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Defining the rehabilitation needs of water networks

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Abstract

High losses in water distribution networks can cause inefficiencies due to the unnecessary expense of pumping and treating water which never reaches the customer. Excessively low losses can be inefficient too because the investment required can exceed the benefit. The optimum leakage level for any water network varies from network to network and is the objective of the PALM+ system. By applying PALM+ it is possible not only to determine the optimum leakage level, but quantify the rehabilitation investment necessary to achieve it. It is applicable also to networks subjected to intermittent supply and has shown remarkable accuracy.

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1. Main text

1. Introduction

Water shortages is becoming an ever common occurrence. It is estimated that 1.2 billion people in the world\textsuperscript{[1]} - the equivalent of four times the current US population - lack access to clean water and the situation is predicted to worsen. Nowhere is this shortage so evident than in water supply and distribution networks, where the flow is regularly interrupted just because demand exceeds supply. This is not a problem that afflicts just the developing countries either; southern Europe, UK and even the US have similar problems as witness most recently in the State of California\textsuperscript{[2]}.

It is commonly thought that these shortages are caused either by insufficient rainfall or wasteful and illegal use. However experience has also shown that an important contributing factor is leakage from the distribution network.
When it is considered that even a small leak is equivalent to the average consumption of a 100 domestic properties, and that it runs 24 hours a day, 7 days a week, the scale of the problem becomes evident.

Water is available typically in natural spring sources and rivers or in large underground aquifers. In the case of the former, the quantity tends to be seasonally variable and can be quite unreliable. The latter needs a lot of pumping, not only to extract the water, but to supply it to the higher ground. Both need treatment to ensure that it is healthy to drink. When up to 50% is then lost through burst pipes, it can be readily appreciated the huge economic and environmental impact that this causes.

If leakage is a major problem, why isn’t more done to reduce it? The answer lies largely in the saying: ‘out of sight, out of mind’. The simple truth is that very few leaks actually come to the surface. Mostly the water is carried away in adjacent sewers or other utility pipes. Unless an active attempt is made to look for them, the situation rapidly gets out of hand. It is not surprising either as locating a leak means identifying a small hole a few millimeters wide in hundreds of kilometers of pipes. The answer lies in dividing the whole into parts, called districts[3] as illustrated in Figure 1, each permanently created and ideally supplied by a single pipe on which is installed a flow meter. In this way it is possible not only to quantify daily the leakage level, but identify immediately the presence of a new leak and where it is located.

Dividing a complex and interconnected web of pipes which forms a water network, is not an easy task. If not undertaken with care, it could result in lowering the quality of service to the consumer. The solution is found in the creation and calibration of a mathematical model which simulates the real network in all of it key characteristics, including pipe diameter, length and connectivity, customer consumption, leakage, pumps, reservoirs and valves. In this way, the optimum configuration can be determined even before the districts are created in the field to virtually eliminate any service problems that this might entail.

Once a leak is identified and the part of the network where it is located is known, the problem of locating it precisely persists, particularly as in all likelihood it will be invisible on the surface. The solution is found in an important characteristic of a leak in any pressure system – the noise that it generates. By installing sensitive
microphones on the pipe, it is possible to detect it. Correlating the same noise from more points, the precise location can be accurately determined.

Lowering leakage is one thing; maintaining a low level quite another. It helps of course that with the district flow meters the current leakage level can be determined daily and any leaks can be located by deploying the acoustic instruments in the worst districts. But hydraulic theory, backed up by experience in the field, shows that once a leak is repaired, the chances are high that the next weak spot of the pipe will break, negating all of the benefit. The reason is pressure. Generally, the higher the value, the higher the leakage, and vice versa[4]. But there is a secondary effect which is very important and that is the phenomenon most commonly called water hammer, which derives from a rapid change in the flow conditions and hence the velocity, leading to dangerously high and low - even negative – pressures, all within the space of a fraction of a second. This mechanism is what breaks the pipes and should be avoided. The solution is to install a pressure reducing valve on the inlet to the district. In this way it is possible to reduce the pressure to lower the leakage level and at the same time protect the network.

2. Optimal Leakage Level

So if high leakage is so harmful, why is more not done to reduce it? The answer is complex and relates to a lack of awareness, knowledge and priority within Water Utilities. Even the way losses are assessed is unhelpful. Typically leakage is considered a technical element which is most commonly expressed as a percentage of the production, a flow per customer connection or compared to a theoretical minimum such as is the case with the IWA promoted ILI (International Leakage Index)[5]. All are flawed, because they fail to take into account the economics - the cost of the intervention and the benefit it yields. Two nominally identical networks, one supplied by an elevated spring source of almost mineral water quality, the other supplied by a contaminated river which has to be treated and pumped into the network, would have the same technical index but vastly differing economic target levels. This is the basis of the innovative PALM+ system which is a heavily modified version of the algorithm originally developed as part of an EU funding program and co-financed by the Italian Ministry of the Environment[6].

The situation is similar to what home owners faces when deciding to installing solar panels. There is an initial investment which should be compensated for by the annual saving it yields. The same is true with leakage. Lowering it requires investment to find and eliminate the breaks, which will result in lower production costs. The key is to find the optimum point – not too low which makes the investment excessive for the returns; not too high which will keep the network operating inefficiently. Furthermore, the optimum will vary from network to network and potentially from year to year. If the cost of producing the water is high, a much lower leakage level is justifiable. If the cost of producing the water is low, then a higher leakage could be tolerated. But if the energy costs increase significantly, or the yield of a source reduces drastically, then the optimum leakage level will change. This is exactly what PALM+ is capable of assessing: the target leakage level for any water network based on the individual network characteristics.

3. PALM+ System

PALM+ is a decisional support tool which allows the optimum leakage level of any network to be determined. By just inserting the readily available key characteristics, it derives the unique production/cost and the intervention/cost curves, which when normalized, the minimum point of the combined curve defines the optimum production level. By subtracting the consumption and any exports, it yields the optimum leakage level. In this way, it is possible not only to determine whether it is worthwhile intervening, but to estimate the investment cost and typical payback.

PALM+ is based on data collected from well over 50 projects undertaken in many parts of the world in lowering and controlling losses from water networks, involving hydraulic modelling, design of permanent leakage and pressure control systems and the location and repair of leaks. The costs and benefits of all activities was assessed and parameterized. As a result, PALM+ is capable of taking into consideration such diverse elements as the loss of efficiency of pumps due to wear and their combined operation, the error in the declared length of network, typical accuracy of customer meters, manpower and equipment required to create the DMAs and eliminate leaks, reduction in maintenance costs due to the lower burst frequency and the effort required to maintain the target leakage level in the future.
Simply by inputting the main characteristics of the network such as the sources and their production, the operating point of the pumps, length of the network, consumption of the customers, electricity costs, reservoir capacity and typical labor costs, it can derive the unique production and normalized intervention costs curves as shown in Figure 2.

![Figure 2. Economic basis of the PALM system](image2)

To test the accuracy of the predictions of PALM+, an analysis was undertaken on a network in northern Italy where a water loss reduction and control project had just recently been completed. Full and detailed data was available not just of the cost of the project, but also of the benefits. It should be noted that this network did not have a high initial leakage value and the cost of producing the water was low. The results are shown in Figure 3 and confirm the surprising accuracy of the system.

![Figure 3. Typical output from the PALM system](image3)

PALM+ predicted an optimum leakage level equivalent to 19.2% - almost exactly the final project value of 19%. More remarkably perhaps was that the estimated intervention cost of €1.07 million was almost identical to the real value of €1.11 million. The payback was just over 5 years. As evident in Figure 4, the PALM+ output compares the actual with the most efficient situation and estimates the rehabilitation costs and compares them with the predicted annual savings.
Defining the economic or sustainable level of leakage has traditionally involved determining the intensity of the leakage detection activity by varying the number of leakage location teams without necessarily considering the cost of rehabilitating the pipes nor the potential variability of the sources of production\cite{7}. To separate these elements which are inherently interconnected, is an over simplification which can lead to potentially costly errors in the final evaluation. For instance, an insufficient production capacity could be caused not just by an increase in demand but by an excessively high level of leakage.

PALM+ on the other hand takes into consideration all of these components, including the various options for reducing leakage (DMAs, pressure management, leakage detection and repair, pipe replacement) to arrive at the most efficient solution. By compiling 5 simple modules as illustrated in Figure 5, it is possible to define the optimum approach, assess its viability and verify the sensibility of the result – something that even the most experienced Water Loss Specialist was previously unable to do satisfactorily and with any degree of confidence.

Another valuable feature of PALM+ is the ability to not only assess the likely cost of achieving an even lower – and hence less economically optimum – target leakage, but also assess what level is possible with a more limited budget to the one required to achieve full efficiency.

4. Intermittent Supply Conditions

When the production is less than the demand, the service reservoir will run dry causing what is referred to as intermittent supply conditions. This is a very common occurrence in many parts of the word, most notably southern

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**Figure 4. Results from trial network**

<table>
<thead>
<tr>
<th>Actual</th>
<th>Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>production (M m$^3$/year)</td>
<td>15.99</td>
</tr>
<tr>
<td>outflow (M m$^3$/year)</td>
<td>9.33</td>
</tr>
<tr>
<td>consumption (M m$^3$/year)</td>
<td>4.34</td>
</tr>
<tr>
<td>technical loss (M m$^3$/year)</td>
<td>2.10</td>
</tr>
<tr>
<td>commercial loss (M m$^3$/year)</td>
<td>0.22</td>
</tr>
<tr>
<td>total loss (M m$^3$/year)</td>
<td>2.32</td>
</tr>
<tr>
<td>total loss (%)</td>
<td>34.85</td>
</tr>
<tr>
<td>total loss (l/s/km)</td>
<td>0.17</td>
</tr>
<tr>
<td>leakage recovery (M m$^3$/year)</td>
<td>1.04</td>
</tr>
<tr>
<td>energy cost (M €/year)</td>
<td>0.73</td>
</tr>
<tr>
<td>maintenance cost (M €/year)</td>
<td>0.30</td>
</tr>
<tr>
<td>intervention cost (M €)</td>
<td>1.07</td>
</tr>
<tr>
<td>economic saving (M €/year)</td>
<td>0.20</td>
</tr>
<tr>
<td>TOE/year</td>
<td>61.24</td>
</tr>
</tbody>
</table>

**Figure 5. Data Input modules**
Europe and most developing countries. To ensure that all of the customers get some supply most of the time, the situation is usually managed with considerable effort by the water utility staff.

The blame is normally attributed to wasteful or illegal consumption, but the real cause is invariably excessive leakage. Ironically, isolating parts of the network in this way, though lessening the consequence to the customers, actually ends up aggravating the cause. This is because of the effects of water hammer. Large pressure peaks and troughs – sometimes negative – can have catastrophic effects on the structural integrity of the pipes leading to an increase in the already high leakage level. To limit the impact on the quality of service, most customers install tanks which store the water to cover the period of interruption. The effects of intermittent supply is usually masked by the simplistic way in which losses are normally determined, involving no more than subtracting the consumption from the total input volume, without considering the fact that the customer consumption will cover a 24 hour period, whilst the leakage will only be for the duration of supply.

Experience in southern Italy[8] has shown that if the period of supply covers at least half of every day, it is economically feasible to return to continuous supply simply by eliminating the largest leaks. In more extreme cases, such as those found in India, where the period of supply can be as little as a few hours per week, the same approach might not be viable without also increasing the production capacity. Furthermore, the creation of a permanent leakage and pressure control system becomes virtually impossible without first increasing the hydraulic capacity of the network.

PALM+ takes all of these factors in to consideration. It determines an equivalent leakage level based on a hypothetical 24 hours supply achieved through the creation of additional production capacity and then applies the algorithm to determine the optimum solution. Applications of PALM+ in such conditions have shown that the most efficient solution is a significant reduction in leakage coupled to the creation of some additional production capacity, thus showing that total replacement of the network to achieve a hypothetical zero leakage is not economically viable. PALM+ is also capable of assessing the sustainability of the most efficient solution by determining the average tariff increase that the investment will entail.

5. On-Going Application of PALM+

PALM+ is applicable for many aspects of water network management, most notably the following:

- Assess the current situation of the network and determine whether it is economically viable to intervene to reduce losses;
- Define the target leakage level;
- Quantify the investment necessary to achieve the target level and determine the likely annual saving in production costs;
- Prioritize the investment between supply systems and sectors.

It is clear though that any change such as an increase in electricity tariff, cost of labor or a reduction in the availability of a source will impact the target leakage level. It is necessary therefore to reevaluate the PALM+ assessment accordingly. This can be achieved with the updating feature which will recalculate the unique system production and intervention curves and potentially change the prioritization of the sectors. This approach has been extended through the PALM+ Control feature to also the continuous management of DMAs at their optimum economic level.

6. Conclusions

The world is already experiencing an acute water crisis and in the coming years it is predicted to get even worse. One important contributing factor is the loss from water supply and distribution networks which can often exceed
half of the production. Such a contradiction might be hard to comprehend, and begs the question; why more is not done about it? The answer is complex and relates mainly to a mentality prevalent in water utilities all over the world, that because the leaks are invisible, they don’t actually exist. If however a simple water balance was undertaken, the reality would quickly become apparent. Relating the results to the economic loss would typically indicate a very rapid payback period on the investment needed for the intervention. Thanks to an innovative decision support system, called PALM+, such an assessment is now a reality.

The PALM+ system is capable of defining the optimum economic leakage level of any network, irrespective of its unique characteristics. By compiling 5 simple modules, it is capable of defining the production/cost and intervention/cost curves for the system and hence define the optimum leakage level, how much the investment will be and the benefit it will yield. This system is already being used in northern Italy to define and prioritize the investment requirements which are then applied to determining the average tariff paid by the customer and its application is expected to grow.

Intermittent supply is a condition which afflicts many of the world’s water supply networks. It’s origins are invariably linked to an excessive level of leakage, which the continuous opening and closing of the line valves exacerbates due to the damaging effects of water hammer. PALM+ is capable of assessing the most appropriate and economically viable solution which could involve simply reducing leakage or in more extreme cases linking it to the creation of a new production capacity.

Achieving the optimum leakage level is one thing; maintaining it quite another particularly in highly dynamic systems like water networks where the customer consumption, resource availability – even the electricity tariff – is frequently changing. This becomes feasible with the application of Decision Support Systems such as PALM+ Control. In addition to yielding significant economic savings, it will lower the huge environmental impact of treating and pumping water which is then lost before reaching the tap as well as ensuring that the customer is not required to pay for inefficiencies.

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