Calculating Economic Levels of Leakage

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Abstract

The paper outlines the approach to determining the economic level of leakage for a water supply and distribution system, which is being developed by a UK based sub-group of the IWA Water Losses Task Force (IWLTF). Each of the principal methods of controlling leakage is considered as either a short run or long run factor, and a methodology is proposed by which the marginal cost of each activity is compared to the marginal benefit. In practical terms each activity is combined in a process, which has been referred to as "squeezing the box". The interaction of each activity, and the comparison of leakage management with other water supply and demand options, is considered as a means of improving the long-term reliability of the water supply. The history and experience of leakage management in the UK is compared with the situation often encountered in other parts of the world, and the recommended approach to ELL is summarised.

Introduction

The level of losses from water systems is often considered by observers from outside the industry to be unacceptable. Environmentalists and regulators have expressed concerns at the level of losses, and believe that lower levels should be achievable. However, any water company has to work within current operating budgets and seek additional finance if these are not sufficient. Leakage control can be expensive, and water companies will seek to achieve an economic balance between the costs of leakage control and the benefits that accrue. This balance between costs and benefits is common in many fields, and the idea of the economic level of operation is commonplace in many industries. The concept of an economic level of leakage (ELL) dates back several decades, and there have been many previous attempts to determine a practical definition and methodology. Previous methodologies tended to confuse the impact of the various leakage management options available. It is only over the past 15 years, due to substantial investments and achievements in the UK, that we now have a better understanding of all the issues.

The current thinking on ELL is based on the knowledge that each and every activity aimed at reducing leakage follows a law of diminishing returns; the greater the level of resources employed, the lower the additional marginal benefit which results. This understanding forms the basis of a new methodology in which every activity is analysed in a similar way to compare its marginal cost with that of other interrelated activities, and with the marginal cost of water in that supply zone.

The time frame of ELL

It is now generally accepted that there are two time frames in which the economic level of leakage should be considered, namely short run and long run. The economists definitions of these are (Parkin, 2005):-

"The **short run** is a period of time in which the quantity of at least one input is fixed and the quantities of the other inputs can be varied. The **long run** is a period of time in which the quantities of all inputs can be varied, and other new inputs can be introduced"

This may not seem all that helpful in practice, but examples that are generally quoted, using manufacturing industry, refer to labour, materials and power as variables that can be changed in the short run, whilst plant capacity can only be changed in the long run. In many respects then it is the question of an investment decision, rather than a routine operating expenditure, that would make the difference between long run and short run. In this case a more suitable definition of long-run is:-

"The time required for a given asset to pay back its investment, or the time required for a given portion of payback. Economic short run is any period shorter than economic long run"

This approach can be applied to the four primary activities that impact on leakage control which are often illustrated as shown in Figure 1. i.e. pressure management, active leakage control (ALC), quality and speed of repairs, and infrastructure improvements. To further the comparison with the examples used in manufacturing industry, the elements such as active leakage control and repair activity can be affected by changes in labour and would therefore be considered in the short run, whereas pressure management and mains rehabilitation would require an investment decision, and would therefore be considered in the long run. There are other activities that can impact on leakage such as sectorisation, customer meter reading policy, customer side repair policy, extent of customer metering etc.

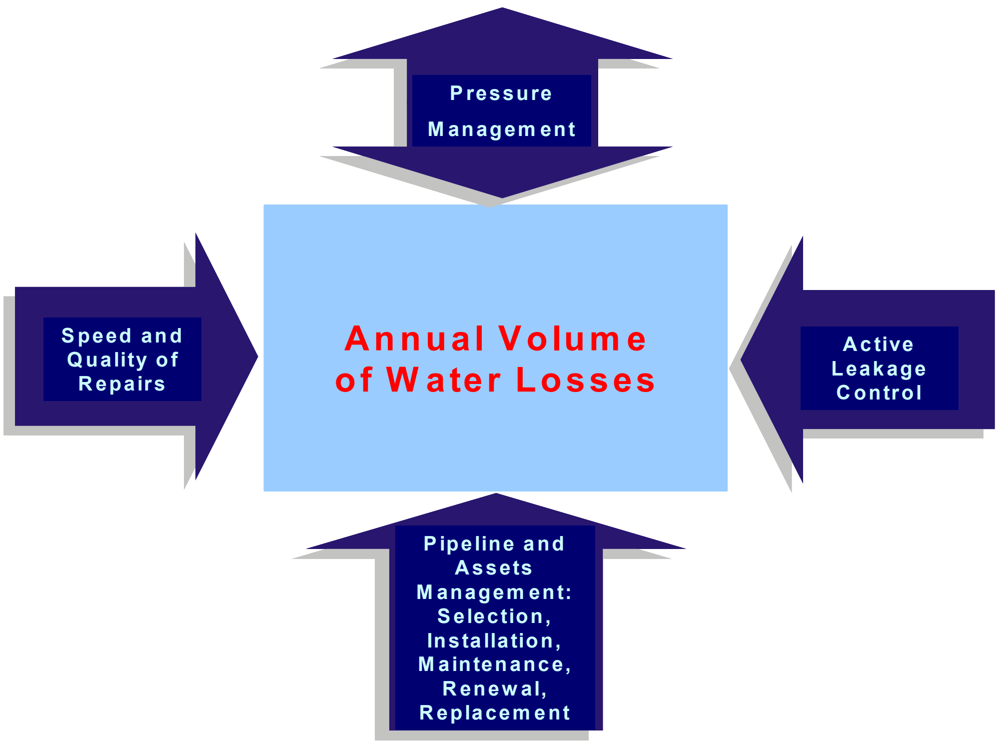

Figure 1. The four primary components of leakage management

Short Run ELL (SRELL)

Active leakage control

The purpose of active leakage control is to find leaks that do not surface or otherwise come to the attention of the operating company through customer contact e.g. poor supply, loss of water etc., (which are known as **reported** leaks). The process of active leakage control involves teams of leakage detection staff sweeping an area to find leaks generally using sounding techniques or similar. This may be in response to an increase in a nightline if the area is sectorised, an increase in the output from a treatment works or service reservoir/tank or simply as a result of a regular sounding programme at an agreed interval.

This ALC activity will locate **unreported** leaks, which will then be repaired, and leakage levels will be maintained. If sweeping is carried out at more regular intervals then leakage will be maintained at a lower level. Thus, there is a relationship between average leakage level and the time between surveys. This is shown as curve A-B in Figure 2 and is referred to as the Active Leakage Control Curve. The vertical axis is usually expressed in cost terms and is simply the cost of the leakage detection resources. The horizontal axis is the average leakage level, over the same period (usually a year). On the assumption that some leaks would never come to the attention of the operating company if they did not come to the surface (e.g. if they break through to a sewer), then the curve will asymptote to the horizontal axis. The curve will also asymptote to a line parallel to the vertical axis. This line will be equivalent to the level of leakage that would result if infinite resources were deployed on leakage control activity. This minimum level of leakage would equate to background leakage plus the leakage from reported leaks plus the leakage from unreported leaks during the period they run between detection and repair, resulting from any given leakage control policy

There has been much debate about the shape of the curve between these asymptotes. In the most simplistic model of regular sounding the curve will be hyperbolic. This is based on the fact that the curve will be defined by the leakage during the period which unreported leaks run until they are detected. This will be directly related to the length of time they run before being detected and hence the intervention interval. As the intervention interval will be inversely related to the resources (doubling the resources will half the intervention interval) then leakage will be inversely proportional (i.e. a hyperbole) to the level of resources and hence the ALC cost. If the area is sectorised, or if other forms of flow measurement are used to direct resources more efficiently compared to simple regular sounding, the curve will be flatter than a pure hyperbole.

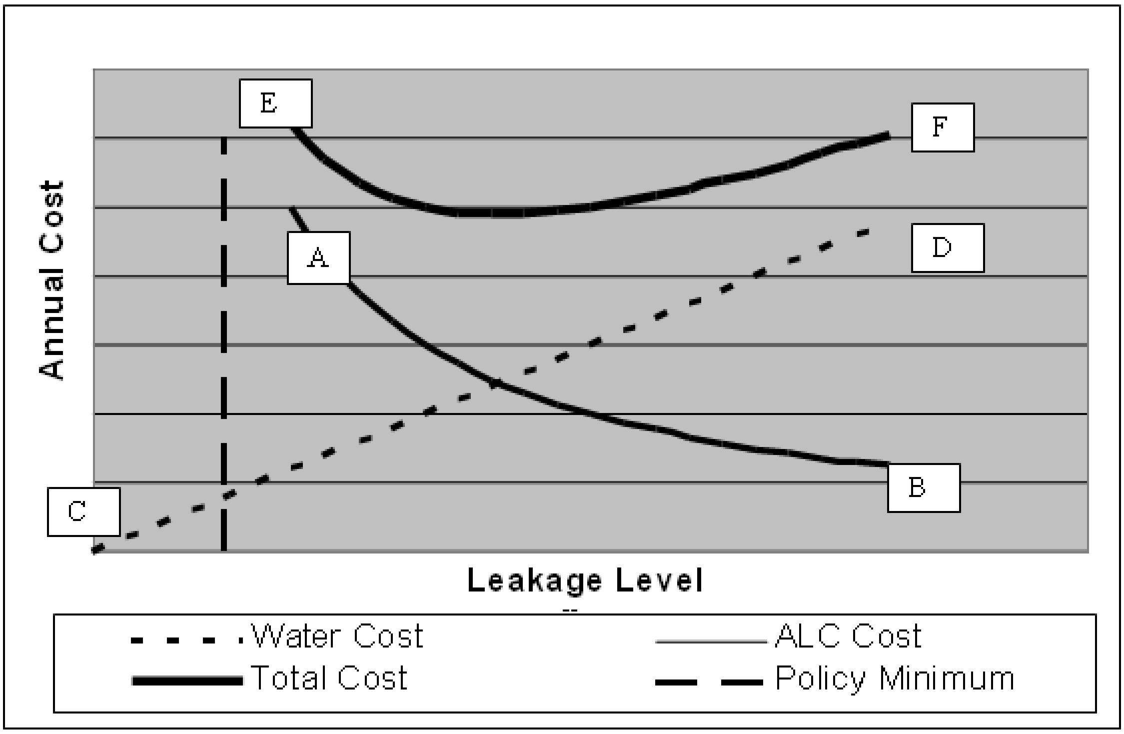

Figure 2. Active Leakage Control (ALC) cost curve

If the cost of the water lost at different levels of leakage is plotted on the same graph this would be represented by the line C-D. Following the definition of short run, the cost will be the simple difference in cost in producing one more or less unit of water in terms of power, chemicals and possibly labour. The slope of this line is referred to as the marginal cost of water. If the marginal cost of water is constant, line C-D will be a single straight line. If the marginal cost of water production is not constant, then line C-D will be made up of a number of straight lines; usually increasing in slope with higher leakage as more expensive water is used. Curve E-F is the total cost of operation i.e. cost of leakage control plus cost of water production. As can be seen, the curve will be high initially due to the high cost of leakage detection required to achieve very low levels of leakage. The total cost then reduces before increasing again as the cost of water lost increases with increasing levels of leakage. The point at which the total cost is lowest will be the short run economic level of leakage. At this point, the marginal cost of leakage detection activity will be equal to the marginal cost of water. This point will also define the economic level of resources to be deployed on leakage detection.

In order to apply this approach in practice, it is necessary to define the ALC curve, both qualitatively and quantitatively. This can be carried out in a number of ways, which can be classified as either empirical or theoretical. The former relies on the establishment of a number of points along the curve by analysing the results from actual ALC operations. When a number of points have been derived then a curve is fitted. This may assume a given shape to the curve (DEFRA et al, 2003). The difficulty with this approach is that the current position on the curve represents a static situation of the balance between average leakage over a number of years at a constant resource level. It may take a number of years to reach stability when detection resources are changed. It is therefore a long process to develop a number of points on the curve.

Alternatively the curve can be derived using a more theoretical approach using Component Loss Modelling methodologies (Lambert et al, 1996). The solution to the calculation of the short run economic level of leakage using regular sounding is reasonably straightforward (Lambert et al, 1998) and this has been developed (Lambert et al, 2005a) into methodologies that can be readily applied to distribution systems. A methodology for sectored District Metered Areas has been developed but is, as yet, unpublished.

A compromise is to establish the current position on the ALC curve by analysing the results of actual operations, and then to estimate the shape of the curve at increased or decreased levels of ALC activity using a component based approach.

The level of background leakage can be assessed using current methodologies (DEFRA et al, 2003). However, the level of background leakage is a function of the extent and method of leakage detection employed, which itself will have different operating costs associated with different levels of leakage. Therefore, a matrix of leakage detection costs versus level of background leakage can be derived, from which a view can be taken on the appropriate economic method of detection, and the associated level of background leakage.

Backlog removal and transition costs

Once an economic level of leakage has been established, then a company should move towards that point. However, as this point is likely to be at a lower level of leakage than the current level, moving to this point will involve one-off costs. These will be associated with the cost of the repair of two groups of leaks:-

Backlog leaks:

These are leaks that have gradually accumulated on the system over a large number of years, and are essentially hidden in minimum historic levels of leakage i.e. what is often believed to be background leakage. The number of backlog leaks and hence the associated repair bill can be substantial but they are one-off costs and the cost benefit can be readily assessed. However, it may be appropriate to take other action, e.g. pressure reduction (described later) to reduce the frequency at which the system is breaking in order to allow for this backlog to be reduced over a period of time within the current repair budget. Alternatively it is possible that these could be considered as a one-off capital cost.

Transition leaks:

As each point on the ALC curve is a static situation, then there are less leaks running at any one time at lower levels of leakage. Thus, moving from one point to a lower point will mean that additional leaks are brought in for repair before the situation reaches equilibrium again. Transitional costs should generally be fairly low and they can be added (with appropriate discounting as if they are a one-off investment – see long run economics) into the calculation of the economic level of leakage to obtain a slightly revised economic level of leakage.

Leak repair activity

A similar methodology as that for ALC can be applied to developing the economic level of speed of repair. Very short repair times can be achieved but at the possible cost of overtime for weekend and evening working for the repair teams. This may or may not be economic. There will be a relationship between cost and repair time as in Figure 3. Leakage level will be related to the average repair time, and so a similar curve to the ALC curve can be produced. The economic repair time can therefore be determined in the same way as described above for ALC. At this point the marginal additional cost of repair (over and above a base cost if there were no time limit on repair) will equal the marginal cost of water production.

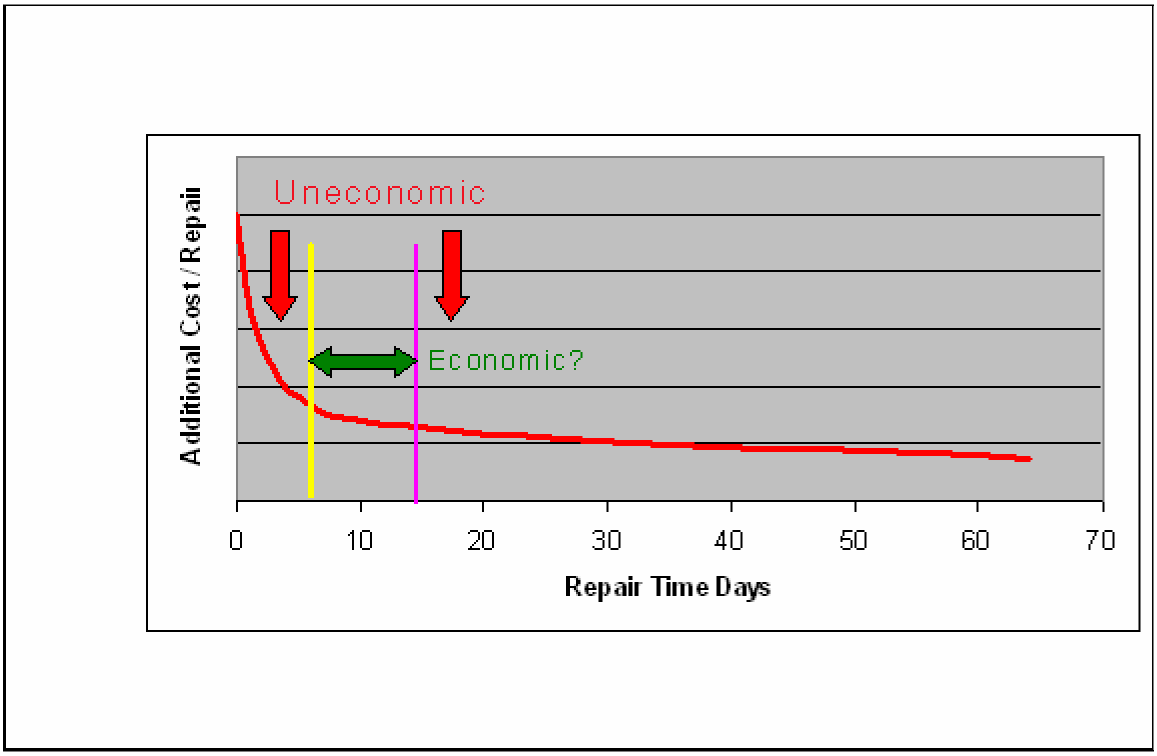

Figure 3. Additional cost of repair with reduced repair time

Long run ELL (LRELL)

Some leakage control activities will involve an investment decision, and hence a pay back longer than the short run period. This will typically apply to options such as pressure management and mains rehabilitation. In these cases, it will be economic to make an investment on pressure management or rehabilitation to reduce leakage if the cost of water saved over the investment period would pay for the cost of carrying out the works. Once the investment has been made, there will be a new (lower) short-run economic level of leakage, which has to be re-calculated using the method above.

Pressure management

In the case of pressure management, the investment costs will include the one-off cost of construction of the chambers, the cost of purchasing the valves and their replacement as well as ongoing maintenance costs. As pressure management is deployed in an area, the average pressure will reduce. Schemes will be deployed on the basis of those which give most benefit first and therefore as more and more schemes are installed, the benefit of each scheme on the average pressure will reduce. Figure 4 shows a typical curve relating the benefit from scheme deployment on average zone night pressure (AZNP). As leakage is proportional to pressure, then there will be a break-even point at which the additional cost of scheme deployment equals the marginal cost of water production.

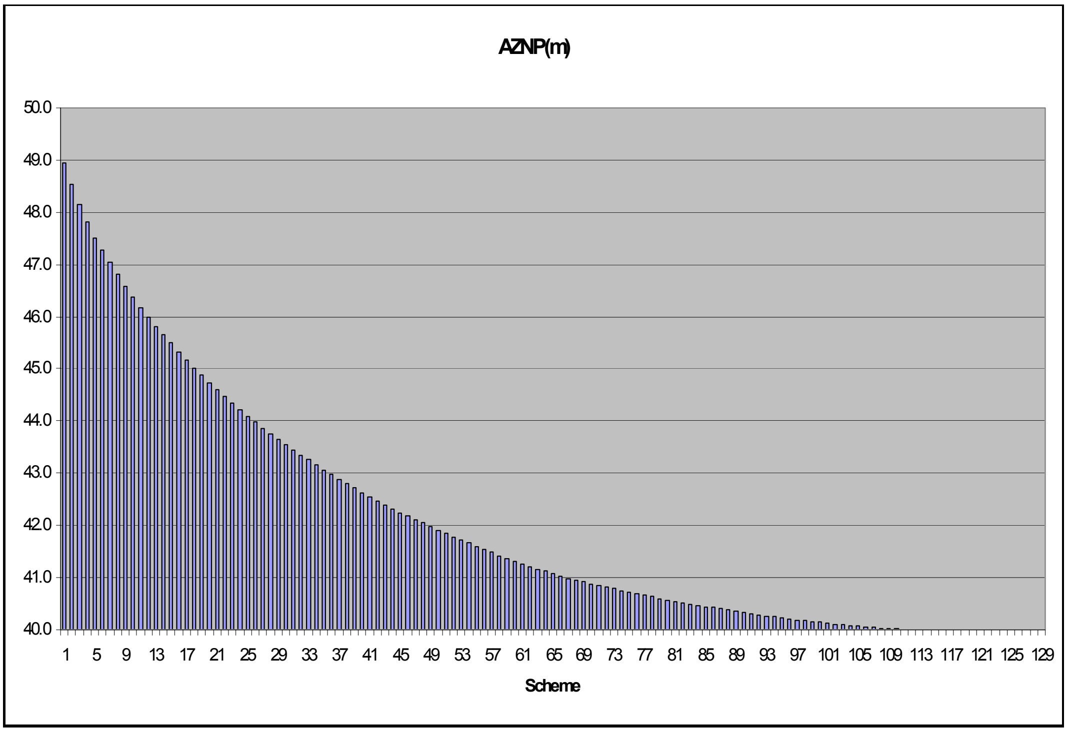

Figure 4 Ranking pressure management schemes by the benefit of reducing AZNP

The process usually involved in calculating this breakpoint is as follows:

- The benefits in terms of pressure reduction from the installation of pressure management valves, and other schemes, is estimated using hydraulic modelling and /or logging of areas
- The cost of construction is estimated, and the cost discounted into an equivalent annual cost using financial accounting methods (usually agreed with the Finance Department of the operating company) such as Net Present Value (NPV)
- The cost of the valve and its replacement (as recommended by the vendor) is discounted in a similar way
- The annual cost of maintenance (as recommended by the vendor) is estimated
- The benefit in terms of leakage reduction is estimated
- The marginal cost is calculated as the sum of the costs divided by the benefit

All the schemes with a cost/benefit greater than the cost of water would be deployed. This will establish the economic level of pressure reduction and the associated leakage level.

Leakage will reduce as a result of pressure reduction due to two factors namely:

- Both background and burst flow rates will reduce, as leakage flow is directly related to pressure by a factor called the N1 relationship (Lambert et al, 2005b)
- Burst frequency rates will reduce, due to reduced stress on the pipe network, the so called N2 relationship (Pearson et al, 2005)

As burst rates are likely to reduce due to the change in pressure, there will be a reduction in the repair budget for the company. This reduction in burst frequency is likely to bring in savings in addition to direct repair costs, these will include:

- Customer contact costs for reported leaks
- Visit/inspection costs for reported leaks
- Active leakage control costs for unreported leaks

An estimate of this reduction should therefore be made, and the saving should be deducted from the costs above prior to calculating the cost/benefit. There will also be less tangible benefits such as:

- Reduced risk of discoloured water events
- Reduced interruptions of supply

These benefits will lead to improved levels of service and customer satisfaction and a reduction in the risk of any regulatory action. A notional monetary value can be placed on these less tangible benefits in order to allow for these in the calculation.

Network rehabilitation

Network rehabilitation (both mains and service pipes) will reduce the rate at which leaks break out on the network. This will reduce leakage, as well as reducing costs associated with inspections and active leakage control activity highlighted above. Figure 5 shows a typical burst frequency distribution curve. This shows that there is a distribution of the frequency at which pipes burst on the network. A small proportion will burst at a high frequency, whilst other parts of the network will burst at a much lower frequency. In order to have the greatest impact on leakage (the best "bang" for your "buck"!) one would try to identify those pipes with a high frequency of failure and replace these first. The benefit of replacing further sections of pipe will then be less. Again the law of diminishing return applies, and a point will be reached when it is not economic to replace pipes. A similar curve will exist for the distribution of service pipe bursts across the network.

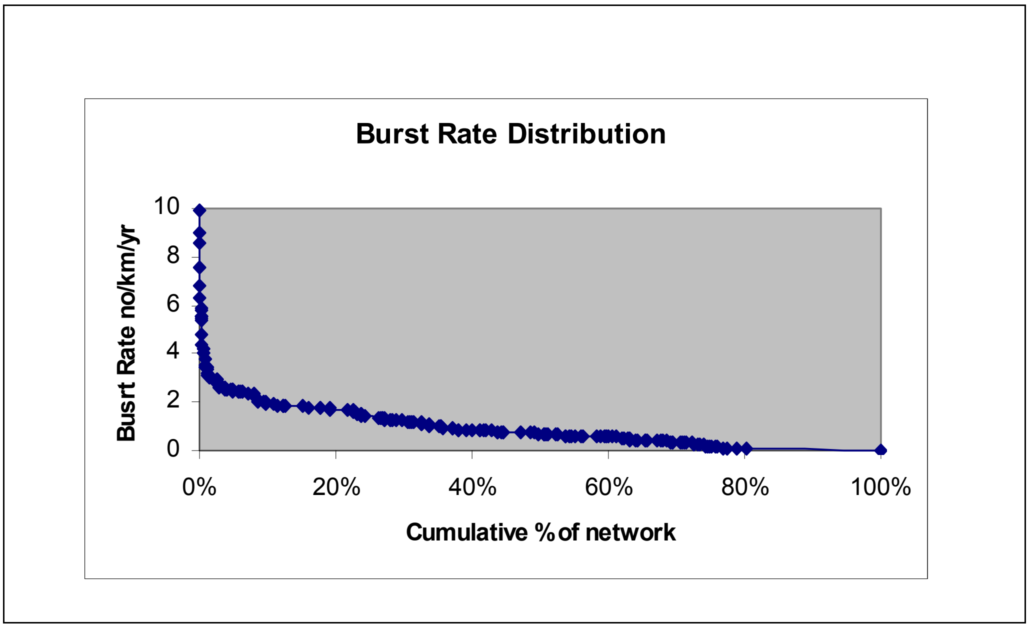

Figure 5. Burst frequency distribution

It has been suggested that there is also a distribution of background leakage, which is not the same as that for burst frequency. Those mains with high burst frequencies may have a low background leakage level and vice versa. Therefore, mains replacement should be targeted at burst and background leakage separately.

To find this economic point, the following calculations are performed:-

- The benefit of replacing a section/group of essentially similar pipes in the same locality in terms of reduction in burst frequency and/or background leakage is assessed
- The cost of replacing these pipes is estimated
- The reduction in leakage is estimated using component loss modelling
- The savings in costs in inspections, repairs and active leakage control are assessed
- The marginal cost is assessed as the cost less the sum of the savings divided by the leakage saving.

All the schemes with a cost benefit greater than the cost of water would be deployed. This will establish the economic level of network rehabilitation and the associated leakage level.

Sectorisation

It is common practice in some parts of the world to split the water network into sectors and monitor flows into and out of these sectors at night. Sector flow data provides information to be able to locate leaks faster and therefore improve leakage detection efficiency. However the introduction of sectoriation involves costs in the following areas:-

- One off cost of construction of meter chambers
- Cost of meter and replacements and/or refurbishment
- Cost of data logging equipment
- Ongoing cost of data retrieval (either manual or by telemetry)

The benefit of introducing sectorisation in terms of leakage will be a function of the natural rate of rise of leakage in the sector. Not all sectors will have the same rate of rise, and so again there will be a curve showing diminishing returns. Other factors affecting costs will be the environment, and complexity of the network, and the degree to which sectorisation has already been established. The calculations are similar to the ones described above for pressure management and rehabilitation. They can be carried out to establish an economic breakpoint that would give the economic level of sectorisation and the optimum size of sectors.

Combination of activities

The methodologies described above all require the assessment of the benefit in leakage terms from the proposed activity. Each case has been considered independently – i.e. the assessment of the economic level of pressure management or rehabilitation. However the implementation of one option will affect the economics of the implementation of the other i.e. the benefits from rehabilitation will be reduced if average pressures have already been reduced due to pressure management. In practice, an operating company will want to develop a strategy that looks to establish the economic balance between all activities i.e. active leakage control, leakage repair, mains rehabilitation, service pipe replacement, sectorisation and pressure management.

The normal approach to solving this problem is to choose a small increment of activity in each area and work out the cost/benefit. These are ranked and the one with the best benefit is “implemented”. The leakage benefit for the other schemes are then reassessed due to the change that this scheme imposes and compared again. The next scheme is then chosen and the leakage benefits reassessed etc. This process is continued until the marginal cost of any activity is equal to or greater than the marginal cost of water. This then establishes the economic level of leakage and the list of schemes and associated costs that will be implemented to achieve this level.

By following this procedure of “squeezing the box” (i.e. the box containing the level of losses shown in Figure 1) using each of the primary activities of a well developed programme of leakage management in turn based on best value, a point will be reached where any further activity is uneconomic i.e. its marginal cost will be greater than the marginal cost or value of the water saved. At this point the marginal cost of further leakage control activity will be the same for all activities (Lasdon, 1970). This point is the **unconstrained long run ELL**.

Deficiency in water supply reliability

The calculations described above establish the economic level of leakage against the marginal cost of water production. In effect, this could be called the unconstrained economic level of leakage (ELL). In practice, this level of leakage, when combined with consumption, may be insufficient to provide the necessary reliability of supply for the operator. The excess of water available for supply compared to the demand, is often referred to as headroom. Some countries have standards for determining the appropriate level of headroom (UKWIR et al, 1998). If after working out the unconstrained ELL there is insufficient headroom, then an operating company needs to decide whether it is more economic to carry out further leakage control or whether to develop a new water resource, or to implement measures to reduce customer demand.

In order to decide this, the cost of leakage control activity described above should be compared to the marginal cost of the optional water resource development. This marginal cost is calculated as follows:

- The one-off capital cost of construction is estimated and discounted using an agreed discount rate
- The ongoing maintenance cost of the resource once constructed is estimated
- A “sensible” yield of the scheme is assessed
- The cost of water production is estimated
- The marginal cost is assessed as the sum of the discounted cost plus the maintenance cost divided by the yield plus the production cost
- Environmental and social costs associated with the resource development can be assessed and added to the cost of the option

Leakage activity schemes would be implemented if these were cheaper than this marginal cost. This could be referred to as the marginal **value** of water. As the marginal cost of the new scheme will be significantly higher than the production cost from existing sources, as it includes the discounted cost of the construction of the works, then it will be economic to carry out further leakage control measures consisting probably of more pressure control, a higher level of active leakage control and possibly more rehabilitation and sectorisation. Schemes would be implemented until the necessary level of headroom was attained. This may be less than the level that would result from the construction of the new resource. This level of leakage could be referred to as the **constrained long run ELL**.

Unsteady long run

In many cases, consumption is not constant due to demographic changes. The rate at which demand is rising may influence the assessment of the economic level of leakage. If demand is rising so fast that resource development will become inevitable no matter what the level of leakage, then the marginal cost of water will be lower after the resource development is completed, leading to a lower ELL. In order to assess the most economic solution, a least cost plan has to be assessed. This is obtained by using an optimisation routine to essentially take all the possible leakage control, demand management and water resource options described above, and calculate the least cost plan necessary to meet the headroom requirement in each year. This is obtained by looking at all the possible options and the order in which the schemes can be implemented and discounting the total cost to a net present value. The plan with the lowest net present value forms the least cost plan. This will give the programme and likely construction and implementation dates of the activities and schemes to achieve the desired reliability. Figure 6 shows a typical plan. Actual timing may be different if demand rises at a faster or slower rate than estimated. The plan would output the economic level of leakage, which will be different for every year – i.e. a profile. In theory, the ELL may be higher once a water resource scheme has been implemented, i.e. it would be possible to reduce the level of active leakage control, but in some countries this may be deemed as unacceptable by the regulators or environmentalists.

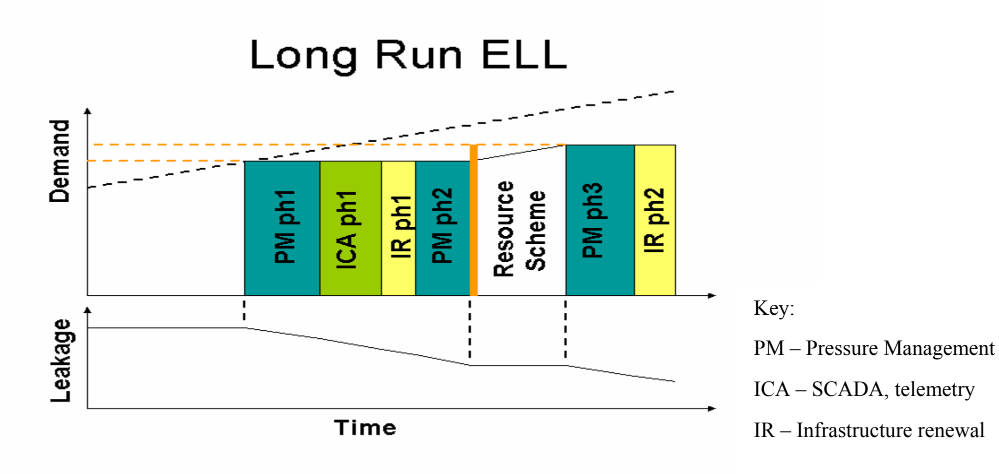

Figure 6. Least cost plan

The decision process as to whether the economic level is derived as simply unconstrained, constrained or as an unsteady state can be summarised in a flow chart – see Figure 7.

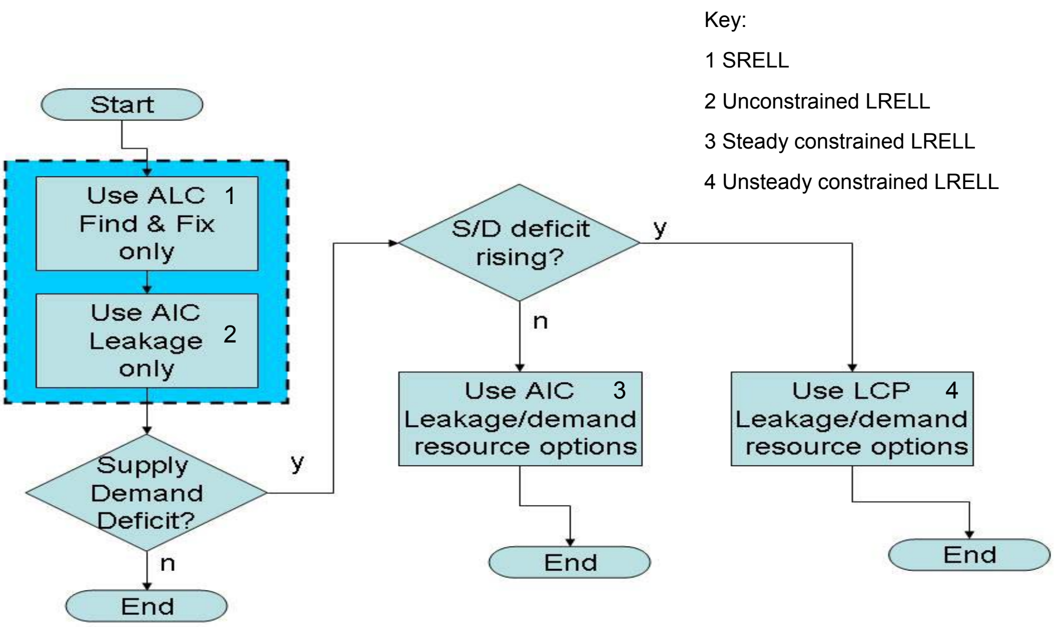

Figure 7. Decision tree for ELL

History and experience

United Kingdom

The United Kingdom has a well-developed supply network with over 99% of properties connected to public water supply networks. Continuous supply is available 24 hours a day with less than 0.05% of premises receiving low pressure (usually taken to be less than 15m) at any time during the year (Ofwat, 2004). Only 25% of properties are metered, the rest pay for water based on the value of the house. However the network is of mixed age with some parts of the network well over 100 years old. There is a small number of operating companies (less than 25 covering over 20 million properties), which were privatised in 1989, and there is a strong environmental and economic regulatory regime. Figures on leakage are reported to the regulators each year and audited by independent assessors. Every five years the companies have to develop business plans for the following 20 years which include a full engineering assessment of their assets and a financial model of forecast income and expenditure. This is used to establish the price limits for the next five years. Part of the engineering submission involves the assessment of the economic level of leakage and whether this is constrained by headroom or not. Following the sever drought in 1995/96 leakage levels have been reduced by over a third and leakage targets are set by the regulator each year based on companies' assessment of their ELL. Most companies are operating at or close to their assessed ELL. Several companies are operating at a level that is constrained by headroom.

The assessment of ELL within the UK has a long history. Although there were many papers on ELL, the first national study and report on the topic was published in 1980 (NWC, 1980). This set down a methodology for the assessment of ELL, and it identified the benefits of pressure control and sectorisation in managing leakage. This led to the implementation of sectors (DMAs) in most companies in the UK. The findings of this report were updated by a major national research programme that reported in 1994 (UKWIR, 1994). This and subsequent reports have lead to greater understanding of the relationship between pressure and leakage and other activities which allow the construction of models to forecast the effect of changes in operating regime on leakage. There is a very high level of monitoring, and hence data availability, within the UK e.g. 15 minute flow and pressure data on each sector. Most companies now have fully calibrated all mains hydraulic models of their networks. As a result of the drought in 1995/96 a number of companies initiated major leakage management programmes based on economic assessment outlined in this paper. One of these involved the construction and implementation of over 2000 pressure management schemes within a three year period. As a result of this a company supplying over 3.2 million properties reduced their average night time pressure from over 50m to under 40m (Lambert et al, 1998).

International Experience

The situation in other parts of the world is quite different from the UK. Water supply is often still in the hands of local municipal authorities each covering a relatively small number of properties. Most connections are metered, but it is common for supplies to be intermittent due to resource shortages. Sectorisation is very rare and proactive leakage control limited. The benefits of pressure management are not widely appreciated and there is generally no assessment of the economic level of leakage. Only limited data is available and there are generally very few hydraulic models. There is therefore the need for advice on the application of ELL in the situation of limited data.

Practical application

Application of the ELL analysis in many situations has shown that pressure management is by far the most cost beneficial activity. Its benefit in reducing burst frequency (Pearson et al, 2005) is such that pressure-reducing schemes will often have pay back periods of much less than 12 months. In fact, the initial schemes can have such a quick and direct influence on the repair budget that they will free up sufficient money to pay for further pressure management schemes, and also some leakage detection resources to start proactive leakage detection. If this resource can be effectively targeted to identify backlog leaks, then it will be found that leakage can be reduced significantly within the existing budget.

The priority in terms of the identification of pressure management schemes should be:-

- Identify any occurrence of surges or instability in pressure on the network using very short time interval logging and identify solutions to the problem
- Identify and, where possible, move from fixed to variable speed pumps.
- Look for areas of high pressure (greater than 30m) that can be controlled by pressure management
- Look for areas with high diurnal flow and pressure variation and look to control using flow modulated pressure control valves

As the benefits of pressure management start to be achieved, then the economic level of regular sounding can be calculated (Lambert et al, 2005a) and appropriate targets can be implemented. If the area is sectorised, then economic leakage detection can be applied practically at sector level (Rizzo, 2002).

Throughout the leakage reduction plan, the performance of the network should be assessed using the IWA ILI approach (Lambert et al, 1999) and information systems should be set up to collect data on the topography, pressure regime, burst frequencies etc so that more detailed analysis of ELL can be carried out as reductions in leakage are made. Whereas initial estimates of ELL will rely on default values and assumptions, the calculations can be refined using actual data from the specific operations which are implemented.

This approach can be described by a flow chart (Figure 8).

Summary

For any system, the economic level of leakage is that which results from a combination of a range of leakage management activities that comprise (in priority):-

- An optimised overall **pressure management** policy in which:
    - the presence of surges are identified and steps are taken to minimise their adverse effects
    - projects are implemented to adopt basic simple reductions of excess pressures
    - further projects are implemented in order of cost / benefit
- An optimised **repair time** policy for all bursts
- An economic **intervention policy** for awareness, location and repair of unreported (hidden) bursts which is:
    - influenced by the level of investment in leakage management infrastructure i.e. Telemetry/SCADA, DMAs, advanced pressure management
    - influenced by the exit level (background and other leaks remaining after interventions)
- An economic level of **investment** in mains and services renewals which takes account of all regulatory factors

If each of these activities is pursued to a logical conclusion in terms of cost and benefit, then the definition of the economic level of water loss can be summarised as:

“That level of water losses which results from a policy under which the marginal cost of each individual activity for managing losses can be shown to be equal to the marginal **value** of water in the supply zone”.

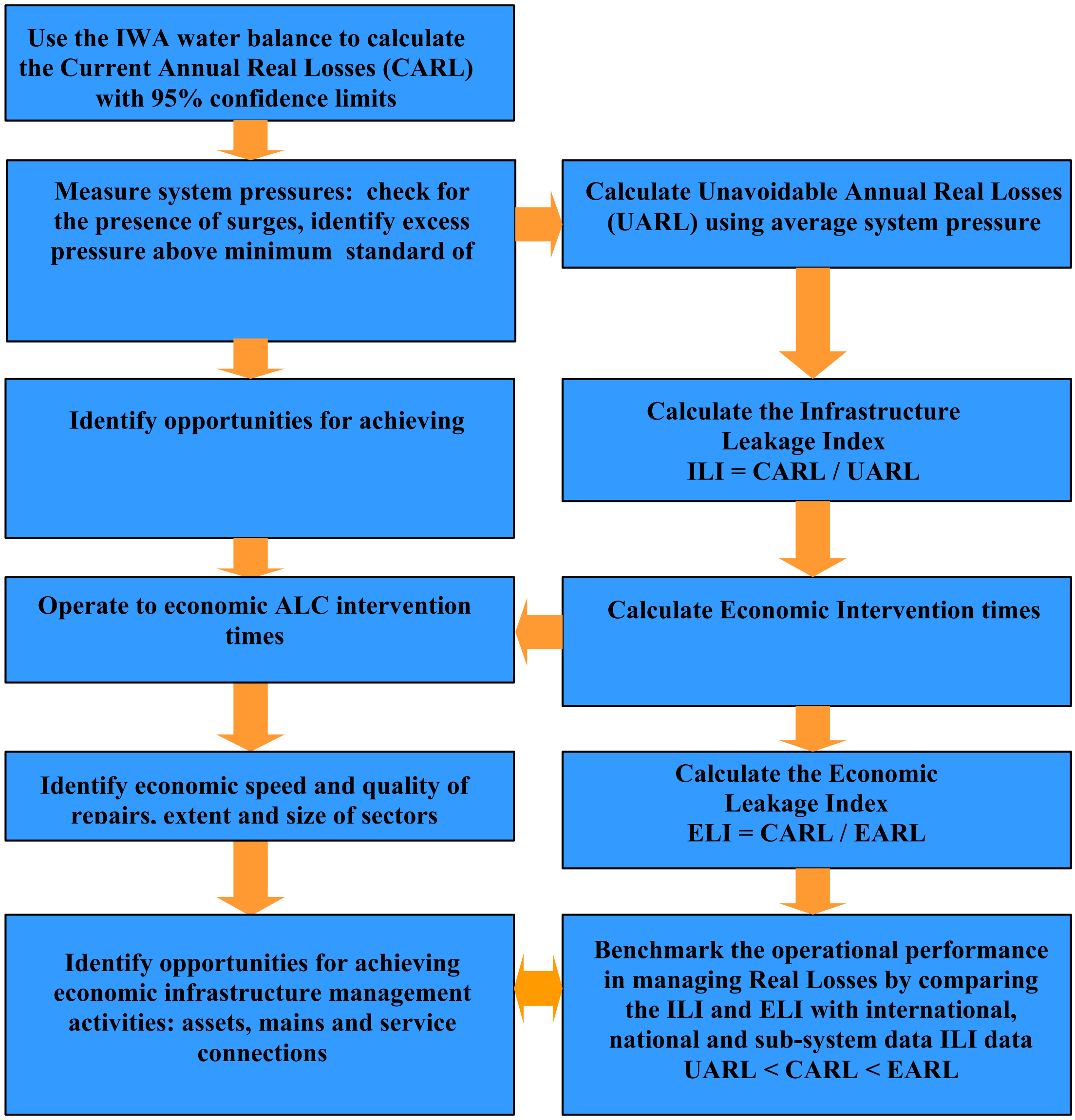

Figure 8. Practical application – flow chart

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