PRACTICAL METHODS FOR LEAKAGE CONTROL, DETECTION AND LOCATION IN PRESSURISED SYSTEMS

DÍDIA COVAS[(1)] ; HELENA RAMOS[(2)]

[(1)]Assistant of Civil Engineering Departments, Technical University of Lisbon, Portugal
[(2)] Assistant Professor of Civil Engineering Departments, Technical University of Lisbon, Portugal

Av. Rovisco Pais 1049-001 Lisboa - Portugal
Tel: +351-1-8418151/2
Fax: +351-1-8497650
e-mail:hr@civil.ist.utl.pt

ABSTRACT

In the last decade, leakage has become a high priority to water, oil and sewage transport industries and to the regulators, in order to fulfil legal milestones, to increase the profits of the companies, to protect the environment and to use the best as possible the scarce natural resource that is water.

Leakage reduction and control can only be achieved with the implementation of an integrated leakage control system that includes the identification and the characterisation of leakage in the hydraulic systems, leaks' detection and location, leaks' repair and, finally, the implementation of a continuous monitoring system.

The aim of this document is to systematise a complete and an integrated methodology to be applied in pressurised hydraulic systems, both conveyance systems and water distribution networks. It includes methods, techniques and equipment used currently and emphasises those more adequate to particular conditions and those with better performance in general cases.

1. INTRODUCTION

The investment in procedures and in an organised policy to reduce and control leakage might be the most efficient measure to answer the consumption growth and to the urgent need in assuring a sustainable development.

The question of whether it is profitable the investment in an integrated system to control leakage can be arisen, and a possible answer might be found in optimal leakage level presented in WRC, 1994 (15) (leakage level to which the cost of reducing one volume unit equals the benefit of selling the same volume). It does not exist a unique and universal value for this indicator, depending on the location of the network, man labour available, the normal pressure of the network, the conservation conditions and the location of ruptures (in main or in branch pipes).

The aim of this subject is to review the common methods and techniques used in water distribution systems to control and detect leaks. They can make part of an organised policy or just be applied in singular cases whenever be required. Complementary and preventive measures for leakage control are also presented.

2. INTEGRATED POLICY FOR LEAKAGE REDUCTION AND CONTROL

Undoubtedly leakage detection and control is more and more an up-to-date issue that companies have to deal within the management of water distribution systems, in order to increase the profits, as well as to satisfy the customer needs. The obvious answer to this problem is not to wait till it increases and ends up in significant and locatable ruptures, but to solve it with the implementation of an integrated strategy of action. This integrated policy can be organised in different stages: i) identification and characterisation of leakage; ii) detection, location and repair; iii) continuous monitoring of the system.

In the first stage, the network characteristics in terms of topology and operational conditions are collected and mapped preferably using Geographic Information Systems (GIS), and it is performed the assessment of the leakage volume by the difference between the water bought and sold.

In second stage, guidelines for leakage detection in the all network and in areas with more serious problems are defined and implemented. Usually the network is divided in several areas where all the inputs and outputs are well controlled by flow meters. Leakage is detected using approximated methods and specific instrumentation for more accurate location. Once located, leaks are, usually repaired, even though that presupposes the replacement of long branches of conduits.

At last, after decreasing the level of leakage to a satisfactory rate, it must be implemented a continuous monitoring system that permanently assesses the performance of the system and induces location of areas with problems in the future. The monitoring system is a computer based system in order to gather, to process and to analyse the greatest amount of data in the shortest period of time. Computer simulation of the hydraulic system would help significantly at this stage.

It will be emphasised expert methods, techniques and instrumentation related with the implementation of each stage.

3. IDENTIFICATION AND CHARACTERISATION OF LEAKAGE

Any water distribution network suffers from leaks and ruptures as a result of inadequate design, construction and operation, the life of pipe material and any unforeseen incidents that might occur. As a rule, one loses the idea of all the water volume lost between the source until the consumers, passing through the water conveyance system, reservoirs and water distribution network. Water losses might vary between 10 to 40% of the total water volume distributed, which can be of great economic importance. According to a study performed in 31 water distribution companies in UK (published in WRc 1994 (15)), almost 50% of water is unmeasured but consumed, 25% measured and consumed, and almost 23% is lost in the network (Figure 1) .

Losses have several costs associated such as, direct costs of the water volume lost and of interrupting the supply, repair of conduits and other devices, environmental clean up costs, and finally, the consequent social costs, not quantifiable, associated to the damages caused to the local consumers.

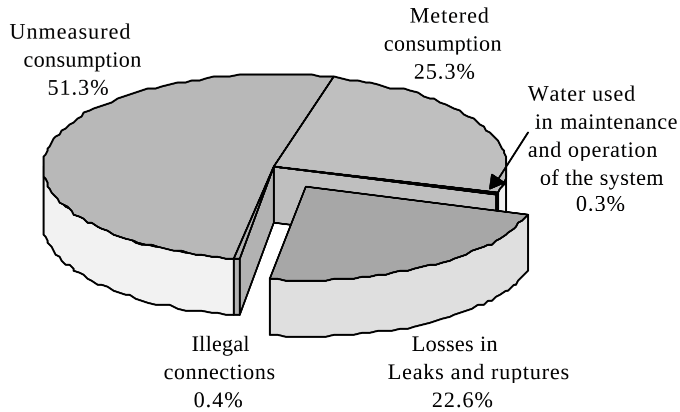

Figure 1 - Water volume distributed and lost in the network (WRC REPORT B 1994)

There are several types of losses that might be distinguished between losses, leaks (leakage) and ruptures. Leakage stands for all the water that is lost unseen, and never used by the consumers. It includes the water lost in the public network and in the interior of the buildings, not including the part that is used illegally without the consent of the water company. It is not possible to assess accurately leakage in a water distribution system (based on flow measurements downstream the reservoir and at the consumers) due to several reasons: measurement errors of the equipment used; a significant part of the consumption being paid by estimation; and the existence of several illegal connections to the network.

Therefore, rises the concept of *losses* as being the water volume given by the difference between the water volume measured at the entrance of the network and measured or estimated at the consumers, during a certain period of time. Losses have two components: a real one, that corresponds to leaks and ruptures, and an apparent one related to measurements and estimation errors, not permitted connections to the network and other unaccounted consumption, such as irrigation of public gardens, street washing and fire combats (Figure 2).

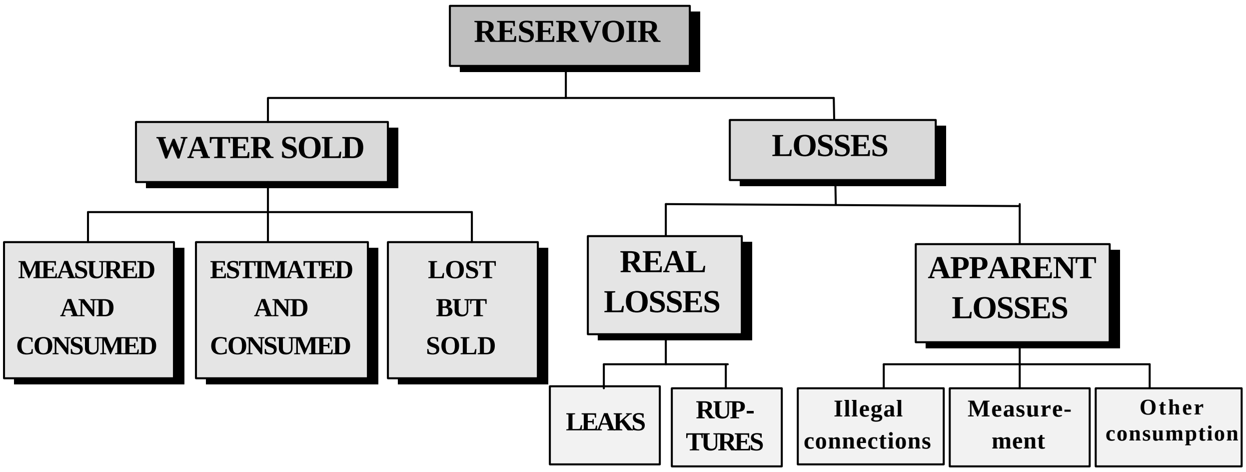

Figure 2 - Water distribution since the reservoir until the consumers
Distinction between losses, leaks and ruptures

Real losses include leaks and ruptures. *Leaks* represent the water volume lost continuously in the network owing to lack of water tight in pipe junctions, valves and other devices, as well as due to small fractures in pipes. Usually leaks' flows are quite small, not being detected easily, although they tend to increase in time becoming more significant.

On the other hand *ruptures* are characterised by sudden accidental bursts in pipes and other devices due to water hammer, structural faults, differential settlements or extreme operating conditions not previewed during design. They are detected immediately after their occurrence.

Leakage and rupture occurrences depend upon several factors, being the most important the following ones: normal pressure of the network, ruptures occurrence frequency, conservation and age of the network, construction processes and placement of pipes, type of ground and frequent circulation of high weighted vehicles.

Ruptures are detected easily and repaired immediately after their occurrence. Apparent losses can only be avoided using more accurate measurement equipment and through the application of higher fines to illegal connections. Leakage has to detected and located using an integrated strategy of action, as well as adequate methods and techniques.

The first stage of an integrated policy for leakage reduction and control, not only includes the first approach of water losses estimated by the water balance upstream and downstream the network, but also the complete characterisation of the network in terms of its topology and operational conditions.

4. LEAKAGE DETECTION, LOCATION AND REPAIR

Once the topology of the network is known and leakage is assessed, and an economic analysis has proved that the implementation of an organised strategy to reduce leakage is profitable, one must proceed with its implementation. The first step is to organise the network in different zones or areas and then apply leakage detection and location methods.

4.1 Implementation of district metered areas

In order to assess the performance of water distribution systems in terms of leaks, it is necessary to quantify the volume of water entered and consumed in the systems with a certain accuracy. This balance should be implemented by sub zones of the network. Therefore the network should be divided in several zones - District Metered Areas (DMA) - according to the topology and topography of the system, and the number of consumers (Figure 3).

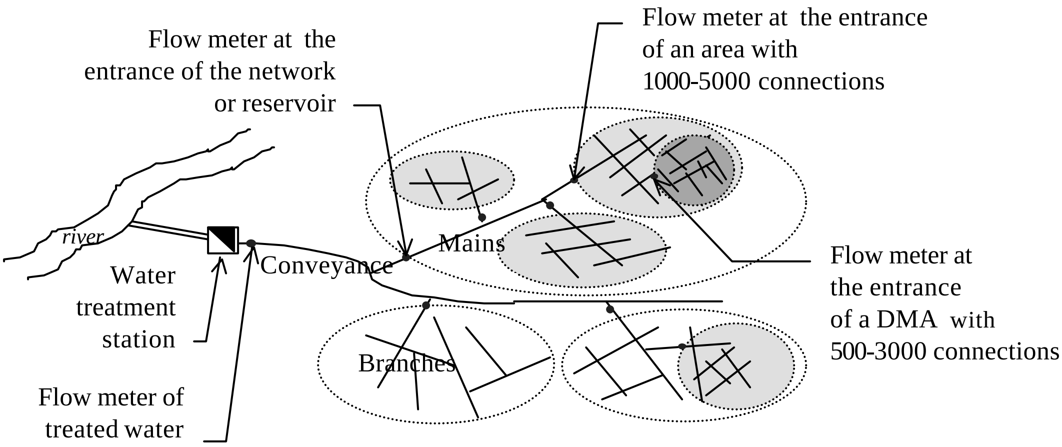

Figure 3 - District metered areas (adapted from WRc Report J, 1994)

The importance to establish a DMA is to control all the inflows and outflows in the area, as well as pressure variation during the day, using volumetric methods or the minimum night flow. Only this way is it possible to control the hydraulic performance of the network and to estimate leakage volume, eventually, determining leaks' positions by step testing or any other method. The leakage level in each area will allow the definition of priorities and adequate strategies for action.

Although the definition of district metered areas might seem an easy task, the zone planning should be performed wisely, since it may require the closure of several valves in order to control all the inflows and outflows of the DMA. This measure alters the normal hydraulic performance of the network with the consequent decrease of level of service to the consumers. Therefore, a set of procedures should be followed in zone planning and district meter implementation (Figure 4).

The implementation of DMAs depends on the complete knowledge of the network in terms of pipe characteristics, location of valves and reservoirs. For the efficient implementation and accomplishment of this task, it should be used a Geographical Information System (GIS) where all the components of the water distribution network would be mapped and characterised.

Afterwards, DMAs are delimited based on the topology of the network, the number of consumers and the topography of the zone. Each DMA should have up to 500 to 3000 connections. Sometimes DMAs are small autonomous networks supplied directly by elevated reservoirs.

The success of the leakage control policy depends strongly on the hydraulic simulation of the network before and after DMAs implementation. The simulation is of the utmost importance to assess the performance of the system under the new hydraulic conditions after the DMA zoning and, eventually, to redefine the DMAs, in case of significant decrease of the level of service. The negligence on this step involving simulation of the network might put at stake the success of the all leakage control system.

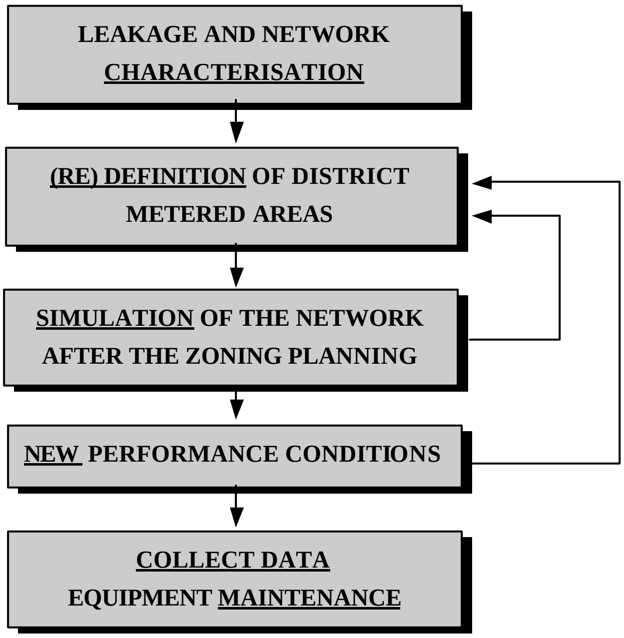

Figure 4 - Procedures of implementation of district metered areas

The delimitation of DMAs presupposes the definition of valves closure and location of flow meters and other measurement equipment. The most efficient way to collect data and control simultaneously all installed meters in different DMAs of the network, is to transfer information by telephone or radio to a central unit. Collected all measured data it is performed the complete diagnostic of the network.

Whenever normal pressure varies or the network is expanded to other areas, it is necessary to review zone planning and, eventual, redefine DMAs.

It is important to build up a data-base with a record and a complete characterisation of all leaks and ruptures occurrences referring the geographical location of the event (main or branch), the type of event, the probable reason for the occurrence, the affected devices and pipes, the detection and location method used, and the pressure measurements before and after the event. Only having an organised data base is it possible to conclude about leakage evolution, occurrence causes and efficiency of the method used, and decide which preventive and corrective measures should be applied in each case.

Since this task involves a significant investment, not only in human resources, but also in hardware, equipment and instrumentation, special care should be taken in their maintenance and operation.

4.2 Techniques for approximated location

Once implemented a district metered area system, whenever it is detected an abnormal and significant increase of water losses in the network, one must resort to more accurate techniques for leaks approximated location. The main principle of leaks' location consists of reducing the network affected area by the division in sub-zones or by step testing.

The sub-zoning consists in the temporary division of the DMA in sub areas, usually during the nocturne period, in order to minimise the negative impacts in the supply. It can be performed by valve closure inside the DMA, or by the installation of moveable flow meters (Figure 5). Usually the use of combined solutions is more efficient.

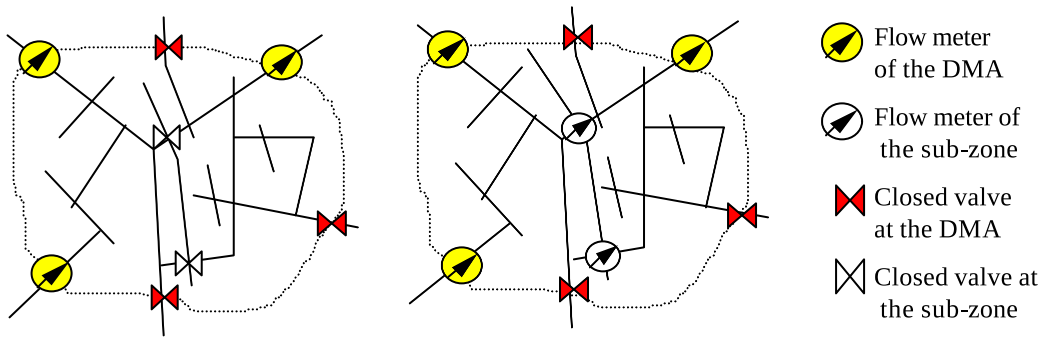

Figure 5 - Sub-zoning by valve closure or flow meters installation in a DMA

The step testing method is often applied either in alternative of sub-zoning or when the sub-zoning efficiency limit is reached. This method consists in progressive valve closure in the direction of an installed flow meter and the measurement of the correspondent flow (Figure 6). The success of step testing requires a well organised plan for the valve closure and meters sensible to very low flows. It should be applied also during the night, so that any significant decrease in flow with no apparent cause, points out to the presence of a leak or a rupture.

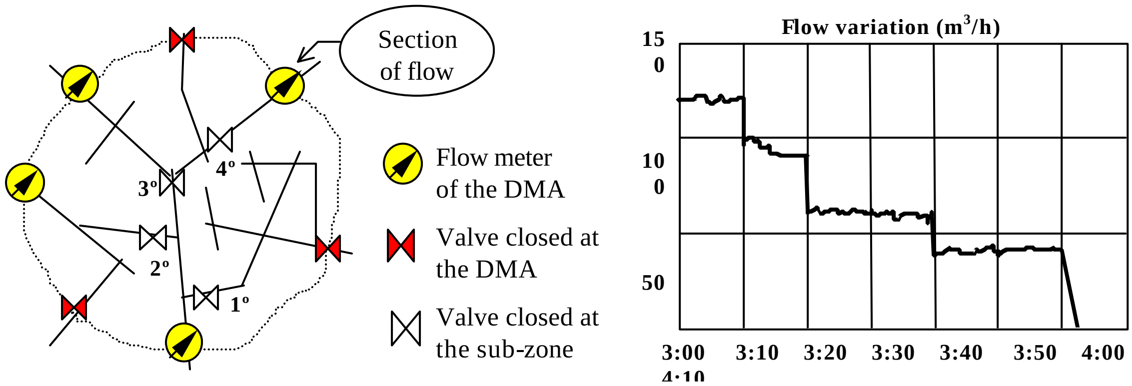

Figure 6 - Step-testing (*left*). Typical flow measurement during step testing (*right*)

In general, the combination of both methods is more efficient: firstly, the application of sub-zoning dividing the area in more restricted areas of the network, and after, performing the step testing. Both methods point out to a branch of pipe where the leak is located, nevertheless, the exact location must be determined applying more accurate location instrumentation.

4.3 Instrumentation for exact location

Once located the branch of pipe with problems, it is necessary to determine its exact location, existing several techniques and instrumentation: acoustic techniques; tracers injection; analysis of soil characteristics; video inspection; amongst other methods.

4.3.1 *Acoustic techniques*

Acoustic techniques are the most efficient compared with time involved and costs associated. They are based on the fact that water discharge by the leak generates uncommon vibrations on the conduit with a certain band of dominant frequencies. The intensity and the frequency of the sound allow the location of the source, the leak.

Probably, the most important instrument for leak detection is the acoustic or the electric stethoscope, usually composed by a metal rod with an ear piece, identifying and pinpointing the leak by direct listening to the sound generated in sections of the network with easy access, such as metal devices, fire hydrants and valves (Figure 7). The electric stethoscope has the advantage of the sound being converted to electronic noise which can be amplified and easily detected.

Figure 7 - Acoustic and electric stethoscope (direct acoustic sounding)

The ground microphone is the indirect acoustic sounding alternative to the latter (direct acoustic sounding) used for surface sounding to pinpoint leakage. It is very useful for leak detection on plastic pipes under hard surface, losing its efficiency in grass and unmade surface (Figure 8). Both instruments' efficiency depends on the staff experience, the existence of other noises, the dimension of the leak and the environmental conditions.

Figure 8 - Ground microphone (indirect acoustic sounding)

Another instrument is the acoustic correlator used to locate the leak with a couple of meters. It is very efficient in quickly defining leak's area, specially accompanied by the latter three instruments. Its main principle is measuring the acoustic wave in two different sections of the pipe with sensors, and the leak's location is calculated by the time difference between the arrival of equal frequencies to each sensor. The distance, X, of the leak from one sensor is:

$$X = \frac{L - a\,\Delta t}{2} \qquad (1)$$

where L is the distance between the two sensors; Δt, a time difference between the arrival of identical frequencies to each sensor; a, wave sound propagation in the pipe. The sensors are usually connected to valves and other devices of the network (Figures 9 and 10).

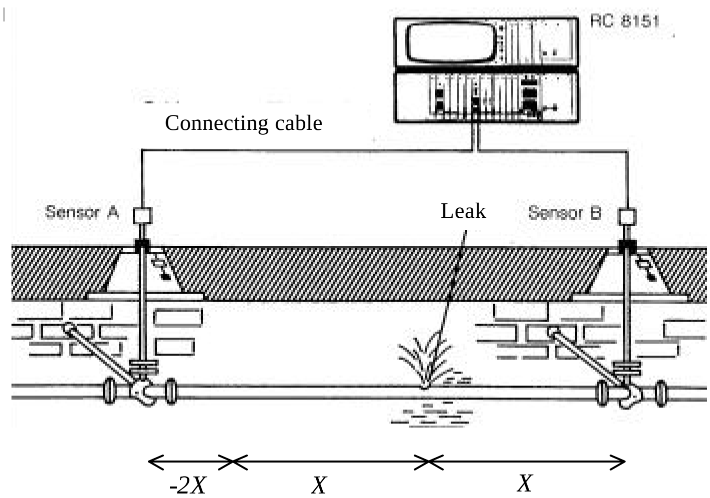

Figure 9 - Acoustic correlation principle

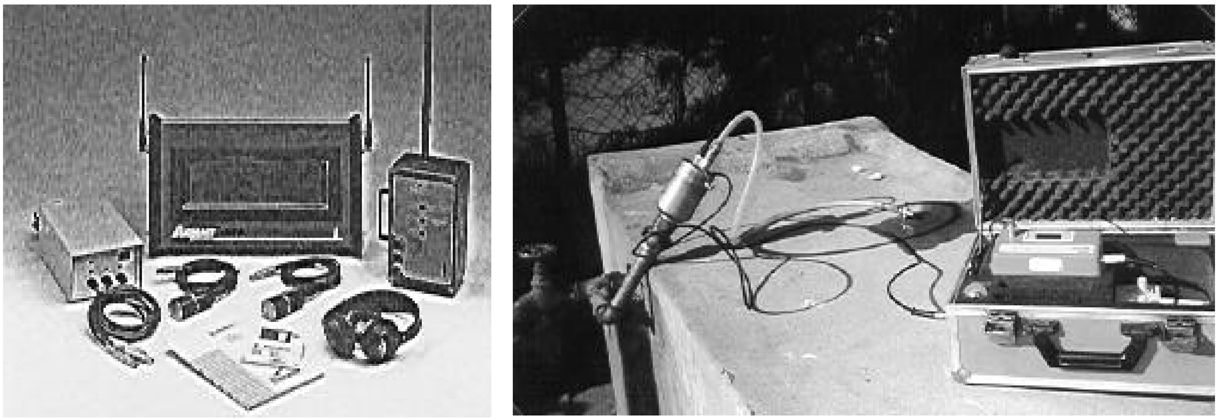

Figure 10 - Acoustic correlator

Continuous monitoring of acoustic sound, known as acoustic wave alert monitor (10) is another method to detect leaks, not to locate them. It is a piezometric sensor (located in a certain section of the network) that gives an alert when dynamically stressed. A leak occurrence generates a low pressure wave that propagates in every direction and is detected by each sensor located along the network. This method is very useful to locate quickly sudden accidental bursts.

4.3.2 *Non-acoustic techniques*

The simplest method to detect a leak is by visual observation of the pipe line site searching for any abnormal spring of water, vegetation, or humidity in the soil. Usually this type of location is performed by people living nearby who alert the water company for that problem.

A very cost-effective method of leak detection is the tracer injection to the fluid either using an odorant (gas) or a radioactive substance. Organic compounds, such as carbon monoxide, are the most useful odorizers, particularly when the water is without smell. The great disadvantages of the method are that the tracer has to be removed before the water can be consumed and the "sniffer" detectors might take some time which can be quite impossible in an urban area, where the supply must be continuous, and the leak location depends strongly on atmospheric conditions.

Another technique is the video inspection of the pipe performed as the pipeline monitoring pigs (Figure 11) . To perform a monitoring system, the supply has to be interrupted, the video pig is introduced inside the pipe and commanded from outside. It requires a significant investment and a well trained staff. The leak can be detected also using acoustic equipment on board. The leak can be repaired immediately after detection using a monitoring equipment depending on the type of leak and the type of pig used.

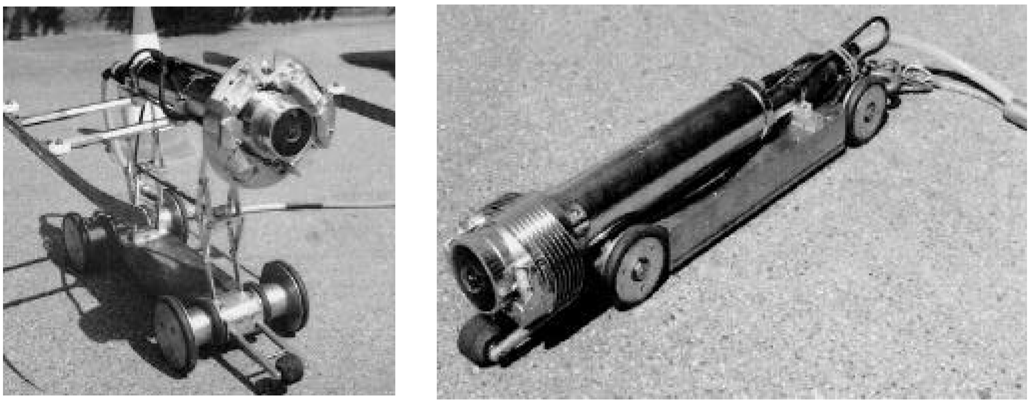

Figure 11 - Pipeline monitoring equipment for video inspection (Brochier)

This type of equipment is very versatile and used with multi-fuctions particularly in sewage transport conduits (Figure 12). This technique is currently used to clean, fill, batch and monitor the pipeline.

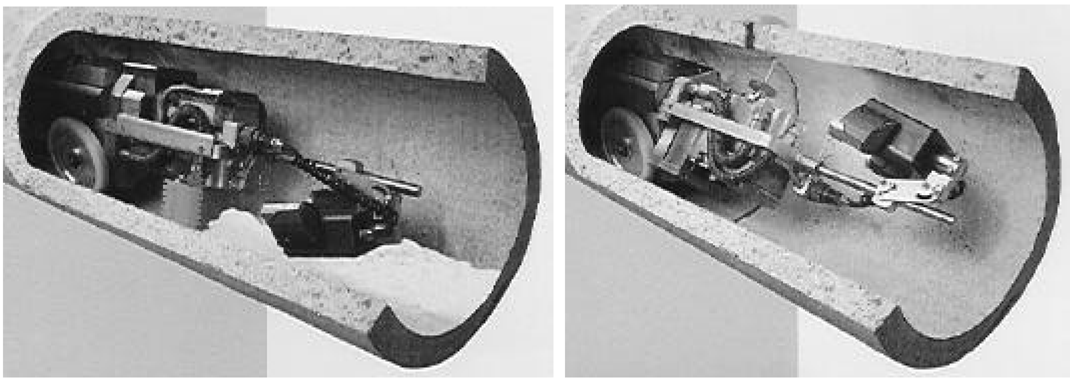

Figure 12 - Pipe line monitoring and rehabilitation pig in sewage systems (Brochier)

The periodic inspection of the pipe allows to collect the past and present history of the pipe and to predict when maintenance will be required.

4.4 Summary of existing methods and techniques

Leakage detection and location methods tend to be more and more sophisticated and its appliance depends, not only on the most cost effective method, but also on the technical and financial resources available. In summary, they can be organised and classified according to the physical factor or hydraulic parameter involved, as synthesised in Tables 1 and 2.

Table 1 - Methods of continuos control of leakage

Physical factor	Method used
Flow and pressure	• Minimum night flow control in DMAs • Flow and pressure control in DMAs • Continuous monitoring of the systems
Sound propagation	• Continuos analysis of acoustic signal variation

Table 2 - Leakage location techniques and instrumentation

Physical factor	Technique used
Sound propagation	• Acoustic or electric stethoscope • Ground microphone • Acoustic correlator
Visual observation	• Direct observation looking for evidence of abnormal vegetation and water losses • Intelligent pipeline pig (video observation)
Smell	• Tracers injection using odorants (gas)
Temperature	• Thermic sensors technology

	• Infrared photos
Radioactivity	• Tracers injection using radioactive substances • Radioactive micro-sphere
Electric conductivity	• Ground conductivity analysis • Sub-superficial radar

5. CONTINUOS MONITORING OF THE SYSTEM

Since leakage phenomenon increases gradually in time, it is necessary to keep active a continuos monitoring system of control, detection and location that overcomes this natural increase. It must include several phases - detection and control, approximated location, accurate location and repair - each of whom has several alternatives and different equipment available. In Figure 13, it is reviewed the set of procedures to implement in an integrated strategy to reduce and control leakage.

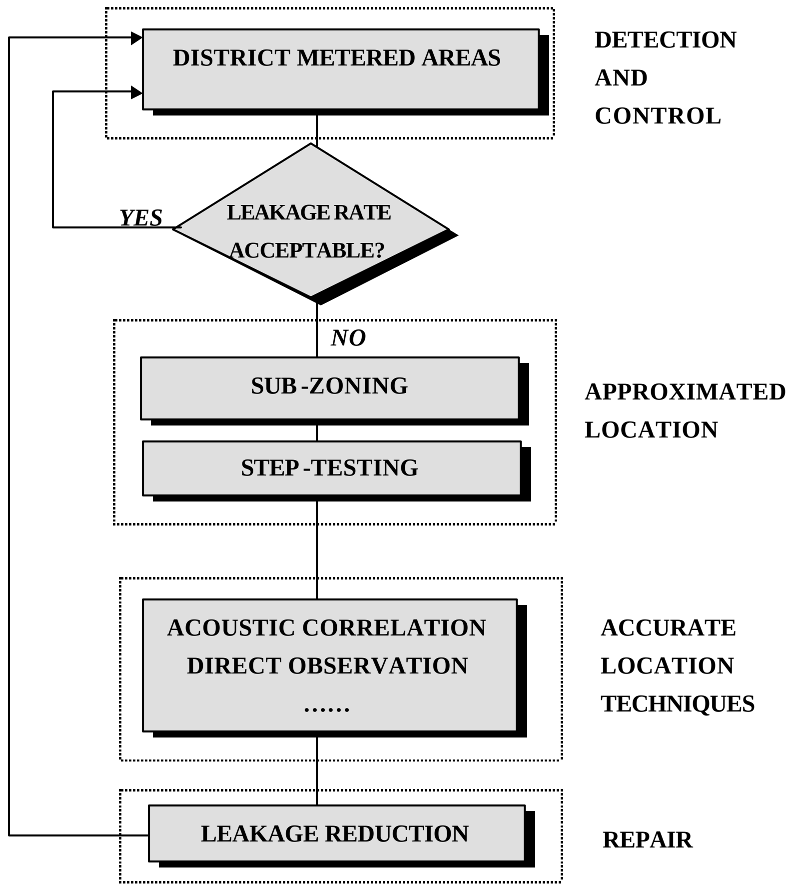

Figure 13 - Leakage reduction and control strategy

An efficient management of a water distribution system and leakage control requires the implementation of a continuos monitoring system of network. The basic idea is to associate the presented strategy to reduce leakage to a SCADA system (Supervisory Control and Data Acquisition), with measurements of head and flow in several sections of the network, defined by the DMAs, allowing the supervision and permanent control of the network, in terms of leakage evolution occurrence of new ruptures, consumption variation, conservation of pipes and operating control of other hydraulic devices.

With a SCADA system, composed by several remote terminals which communicate with a central terminal unit, all measurements would be gathered in a master site where the collected data would be analysed using computer headed simulation.

The implementation of the system would be organised in several phases. Firstly, it would be collected all the information about the system, the network would be analysed and would be defined measurement sections. This information would came from a GIS or consumers data base. Secondly, it would be installed all the equipment required to perform the measurements and a mathematical model of the network would be calibrated. Finally, it would be applied the proposed monitoring of the system using adequate computer headed simulation.

Every time that an irregularity is detected that seems like a leak or a before resorting to a more accurate method for leaks detection and location, it must be analysed any type of consumption not accounted. If there is not anything that justifies the local consumption or the singular head dumping, then it will be possible leaks or ruptures. In those areas, there must be applied other methods such step-testing or sub-zoning and, even more accurate techniques.

The leakage control policy associated to a SCADA system that transmits all the information (measurements of heads and flows) to a central unit, associated to Geographic Information Systems and different databases, that allow physical and hydraulic characterisation of the network, would provide undoubtedly an efficient management of the water distribution network simultaneously with leaks' detection and location (Figure 14).

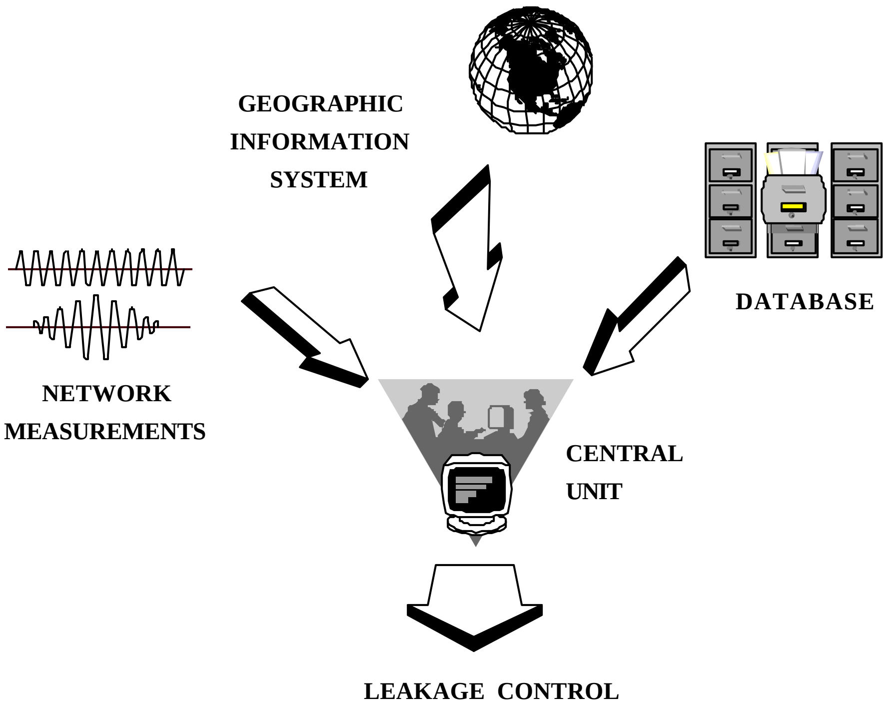

Figure 14 - Integrated leakage control based on continuous monitoring of the system

6. COMPLEMENTARY AND PREVENTIVE MEASURES

Amongst several factors upon which leakage depends, pressure is the most significant and easily controllable. It is well known that a water distribution network subject to high pressures, not only, is more susceptible of suffering serious accidents, but also, in case of having leaks, losses much more water. In fact, pressure control assures a more uniform service level to the consumers, reduces the frequency of sudden bursts and postpones leaks evolution. The investment in measures to reduce pressure in the network might be an efficient measure to reduce leakage with the consequent financial savings in water treatment and pumping costs.

In cases where it proves to be economically and technically appropriate, the leakage control policy can be complemented with other pressure control measures applied to DMAs such as pressure reducing valves (PRV) or micro-turbines, and the definition of pumping schemes, the use of stage pumps or variable speed pumps.

Pressure in a water distribution system can be controlled by different ways, being the most used dividing the system in different pressure zones according to their topography. Each zone is supplied with a controlled head maintain either by a reservoir or by **pressure reducing valves** installed in all entrances of the zone. The use of pressure reducing valves is common to dissipate the excess energy, being one of the most efficient and easily applicable alternatives to uniform and control network pressure. Nowadays, PRVs can be controlled either mechanically or electronically, in order to assure, at downstream, a fixed head, or a time dependent variable head, which allows an efficient management of service level and a better performance of the network.

A very promising alternative to PRVs, in what concerns to pressure control and consequent leakage reduction, not very common yet, is the use of **micro-turbines**. These devices have the advantage of, instead of dissipating the excessive flow energy, transforming it in electric power that can reinforce the base load energy. Micro-turbines are particularly adequate to water conveyance systems with significant difference in topographic levels, not only avoiding the use of higher classes of pipes, but above all, having the benefit associated to the renewable energy production. Similarly to PRVs, the day consumption law will influence the performance of the micro-turbine and the energy production as well. Depending on the micro-turbine types, they will be able to work with small discharge values and high heads, correspondent to the night consumption, and high discharge values associated with low heads, in rush hours.

In raising systems when several pumps are required either in parallel or in series, it should be defined, during the design process, the **adequate pumping schemes** in order to adjust the flow and head to the variation of consumption during the day, working only one pump to assure the minimum night flow and several pumps during the consumption peak.

In case of a pumping station with only one active group (and another one for the emergencies), it should be analysed the feasibility of using a stage pump, or a variable speed pump controlled by the pressure in a critical section of the network. A **stage pump** is used when, for the same flow, pressures varies significantly during the day. A **variable speed pump**, characterised by the set of curves represented in the Figure 14, is used to maintain a constant head in a certain section of the network, when flow varies during the day. It keeps the head constant for different flows, varying the pump speed.

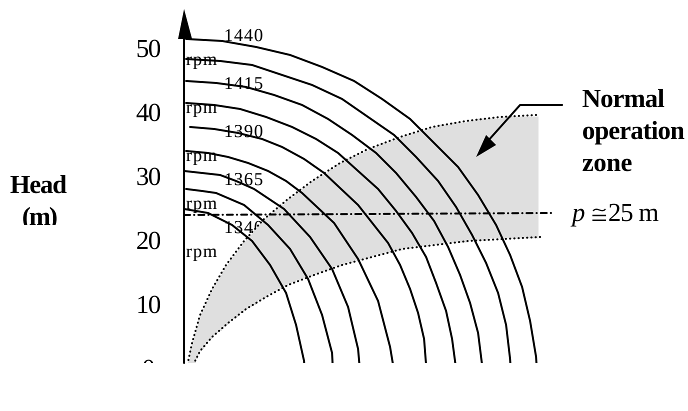

Figure 14 - Characteristic curves of a variable pump speed (adapted from WRC 1994)

7. FINAL REMARKS

Any water distribution system has from leaks and ruptures that might result from an inadequate design, installation or performance of the system, mechanical behaviour of pipes material and, eventually, accidents that might occur in the system. Water volume lost, varying between 10 to 40% of the total water distributed, can be of great economic importance.

Water distribution companies are responsible for leakage reduction and control, which can only be achieved with an integrated leakage control system including the characterisation, detection, location and repair of leakage, and the implementation of a continuous monitoring system. In fact, after reducing leakage rates, it is important to monitor the network operation and to assess its performance in terms of consumption growth and leakage evolution. This task can be improved using computer headed simulation of the network.

Being pressure one of the most important factors upon which leakage depends, the investment in devices to control pressure, such as pressure reducing valves, variable speed pumps and micro-turbines, might be an efficient measure to reduce leakage occurrence.

REFERENCES

(1) BILLMAN, L.; ISERMANN, R.. – Leak Detection Methods for Pipelines. Automatica, Vol 23, No. 3, 1987 (pp. 381-385)

(2) CABRERA, ENRIQUE; VELA, ANTONIO F. - Improving Efficiency and Reliability in Water Distribution Systems. Water Science and Technology Library. Valencia, 21-25 November 1994.

(3) CABRERA, ENRIQUE; MARTINEZ, F. - Water Supply Systems. State of Art and Future Trends. Valencia, 19-23 October 1992.

(4) CHILTON, R. - Water Pipeline Systems - Leakage Management, Network Optimisation, and Pipeline Rehabilitation Technology. BHRGroup Conference Series,Pub.No.23, 1997.

(5) COULBECK, BRYAN - Integrated Computer Applications in Water Supply - Volume I - Methods and procedures for systems simulation and control. Research Studies Press, 1993.

(6) COVAS, D. - Leaks' detection and location in water distribution networks - Hydrodynamic Analysis's Method (MSc thesis in Portuguese). Lisbon, July 1998.

(7) COVAS, D.; ALMEIDA, A.B.; RAMOS, H. - Leaks' Detection and Control for a Better Environment. BHrGroup Publication 30. 1st International Conference on Protecting the Environment - in Process Industry.Rome, Italy, 11-12 Maio 1998.

(8) COVAS, D.; RAMOS, H. - A Utilização de Válvulas Redutoras de Pressão no Controlo e Redução de Fugas em Sistemas de Distribuição de Água. VIII Encontro Nacional de Saneamento Básico, Barcelos, 26-30 Outubro 1998.

(9) FURNESS, R.A.; REET, J. D. - Leak detection - chapter 17 of the book: Pipe Line Rules of Thumb Handbook - Manual of quick, accurate solutions to everyday pipe line problems. E.W. McAllister, Editor.Third Ed. 1997

(10) HRLimited - Cost-effective Management of water pipelines & networks. Mayfair Conference Center, London, 24th & 25th January 1996.

(11) LNEC - Caracterização das Origens de Fugas e Outras Perdas na Rede de Distribuição de Água. Departamento de Hidráulica do LNEC. Lisboa, Agosto 1994.

(12) RAMOS, H.; COVAS, D. - Aproveitamento da Energia em Excesso em Sistemas de Abastecimento de Água. VIII Encontro Nacional de Saneamento Básico, Barcelos, 26-30 Outubro 1998.

(13) RAMOS, H. COVAS, D.- Pressure Reducing Valves and Micro-Turbines for Leakage Control in Water Supply Systems. " Manutenzione on industrial plans". Bologna, February 1999

(14) UNIVERSITY OF LIVERPOOL - Managing of Water Distribution and Leakage Control. Course developed between 27th April to 1st May, 1998.

(15) WRC - Water Industry: Managing Leakage. Engineering and Operations Committee. October 1994. Reports A to F.