PRV flow modulation curves, for instance, for large consumers with stochastic demand. This helps ensure optimal PM in districts with hydraulic conditions that are less deterministic.

Another difference between these two methods is the location of the input signal. Given that FM is based on the flow measured at the same place the valve is located, the signal can be received locally. RNM must be accompanied by communication systems that allow reception of the remote signal. Therefore, this option requires good communication conditions. In addition, it should be noted that as the technology needed for this control entails higher costs, this is not recommended when financial constraints are present.

5.4 New criteria for designing PMAs

A previous section mentioned some of the most important features that should be considered when designing a PMA. The present study revealed that some of these features have undergone a transformation in recent years, with the most significant related to sizing criteria and topology considerations.

5.4.1 Sizing criteria

Water utility criteria for sizing DMAs and PMAs have been traditionally based on empirical suggestions or size indicators (i.e., geographical area, main-pipe length, service connections and properties). Experience has shown that service connections and pipe length are the most suitable indicators; while service connections are the most widespread parameter (Gomes et al. 2012), pipe length is a more reliable indicator in areas with low density of connections (Morrison et al. 2007; MacDonald and Yates 2005). Pipe length can also be a suitable indicator when friction losses in a district are significant. Considering this, some case studies have proposed methodologies that can be broadly applied. Yates (2005), for example, determined the maximum DMA size and introduced the ‘leakage run-time’ concept, which entails three components: awareness time of the leak, location time and repair time. In more conceptual approaches, optimization methods have involved optimal sizing of isolated districts. Hunaidi and Brothers (2007) presented an optimization model for DMA sizing with three different intervention assumptions, all of which considered economic criteria in the optimization formulation. In addition, graph partitioning techniques have been used to define optimal districts. For example, Diao et al. (2013) used a dendogram cutting method to develop an algorithm for automatically creating boundaries on the basis of the structure of the WDS. Graph theory, together with hydraulic simulation techniques and heuristic optimization criterion, has been used to develop a tool for DMA design support (Di Nardo and Di Natale 2013; Di Nardo et al. 2011). Both topological and sizing optimization have also been included in multi-objective evolutionary algorithms and a numerical technique termed the ‘network repairing technique’ (Bureerat and Sriworamas 2013).

5.4.2 Topology considerations

Traditionally, two features have been associated with districts: a single feed point and a permanent boundary. These have been applied successfully for leakage management purposes given that they facilitate flow metering and water balance audits. However, both features present some disadvantages: suboptimal PM, reduced resilience to failure, inefficient response to special flow requirements (firefighting) and water quality (more dead-end points) (Wright et al. 2013; Thornton et al. 2008; Sturm and Thornton 2005).

In recent years, two innovative approaches have emerged that have proven successful for the introduction of APM techniques while solving some of the aforementioned disadvantages: (1) the introduction of multiple feed points with FM controllers (Yates et al. 2014) and (2) the concept of dynamic topology (Wright et al. 2014, 2013).

Multiple feeds with APM methods

An option increasingly used by several water companies is the inclusion of multi-feed PMAs, which may overcome some of the aforementioned problems. One particularly relevant example is North America and the firefighting requirements associated with this region. In this context, an approach that is systematically used in almost all North American cases has been found. This involves the inclusion of one valve with APM control to act as the primary or master regulation element during normal demand periods while the others act as slave or supporting valves set with an FO pressure profile (Yates et al. 2014; Kunkel and Sturm 2011; Lalonde et al. 2008; Lalonde 2005; Sturm and Thornton 2005). With this configuration, supporting valves are set to open only during peak demand and fire-flow conditions.

Some attempts have been made to include APM techniques simultaneously in more than one valve for multi-feed PMAs. One of the first instances was described by Yates and MacDonald (2007). Tests were carried out in a district of Halifax, Canada with two strategies: the first with two FM controllers and the second with TM and FM controllers. In both cases, the behavior of one valve was influenced by the other. In the first case, a hunting phenomenon was created, which eventually resulted in the complete closure of one valve. AbdelMeguid and Unalicki (2010) also found this phenomenon from a scientific point of view when they sought to implement an optimization problem on a multi-feed network model. In the second case, it was believed that the use of a TM controller to regulate the second valve was a good idea while the main valve would ensure additional supply for emergency demands if required. However, its success was limited.

An important step to overcome this problem has recently been made. The same authors of the Halifax case study, which identified the hunting phenomena with two FM controllers, developed a method to solve the issue (Yates et al. 2014). First, they identified the problem and attributed it to the fact that the two valves were operating independently at the control level. Each controller used its own flow meter to regulate the corresponding valve. To correct the problem, the controllers at each supply station had to use the same process variable, that is to say, the total flow from both meters. Then, they developed a control algorithm that combined the real-time flow for each meter into a single-total district flow that was inserted into the PRV controllers at each station. With this method, controllers at each location increased and decreased pressure in response to total district demand.

Dynamic topology

Conflicting interests between DMAs and PMAs have led to a search for alternatives to the classic permanent boundaries. One emerging alternative is the implementation of open and adaptive districts. This allows the aggregation of original DMAs into larger pressure zones for improved PM and redundancy while at night the network reverts back to the original DMA structure for leakage-detection purposes. In 2010, a Spanish company launched 'the micro-metering district area enabler' project (Jiménez 2015) that is now being implemented successfully in many Spanish cities (e.g., Murcia, Tarragona, and Torremolinos) and globally (e.g., Santiago de Chile, Chile). The project consists of the introduction of a self-powered hydraulic actuator that activates butterfly valves to enable new DMA structures in the network at night. However, the main goal of these dynamic districts is to estimate leakage during the minimum night-flow period.

An essential step with regard to the use of 'dynamic topology' for PM purposes was later made by Stoianov and Henderson (2014) and Wright et al. (2013; 2014). They examined a pioneering method to adjust the network and monitor hydraulic conditions through the introduction of multi-function network controllers. In addition, they proposed an optimization method for programming each control valve with an optimal pressure outlet profile. This methodology and technology, currently implemented in two districts of a WDS in the United Kingdom, is focused on eliminating the disadvantages of a closed topology such as reduced resilience to failure and suboptimal PM.

5.5 Optimization models

The present analysis revealed a lack of connection between theoretical optimization models related to some aspect of PM and their use in practical systems. Only a few studies (Wright et al. 2014, 2013) have attempted to implement the results obtained from an optimization problem in an actual WDS. An alternative that bridges the gap between theoretical and practical approaches is testing an optimization problem with a model that represents an actual network. This has been done in a significant number of studies (Eck and Mevissen 2013; Gomes et al. 2012; Nicolini et al. 2010; Awad et al. 2010). In contrast, the use of schematic models, which are less representative of real systems, is more common.

One of the first models created with this approach was proposed by Germanopoulos and Jowitt (1989) and extended by Jowitt and Xu (1990). The authors developed a model that consisted of a 25-node network in which valve location and valve control settings are optimized by the LP method. This network has been widely cited in the literature, thus establishing a scientific benchmark for future optimization PM models. Several authors have used this reference example for different purposes that include solving a valve setting optimization problem (Vairavamoorthy and Lumbers 1998; Savic and Walters 1995), optimizing both valve location and setting (Liberatore and Sechi 2009; Reis et al. 1997), and simultaneously finding the optimal number of valves (Nicolini and Zovatto 2009; Araujo et al. 2006). Finally, Giugni et al. (2014) also used the same network but assessed the recoverable hydropower potential instead of minimizing leakage. They replaced PRVs with turbines and pumps as turbines and maximized hydropower generation while maintaining minimum pressure for all nodes. Apart from Germanopoulos and Jowitt's (1989) model, other approaches have been published. Gomes et al. (2012) presented an optimization model to identify the optimal entry points at districts that differed from previously mentioned works related to optimal valve location (which often referred to internal PRVs). The model, based on a meta-heuristic optimization model called simulated annealing (SA), also divided the system into smaller districts where necessary.

Referring to valve setting optimization problems, most of the above mentioned papers refer to FO control method. The formulation proposed to optimize the opening adjustment of each valve can be developed for simulation models over an extended period. Optimization valve setting problems for further regulation techniques such as time or flow modulation have also been reported. Ulanicki et al. (2008) described an NLP method to optimize a time-schedule curve in DMAs with boundary and internal PRVs with the objective of minimizing leakage. Awad et al. (2010) used GA as an optimization method to determine the most appropriate type of regulation between FO and TM and later optimize the location and setting of the PRV. Awad's approach added several terms to the optimization problem, including leakage, burst frequency and consumption reduction. Ulanicki et al. (2008) and AbdelMeguid and Ulanicki (2010) also explored FM, where the optimal coefficients of a second order relationship curve between the flow and the outlet pressure for a PRV were determined by GA.

Regarding the optimization techniques used, there is a clear trend of a move from using linearization and NLP methods to meta-heuristic algorithms. Initially, Germanopoulos and Jowitt's (1989) and Jowitt and Xu's (1991) models were examined with LP methods. The linear theory method was used to turn the constraint nonlinear equations into linear equations. LP problems were characterized by a rapid convergence and the achievement of a global optimal solution although it should be noted that they introduced simplifying assumptions. The nonlinear nature of PM equations has resulted in the use of NLP approaches when seeking the optimal valve location and valve setting solutions for different types of regulation (Dai and Li 2014; Pezzinga and Pititto 2005; Ulanicki et al. 2000; Alonso et al. 2000; Vairavamoorthy and Lumbers 1998). The main drawback of NLP is that while a local optimum may be found, additional knowledge is required to assess the quality of the solution. With the aim of avoiding this problem, many authors have proposed new optimization problems based on meta-heuristic or stochastic methods such as GA or SA algorithms. As heuristic techniques compute solutions by probabilistic approaches, a global optimum is not guaranteed although the solution may be close. Several researchers have addressed the PM problem by applying GA algorithms (Giugni et al. 2013; AbdelMeguid and Ulanicki 2010; Nicolini and Zovatto 2009; Araujo et al. 2006; Reis et al. 1997; Savic and Walters 1995). SA is an additional heuristic technique often used. Gomes et al. (2012) proposed an SA algorithm to identify the most appropriate number of DMA inlets and their location. Tucciarelli et al. (1999) also drew on an SA technique for determining the optimal setting of regulation valves and the parameters in a network simulation model. In addition, Liberatore and Sechi (2009) proposed a scatter-search, meta-heuristic procedure. Scatter search has been successfully applied in challenging optimization problems. In contrast to other evolutionary methods such as GA, which generates random solutions, the procedure uses strategic search methods to select a set of points in the research space as data for generating the candidate solution population. Hence, it has significant benefits given that it leads to a smaller population than using GAs.

To facilitate an understanding of the analysis carried out in this section, some of the mentioned papers are presented chronologically in Table 2. In this table, the main features of each optimization problem—decision variables, objective function, optimization method used—can be found.

6. Conclusions and further work

The task of PM continues to evolve due to its technological and practical nature. The emergence of new devices, techniques and strategies requires a constant updating of knowledge to keep the scientific community informed of the latest developments. To acquire such knowledge, this research collected information from several sources and analyzed it, providing a valuable reference contribution for practitioners and researchers that are addressing PM activities. Some conclusions can be drawn regarding the current status and future work of the main topics studied in this paper:

- Benefits of PM

  Several objectives can be achieved with PM, including leakage decrease, new burst frequency reduction and consumption reduction. Leakage reduction remains the most significant objective pursued by water utilities.

  It is clear that relationships between pressure and each target analyzed require further research for the following reasons. (1) The pressure/leakage relationship involves several approaches, with the FAVAD concept providing the base of several. Nevertheless, owing to the interaction of other parameters, it is difficult to extrapolate an analytical relationship in practical cases. To this end, more simplified expressions such as the 'N_1 exponent' approach proposed by Lambert (2001) are more commonly used in practical programs. (2) While the influence of pressure on bursts is now generally recognized, the relationship between pressure changes and new burst frequency has not been clearly defined. The difficulty associated with most breaks is due to factors of both a static and dynamic nature. (3) Consumption reduction is a crucial objective that can be achieved with the reduction of pressure, particularly in water scarcity scenarios, although its effectiveness requires better understanding. The disaggregation of demands in different components has been addressed from several approaches, confirming the need for further research.

- Geographical considerations

Despite the clear benefits obtained from PM, its degree of acceptance varies around the world. While European water utilities use PM as a common activity in their practice, other regions such as North America are still reticent to employ PM. Some of the main reasons for this are the differences between WDS designs and flow requirements for firefighting. Other examples of large-scale PM schemes can be found globally. Some particular examples are those of Australia, which are focused on reducing total demand, and South Africa and Malaysia, which show how PM programs can be effective in developing countries.

- Types of PRV regulation

Fixed-outlet control is still the most common solution identified in pressure regulation, and due to its low cost, is the best solution for districts with low head losses. Electronic controllers can significantly improve the operation of PM since they can better adapt to different scenarios. Time-based modulation, flow-based modulation and remote node-based modulation are the three most common advanced techniques currently used. (a) The first, time-based modulation, is the least expensive technique and is effective for areas with stable profiles or when the demand pattern is repetitive on a daily/weekly basis. (b) The main advantage of flow-based modulation is the adaptability to demand profiles in real time. This makes it highly suitable for satisfying sudden and unexpected demand such as fire-flow requirements. This adaptability is also beneficial for demand profiles that vary throughout the day and for systems with significant head losses. (c) The third, remote node-based modulation, is one of the latest advanced control techniques and its implementation is less widespread than the others. In addition to the advantages it shares with flow-based modulation due to its adaptability in real time, is useful in scenarios where it is difficult to calculate PRV flow modulation curves, for instance, because of large consumers with stochastic demand. The main disadvantage of this type of control is that it entails a higher cost.

- New criteria for designing PMAs

  Some criteria for designing PMAs have undergone a transformation in recent years, with the most significant change related to sizing criteria and topology considerations. Regarding sizing criteria, a lack of connection between theoretical and practical approaches has been detected. While some scientific approaches have proposed innovative optimization models to determine the optimal size of a district, they are still far from being implemented in real systems. With respect to topology considerations, two solutions merit mention. (1) First, Yates et al. (2014) proposed a control algorithm for introducing flow-based modulation controllers in multiple feed districts. This would address the problem of supply resilience while adapting pressure to demand profiles in real time. (2) Second, the recent emergence of the dynamic topology concept (Wright et al. 2014, 2013) also provides a new direction. Through the implementation of new devices and control algorithms, dynamic districts enable the aggregation of original DMAs into larger PMAs for improved pressure management and redundancy. At night, the network reverts to the original DMA structure for leakage-detection purposes.

- Optimization models

  A lack of connection between theoretical optimization models and their use in real systems has been detected. A majority of studies that address this topic use schematic networks to test the developed optimization models. This results in a lack of knowledge about how the practical implementation of such theoretical algorithms would work.

  Most of the optimization problems seek an optimal solution to minimize leakage. Nevertheless, the increasing prominence of other required benefits has led to another objective. The most frequently used decision variables have traditionally been valve location and valve setting for fixed-outlet valves. As APC techniques continue to be an active research area, optimization of their profiles has been addressed in only few academic papers (AbdelMeguid and Ulanicki 2010; Awad et al. 2010), making this issue a potential research line for future studies. Regarding the methods used to solve the optimization problems, the trend is changing from mathematical optimization techniques to meta-heuristic methods.

Acknowledgments

The authors acknowledge the financial support received from the Spanish Centre for Technological Industrial Development (CDTI) through the CENIT-E TecoAgua Project (Sustainable Development of Technologies for the Integral Water Cycle).

They also appreciate the help provided by Canal de Isabel II Gestión S.A. through scientific and technological support and the many expert practitioners that have helped and provided valuable information: Allan Lambert, Julian Thornton, George Kunkel, Orazio Giustolisi, Carles Yates, Kobus Van Zyl, Francisco Cubillo and Alberto Jiménez.

References

2030 WRG-Water Resources Group (2013). “Leakage reduction in a city – City of Jeddah, Saudi Arabia.” <http://www.waterscarcitysolutions.org> (Dic. 28 2014).

AbdelMeguid, H., and Ulanicki, B. (2010). “Pressure and leakage management in water distribution systems via flow modulation PRVs”. *Proc. of the 12th Water Distribution Systems Analysis Conf.*, ASCE, Tucson, Arizona, U.S., 1124-1139.

AbdelMeguid, H. (2011). “Pressure, leakage and energy management in water distribution systems”. Ph.D. thesis, De Monfort Univ., Leicester, United Kingdom.

Alonso, J. M., Alvarruiz, F., Guerrero, D., Hernández, V., Ruiz, P. A., Vidal, A. M., Martínez, F., Vercher, J. and Ulanicki, B. (2000). "Parallel computing in water network analysis and leakage minimization". *J. Water Resour. Plann. Manage.*, 126(4), 251-260.

Anuvongnukroh, V., Makmaitree, U., Chuenchom, T., Sethaputra, S. and Waldron, T. (2007). "Design and establishment of a very large scale low pressure DMA project". *Proc., IWA Int. Specialized Conf. Water Loss 2007,* IWA, Bucharest, Romania, 226-236.

Araujo, L. S., Ramos, H. and Coelho, S. T. (2006). "Pressure control for leakage minimisation in water distribution systems management". *Water resour. manag.*, 20(1), 133-149.

Awad, H., Kapelan, Z. and Savić, D. (2008). "Analysis of pressure management economics in water distribution systems. *Proc. of the 10th Annual Water Distribution Systems Analysis Conf.*, Kruger National Park, South Africa, 1-12.

Awad, H., Kapelan, Z., Savić, D.A. (2010). "Optimal setting of time-modulated pressure reducing valves in water distribution networks using genetic algorithms". *Proc. of the 10th Int. on Computing and Control for the Water Industry*, Integrating Water Systems, Taylor and Francis Group, London, UK, 31-37.

AWWA (2009). "Water audits and loss control programs – 3rd Edition (Manual of water supply practices – M36". *American Water Works Association*, Denver, CO, USA.

Bailey, R. (2009). "Managing the risk of constructing DMAs in the implementation of a large scale pressure and leakage management program". *Technical Report,* Logan City Water, Queensland, Australia.

Bamezai, A. and Lessick, D. (2003). "Is system pressure reduction a valuable water conservation tool? Preliminary evidence from the Irvine Ranch Water District". <http://www.irwd.com/save-water-money/irwd-research-studies> (Jan. 08, 2013).

Bartlett, L (2004) Pressure dependent demands in Student Town Phase 3: B.Eng Final Year Project Report Dept of Civil and Urban Engineering, Rand Afrikaans University (now University of Johannesburg), South Africa.

Babic, B., Dukic, A., and Stanic, M. (2014). “Managing water pressure for water savings in developing countries”. *Water SA*, *40*(2), 221-232.

Beaton, R. and Lambert, A. (2013). “Influence of Pressure/Burst Relationships on asset renewal planning – Australian Experiences.” *Global Leakage Summit, London, March 2013*

Benahmed, E., Lucente, D. and Lorrain, G. (2007). “The modulation of the pressure in Casablanca – LYDEC”. *Proc., IWA Int. Specialized Conf. Water Loss 2007,* IWA, Bucharest, Romania, 237-240.

Bermad (2008). Model 718-03. <http://www.bermad.com/Data/Uploads/WW%20718-03.pdf> (Oct. 02, 2014).

Bermad – Water Control Solutions (2010). Model 7 PM – Pressure management valve; flow compensated pressure reducing valve. <http://bermad.com/product/product=model-7pm-ww/cat=50539> (Oct. 02, 2014).

Bureerat, S. and Sriworamas, K. (2013). “Simultaneous topology and sizing optimization of a water distribution network using a hybrid multiobjective evolutionary algorithm”. *Applied Soft Computing*, 13(8), 3693-3702.

Burrows, A. (2014). “Advanced pressure management Durban – South Africa case study.” *Proc., IWA Int. Specialized Conf. Water Loss 2014, IWA, Viena, Austria. 30 Mar. – 2 Apr, 2014.*

C-Valve (2010). “PFR. Hydraulically flow modulated pressure control – is this the way forward?”. <http://www.cvalves.com/pics/content/2552010132055.pdf> (Oct. 02, 2014).

Campisano, A., Creaco, E., and Modica, C. (2010). “RTC of valves for leakage reduction in water supply networks”. *J. Water Resour. Plann. Manage.*, 136(1), 138-141.

Campisano, A., Modica, C., and Vetrano, L. (2012). “Calibration of proportional controllers for the RTC of pressures to reduce leakage in water distribution networks”. *J. Water Resour. Plann. Manage.*, 138(4), 377-384.

Cassa, A. M., Van Zyl, J. E., and Laubscher, R. F. (2010). “A numerical investigation into the effects of pressure on holes and cracks in water supply pipes”. *Urban Water J.*, 7 (2), 109-12.

Chai, A. (2006). “A Case Study on Leakage Management in Sandakan, Malaysia”. *32nd WEDC International Conference, Colombo, Sri Lanka, 2006.*

Charalambous, B. (2005). “Experiences in DMA redesign at the Water Board of Lemesos, Cyprus”. *Proc., IWA Int. Specialized Conf. Leakage 2005*, IWA, Halifax, Canada, 403-413.

Charalambous, B. (2007). “Effective pressure management of district metered areas”. *Proc., IWA Int. Specialized Conf. Water Loss 2007,* IWA, Bucharest, Romania, 241-255.

Charalambous, B. and Kanellopoulou, S. (2010). “Applied pressure management techniques to reduce control leakage”. *Proc., IWA Int. Specialized Conf. Leakage 2010,* IWA, Sao Paulo, Brazil, Jun. 06-09, 2010.

Creaco, E., and Franchini, M. (2013). “A new algorithm for real-time pressure control in water distribution networks”. *Water Sci. Technol.: Water Supply*, 13(4), 875-882.

Cullen, R. (2004). “Pressure vs. consumption relationships in domestic irrigation systems”. B. Sc.Thesis, Univ. of Queensland, Queensland, Australia.

Dai, P. D. and Li, P. (2014). “Optimal Localization of Pressure Reducing Valves in Water Distribution Systems by a Reformulation Approach”. *Water Resources Management*, 28(10), 3057-3074.

Davis, P., Burn, S., Moglia, M., and Gould, S. (2007). A physical probabilistic model to predict failure rates in buried PVC pipelines. *Reliability Engineering and System Safety*, *92*(9), 1258-1266.

Di Nardo, A., and Di Natale, M. (2010). “A design support methodology for district metering of water supply networks”. *Proc. 12th Annual Int. Conf. on Water Distribution Systems Analysis,* ASCE, Tucson, Arizona, U.S. 870-877.

Di Nardo, A., Di Natale, M., Santonastaso, G. F., and Venticinque, S. (2013). “An automated tool for smart water network partitioning”. *Water resour. manag.*, 27(13), 4493-4508.

Diao, K., Zhou, Y., and Rauch, W. (2013). “Automated creation of district metered area boundaries in water distribution systems”. *J. Water Resour. Plann. Manage.*, 139(2), 184-190.

Dijk, A. I., Beck, H. E., Crosbie, R. S., Jeu, R. A., Liu, Y. Y., Podger, G. M., and Viney, N. R. (2013). “The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society.” *Water Resources Research*, *49*(2), 1040-1057.

Dimitrov, G., Tenev, G., and Krustev, T. (2011). “Regulation of the water pressure in the water supply network in the residential areas of Burgas”. *Water Utility Journal*, (1), 49-55.

Eck, B. and Mevissen, M. (2013) “Fast non-linear optimization for design problems on water networks” World Environmental and Water Resources Congress 2013.

Eguia, E.M., Acosta, J.A. and Palomas, N.S. (2102). “Utilisation of a calibrated hydraulic model for water supply optimization”. *Proc., IWA Int. Specialized Conf. Water Loss 2012,* IWA, Manila, Philippines, Feb. 26-29, 2012.

ElFarissi, Z. and Boudan, Y. (2010). “Water pressure management”. *Technical report, ONEP*, Office National Eau Potable Maroc, Tanger, 2011.

Fanner, P.V. (2007). “Pressure management works……and doesn’t!” *Proc., IWA Int. Specialized Conf. Water Loss 2007,* IWA, Bucharest, Romania, 214-225.

Fanner, P.V., Sturm, R., Thornton, J., Liemberger, R., Davis, S.E. and Hoogerwerf, T. (2007). “Leakage Management Techonologies”. *Pressure management as a leakage management tool,* AWWA Research Foundation, Denver, CO, USA, 119-142.

Fantozzi, M., Calza, F., and Kingdom, A. (2009). "Introducing advanced pressure management at Enia utility (Italy): experience and results achieved". *Proc., IWA Int. Specialized Conf. Water Loss 2009*, IWA, Cape Town, South Africa, Apr. 26-29, 2009.

Fantozzi, M. and Lambert, A. (2010). "Recent developments in pressure management". *Proc., IWA Int. Specialized Conf. Leakage 2010*, IWA, Sao Paulo, Brazil, Jun. 06-09, 2010.

Farley, M. (2001). "Leakage management and control. A best practice training manual". World Health Organization, eds., Geneva, Switzerland, 2001.

Farley, M. and Trow, S. (2003). "Losses in water distribution networks: a practitioner's guide to assessment." *Pressure management,* IWA Publishing, London, UK, 145-182.

Fast S.p.A. (2014). Aqualog Master. <http://www.fastonline.it/pdf_eng/RetiH2O/_AqualogMaster.pdf > (Oct. 02, 2014).

Feldman, M., Geller, Y., and Fantozzi, M. (2012). "Pressure and leakage management in a water system using integrated mathematical models and specialist water loss software: Mei Sheva case study in Israel". *Proc., IWA Int. Specialized Conf. Water Loss 2012*, IWA, Manila, Philippines, Feb. 26-29, 2012.

Fontana, N., Giugni, M., and Portolano, D. (2012). "Losses reduction and energy production in water-distribution networks". *J. Water Resour. Plann. Manage.*, 138(3), 237-244.

Germanopoulos, G., and Jowitt, P. W. (1989). "Leakage reduction by excess pressure minimization in a water supply network". *ICE Proceedings,* Ice Virtual Library, 87(2), 195-214).

Girard, M., and Stewart, R. A. (2007). "Implementation of pressure and leakage management strategies on the Gold Coast, Australia: case study". *J. Water Resour. Plann. Manage.*, 133(3), 210-217.

Giugni, M., Fontana, N., and Ranucci, A. (2014). "Optimal location of PRVs and turbines in water distribution systems". *J. Water Resour. Plann. Manage.*, 140(9), Giustolisi, O., and Walski, T. M. (2012). “Demand components in water distribution network analysis.” *J. Water Resour. Plann. Manage.*, 138(4), 356-367.

GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) (2011). “Guidelines for water loss reduction: a focus on pressure management”. *Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH* and *VAG-Armaturen GmbH.* <http://www.waterlossreduction.com> (Jan. 17, 2014)

Gomes, R., Sa Marques, A., and Sousa, J. (2011). “Estimation of the benefits yielded by pressure management in water distribution systems”. *Urban Water J.*, 8(2), 65-77.

Gomes, R., Sá Marques, A., and Sousa, J. (2012). “Identification of the optimal entry points at District Metered Areas and implementation of pressure management”. *Urban Water J.*, 9(6), 365-384.

Greyvenstein, B., and Van Zyl, J. (2007). “An experimental investigation into the pressure – leakage relationship of some failed water pipes”. *J. Water Supply Res. Technol. - Aqua*, 56(2), 117-124.

Guo, S., Zhang, T. Q., Shao, W. Y., Zhu, D. Z., and Duan, Y. Y. (2013). “Two-dimensional pipe leakage through a line crack in water distribution systems”. *J. Zhejiang Univ.-SCI A*, 14(5), 371-376.

Hunaidi, O., and Brothers, K. (2007). “Optimum size of district metered areas”. *Proc., IWA Int. Specialized Conf. Water Loss 2007,* IWA, Bucharest, Romania, 57-67.

HWS-Water Ltd (2010). SiClops Intelligent Control. <http://www.hwm-water.com/products/palmer-environmental-products/pressure-control/si-clops-intelligent-control/> (Oct. 02, 2014).

I2O Water Ltd – Burrows, A. (2010). Controller and control system for a pressure reducing valve. *United States Patent Application Publication.* Pub. Number: US 2010/0168927 A1.

I2O Water (2011). “Improving customer service and leakage reduction through advanced pressure management; project profile: Veolia Water Central”. Internal report.

<http://www.i2owater.com/solutions/advanced-pressure-management/cases/ > (Jan. 29, 2014).

I2O Water (2014) – official website. < http://www.i2owater.com> (Jan. 02, 2015).

Jiménez, A. (2015). “Control activo de fugas. (CAF).” Aqualogy brochure - Internal report

Jowitt, P. W., and Xu, C. (1990). “Optimal valve control in water-distribution networks”. *J. Water Resour. Plann. Manage.*, 116(4), 455-472.

Kanakoudis, V. and Gonelas, K. (2014). “Applying pressure management to reduce water losses in two Greek cities’ WDSs: Expectations, problems, results and revisions.” *16th Conference in Water Distribution System Analysis, WDSA 2014, Bary, Italy. 14-17 July.*

Karadirek, I. E., Kara, S., Yilmaz, G., Muhammetoglu, A., and Muhammetoglu, H. (2012). “Implementation of hydraulic modelling for water-loss reduction through pressure management”. *Water Resour. Manag*, 26(9), 2555-2568.

Kovac, J. (2007). “Case studies in applying the IWA WLTF approach in the West Balkan region: pressure management”. *Proc., IWA Int. Specialized Conf. Water Loss 2007*, IWA, Bucharest, Romania, 199-215.

Kunkel, G., and Sturm, R. (2011). “Piloting proactive, advanced leakage management technologies.” *Journal-American Water Works Association,103*(2), 62-75.

Lalonde, A.M. (2005). “Use of flow modulated pressure management in York Region, Ontario, Canada”. *Proc., IWA Int. Specialized Conf. Leakage 2005,* IWA, Halifax, Canada, 176-184.

Lalonde, A.M., Au, C., Fanner, P. and Lei, J. (2008). “City of Toronto water loss study and pressure management pilot.” <http://www.miya-water.com/data-and-research/articles-by-miyas-experts/case-studies/> (Oct. 29 2013)

Lambert, A. (1994). Accounting for losses: The bursts and background estimates (BABE) concept. *Water and Environment Journal, 8 (2), 205–214.*

Lambert, A. (2001). “What do we know about pressure-leakage relationships in distribution systems”. *Proc. IWA Conf. on System Approach to Leakage Control and Water Distribution Systems Management*, ISBN 80-7204-197-5, IWA, Brno, Czech Republic.

Lambert, A. O. (2002). “International report: water losses management and techniques”. *Water Sci. Technol.: Water Supply*, 2(4), 1-20.

Lambert, A. and Thornton, J. (2012). “Pressure:bursts relationships: influence of pipe materials, validation of scheme results, and implications of extended asset life”. *Proc., IWA Int. Specialized Conf. Water Loss 2012*, IWA, Manila, Philippines, Feb. 26-29, 2012.

Levine, B., Lucas, J., Cynar, P., Hildebrand, T., Morgan, W. (2005). “Pressure management in the Pittsburgh area: a working and economical solution”. *Proc., IWA Int. Specialized Conf. Leakage 2005*, IWA, Halifax, Canada, 159-167.

Li, P., Postlethwaite, L., Prempain, E., Ulanicki, B. (2010). “Flow modulated dynamic pressure control with Aquai-Mod controller”. *Proc. 10th In. Conf. on Computing and Control for the Water Industry*. Integrated Water Systems, Boxall J. and Maksimovic, C., eds., 63-69.

Liberatore, S., and Sechi, G. M. (2009). “Location and calibration of valves in water distribution networks using a scatter-search meta-heuristic approach”. *Water Resour. Manag*, 23(8), 1479-1495.

Liu, J., Yu, G., and Savic, D. (2011). “Deficient-network simulation considering pressure-dependent demand”. *Sustainable solutions for water, sewer, gas, and oil pipelines (ICPTT 2011)*, 886-900.

MacDonald, G., and Yates, C. D. (2005). “DMA design and implementation, a North American context”. *Proc., IWA Int. Specialized Conf. Leakage 2005*, IWA, Halifax, Canada, 168-175.

Mahdavi, M., Hosseini, K., Behzadian, K., Ardehsir, A., and Jalilsani, F. (2010). “Leakage control in water distribution networks by using optimal pressure management: A case study”.

Proc., of the 12thWater Distribution Systems Analysis 2010, ASCE, Tucson, Arizona, United States, 1110-1123.

Martinez-Codina, A., Cueto-Felgueroso, L., Castillo, M. and Garrote, L. (2015). “Use of pressure management to reduce the probability of pipe breaks: A bayesian approach.” *J. Water Resour. Plann. and Manage. In press.*

Marunga, A., Hoko, Z., and Kaseke, E. (2006). “Pressure management as a leakage reduction and water demand management tool: The case of the City of Mutare, Zimbabwe”. *Physics and Chemistry of the Earth, Parts A/B/C*, 31(15), 763-770.

May, J. (1994). “Pressure dependent leakage.” World Water and Environmental Engineering, Oct. 13, 1994.

Mckenzie R.S., Bhagwan, J.N., and Wegelin, W.A. (2000). “Some recent developments in water demand management in South Africa.” *Presented at WISA 2000, Sun City, South Africa, 28 May – 1 June, 2000.*

Mckenzie R. S., Wegelin, W. (2009). “Implementation of pressure management in municipal water supply systems”. *EYDAP Conference ‘Water: the Day After’*, EYDAP, Athens, Greece, March 2009.

Mejoras Energéticas, S.A. (2015). Pegasus P3. < http://www.mejoras-energeticas.com/gestion-presiones.html> (Jan. 10, 2015).

Meyer N., Engelbrecht M., Wright D. (2009). “Large scale pressure management implementation in the City of Cape Town”. *Proc., IWA Int. Specialized Conf. Water Loss 2009,* IWA, Cape Town, South Africa, Apr. 26-29, 2009.

Miguel, R. and Rodriguez, L. (2009). “Diseño de la sectorización de la red de distribución de Canal”. *I Jornadas de Ingeniería del agua JI.* 27, 28 October, 2009. Madrid, Spain.

Mistry P. (2007). “Pressure management to reduce water demand and leakage”. <http://findmoreleaks.com/case_studies.php> (Jan., 20 2014)

Morrison, J. (2004). “Managing leakage by District Metered Areas: a practical approach”. *Water21, February 2004*. 44-46.

Morrison, J., Tooms, S., and Rogers, D. (2007). “District metered areas; guidance notes”. International Water Association (IWA), specialist group on efficient operation and management of urban water distribution systems, water loss task force, version, 1. <http://www.pseau.org/outils/biblio/resume.php?d=2682> (Jan., 10 2014)

Mutikanga, H. E., Sharma, S. K., and Vairavamoorthy, K. (2013). “Methods and tools for managing losses in water distribution systems”. *J. Water Resour. Plann. Manage.*, 139(2), 166-174.

Nicolini, M., and Zovatto, L. (2009). “Optimal location and control of pressure reducing valves in water networks”. *J. Water Resour. Plann. Manage.*, 135(3), 178-187.

Nicolini, M., Giacomello, C., and Deb, K. (2010). “Calibration and optimal leakage management for a real water distribution network”. *J. Water Resour. Plann. Manage.*, 137(1), 134-142.

Paskalev, A., Ivanov, S. and Tanev, M. (2011). “Water loss reduction in Razgrad demonstrative project through active leakage control, pressure management and the relationship between pressure management and leakage: The case of Kooperative Pazar DMA”. *Water Utility Journal*, (2), 3-21.

Pathirana, A. (2010). “EPANET2 desktop application for pressure-driven demand modeling”. *Proc. 12th Annual Int. Conf. on Water Distribution Systems Analysis*, ASCE, Tucson, Arizona, U.S.

Pezzinga, G., and Pititto, G. (2005). “Combined optimization of pipes and control valves in water distribution networks”. *J. Hydraul. Res.*, 43(6), 668-677.

Pilipovic, Z. and Taylor, R. (2003). “Pressure management in Waitakere city, New Zealand – a case study”. *Water Sci. Technol.: Water Supply* 3 (1-2), 135–141.

Prescott, S. L., and Ulanicki, B. (2008). “Improved control of pressure reducing valves in water distribution networks”. *J. Hydraul. Eng.-ASCE*, 134(1), 56-65.

Puust, R., Kapelan, Z., Savic, D. A., and Koppel, T. (2010). “A review of methods for leakage management in pipe networks”. *Urban Water J.*, 7(1), 25-45.

Reis, L. F. R., Porto, R. M., and Chaudhry, F. H. (1997). “Optimal location of control valves in pipe networks by genetic algorithm”. *J. Water Resour. Plann. Manage.*, 123(6), 317-326.

Ristovski, B. (2011). “Pressure management and active leakage control in particular DMA (Lisiche) in the city of Skopje, FYROM”. *Water Utility Journal*, (2), 45-49.

Rogers, D. (2005). “Reducing leakage in Jakarta, Indonesia”. *Proc., IWA Int. Specialized Conf. Leakage 2005*, IWA, Halifax, Canada, 253-260.

Sanz, G., Pérez, R., and Sánchez, R. (2012). “Pressure control of a large scale water network using integral action”. *Proc. Conf. on Advances in PID Control*, IFAC, Brescia, Italy, 2(1), 270-275.

Savic, D. A., and Walters, G. A. (1995). “An evolution program for optimal pressure regulation in water distribution networks”. *Eng. Optimiz.*, 24(3), 197-219.

Savic, D. A., Boxall, J. B., Ulanicki, B., Kapelan, Z., Makropoulos, C., Fenner, R., Soga, K., Marshall, I.W., Maksimovic, C., Posthlethwaite, I., Ashley, R. and Graham, N. (2008). “Project Neptune: Improved operation of water distribution networks.” In *The 10th Water Distribution System Analysis Symposium*, August 2008.

Shepherd, M.A. and Poona, V.A. (2010). “Reducing non-revenue water in the Durban Central Business District” <http://www.ewisa.co.za/literature/files/69_21%20Shepherd.pdf>

Shirzad, A., Tabesh, M. and Farmani, R. (2014). “A comparison between performance of support vector regression and artificial neural network in prediction of pipe burst rate in water distribution networks”. *KSCE Journal of Civil Engineering*, 18(4), 941-948.

Stoianov, I. and Henderson, K. (2014). “From static to adaptative control of network topologies for improving systems resilience [DMA v2.0].” *SWIG workshop (Sensors for*

Water Interes Group), October, 2014 Telemetry & Control Systems for Smarter and Resilient Operation of Water Supply Networks, 15th October, London.

Sturm, R., and Thorton, J. (2005). “Proactive leakage management using District Metered Areas (DMA) and pressure management–Is it applicable in North America.” *IWA International Specialised Conference ‘Leakage 2005’. Halifax, Canadá* (pp. 415-427).

Sydney Water (2005). “Water conservation and recycling; implementation report”. <http://www.sydneywater.com.au/swe/index.htm > (Nov. 22, 2013)

Technolog (2010). Regulo – SMS/GPRS Electronico PRV controller. <http://www.technolog.com/water/products/pressure-control/12/regulo-sms-gprs-electronic-prv-controller.html> (Oct. 02, 2014).

Thornton, J. (2003). “Managing leakage by managing pressure: a practical approach”. *Water21*, October 2003. 43-44.

Thornton, J., and Lambert, A. (2005). “Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships”. *Proc., IWA Int. Specialized Conf. Leakage 2005,* IWA, Halifax, Canada, 347-357.

Thornton, J. and Lambert, A. (2007). “Pressure management extends infrastructure life and reduces unnecessary costs”. *Proc., IWA Int. Specialized Conf. Water Loss 2007,* IWA, Bucharest, Romania, 511-521.

Thornton, J., Sturm, R. and Kunkel, G. (2008). “Water loss control”. *Controlling real losses - pressure management.* McGraw-Hill Companies – 2nd edition, USA, 301-343.

Tucciarelli, T., Criminisi, A., and Termini, D. (1999). “Leak analysis in pipeline systems by means of optimal valve regulation”. *J. Hydraul. Eng.*, 125(3), 277-285.

UK Water Industry (1994a). “Managing leakage – Report G: Managing water presure”. UK Water Industry, Engineering and Operations Committee. ISBN: 1 898920 12 5.

UK Water Industry (1994b). “Managing leakage – Report E: Interpreting measured night flows”. UK Water Industry, Engineering and Operations Committee. ISBN: 1 898920 10 9.

Ulanicki, B., Bounds, P. L. M., Rance, J. P., and Reynolds, L. (2000). “Open and closed loop pressure control for leakage reduction”. *Urban Water*, 2(2), 105-114.

Ulanicki, B., AbdelMeguid, H., Bounds, P., and Patel, R. (2008). “Pressure control in district metering areas with boundary and internal pressure reducing valves.” *Proc. 10th Int. Water Distribution System Analysis Conf.*, ASCE, Kruger National Park, South Africa, Aug. 17-20, 2008.

UN-HABITAT (2006). “Water Demand Management Strategy and Implementation Plan for Indore”. UN-HABITAT, eds., Nairobi, Kenya.

VAG (2009). “Pressure management in Bardejov.” *VAG-Armaturen GmbH* <http://www.vag-india.com/es/fields-of-application/pressure-management.html> (Jan. 10, 2014).

Vairavamoorthy, K., and Lumbers, J. (1998). “Leakage reduction in water distribution systems: Optimal valve control”. *J. Hydraul. Eng.-ASCE,* 124(11), 1146-1154.

Van Zyl, J. E., and Clayton, C. R. I. (2007). “The effect of pressure on leakage in water distribution systems”. *Proc. of the ICE-Water Management*, 160(2), 109-114.

Van Zyl, J. E., and Cassa, A. M. (2011). “Linking the power and FAVAD equations for modeling the effect of pressure on leakage”. *Proc. 11th Int. Conf. on Computing and Control of the Water Industry*, CCWI, D. A. Savic, Z. Kapelan, and D. Butler, eds., Univ. of Exeter, Exeter, UK.

Van Zyl, J.E. (2014). “Theoretical modeling of pressure and leakage in water distribution systems”. *16th Conference in Water Distribution System Analysis, WDSA 2014, Bary, Italy. 14-17 July.*

Walski, T., Bezts, W., Posluszny, E. T., Weir, M., & Whitman, B. E. (2006). “Modeling leakage reduction through pressure control”. *Journal (American Water Works Association),* 147-155.

Wang, Y., Zayed, T., and Moselhi, O. (2009). "Prediction models for annual break rates of water mains". *J. Performance of Constructed Facilities*, 23(1), 47-54.

WaterWorld (2011). "Pressure management system to help UK's Severn Trent cut water leakage" <http://www.waterworld.com/articles/2011/03/pressure-management-system-in-uk.html> (Jan. 02, 2015).

Watson, T., Christian, C., Mason, A., Smith, M., and Meyer, R. (2004). "Bayesian-based pipe failure model". *J. Hydroinform.*, 6, 259-264.

Wright, R., Stoianov, I. and Parpas, P. (2013). "Dynamic topology in water distribution networks". CCWI 2013, Perugia, Italy.

Wright, R., Stoianov, I., Parpas, P., Henderson, K. and King, J. (2014). "Adaptive water distribution networks with dynamically reconfigurable topology". Journal of Hydroinformatics, doi:10.2166/hydro.2014.086.

Wyeth, G. and Chalk, R. (2012). "Delivery of 30 Ml/d Leakage Reduction Through Intelligent Pressure Control". *Proc., IWA Int. Specialized Conf. Water Loss 2012*, IWA, Manila, Philippines, Feb. 26-29, 2012.

Xu, Q., Chen, Q., Li, W., and Ma, J. (2011). "Pipe break prediction based on evolutionary data-driven methods with brief recorded data". *Reliability Engineering and System Safety*, 96(8), 942-948.

Xu, Q., Chen, Q., and Ma, J. (2013). "Optimal pipe replacement strategy based on break rate prediction through genetic programming for water distribution network". *J. Hydro-environ. Res.* 7(2), 134-140.

Xu, Q., Chen, Q., Ma, J., Blanckaert, K. and Wan, Z. (2014). "Water Saving and Energy Reduction through Pressure Management in Urban Water Distribution Networks". *Water Resources Management*, 28(11), 3715-3726.

Yates, C. (2005). "Water Accountability–The New Way". *Proc., IWA Int. Specialized Conf. Leakage 2005*, IWA, Halifax, Canada, 15-21.

Yates, C. and MacDonald, D. (2007). “Advanced Pressure Management via Flow Modulation: The Dartmouth Central PMA”. *Proc., IWA Int. Specialized Conf. Water Loss 2007,* IWA, Bucharest, Romania, 541-548.

Yates, C., Campbell, R. and MacDonald, G. (2014). “Advanced pressure management utilizing automated PRV control in a dual supply DMA.” *Canadian Society of Civil Engineering Annual Conference 2014, CSCE, Halifax, Nova Scotia. 28-31 May, 2014.*

Table 1. Real cases with PM programs and objectives

Continent	Reference	Country	City/Region	Real or Model[1]	Type of Regulation[2]	Objectives[3]
Africa	Marunga et al. 2006	Zimbabwe	Mutare	R, M	FO	L, C
	Benahmed 2007	Morocco	Casablanca	R	FM	L, C
	Mckenzie et al. 2009	South Africa	Emfuleni	R	FO	L, B, C
	Meyer et al. 2009	South Africa	Cape Town	R	FO	L, B, C
	ElFarissi et al. 2010	Morocco	Chefchaouen	R	FO, FM	L
	Shepherd and Poona 2010	South Africa	Durban	R	FO, TM, FM	L, C
	GIZ 2011	Burkina Faso	Ouagadougou	M	FO	L
	Burrows 2014	South Africa	Durban	R	RNM	L, B
America	Lalonde 2005	Canada	York Region	R	FM	L
	Levine et al. 2005	United States	Pittsburgh, PA	R	FO	L, B
	Sturm and Thornton 2005	United States	Seattle, WA	R	FO, FM	L
	Fanner 2007	The Bahamas	New Providence	R	FO, TM, FM	L, B
	Lalonde et al. 2008	Canada	Toronto	R	FM	L, B
	GIZ 2011	Brazil	Sao Paulo	R	TM, RNM	L, B
	GIZ 2011	Peru	Lima	R	*N.C*	L
	Kunkel and Sturm 2011	United States	Philadelphia, PA	R	FM	L
	Yates et al. 2014	Canada	Halifax	R	FO, FM	L, B
Asia	Rogers 2005	Indonesia	Jakarta	R, M	FO, TM	L
	Chai 2006	Malaysia	Sandakan	R	*N.C*	L
	UN-HABITAT 2006	India	Indore	R	*N.C*	L
	Anuvongnukroh et al. 2007	Thailand	Bangkok	R	*N.C*	L
	Morrison et al. 2007	Malaysia	Johor	R	TM	L
	Mahdavi et al. 2010	Iran	Mahalat	M	FO	L
	Eguia et al. 2012	The Philippines	Manila	M	FO, TM, FM	L, B
	Feldman et al. 2012	Israel	Beer Sheva	M	*N.C*	L
	Karadirek et al. 2012	Turkey	Antalya	M	FO	L
	Wyeth and Chalkl. 2012	Malaysia	Selangor	R	RNM	L, B
	2030 WRG 2013	Saudi Arabia	Jeddah	R	RNM	L, B
	Xu et al. 2014	China	Beijing	R	*N.C*	L
Europe	Charalambous 2007	Cyprus	Limassol	R	FO, FM	L, B
	Kovac 2007	Bosnia & Herzegovina	Grazanica	R	FO, FM	L, B
	Kovac 2007	Croatia	Zagreb	R	FO, FM	L
	Awad et al. 2008	United Kingdom	Yorkshire	M	FO, TM, FM	L, B, C
	Fantozzi, et al. 2009	Italy	Reggio Emilia	R	RNM	L, B, C
	Miguel, 2009	Spain	Madrid	R	FO, TM, FM, RNM	L
	VAG 2009	Slovakia	Bardejov	R	RNM	L, B
	Awad et al. 2010	United Kingdom	Yorkshire	M	FO, TM	L, B, C
	Li et al. 2010	United Kingdom	-	M	FM	L
	Nicolini et al. 2010	Italy	Udine	M	FO	L
	AbdelMeguid 2011	United Kingdom	Oldham	M	TM, FM	L
	Dimitrov et al. 2011	Bulgary	Burgas	R	FO	L
	I2O 2011	United Kingdom	London	R	RNM	L, B
	Paskalev et al. 2011	Bulgary	Razgrad	R	FO	L
	Ristovski 2011	Macedonia	Skopje	R	FM	L
	Fontana et al. 2012	Italy	Napoli	R, M	FO	L
	Babic et al. 2014	Serbia	Belgrade	R	FO	L, C
	Kanakoudis et al., 2014	Greece	Kos and Kozani	R, M	FO, TM	L, C
	Wright et al. 2014	United Kingdom	-	R, M	FO, FM	L
	Jiménez 2015	Spain	Murcia	R	FO	L, B
	Martinez-Codina et al. 2015	Spain	Madrid	R, M	FO	B
Oceania	Pilipovic et al. 2003	New Zealand	Waitakere	R	FO	L, B, C
	Sydney W.C. 2005	Australia	Sydney	R	*N.C*	L, B, C
	Girard et al. 2007	Australia	Gold Coast	R	FM	L, C
	Mistry 2007	Australia	Hervey Bay	R	FO, FM	L, C
	Bailey 2009	Australia	Logan city	M	FM	L, C
	Beaton and Lambert 2013	Australia	Yarra Valley	R	*N.C*	L, B, C

1) Case studies implemented in 'Real programs – R' or developed in hydraulic models – M'.

2) Type of regulation: 'Fixed Outlet – FO', 'Time-based modulation – TM', 'Flow-based modulation – FM' and 'Remote node-based modulation – RNM'.

3) Objective pursued: 'Leakage reduction – L', 'new burst decrease – B', 'consumption reduction – C'.

Table 2. Optimization models for pressure management, chronologically ordered

Authors	Year	Decision variables[1]	Objective function[2]	Optimization method[3]
Gemanopoulos and Jowitt	1989	L, S	L	LP
Jowitt and Xu	1991	S	L	LP
Savic and Walters	1995	S	L	GA
Reis et al.	1997	L, S	L	GA
Vairavamoorthy and Lumbers	1998	S	L	NLP
Tucciarelli et al.	1999	S	L	SA
Unalicki et al.	2000	S*	L	NLP
Pezzinga and Pititto	2005	L, S	L	GA, NLP**
Araujo et al.	2006	N, L, S	L	GA
Liberatore and Sechi	2009	L, S	L	MH
Nicolini and Zovatto	2009	N, L, S	L	GA
AbdelMeguid and Ulanicki	2010	S***	L	GA
Awad et al.	2010	L, S	L, B, C	GA
Mahdavi et al.	2010	L, S	L	GA
Gomes et al.	2012	L, S	L, C	SA
Eck and Mevissen	2013	L, S	L	MINLP
Giugni et al.	2013	L, S	L	GA
Wrigth et al.	2014	S	L	NLP
Dai and Li	2014	L, S	L	MILP-NLP

1) Valve location: L – valve setting: S – number of valves: N

2) Leakage reduction: L – burst frequency decrease: B – consumption reduction: C

3) Linear Programming: LP – NonLinear Programming: NLP – Mixed Interger Linear Programming: MILP – Mixed Interger NonLinear Programming: MINLP – Genetic Algorithms: GA – Simulated Annealing: SA – other Meta Heuristic methods: MH

*) ‘Valve setting’ for a time-based modulation profile.

**) Two optimization problems: ‘Valve location’ solved with GA, and ‘valve setting’ with an NLP algorithm.

***) ‘Valve setting’ for a flow modulation profile.