

Saving the World's Most Precious Resource

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1. Introduction

Water is probably the world's most precious natural resource. Without it, there would be no life. It's sad then to think that so many people already live with less than their daily needs and that this situation is predicted to get even worse. In fact, according to an UN assessment, by 2025, around two-thirds of the world's population will have insufficient supply.

The traditional solution to a water shortage problem has been to develop new sources. But as the easily extractable ones have already been exploited, this quest is becoming increasingly difficult. Little wonder then, that even London, the capital city of what is considered to be one of the wettest countries in the world, is turning to desalination as a solution. Not only is this very expensive, but it is has a huge environmental impact. Furthermore, it addresses just the consequence of the problem and not its root cause, which invariably relates to inefficiencies.

So why then, has such a disastrous situation arisen in the first place, particularly when the water utility personnel is amongst the most dedicated of any industry? The answer lies in the traditional approach to water network management, where the objective was not necessarily to improve efficiency, but to ensure that the customers had some supply for a part of the time. Unknowingly, the leakage level was increasing, probably because only a small proportion of leaks ever come to the surface. As the reservoirs ran dry, water was rationed, making things even worse. In some cities water supply is counted in just a few days of the week. The answer appears obvious: reduce the losses. So why is this not done? Probably because the solution is not as easily defined as the problem itself.

2. Water balance

In its simplest definition, water loss is the difference between the total production and total consumption. However, there is a lot more to it than this, as the International Water Association's (IWA) standard water balance, (reproduced below in Figure 1), shows.

The loss is composed of two main components: commercial (or apparent) and physical (or real). The former comprises inaccurate measurement and illegal use, whilst the latter includes leakage from the reservoirs and from the supply and distribution network, including service pipes.

Commercial losses is often thought to be the main cause of water loss, probably because of the impression given by images such as the one in Figure 2, where numerous customer service pipes are illegally tapped into the distribution network.

System input volume (corrected for known errors)	Authorised consumption	Billed authorised consumption	Billed metered consumption (including water exported)	Revenue water
			Billed unmetered consumption	
		Unbilled authorised consumption	Unbilled metered consumption	Non-revenue water (NRW)
			Unbilled unmetered consumption	
	Water losses	Apparent losses	Unauthorised consumption	
			Customer metering inaccuracies	
		Real losses	Leakage on transmission and/or distribution mains	
			Leakage and overflows at utility's storage tanks	
	Leakage on service connections up to point of customer metering			

Fig. 1. IWA Water Balance



Fig. 2. Illegal customer connections

A more detailed study, rather than a subjective observation, has shown otherwise, with leakage representing around 80% of total water loss. This is not surprising when it is considered that a typical leak is between 500 and 1000 times greater than the average consumption of a domestic property. Furthermore, the cost of recovering much of the commercial loss is often uneconomic.

Leakage from reservoirs is usually visible and as the number of such structures in a network is limited, it is considered less problematic and more easily checked and recovered. Leakage from the network on the other hand, is a different proposition, not only because the pipes extend for hundreds and thousands of kilometres and are almost all buried, but mainly because only a small proportion of leaks are visible. This is due to many factors, including the ground conditions and the location of other services such as sewers, in the vicinity. So finding leaks in such circumstances is quite literally a needle in a haystack problem and probably explains why leakage is so high all over the world, with values often exceeding 50% of production.

It is clear that to undertake a proper water balance, it is first necessary to collect a lot of detailed information about the flows and consumptions. Unfortunately this is not always available. Even if it were, such an assessment inevitably ends up being a long term one, normally annual, which means that an invisible leak might run for a long time before its consequence is detected. What is needed then, is a more immediate and precise way of quantifying leakage – one that is not subject to measurement errors. This is precisely the reason the minimum night flow approach was developed. It is based on the principle that as the customer consumption is usually very low at night, the flow into a network at that time corresponds almost entirely to the leakage. Not only does this allow a more accurate assessment, but it also enables a daily check to be performed. As headloss and consequently the operating pressures, are directly related to the flow, it follows that at night, the pressures will tend to be higher, causing leakage to increase. Care is therefore needed when extrapolating the night time value to an average one.

Having derived the leakage level from the water balance, it is necessary to interpret the result. Traditionally, leakage is expressed as a percentage of the inflow. However this gives no indication of the quantity being lost, the area it covers nor how difficult it will be to recover. To overcome this, it has been suggested that leakage is expressed either in terms of the customer connections (l/connection/day) or in proportion to the extension of the network (l/km/hour). The former is better suited to urban areas, whereas the latter is more universally applicable and has the advantage of being directly related to the effort needed to recover it. The IWA Water Loss Specialist Group also propose the ILI (International Leakage Index) as a performance indicator, which relates the existing leakage to a minimum or unavoidable value, with 1.0 representing the optimum. There are some doubts though over the validity of accepting a minimum level for leakage other than zero, and how this value is defined.

The real answer though, lies in considering leakage not as a technical parameter, but as an economic loss, caused by treating and pumping water that never reaches the final customer. To recover it requires an economic investment, which increases significantly if very low leakage levels are to be attained. It follows therefore that there will be an optimum balance between investment on the one hand and savings on the other, which will vary from

network to network. Finding this point is the objective of the EU-funded PALM project which is currently being developed in Perugia, central Italy.

3. Optimum leakage level

A water network typically evolves in response to the growing needs of the population that it serves. Surface sources are often the first to be exploited. Then as the demand exceeds supply, a new and more expensive resource has to be developed, usually by tapping underground aquifers. As more and more water is extracted, the available resource risks becoming depleted and contaminated, leading to even more costly treatment and pumping. In extreme cases, particularly when the existing sources are unable to satisfy demand, desalination has to be introduced, which is very expensive and environmentally unfriendly due to the huge energy requirements of the process.

Reducing leakage will halt this viscous circle. When leakage is lowered, it is possible to optimise the production, by both extracting less from the most costly sources and exploiting lower electricity tariffs to fill the reservoirs at night. This offsets the initial cost of the intervention. The objective of the PALM (Pump And Leakage Management) project is to find the optimum leakage level for every network.

The project, which is based in Perugia in central Italy, is co-financed by the EU's LIFE Programme and involves experts from three international companies, some of which having a long and distinguished experience in leakage control. The water network of Perugia is currently managed by Umbra Acqua SpA. which is part of the ACEA group in Rome and was chosen for its complexity (2 spring sources, 3 wells, 20 reservoirs and over 100 pumps) and the long experience of controlling leakage which exists there.

The definition of the optimum level of leakage is obtained by the creation of the "Efficiency Calculator". This will be a freely available web-based software, where the main characteristics of the network will be inserted and an assessment made of the scope for reducing leakage. The key data required include the following:

- Current production volume;
- Customer consumption volume;
- Characteristics of the sources;
- Characteristics of the pumps;
- Capacity of the reservoirs;
- Length of mains;
- Energy costs;
- Treatment costs;
- Intervention costs;
- Cost / m³ of developing new sources in the case of intermittent supply or insufficient current production.

It is recognised that the records of the water utilities are often incomplete and rarely up to date. One example of this, is with the pumps. Even if the characteristic curve is available, it invariably refers to the operation of the pump when it was new and not to its current performance which deteriorates over time. Consequently a typical wear factor will be applied which will be derived from the testing in Perugia. In addition, the flow resulting

from a combination of pumps is lower than the sum of the single units. Again, a typical factor will be derived. Few water utilities have detailed information about the cost of creating a permanent leakage control system and locating and eliminating the leaks. The Perugia network will be used to collect this information, supplemented by data derived from other projects undertaken by the partners.

The Efficiency Calculator is a DSS which compares the cost of reducing leakage with the economic benefit obtained from improving the efficiency of production. It works by integrating the network's cost / recovery curve for reducing leakage with the system cost / production curve to determine the quickest return on the investment.

Although the input data will be kept to a minimum, it will still be sufficient to provide a realistic evaluation of the situation, particularly with the application of the factors derived from Perugia and elsewhere.

The Efficiency Calculator is a tool for Water Utilities and Regulators alike, which aims to set realistic targets for improving the efficiency of a water network, as opposed to the often arbitrary percentage values which are used today. Once the target has been set, it is then necessary to achieve it, by locating the leaks. This is by no means as straight forward as it might seem, particularly as it involves finding breakages a few millimetres wide in underground networks hundreds of kilometres long.

4. Leakage control

A leak in a pressurised system generates a noise. This is the operating principles of acoustic instruments, developed specifically to locate invisible leaks. They comprise correlators, noise loggers and ground microphones which can "listen" to the noise of the leak. They have been successfully applied all over the world to accurately detect hidden leaks, provided that the knowledge of the network is good, the leak generates sufficient noise and that the pipe has good noise propagation qualities. This means that a pinhole leak in a metallic pipe subjected to high pressures is more easily detected than a split in a plastic pipe operating under low pressures. Special sensors have been developed which can be inserted through hydrants or other fittings, which improves the distance over which the noise can be detected, particularly for non-metallic pipes. However, locating leaks on such pipes is still a severe limitation of the acoustic methodology in much the same way as denying fuel is to a thoroughbred engine.

The unfortunate reality is that very few water utilities have accurate and up-to-date maps showing the characteristics of the network. Even when the knowledge is complete, to blanket survey the network is highly inefficient and not always an entirely successful exercise either, as a new leak can easily appear following the repair of a previous one. What is needed then is to be able to quantify the extent of the leak and target more precisely the detection activity with the acoustic instruments, to just the leaky pipes. This is the motivation behind the development of the District Meter Areas (DMA) methodology.

The chances of finding a lost personal item is much greater if the search is directed to just one room of a house rather than the whole town. The same principle applies to locating leaks. The key is to divide the network into a number of sectors called DMAs, in which the inflow is permanently monitored so as to immediately identify the presence of a new leak

and allow its rapid location. This is achieved by permanently closing the boundary valves and preferably supplying the DMA from a single pipe on which is installed a flow meter. An example of the division of a network into DMAs is shown in Figure 3 where the different colours refer to the degree of leakage.

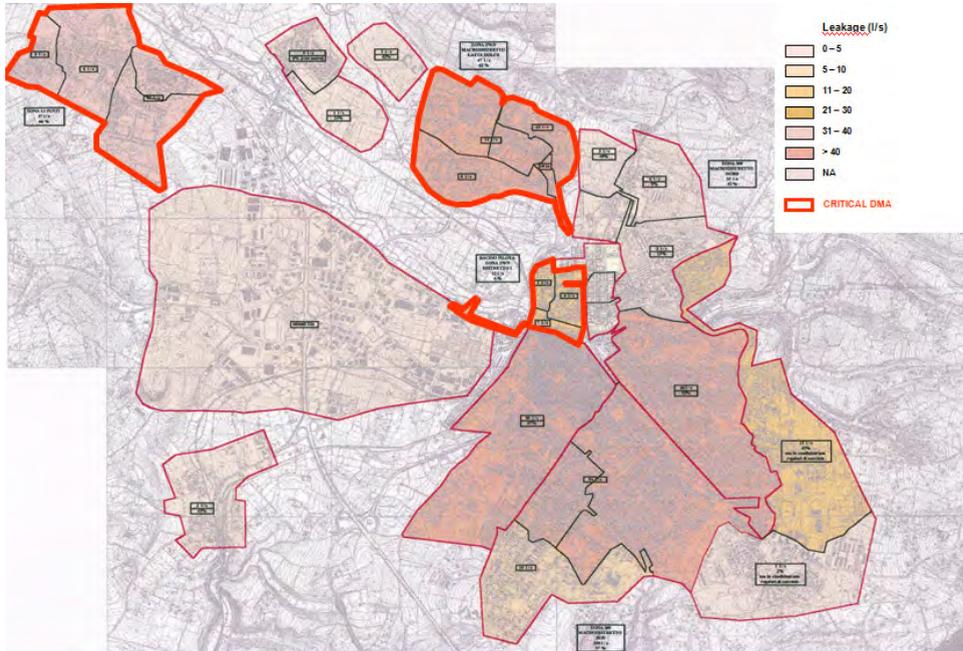


Fig. 3. Division of a network into DMAs with the critical one highlighted with a red boundary

To simplify the detection activity even further, a night step test can be performed which involves progressively isolating the DMA network. The reduction in flow following the closure of each area or step, corresponds almost directly to the leakage in the isolated pipes. This approach is also useful to verify the accuracy of the maps and identify previously unknown connections. To be effective, the test does require efficient line valves.

One significant advantage of a single supply pipe to the DMAs is that it allows a more accurate measurement of the flow than would otherwise be possible with multiple feeds, particularly cascading ones. In some situations, such as for fire fighting requirements, it might be necessary to have a reserve supply, preferably controlled by a hydraulic valve, which would open only in case of an emergency. An added benefit is that a pressure control system can be created by installing a pressure reducing valve (PRV) downstream of the flow meter, without risk of generating undesirable oscillations that might otherwise occur with multiple inlets. In this way, it is possible to maintain the optimum pressure in the DMA at all times.

Leakage is directly dependent on pressure. The higher the pressure, the higher the leakage. Experience has shown that unlike the theoretical exponential relationship derived from assessing a round orifice in a metallic pipe, in a real network it is almost linear. This

difference is thought to be due to non-homogenous pipe materials and varying breakage sizes. As the network pressure is dependent on the flow, it follows that higher pressures are likely at night when the consumption is a minimum, leading to increased leakage. This means that there is often considerable scope to lower even further the night-time pressure, to recover some of the leakage. This can be done either by installing a twin-pilot PRV, controlled by a timer, or in more sophisticated installations, to relate the downstream pressure of the PRV to the flow through the DMA meter. In addition to lowering the existing leakage level, it has been shown that a PRV also reduces the burst frequency, allowing a lower leakage level to be maintained for a longer period of time.

There are many successful applications of the permanent leakage and pressure control systems all over the world, and the results have been very positive. The difficult always relates to creating the optimum single inlet configuration without affecting the standard of service to the customers. The answer is found in the application of a fully calibrated hydraulic model.

5. Hydraulic model

A hydraulic model accurately simulates the operation of the real network in all of its key features. It is therefore a very powerful tool, not only to understand the current system operation, but also to design the optimal configuration of a network. As such, it is the key to dividing a complex water system into DMAs. A model is composed essentially of nodes and arcs; the former representing the junctions and the latter the pipes as shown in Figure 4.

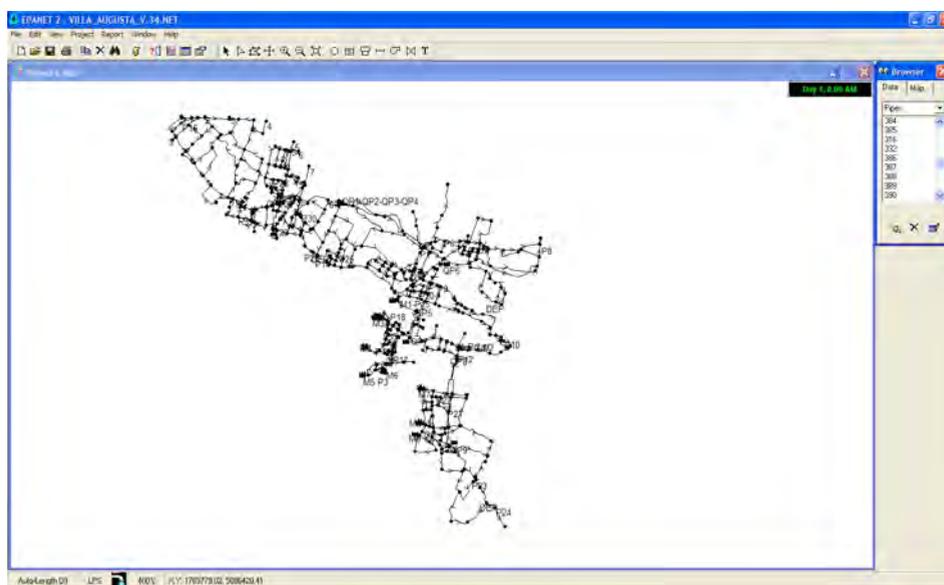


Fig. 4. Typical structure of a hydraulic model

Consumption is assigned to the nodes and ideally should be classified into the key customer categories, to which are associated typical demand profiles representing the daily variation

of consumption. Water loss should also be assigned a separate demand category to allow the assessment of a reduction in leakage on the overall network operation. An essential part of creating a hydraulic model, is to verify its accuracy. This is undertaken by comparing the pressures and flows calculated by the model with those measured in the field. Any differences indicates an error in the historical knowledge and should be investigated and resolved. Anomalies typically relate to an unknown status of line valves, with throttled or fully closed valves being particularly prevalent.

Undertaking a field monitoring exercise can be a costly operation as it requires the contemporary installation of a significant number of data loggers, pressure transducer and portable flow meters. However, to limit or even avoid completely this activity, represents a false economy, particularly when compared with the cost of an erroneous design derived from an incorrect model. Only after the model is confirmed to accurately represent the reality and all the important anomalies have been resolved in the field, can it be applied with confidence to the design of the optimum DMA boundaries. This is particularly important in networks having low operating pressures, which invariably have a high leakage level in the first place and represents a classic chicken and egg situation: leakage causes low pressures; leakage cannot be recovered without first dividing the network into DMAs; dividing the network into DMAs tends to lower the operating pressures. A well calibrated hydraulic model solves this vicious circle. By identifying the pipes having little or no hydraulic importance which can therefore be closed, the current level of the service to the customers can be maintained even with a single supply pipe.

The model can also be used to assess how the DMA design will operate with future consumptions and to define a pressure control system. In fact, it is very useful to determine the critical customer, the optimum position and correct size of the valve so that it doesn't cause operational problems in the future.

The application of hydraulic modelling for the design of DMAs is still not particularly common. This is unfortunate and severely limits the creation of permanent leakage control systems. Part of the reason is the mistaken idea that to build a model, first it is necessary to have perfectly accurate data. This is not the case, as the calibration of the model acts as a check of all of the historical information used to build it. In fact the verification of the model highlights where the historical knowledge is incomplete or incorrect. As such, it is an extremely powerful tool, which can be applied for most if not all of the design, management and maintenance activities regarding a water network.

Once the design has been defined with the model, it is possible to create it with confidence in the field. It is necessary to ensure that all the boundary valves are operational and the inefficient ones are replaced. A check should be carried out to ensure that there are no unknown connections which could falsify the monitoring. The flow meter on the inlet pipes needs to be installed and commissioned, coupled where possible to a PRV.

The creation of DMAs does not in itself reduce leakage, although the reduction of pressure will be beneficial. What it does, is allow the identification of the leakiest parts where a detection activity should be targeted. It follows therefore, that it is essential to manage diligently the DMAs, which when undertaken manually can be a laborious, repetitive and time-consuming activity. For this reason it is preferable to automate the process. This is the object of the EU funded project called Autoleak.

6. Optimum management of DMAs

The division of the network into DMAs allows a constant control to be kept on the situation at all times. In most cases, this involves simply checking the minimum night flows to see if there has been any variation. The flow data can be transmitted daily to the control room thanks to the deployment of simple, low cost GSM data loggers. Despite all of this, leakage levels are still higher than optimal in many of the world's water network. Most surprisingly perhaps, is that this even applies to networks where DMAs have been constructed. The question is why?

The answer can be found in the repetitiveness of the manual process and the lack of priority given to maintaining a low leakage level. The solution is to automate as much as possible, preferably by relating the leakage to the economic loss and environmental impact. This is the objective of the Autoleak project funded by the ECO-INNOVATION programme of the European Union.

As the name implies, Autoleak aims to automate the process of managing leakage by integrating readily available technology. For instance, it combines the flow from the DMA meters transmitted by GSM loggers, with the customer consumption, to determine daily the leakage level. It then introduces the historical information regarding the minimum leakage level, past interventions and the production cost of the water in each DMA to define the typical cost of the intervention and the likely benefit.

Leakage is like hair: if not cut regularly, it just keeps on growing. This process is clearly seen in Figure 5 and is termed the natural rate of rise of leakage and is determined in Autoleak from the historical data for each singular DMA.

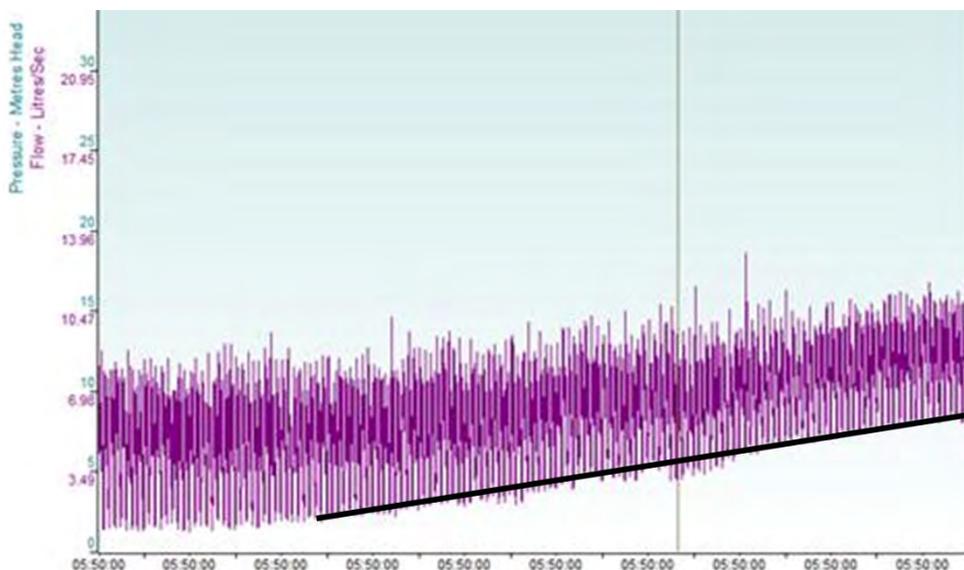


Fig. 5. The natural rate of rise of leakage can be seen from the steady increase in the minimum night flow.

As a result, it is possible to predict the duration of the recovery and hence the total value of the recovered water. This can be compared with the estimate of the cost of intervention which again is based on historical information for the DMA. If the value of the recovered water (V) is greater than the intervention cost (X) then it is worthwhile reducing the leakage. The mechanism is shown graphically in Figure 6.

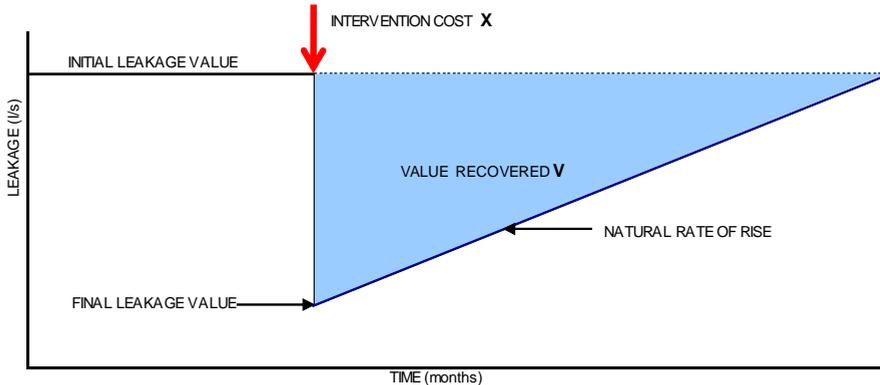


Fig. 6. Operating mechanism of Autoleak where an Intervention (red arrow) will yield a benefit (blue triangle)

Autoleak is notable for its innovative approach to managing DMAs which exploits and integrates existing and readily available technology with a self-teaching mechanism. It can be configured for different degrees of sophistication, ranging from the minimum night flow analysis to full integration with Automatic Meter Reading systems (AMR). This last aspect, which probably represents the maximum expression of today's technology, can be used also to gather information from noise loggers which are permanently positioned in the network and communicate the position of a leak without having even going out on site.

In addition to the economic evaluation, Autoleak will also determine the environmental benefit from recovering the leaks. Water is often considered to be one of the cleanest and purest of the earth's natural resources. This does not take into consideration however the significant environmental impact of pumping and treating water which is then lost. This aspect is likely to become an important issue in the future.

7. Conclusions

The world is already facing an acute water crisis and in the coming years it is predicted to get even worse. One important contributing factor is the losses from water supply and distribution networks which can often exceed 50% of the production. Such a contradiction might be hard to comprehend, particularly when it relates to probably life's most important natural resource. But the number of water networks in the world subjected to intermittent supply is ample testimony to the seriousness of the situation. It begs the question then, why is nothing done about it.

The answer is complex and relates mainly to the 'out of sight out of mind' mentality which is so prevalent in water utilities all over the world. If however a simple water balance was

undertaken, the reality would quickly become apparent. Relating the results to the economic loss, would show a very rapid payback period on the investment needed for the intervention. Thanks to an innovative decision support system, developed as part of the EU-PALM project, such an assessment is now a reality.

But even if it was worthwhile economically to do something about the leakage, what is the solution? The classic answer would be to replace most of the pipes, on the basis that they are old. But this is far from the optimum approach which is to identify and fix what is broken. This is achieved by applying a step by step approach which involves dividing the whole network into sectors, called District Meter Areas (DMAs), supplied by a single pipe on which is installed a flow meter. In this way it is possible not only to identify immediately the presence of a leak, but know in which part of the network it is located.

A broken pressurised pipe generates a noise. By applying specially developed acoustic instruments, it is possible to accurately locate the position of an invisible leak. The area of application of these instruments can be further restricted by isolating at night the DMA network during a step tests to identify the leakiest pipes, allowing an almost instant recovery of the leak.

The key to maintaining a low leakage level in a water network is to reduce the frequency of failure. An important contribution to achieving this goal is provided by the permanent control of pressure through the installation of pressure reducing valves (PRV). The single supply to each DMA not only allows the optimisation of the system by avoiding potentially damaging pressure oscillations which might otherwise occur with multiple feeds, but lowers the night operating pressure to reduce even further the leakage level.

The reality of water networks in many parts of the world is that the information regarding them is often incomplete and out of date. Probably, for this reason, leakage is such a problem in the first place. It does make dividing the network into permanent districts, by the closure of line valves, all but impossible. The solution is found in the application of a fully calibrated hydraulic model which simulates the real network in all of its key features. In this way, by first eliminating the previously unknown anomalies, it is possible to define the optimum DMA boundaries which when constructed will not affect the existing quality of the service to the customers.

The creation of DMAs has in itself little impact on the leakage level, but is the key to resolving the problem. What it does, is to allow the situation to be kept permanently under control, so that when a new leak breaks out, its size and position is easily identified. The difficulty is that if undertaken manually, this constant checking becomes tedious, repetitive and time consuming activity which ends up eventually being neglected. Inevitably the leakage level starts to climb again. The solution is to apply a Decisional Support System which automatically evaluates not only the current leakage level and assesses how much can be recovered, but from historical data, can predict the future trend so as to quantify the total potential saving and compare it with the likely cost of the intervention. The innovative Autoleak system, developed as part of an EU-financed project, represents such a system.

With the application of the latest technology, including hydraulic modelling and Decision Support Systems, it is feasible to not only lower significantly the existing leakage levels in water networks around the world, but just as importantly, maintain a low level in the future

– all for a relatively low investment. This will contribute to alleviating the severe water crisis that the world is already facing, the solution to which must start from a more efficient use of the available resource.

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