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Integration of modelling and monitoring to optimize network control: two case studies from Lisbon

N. Dias[a,*], N. Ferreira[a], A. Donnelly[a]

[a]EPAL, S.A, Av. Berlim, 15, 1800-031 Lisboa, Portugal

Abstract

In recent years, EPAL, Portugal's largest water supply company, has successfully implemented projects for optimizing control of the Lisbon distribution network, which include the implementation of a network monitoring project (WONE) aimed at reducing water losses, as well as the development of an EPANET based all-pipe hydraulic network model. Building on the individual success of each of these projects, the integration of these two base tools has proved to be extremely useful as regards managing situations of great complexity, as demonstrated in the two case studies that are presented in this paper.

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Keywords: Modelling; Monitoring; Network control

1. EPAL's water supply system and distribution network

EPAL - Empresa Portuguesa das Águas Livres, S.A. is the successor to the CAL - Water Company of Lisbon, a concession for water supply to the city of Lisbon from 1868 to October 1974, when the concession contract finished and when EPAL was formed.

EPAL abstracts, treats, transports and distributes water for human consumption through the management and operation of its supply system that encompasses around 740 km of mains from the Castelo de Bode reservoir to several municipalities. Among its main production and transport infrastructure, the company has three main

* Corresponding author. Tel.: +351-918-593-203; fax: +351-218-552-164.
E-mail address: nunodias@epal.pt

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subsystems, whose daily production capacity amounts to 1,017 million m^3: Alviela Aqueduct in operation since 1880; Tejo Aqueduct opened in the 1940s and Castelo do Bode subsystem in operation since 1987.

EPAL supplies about a quarter of Portugal's population, living in 34 municipalities on the north side of the Tagus River, which corresponds to a total area of 7,005 km^2. In Lisbon, EPAL is also responsible for water distribution with over 350,000 customers, serving a population of around 550 000. The average daily consumption within the city of Lisbon was around 170,000 m^3/day in 2012.

Lisbon distribution network has a total length of over 1 450 km of pipes and about 73,000 service connections, which are supplied by 14 reservoirs, ten pumping stations and five chlorination stations.

Fig. 1 shows the Lisbon distribution network which has five altimetric supply zones, as well as a three-dimensional representation of the city elevation and its correspondence with the altimetric zones of the EPAL distribution network.

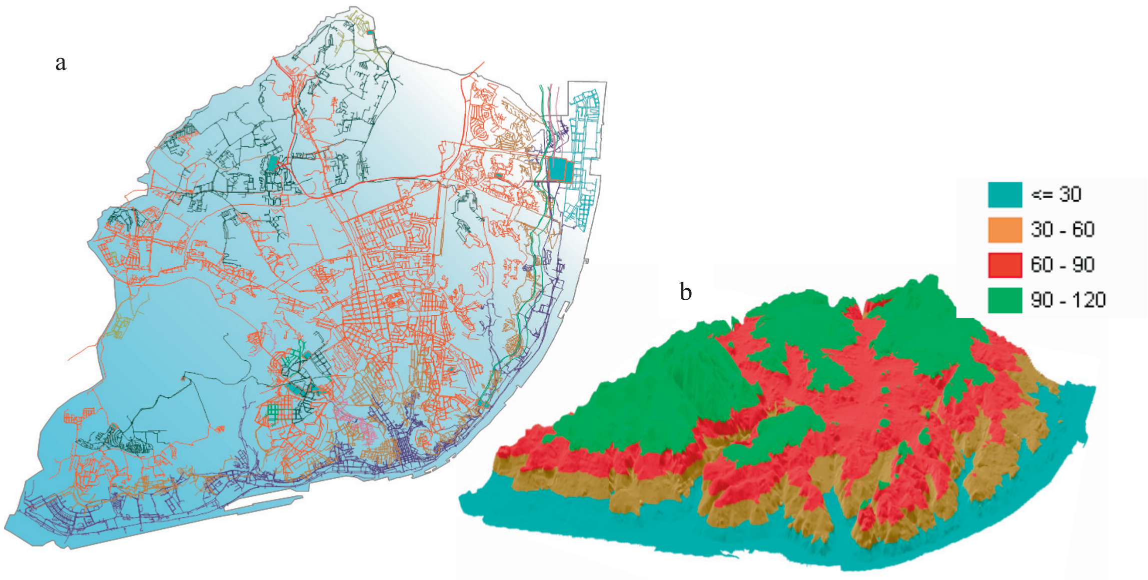

Fig. 1. (a) EPAL distribution network; (b) Tridimensional view of Lisbon elevation.

EPAL network operations and maintenance are supported by a full set of information systems, which includes the SCADA system, maintenance information system, GIS, billing customer system and mathematical model. The company has a Command Centre which operates 24 hours a day, 365 days per year, comprising both Operation and Maintenance areas.

Aiming at the development of excellent standards in management indicators as regards its principal activities, EPAL has implemented quality control systems, particularly as regards environmental and social responsibilities, ensuring that network interventions, such as burst repairs, mains flushing and reservoir cleaning, amongst others, are performed in accordance with a set of well established procedures, including hygiene and safety practices.

2. Distribution network segmentation and monitoring

In recent years, EPAL has successfully implemented a network monitoring project (WONE) aimed at reducing water losses. Increasing efficiency and reducing water losses is economic and environmental good practice, with EPAL having established itself as a company with the ability to anticipate and resolve problems associated with water losses, which has been achieved through the successful implementation of the WONE Non-Revenue Water (NRW) reduction project. The basis of this project has been the progressive implementation of more than 150 District Metered Areas (DMAs), along with associated flow and pressure monitoring equipment and telemetry systems, undertaken in parallel with the renewals and rehabilitation program. Through this process of network segmentation and increased monitoring and analysis, a far greater understanding of performance and systems dynamics has been obtained.

The process of network segmentation into DMAs with telemetry systems, set to record data every 15 minutes, has allowed the rapid intervention in case of pressure or demand anomalies. Note that when an anomaly occurs in pressure, such as when pressure at the critical (highest) point within the DMA is less than 5 m, telemetry equipment reports an alarm and sends updated pressure and flow data. In June 2010, this project reached conclusion with 151 DMAs implemented, covering around 97% of clients and 87% of network length.

3. Hydraulic modelling

Although, for many years, there have been several generations of mathematical models, it was only in 2008 that EPAL developed internally a complete all-pipe model of its distribution network, which was based on EPANET 2.0. Evolution, since beginning of this project through to the integration and practical application in 2009, shows that EPAL has recognized modelling as an analytical tool with strategic importance.

Through practical applications of these models a gradual but progressive deviation between the modelling results and 'real' monitoring data has been noted, being explained the increasingly out of date data and the models themselves, which were based on 2007 scenarios. This led to a general update of the models in 2012 given the significant differences between these two realities in relation to:

- Existence of 152 DMAs in the distribution network, compared to 53 extant in 2007;
- Reduced water losses in the distribution network of 19.4 M m^3/year in 2007, equivalent to 17.2 % of the volume entered in Lisbon, to 11.6 M m^3/year (10.0 %) in 2011;
- Pipe renewals around 120 km between 2007 and 2011, which corresponds to approximately 8.4 % of the distribution network (approximately 2.1 %/year);
- Implementation of a monitoring program for large volume users in Lisbon - in 2011 were monitorized about 750 users compared to 15 users monitored in 2007.

To develop these models two distinct stages were considered, which correspond to:

- Stage 1 – extended period calibration for 24 hours (96 timesteps) applied to each altimetric supply zone and for maximum and average daily demand;
- Stage 2 – definition of representative days of typical characteristics and profiles for the distribution network.

To update the hydraulic models, it was necessary to review and validate physical data from GIS (mains, valves, elevation pumps, reservoirs, etc.), to define the height of every node within the network and to associate demand of all clients to the models nodes, especially in relation to large volume users with telemetry (for which specific demand patterns were defined), status and valve timing, amongst others. Next, to the calibration of each altimetric supply zone model for two specific days was undertaken from 2011 (maximum and average days), so that the models results agreed reasonably with the observed 'real' behavior , in terms of levels and flow rates from tanks as well as pressure and flow at the elevation pumps, DMA metering points and large volume users.

Given the uncertainties as regards accuracy, pressure and flow measurements from EPAL's distribution network were adjusted according to the criteria recommended by the WRC (referred in Coelho et al. (2006)), to calibrate each model. Therefore, in terms of pressure all simulated values equaled the real measurements with a tolerance of 2 m of pressure, whereas the modelled flow equaled the measured flow with a 5% tolerance.

The second stage was to estimate and define the typical behavior of the distribution network on weekdays, Saturdays and Sundays, as well as maximum and average demand, so that models are not just discrete representation of the two historical days of data used.

In summary, at present, the models represent all of EPAL distribution network through a dynamic analysis of the flow with 15 minutes time patterns, which are characterized by the following physical and non-physical components:

- 40,067 nodes and 20 tanks;
- 37,337 mains sections, with over than 1,450 km of length and diameters between 20 and 1500 mm;
- 51 elevation pumps with respective characteristics curves Flow-Head;
- 6,970 valves, 30 of which are pressure reducing valves;
- 73,734 demand points with associated pattern;
- 954 elevation and demand patterns;
- 2,400 simple controls and 1,026 rule-based controls.

4. Integration of modelling and monitoring

4.1. Overview

The company strategy to combine network monitoring with mathematic modelling has been aimed at improving capacity in resolving suspected leaks in the distribution network as well as undertaking diagnostic investigations of network performance whilst supporting planning, mains sizing and operational interventions.

The first case study demonstrates the benefit of modelling optimization integrated with real pressure and flow data to prove the existence of a suspected leak.

The second case study reveals the great potential for water utilities which are faced with emergency situations, where modelling can be a support tool for rapidly optimizing operational actions and procedures to mitigate and manage the potential impact on service with real network validation from monitoring data during and after implementation of the optimal solution.

4.2. First case study – Leak location with modelling and monitoring

An optimization methodology has been applied to support leak location based on hydraulic modelling. The objective is to find probable leak locations with the highest accuracy possible, along with quantification of water losses. This methodology is based on obtaining pressure profiles at three locations around a suspected leak location, allowing a correlation and optimization of the hydraulic model with the real data obtained from pressure loggers.

This case study was developed to address an outstanding issue identified during a step-test in a DMA, namely DMA1060 Vale de Alcântara. A leak had been identified but not located or repaired due to a lack of accessible points for applying acoustic correlators on the suspect main.

To obtain further proof of existence of the leak as well as indications as to its location, two additional pressure loggers were installed at strategic points to supplement the existing pressure and flow monitoring point associated with the adjacent wastewater treatment plant (large volume user with permanent telemetry), as shown at Fig. 2a.

This allowed the use of real data as a base reference for calibration of a simplified and adjusted mathematic model for the sub-area under analysis. The objective of applying the optimization tool consisted of testing multiple possible locations for the leak, in this case 45 nodes within the model, as well as varying potential emitter coefficient of the leak orifice over a simulation period of six days.

In addition, analysis was undertaken on roughness coefficient alteration along the cast iron main, which crosses a main avenue and which was the suspected location of the undetected leak. Results obtained from the various simulations were systematically compared with the real pressure data from the loggers, with the lowest error scenarios representing the actual reality of the network in the area with the highest accuracy. As a result of mathematic optimization analysis, the suspected leak was actually located on the cross-connection main with a reasonable error of accuracy – indeed accuracy was within the radius of the excavation required to access the main, given the depth at which it was buried at the suspected point.

It is important to note that the greatest error associated with this methodology is essentially the unknown real roughness of the cast iron DN50 main, which creates the need to make assumptions of various possible roughness values. The Fig. 2b shows the comparison between the simulated and real pressure profiles along the suspected cast iron main, in one of the most probable scenarios for the leak location.

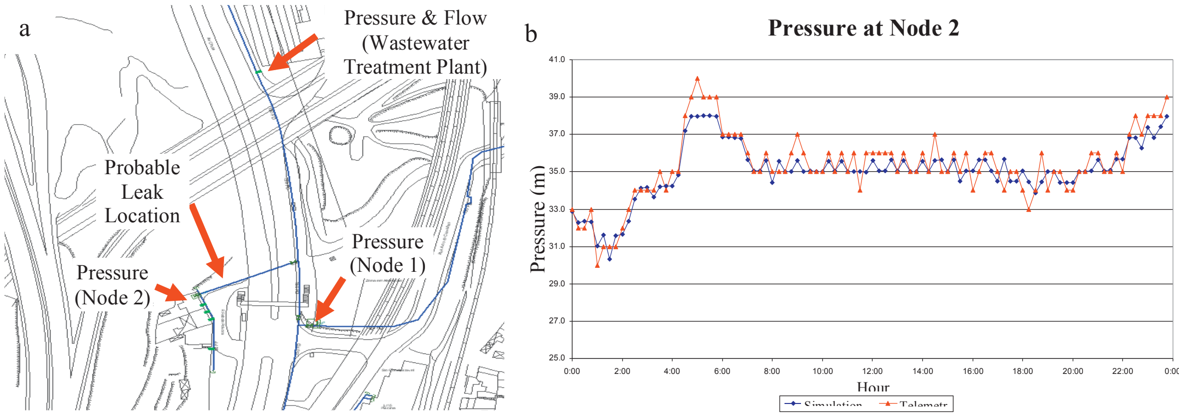

Fig. 2. (a) Loggers location around the suspected leak; (b) Comparison between the simulated and real pressure profiles at Node 2.

4.3. Second case study – Operational optimization in emergency situations

4.3.1. First event – Description and operational measures to reduce pressure impact

The event that triggered this case study occurred on March 9th, 2010 when there was a landslide on the 10 m tall slope adjacent to the main, which forced the need to suspend one of the trunk mains for the largest altimetric supply zone in Lisbon, referred to as the Chelas-Olaias main. Considering the proximity of the main to the landslide, less than 1 m and the type of mains section, namely a DN600 ductile iron pipe without self-anchored joints, the maintenance team decided to suspend the section immediately and indefinitely. The risk of keeping the main in operation was considered high with various hazards identified, namely immediate flood the surrounding area, third party damage and elevated risk to human life.

Based on empiric experience, it was known that closing this main would cause serious supply problems in the central and eastern areas of the supply zone. The known alternatives are through smaller diameter distribution mains, unable to supply the necessary volume in order to ensure the normal pressure, estimated increase of 12 400 m^3/day with 700 m^3/h at peak hour, with these estimated values being based on the model for a weekday with average demand.

Before the suspension of the trunk main, the empiric analysis based on experience, 13 DMA valves were opened to create alternative supply lines. However, through the hydraulic model analysis, it was found that there might be a better solution to supply the area, so five additional DMA valves were opened. At the peak consumption hour during the day following the suspension of the main, there were six DMA pressure alarms (Fig. 3a – noted as the grey areas), having a maximum pressure variation of 12 m head. Despite efforts to mitigate the negative effects of this suspension to clients, there was a decrease in pressure, as noted in Figure 3b on March 10th, which shows the comparison between the real telemetry before and after the suspension.

Consequently, there was a need to optimize network management, based on the hydraulic model, in order to maximize the transport capacity in the several DN300 mains.

The optimal theoretical solution was then determined and implemented in a phased manner to ensure network stability and determine the real implication of each step adopted against that predicted by the model. After three days the optimal solution was implemented in the distribution network, having improved pressures by around 4m and low pressure alarms for just two DMAs. Note that throughout these few days there were operated 68 valves to ensure the transport optimizations for the most critical areas of the distribution network, as presented in Fig. 3b.

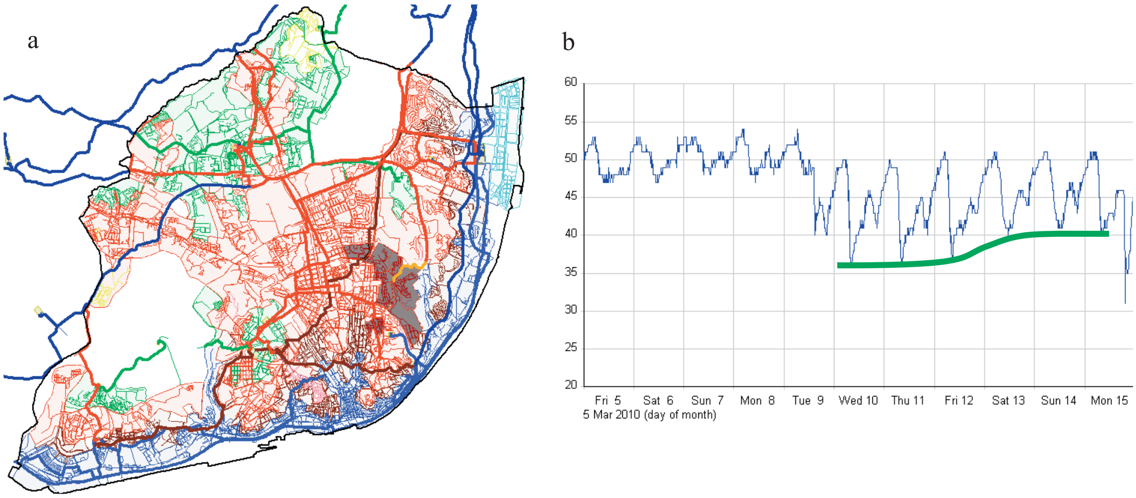

Fig. 3. (a) First event: DMAs with pressure alarms (gray areas) and closed main pipe (orange)
(b) Pressure data evolution with the optimization of transport supply after the suspension.

4.3.2. Second event – Burst at DN1000 main simultaneously

The second event of this case study occurred six days after the first event (March 15th, 2010), on the main pipe referred to as the Campo Grande-Pombal trunk main, which serves to transport water to the centre of this supply zone, with an estimated daily transport volume of 37,360 m^3/day with 2,150 m^3/h at peak hour.

Due to a large burst that threatened traffic on a main road in the city of Lisbon, the maintenance team was forced to suspend of this reinforced concrete DN1000 pipe, simultaneously with the limitations imposed by the previous event. Again, using the hydraulic model, the need to operate valves was study to ensure the best supply scenario before starting the suspension of the main pipe.

At peak hour of the next day were recorded 21 DMA pressure alarms (Fig. 4a), with a maximum pressure variation of 20 m head (Fig. 4b), leaving in some cases the distribution network with only 9 m of pressure.

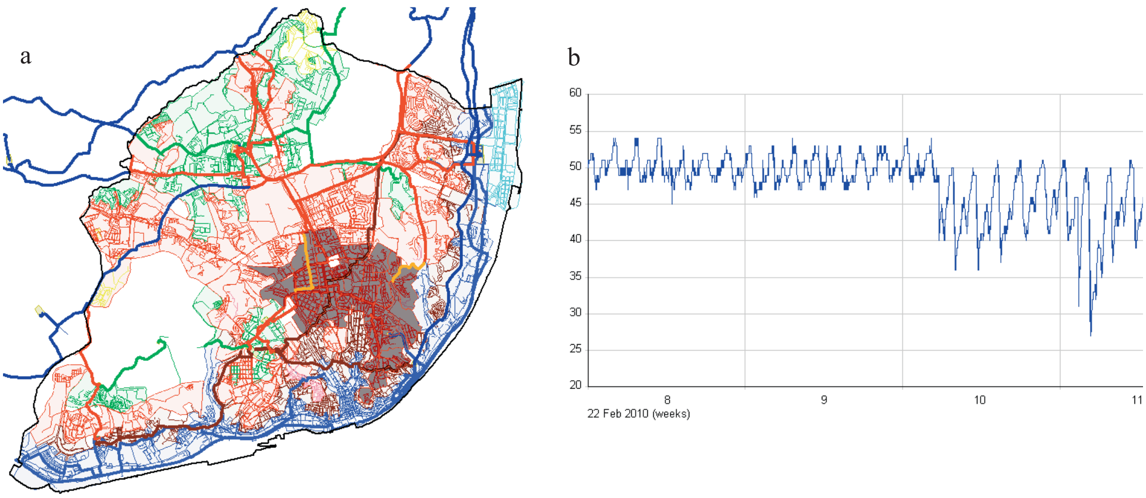

Fig. 4. (a) Second event: DMAs with pressure alarms (gray areas) and closed main pipes (orange)
(b) Pressure data evolution with the optimization of transport supply after both suspensions.

Due to the nature of the burst (at the joint between pipe sections), this main was ready for operation after 30 hours of repair interventions from the outside of the main. However, two days later, a second burst occurred, in this case on a curve section, forcing a new suspension for repair.

Knowing that this suspension would cause supply problems similar to the previous event and that, in this case, the repair suspension would have an extended duration of up to 96 hours, given the requirement to demolish the concrete block to support the curved section, exterior repair and rebuilding the concrete block again, the maintenance team was forced to adjust the repair procedure. Hence, it was considered repairing the pipe section from the interior, by installing a type "AMEX" joint. Although this repair is faster, normally taking around 14 hours to complete, the second valves away from the suspension valves are required to be closed to ensure staff safety within the main.

5. Tools to simplify the models usage

To increase the capacity to create different scenarios for the hydraulic model and simplify use of models within the company, EPAL has created an Excel application with Visual Basic programming based on a simple and user-friendly interface to process the necessary changes and create a new input file for EPANET, as mentioned in Rossman (2000). This base tool also allows the user to develop alternative scenarios of automatic operation, allowing the modification of operating days (weekdays, Saturdays or Sundays) or demand volumes, opening or closing of DMAs, changing mains diameters and material, altering valve status, preparing discharge plans and increased consumption due to new customers. These new capabilities aimed at simplifying the use of models by technicians from different areas of EPAL, without having to make changes in the EPANET graphic user interface.

Also, with the aim of making a more adaptive modeling tool it was created the possibility for the user to choose, in the same Excel file, preferences within the model for one altimetric supply zone (Fig. 5a), or integrated model for the five supply zones (Fig. 5b), that allow a series of scenarios covering the whole distribution network. This is extremely important in large-scale interventions or emergencies, involving several altimetric supply zones and is also essential to optimize energy consumption due to pumps elevation for the entire distribution network, according to network demands and minimum and maximum pressures at critical points, thus contributing to improving the efficiency and effectiveness of the company.

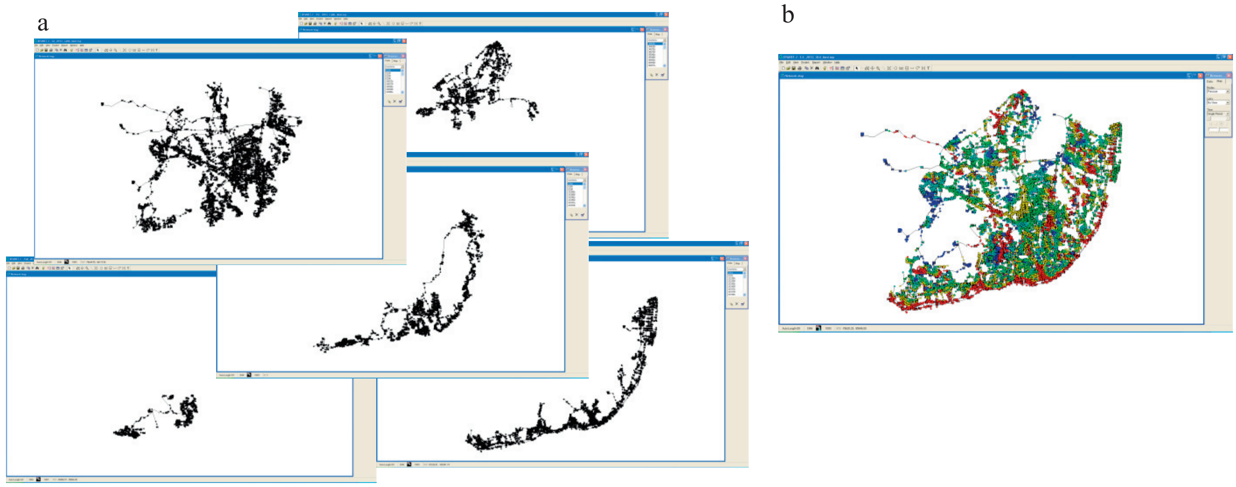

Fig. 5. (a) Hydraulic models for each altimetric supply zone; (b) Integrated hydraulic model for the distribution network.

Also, to simplify scenario analysis and comparison, EPAL has created another Excel file, with EPANET Programmer's Toolkit programming, to run each scenario and provide comparative graphs and tables for extended period simulations to a list of selected nodes or links (or to all nodes and links) and selected parameters such as pressure, head or demand in nodes, flow or velocity in links.

6. Conclusions

Nowadays, operational interventions within water distribution utilities cannot be sustained based only on intangible factors, namely the intuition of their technical staff or empirical knowledge that they hold. Improved service and quality levels that these companies are expected to deliver by their stakeholders are increasingly demanding so that there is no second chance to take corrective actions. Thus, the existence of decision support tools are essential to optimize either action plans, or in response to emergency situations.

During maintenance interventions in the water distribution network, the mathematical model highlights as one of the essential tools for promoting improvements in service quality, which although they may appear to be irrelevant at first, but have, in practice, a significant impact on client service.

In the first case study, it was demonstrated that practical integration of monitoring with hydraulic modelling obtained evidence of a leak and an indication of its most likely location. With this proof, the maintenance team has created the necessary access points to the pipe to apply acoustic correlation.

In the second case study, the hydraulic model allowed a pressure increase of about 4 m at the critical point, which improved the supply to nearly two floors of a building, which in turn led to a drastic reduction in the number of complaints and a clear improvement in service quality.

However, the use of the model alone, when any major event occurs is not sufficient to achieve the required results. It is necessary to undertake daily analysis using continuous network monitoring, experience of technical staff and the inputs of clients through complaints or warnings of poor quality supply. This continued analysis allowed the optimization of service levels within three days, through valve operation in order to increase the transport capacity through alternative mains, as well as understanding and learning, as regards the maximum achievable limits for each sector of the network.

The introduction of mathematical model within a company has been a slow and gradual process that has to gain credibility among technicians. When this status has been achieved, the level of trust and confidence in terms of decision making, reaches standards that allow changes and improvements within the usual modus operandi. A greater level of trust and confidence promotes better planning, regardless of the level of intervention urgency, allowing efficiency and effectiveness gains in the intervention actions, which originate optimized service levels.

As a practical outcome, modelling becomes a tool for decision support that reduces risk, increases the audacity, innovation and enabling high consequence interventions, with a greater level of confidence.

Within the water sector, any intervention can have a direct impact on everyday life of end users, so decision support tools which improve engineering knowledge are a key tool to assist with achieving improved efficiency levels that are consistent with stakeholder expectations.

Whilst the base tools created over recent years are proving to be useful, EPAL, as national reference water utility, has made a commitment to be prepared for the future, applying methodologies and analytical tools to support forecasting and optimizing the daily management of water supply systems. In addition, water utilities such as EPAL, will expect to increase their service efficiency and effectiveness, whilst reducing their carbon footprint. To achieve this goal, EPAL is interested in learning about other innovative projects supported by research and development institutes which may be useful in applying, developing and improving our base tools towards resolving potential future scenarios.

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