Practical Experience in using the Infrastructure Leakage Index

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ABSTRACT
The Infrastructure Leakage Index (ILI) – being the ratio of Current Annual Real Losses to Unavoidable Annual Real Losses (UARL) – is proving to be a most useful and practical performance indicator. It is being used for rapidly assessing efficiency in management of Real Losses, setting targets, and prioritising remedial activities (using a 'twin-track' approach which considers pressure management in parallel with more traditional forms of leakage management). The ILI approach was developed and tested over a period of several years by the IWA Water Losses Task Force; it was first published in December 1999 in "AQUA", and included in the IWA 'Best Practice' Performance Indicators Manual (July 2000). The paper addresses some queries raised by practitioners applying the ILI approach. Some recent international applications are presented, including Utilities with exceptionally good performance (ILI less than 1.5). The introduction of 95% confidence limits into calculations of Water Losses and associated Performance Indicators is also discussed and recommended.

KEYWORDS
Apparent Losses, Background Leakage, Non-Revenue Water, Real Losses, Unavoidable Losses, Infrastructure Leakage Index. Leakage Management, Pressure Management

INTRODUCTION

A Practical Approach to Assessing, Comparing and Managing Real Losses

Practical approaches to Leakage Management – the theme of this conference – need to include:
- meaningful assessments of volumes of annual Real Losses, preferably with confidence limits
- authoritative guidance on selection and use of appropriate performance indicators
- effective prioritisation of leakage management options likely to give greatest benefits for least cost

In the authors' experience of leakage management in numerous diverse international situations, the UARL and ILI approach (coupled with the IWA standard water balance) satisfies these practical criteria better than any of the traditional approaches previously available.

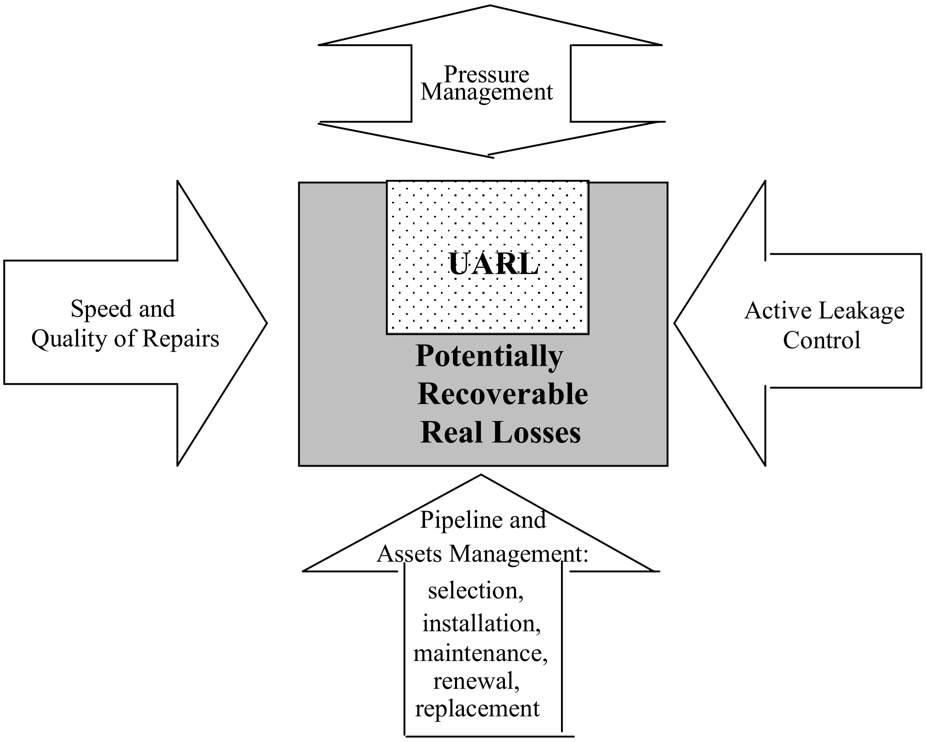
The Concept of Infrastructure Leakage Index

In Figure 1, consider that the current annual volume of Real Losses (CARL) for a distribution system is represented by the large rectangle. As new leaks occur each year, this volume will gradually increase unless all four basic methods of managing Real Losses (represented by the four arrows) are effectively applied. The volume of current annual Real Losses represents the average picture over a 12-month period in which the natural rate of rise of leakage is constrained, to a greater or lesser degree, by leakage management activities.

Leakage management practitioners are well aware that Real Losses cannot be totally eliminated. The volume of Unavoidable Annual Real Losses (UARL) - the lowest technically achievable annual Real Losses for a well-maintained and well-managed system – is represented in Figure 1 by the smaller inner rectangle.

The Infrastructure Leakage Index (ILI) is the dimensionless ratio of the large rectangle to the smaller rectangle, calculated as CARL/UARL. As a Performance Indicator, it is a measure of the combined performance of the three 'Infrastructure Management' methods of Real Losses – the East, South and West arrows in Figure 1 – under the current pressure management regime. The ILI is the IWA 'Best Practice' Level 3 (Detailed) Performance Indicator for Operational Management of Real Losses (Alegre et al, 2000)

Figure 1. The Four Basic Methods of Managing Real Losses



Equations for calculating UARL for individual systems were developed and tested by the IWA Water Losses Task Force (Lambert et al, 1999), allowing for:

- background leakage – small leaks with flow rates too low for sonic detection if non-visible
- reported leaks and bursts – based on frequencies, typical flow rates, target average durations
- unreported leaks and bursts – based on frequencies, typical flow rates, target average durations
- pressure:leakage rate relationships (a linear relationship being assumed for most large systems)

The equations used for calculating UARL are based on clearly stated auditable assumptions for frequencies and durations of the different types of leaks, and their typical flow rates related to pressure. These assumptions were outlined in Tables 2 to 4 of the AQUA paper. The actual calculations are detailed in Appendix A of the current paper. The 'user-friendly' versions of the UARL equations (reproduced later in this paper) require data on four key system-specific factors:

- Length of mains
- Number of service connections
- Location of customer meter on service connection (relative to property line, or curb-stop in N. America)
- Average operating pressure (when system pressurised)

With current knowledge and experience, UARL can be calculated for any system or sub-system with:

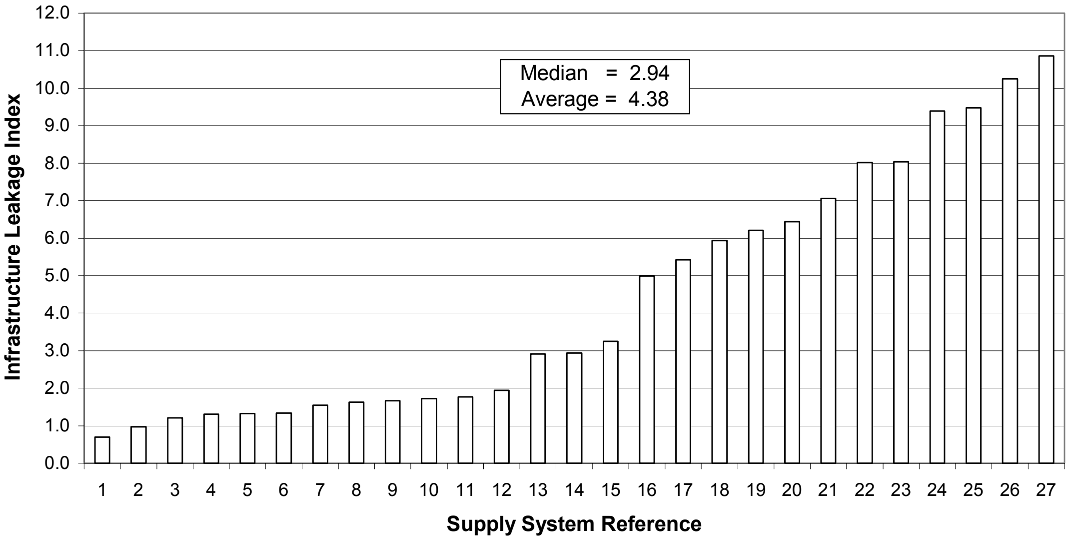
- more than 5000 service connections
- density of connections greater than 20 per km of mains
- average operating pressure more than 25 metres.

For smaller systems, the Unavoidable Background Real Losses (UBRL) can be calculated (working to even lower pressures and connection densities) for the analysis of night flows. The ability to calculate UARL for most medium to large systems, and UBRL for district metered areas and small systems, has significantly improved the analytical tools available to the leakage practitioner.

The 'AQUA' 1999 International Data Set of ILIs

The IWA Water Losses Task Force (Lambert et al, 1999) assembled an anonymous data set of 27 diverse distribution systems in 20 countries, as shown in Figure 2. The ILI values in Figure 2 ranged from 0.7 to 10.8, with a median of 2.94 and an average of 4.38.

Figure 2: Infrastructure Leakage Index (ILI) Values for 27 Supply Systems in 20 Countries



It is important to note that the systems represented in Figure 2 all had reasonably reliable data and active policies (to a greater or lesser extent) to try to manage Real Losses. Since 1999, many more ILI values have been calculated for systems in more than 40 countries. ILI values far higher than those in Figure 2 - several in excess of 50, and a few in excess of 100 - have been identified by consultants (e.g. Liemberger, 2002) for individual badly deteriorated systems. Appendix B shows ILI values for groups of Utilities in North America (Lambert et al, 2001), Australia (Carpenter et al 2002), and South Africa (McKenzie et al, 2002).

Interpreting ILI Values

If the ILI for a particular system is calculated, and is, say, 3.0, this means that:

- the current annual Real Losses are assessed as being around three times as high as the Unavoidable Annual Real Losses for a system with this length of mains, number of connections and customer meter location, under the same pressure management regime as the particular system under review
- options may exist for lowering Annual Real Losses to around one-third of the Current Annual Real Losses, if there are no changes in the current pressure management regime
- additional changes in Real Losses will result from changes in the pressure management regime

In practical terms, ILI values close to 1.0 mean that 'world-class' leakage management is ensuring that annual Real Losses are close to the 'Unavoidable' or 'Technical Minimum' value at current operating pressures. However, such low ILI values are only likely to be economically justified when marginal costs of water supply are relatively high (e.g. desalination), or water is scarce, or both. Some Water Utilities with well-deserved reputations in advanced management of Real Losses, and ILI values of less than 1.5, are listed in Appendix C, with comments.

Influence of Pressure Management

Pressure management is one of the most effective forms of leakage management, particularly in systems with deteriorated infrastructure. The presence of surges and high pressures influence the rate at which new leaks occur. Flow rates from existing leaks are more sensitive to average pressure than the traditionally assumed 'square root' relationship, except for all-metal pipe systems with very high leakage rates. For large systems with mixed pipe materials the relationship is usually approximately linear, and for all-plastic systems leak rates the leak rates vary approximately with pressure to the power 1.5 (Lambert, 2001a).

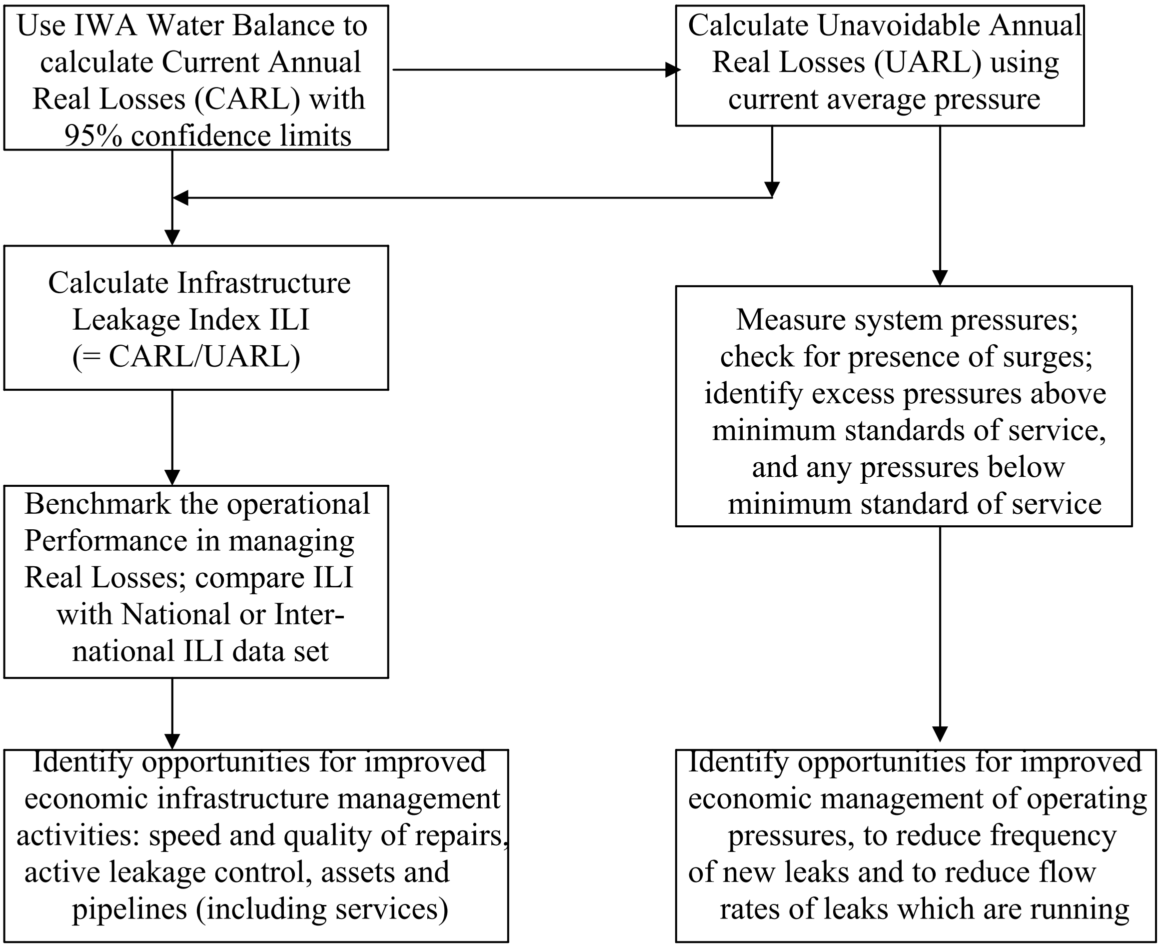
Yet, surprisingly, traditional performance indicators for Real Losses have never included operating pressure. Supporters of this traditional position argue that pressure should not be included in Performance Indicators for Real Losses, on grounds such as:

- average pressures in distribution systems are not known, or are difficult to calculate (not true!)
- any incentive for Utilities to undertake pressure management may be reduced

However, omitting pressure from PIs implicitly assumes that it is economic for all Utilities to operate at the same pressure, irrespective of topography or minimum standards of service – which is clearly impractical.

The ILI approach provides a practical 'Twin Track' compromise to this problem. First, the current average pressure is used to calculate the UARL (using the simplified assumption of a linear pressure:leakage rate relationship). The ILI is then calculated, thus benchmarking the 'Infrastructure Management' activities in Figure 1 at the current operating pressure. The additional essential step is to consider if there is any scope for improved management of pressures. This 'Twin-Track' procedure for benchmarking Real Losses and progressing towards economic leakage management is illustrated in Fig 3.

Fig .3 The Twin-Track Approach to Benchmarking and Improving Leakage Management



The ILI approach allows the influence of operating pressures (and pressure management) to be separated from the influence of the 3 Real Losses management activities in Figure 1 which relate directly to infrastructure. Later in the paper, in Table 1, this approach will be shown to be both useful and practical for rapidly identifying priorities for leakage management activities.

Practical Applications of ILI Values

ILI values can be, and have been, used for:

- International benchmarking (Lambert et al, 1999)
- National benchmarking (e.g. North America, Australia, South Africa in Appendix B; NZWWA 2002)
- Benchmarking of sub-systems within Utilities (WSC Malta 2001; several England/Wales Companies)
- Target setting and reporting to national regulator (WSC Malta 2001)
- Initial assessments for International Funding Agency projects (e.g. Kazakhstan, Moldavia, Saudi Arabia, Tajikistan, Uzbekistan for World Bank)
- Identifying and prioritising actions for Real Losses reduction in individual systems (e.g. Brazil, Sao Paulo; Canada, Halifax; Caribbean, Bahamas; Cyprus, Paphos; Malaysia, Selangor State; New Zealand, Auckland and Christchurch; Portugal, Porto; USA, Philadelphia)

The remainder of the paper will consider some typical queries on detailed aspects of the approach, raised by practitioners who have applied it.

TYPICAL FREQUENTLY ASKED QUERIES

Queries related to the Water Balance Calculation

Where can I find information on the IWA Standard Water Balance, used to calculate Real Losses?
The clearly defined procedure and terminology of this long-overdue standard approach is already being used or recommended (with minor modifications) by national organisations and consultants in Australia, Austria, Brazil, Canada, the Caribbean, Germany, Malaysia, Malta, Poland, Portugal, South Africa, UK and USA.

A simplified version of the IWA 'best practice' standard water balance is presented in Figure 4. Readers of this paper who are not already reasonably familiar with the terminology can obtain further information from Hirner and Lambert, 2000; or pages 9-12 of Alegre et al, 2000. Note that the term Unaccounted-for-Water (UFW) is not recommended because it is imprecise, meaning different things to different users.

Figure 4. IWA 'Best Practice' Water Balance

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	
			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	

How reliable are the calculations of Non-Revenue Water, Apparent Losses and Real Losses?
The question of accuracy and reliability of the annual volumes input and calculated in a Water Balance often arises (e.g. Sattery et al, 2002). This is because any errors in the measured or estimated components input to the calculation – such as errors in input volumes, metered or unmetered consumption, apparent losses etc – end up as errors in the components of Non-Revenue Water and Real Losses.

The IWA 'best practice' approach addresses this problem (in respect of Real Losses volume) by recommending that an alternative calculation of Real Losses is carried out to check the value derived from the water balance. This is particularly important for systems where the apparent losses are likely to be substantial (e.g. systems with customer roof tanks). Alternative calculation can be based on analysis of continuous night flows, as in England & Wales (Ofwat, 2001) and Malta; or by component analysis of Real Losses using leak frequency/flow rate/duration analyses (e.g. Lambert and Morrison 1996, Morrison 2002).

Unfortunately, practical constraints of data availability and reliability often mean that Water Balance calculations cannot be checked by alternative calculations. Accordingly, an increasing number of leakage practitioners are finding it useful to calculate 95% confidence limits to assist data interpretation. Using customised software (e.g.NZWWA Benchloss, 2001; Fastcalc 2001), estimated 95% confidence limits are assigned to each of the volume components entered into the Water Balance calculation. Assuming these errors are normally distributed (Gaussian distribution) and independent of each other, 95% confidence limits are automatically calculated for the resulting volumes of Non-Revenue Water, Apparent Losses and Real Losses; 95% confidence limits are also calculated for the Performance Indicators (see note 3 to Appendix C).

The calculation of 95% confidence limits can (and should) also be applied to Real Losses calculated from night flows (Paracampos and Thornton, 2002).

Queries relating to Unavoidable Annual Real Losses (UARL)

Is this the first attempt to predict Unavoidable Annual Real Losses?
No. Previous attempts to estimate lowest achievable annual losses (DVGW, 1984; Agence l'Eau Rhone, 1990; AWWA 1998) looked at lowest values of Water Losses reported by Utilities, on a 'per length of mains per unit time' basis. However the resulting range of values (typically 1 to 8 m3/km of mains/day) is so large as to be impractical for predicting UARL for individual systems outside the individual study areas.

The German DVGW and French studies recognised the influence of density of connections – this is because unavoidable losses in m3/km mains/day rise rapidly as density of connections increases. In the USA (Smith, 1984) also recognised the influence of operating pressure, but assumed a 'square root' relationship, rather than the more appropriate linear relationship identified by more recent international research. None of these studies identified the influence of the location of customer meters on the service connections.

How was the IWA Water Losses Task Force equation for Unavoidable Annual Real Losses derived?
Annual Real Losses in any system are the aggregation of the real losses volumes from individual leaks, bursts and overflows, and the volume lost from each event is the product of duration and average flow rate. The IWA approach, explained in Appendix A, was based on a relatively simple component analysis of Real Losses, assuming well-maintained infrastructure in good condition.

Assumptions for new leak frequency on mains (13/100 km/year) and service connections (5/1000 service connections/year) in good condition were based on published studies of repair statistics (notably. Hirner and Sattler, 2001). However, simply attributing the same average flow rate and the same average duration to every class of leak would be too crude an approach to yield reliable predictions. Accordingly:

- Assumed frequencies for detectable leaks were split into groups of 'reported' events (usually short duration) and 'unreported' events (average duration depends upon frequency of active leakage control)
- Burst frequencies on service connections were split into 'main to property line', and 'property line to meter' (for service connections where meters are located after the property line).
- Typical flow rates for leaks on mains, and leaks on service connections, were collated from several countries (notably Germany, the UK, and Brazil), and were standardised to flow rates at 50m pressure.
- An average target duration (in days) considered appropriate for 'best practice' intensive leakage management for each group of events was then specified, and the typical volume lost for each class of reported and unreported leak at 50m pressure was calculated.
- The typical volume lost per leak was then multiplied by the appropriate assumed new leak frequencies to obtain the annual Real Losses from each class of leak (see Table A1 of Appendix A).

In addition to the real losses volume generated by reported and unreported detectable leaks, there is also 'background' leakage from small non-visible leaks (usually individually less than several hundred litres/hour). Background leaks occur mainly at joints and fittings, they run continuously, but do not generate sufficient noise to be detected by existing equipment. Estimates of lowest achievable background leakage (at 50m pressure) are based on analyses of 'best achieved' night flows in small sectors with reliable low-flow metering, immediately after leak detection and repair (after deducting allowances for customer night use).

Finally, the UARL components in Table A1 of Appendix A were converted to a more 'user friendly' pressure-dependent format for practical use, as shown in Table A2 of Appendix A. The simplest practical metric form, Equation (1) below, can be manipulated (equations (2) to (5)) so that the UARL is calculated in different units, although the coefficients (18, 0.8, 25) remain the same.

$$\text{UARL (litres/day)} \quad = (18 \text{ x } Lm + 0.8 \text{ x } Nc + 25 \text{ x } Lp) \text{ x } P \quad \ldots\ldots(1)$$

or UARL (litres/service conn.day) $= (18/DC + 0.8 + 25 \times Lp/Nc) \times P$ …….. (2)
or UARL (l/service/day/m pressure) $= (18/DC + 0.8 + 25 \times Lp/Nc)$ ………(3)
or UARL (litres/km mains/day) $= (18 + 0.8 \times DC + 25 \times Lp/Lm) \times P$ …….. (4)
or UARL (litres/km mains/day/m pressure $= (18 + 0.8 \times DC) + 25 \times Lp/Lm)$ …….. (5)

where Lm = mains length (km); Np = number of service connections; Lp = total length of private pipe, property line to customer meter (km); P = average pressure (metres); DC = density of connections/km mains

If different measurement units are required (e.g. US Gallons, miles, psi etc as in Lambert et al, 2000b), the three coefficients in the equation (18, 0.8, 25) can easily be recalculated from first principles to suit the alternative units. However, when the ILI is calculated, because it is non-dimensional, it is always internationally comparable, whatever initial measurement units have been used to calculate the UARL.

Why are the UARL equations in the AQUA Paper and the Performance Indicators Manual (2000) different?
This problem arose because the term 'Lp' has been used for two different purposes in the two publications:

- In the 1999 AQUA paper, and equations (1) to (5) above, Lp represents the total length (km) of private pipe between the property line and customer meters
- In the 2000 PIs Report, Lp is used to represent the average length (m) of service connection between the main and the customer meter

Accordingly, in the PIs Report (and it's associated software) the original coefficients in the UARL equation (1) from AQUA had to be modified, by assuming that the average length of service connections (main to property line) was 4 metres. The 'PIs Report' version of the UARL equation appears in on page 47 of Alegre at al, 2000, in the modified form:

UARL (litres/service conn.day) $= (18/DC + 0.70 + 0.025 \times Lp/Nc) \times P$ …….. (2a)

In both the AQUA and PIs Report equations, it is necessary to know (or assess) the number of service connections, defined on p25 of the PIs Report as 'the authorised pipe connecting the main to the measurement point or to the customer stop valve, as appropriate'.

However, for practical application, the AQUA version in equations (1) to (5) is preferred to the PIs Report equation 2b, because:

- comparatively few Utilities know their average length of service connections (main to customer meter),
- in some 50% of situations world-wide (based on the international data set), customer meters are located close to the property line; using the AQUA equations, Lp is effectively zero, and only mains length (Lm km), number of service connections Nc, and average pressure (P metres) are required to calculate UARL.
- In the remaining cases, where customer meters are located some distance after the property line or curb-stop, it is relatively easy to estimate the average and total length of underground pipe from the property line (or curb-stop) to customer meters by inspecting a quite small random sample of service connections.

Why is 'Number of Service Connections' used rather than to 'Number of Properties'?
In many countries, a single service connection serves a much larger number of properties. However, even where apartments are individually metered, the water balance calculation is usually based on the leakage up to a single master meter on the service connection. The definition on p47 of the PIs Report (Alegre et al, 2000) is very clear on this point, stating that:

> 'Where several registered customers or individually occupied premises share a physical connection or tapping off the main, e.g. apartment buildings, this will still be regarded as one connection for the purposes of the applicable PI, irrespective of the configuration and number of customers or premises'

Where the connections to mains for fire-fighting purposes are similar to service connections to properties (having a mains connection, a length of underground pipe and a stop-valve), the authors recommend counting these as service connections to 'registered customers for public or institutional use'.

What is the sensitivity of the UARL equation to assumptions of leak frequency, proportions of reported/unreported leaks, assumed flow rates and average duration?

World class best practice leakage control should ensure that all detectable leaks and bursts – whether reported or unreported – are located and repaired promptly. In the UARL calculations (see Appendix A) the average durations assumed for different groups of leaks range from 3 days for reported main leaks, to 101 days for unreported leaks on private pipes after the property line (approximately equivalent to the average duration for leaks on private pipes with meters at the property line which are read every 6 months).

Applying these targets for average leak durations to leak frequencies consistent with well maintained infrastructure (see Tables A1 and A2 of Appendix A), it can be easily demonstrated that the greatest proportion of UARL occurs from background (undetectable) leakage, rather than detectable leaks (reported and unreported). Sensitivity testing described in the AQUA paper shows that moderate differences in assumptions for parameters used in the 'reported leaks' and 'unreported leaks' components have relatively little influence on the coefficients in Equation (1) for UARL. A simple spreadsheet is available free of charge from the authors, for practitioners who wish to satisfy themselves as to the validity of this statement.

Why is there no allowance for Service Reservoir Leakage/Overflows in the UARL formula?
The IWA Water Losses Task Force view was that service reservoirs should be constructed and maintained so as to be watertight, or made watertight if significant leakage is detected; also, service reservoir overflows can be eliminated by installation of level control, telemetry, altitude valves, and other means. However, the absence of any allowance for service reservoir losses in the UARL formula will tend to slightly favour Utilities which have no underground service reservoirs, as compared to those which do. Accordingly if the UARL formula is revised on some future occasion, it may be reasonable to include some small allowance – perhaps 0.25% of capacity per day or thereabouts – as an additional allowance for undetectable background leakage from underground service reservoirs in the UARL formula.

How reliable are the values used for unavoidable background leakage from mains and service connections?
They represent 'best estimates' based mainly on large amounts of unpublished England/Wales district meter data for small sectors, following the introduction of mandatory leakage targets in 1996. They correspond well with results from a limited number of tests on well maintained infrastructure in Australia and New Zealand, and experience in Germany and Austria. However, further checks based on reliable analyses of good quality data would be welcomed. As leak detection technology continues to improve, some moderate reduction in the values assumed for unavoidable background leakage from mains and service connections may be expected. However, because the assumptions used in the IWA Water Losses Task Force 1999 UARL formula have been clearly shown, it will be easy to modify the UARL formula on an auditable basis.

Note that, when analysing components of night flow, it should be generally assumed that background leakage values will vary with pressure to the power 1.5, rather than a linear relationship. This recommendation is based on many observations internationally, and is attributed at least in part to the fact that many small background leaks have laminar flow characteristics, in which the coefficient of discharge changes rapidly with pressure (and velocity, and Reynolds Number).

How reliable is the assumption of a linear pressure:leakage relationship when calculating UARL?
This depends on a combination of factors; the assumption is most reliable for large systems with mixed metal and non-metal pipework, with average pressure in the range 30 to 70 metres. A recent extensive study of some 70 mixed-pipework sectors in the UK produced an almost exact linear relationship for the pooled data (UKWIR, 2002)..

For systems using only plastic pipes, overall leakage rates are likely to vary with pressure to the power 1.5, irrespective of the ILI value (see Fig 5 of Lambert 2001a), and the linear relationship used in equation (1) would be expected to over-estimate UARL as pressures drop below 50 metres. However, this effect could in practice be limited because leaks in plastic pipes are more difficult to detect and locate by sonic methods, particularly at low pressures.

For systems using only metal pipes, the relationship is more complex, and at high ILI values, overall leakage rates are likely to vary with pressure to a power only slightly greater than 0.5 (see Fig 5 of Lambert 2001a). In such circumstances, equations (1) to (5) will increasingly under-estimate UARL as pressures drop below

50 metres. Practitioners wishing to refine the calculation for all-metal high leakage systems should first calculate UARL and ILI assuming a linear relationship; then estimate an N1 value from the lower line in Figure 5 of Lambert 2001a; then calculate a revised UARL using the equation:

$$\text{Revised UARL} = (\text{UARL at 50m pressure from Table A1, Appendix A}) \times (P/50)^{N1} \quad \ldots\ldots\ (6)$$

What are the practical limitations on using the UARL Formula?
With present experience, the UARL formula cannot yet be recommended with confidence for

- Systems with fewer than 5000 service connections; because the numbers of certain classes of new leaks from year to year may be so small that the assumption of typical average flow rates for each class in component analysis may be invalid
- Systems with less that 25 metres average pressure; because the assumption of a linear relationship may be questionable at such low pressures for all metal, or all non-metal, systems
- Systems with density of connections less than 20 per km; because very few well-managed fully metered systems have so far been found to adequately test the UARL predictions and assumptions at such low connection densities. The UARL assumptions for frequencies of unreported leaks may be too high for long rural systems, where any significant new leak may cause a low pressure complaint or supply failure.

Queries relating to Performance Indicators

Which is the "best" of the traditional Performance Indicators for Real Losses?
The traditional PIs for Real Losses - % of system input volume, per property, per service connection and per km of mains – can best be judged by reference to the key system parameters which influence lowest achievable Real Losses in well-maintained systems – length of mains, number of service connections, location of customer meters and average operating pressure.

" % of system input volume" is easily calculated and frequently quoted. However, in IWA 'best practice' (Alegre et al, 2000), it is used as a Level 1 Financial PI for Non-Revenue Water (NRW) and is clearly stated as being "unsuitable for assessing the efficiency of management of distribution systems". This is because calculated values of % NRW:

- do not distinguish between Apparent and Real Losses (see Fig 4)
- are strongly influenced by consumption (and changes in consumption)
- are difficult to interpret for intermittent supply situations

Real Losses expressed as a % of system input volume also suffer from the deficiencies highlighted in the last twp bullet points above.

Of the three other traditional 'Operational' PIs for Real Losses – per property, per service connection, and per km of mains – 'per property' has been rejected for reasons previously explained in this paper. The IWA recommended 'Best Practice' Level 1 (basic) PI for systems with more than 20 service connections/km of mains is:

'volume/service connection/day when the system is pressurised'

Principal reasons for this recommendation are as follows:

- For well-managed distribution systems with more than around 20 service connections/km of mains, component analysis shows that the greatest proportion of annual real losses volume occurs on service connections; this conclusion is supported by comparisons of new leak frequencies per km of pipe, and practical experience (only a small proportion of systems have less than 20 connections per km of mains)
- 'Real Losses per day' calculated from an annual water balance should not simply be divided by 24 hours and expressed 'per hour'; in many systems leakage rates vary significantly between night and day, because of variations in pressure, so leakage rate 'per hour' in such systems is not 1/24th of the daily Real Losses volume.
- Expressing real losses per day 'when the system is pressurised' allows comparisons to be made between systems with continuous supply, and those with intermittent supply.

Distribution losses expressed in litres/service connection/day are less influenced by density of connections than distribution losses expressed in m^3/km of mains/day; this point is clearly demonstrated in Figure 5 of the IWA International Report on Water Losses Management and Techniques (Lambert, 2001b). Practitioners who continue to use 'per km of mains' in preference to 'per service connection', for reasons of tradition and familiarity, need to specifically recognise that Real Losses targets and PIs expressed in m^3/km mains/day are very strongly influenced by density of connections. For example, in Germany, where connection density varies from 5 to 60 connections/km, the new draft German DVGW proposed 'low water loss' targets more than double (from 1.2 to 3.1 m^3/km mains/day) as density of connections rises 25 to 40 connections/km.

What is the advantage of using the ILI, rather than the IWA Level 1 Performance Indicators?
Because it provides greater insight into the systems you are analysing, without much additional effort. Although 'per service connection/day' is the most robust of the traditional PIs for operational management of Real Losses, it does not take account of mains length, customer meter location (relative to the property line) or average operating pressure. For these reasons, the ILI is a more meaningful basis for performance comparisons, benchmarking, target setting and analyses.

For example, consider two Systems (A and B) in Table 1, each of which has an IWA Level 1 (basic) Performance Indicator for Operational Management of Real Losses of 120 litres/service connection/day. This is quite a reasonable performance based on international comparisons; in the IWA Task Force data set only 8 of the 27 systems had Real Losses less than this.

Table 1 How ILI gives greater insights into performance than litres/connection/day

System	Current Annual Real Losses	Density of Connections DC	Length of private pipe per connection, property line to meter Lp/Nc	Average Pressure	UARL, calculated using Equation 2	Infrastructure Leakage Index ILI = CARL/UARL
	l/conn/day	Per km mains	m/conn	Metres	l/conn/d	
A	120	40	15	65	98	1.2
B	120	100	0	30	29	4.1

However, allowing for the system-specific factors of density of connections, customer meter location (relative to property line) and average pressure, UARL calculated using Equation (2) is 98 l/conn/day for System A, but only 29 l/conn/day for System B. System A therefore has an ILI of 1.2 (120/98), while System B's ILI is 4.1 (120/29). System A's ILI of 1.2 would put it amongst the world best performers (see Appendix C), but System B's ILI of 4.1 is significantly above the median value (and close to the average) of the International data set in Figure 2. This is a quite different perspective from the apparent 'equality' of performance of 120 litres/connection/day, provided by the 'basic' performance indicator.

The 'Twin Track' approach advocated in Figure 3 encourages further diagnosis of potentially beneficial leakage management investigations and activities. In System A, the average pressure of 65 metres is quite high by international standards, and an investigation of potential for further pressure management is likely to be a first priority. In System B, with a relatively low pressure (30 metres) the pressure management options (although always worthy of investigation, particularly for surge control) may prove to be more limited; a review of speed and quality of repairs, active leakage control and infrastructure management policies is likely to identify the most beneficial options.

To what extent can pressure alone influence simple perceptions of true performance?
For practical purposes, the most appropriate simple form of the relationship between average pressure (P) and leakage rate (L) is:

$$L \text{ varies with } P^{N1} \quad \text{or } L1/Lo = (P1/Po)^{N1}$$

A fundamentally important property of this relationship is that it is the ratio of pressures (P1/Po) and the N1 value which determine the relative leakage rates from existing leaks and bursts. Values of N1 for individual small sectors depend upon the predominant type of leaks and the pipe materials; system average N1 can also be provisionally linked to ILI for metal and non-metal systems (see Fig. 5 of Lambert, 2001a). The typical range of N1 observed is between 0.5 and 1.5. For large systems with mixed pipe materials, a linear relationship (N1 = 1.0) is usually assumed if no other information is available.

Average operating pressures for Utilities in the AQUA International data set varied between 30 metres and 100 metres, (median 45 metres) despite the fact that all these Utilities practised pressure management to some extent, limited by local circumstances – notably local topography and minimum standards of service.

In the UK, a linear relationship between leakage rate and pressure for aggregated sector data (equivalent to a large system) has recently been confirmed in a major research project (UKWIR 2002). Table 2 shows how the perspective on leakage management performance can change markedly when pressure is taken into account. System X is located in a flat area with low pressures; System Y in a hilly area with quite high pressure, even after extensive pressure management. Without allowing for average pressure, Real Losses in System Y (in litres/service connection/day) appears to be around 50% higher than Real Losses in System X. Allowing for average operating pressures, it is seen that Real Losses in System Y are in fact 33% lower (not 50% higher) than in System X.

Table 2: How Inclusion of Average Pressure changes simple perception of Performance

	Current Annual Real Losses	Average Operating Pressure	Current Annual Real Losses
	Litres/connection/day	Metres	l/conn/day/m pressure
System X	80	25	3.20
System Y	120	56	2.14

How can you systematically assess average pressure in distribution systems?

There are several options, varying in complexity, (see Appendix C of McKenzie et al (2002) :

- for each individual zone or sector, calculate the weighted average ground level of some clearly defined component of the infrastructure (service connections, or mains, or hydrants); simple spreadsheets or network analysis models (if available) can be used to facilitate these calculations
- near the centre of each zone, identify a convenient measurement point with the same weighted ground level – this is known as the Average Zone Point
- measure the pressure at the Average Zone Point and use this as a surrogate for the average pressure in the Zone

Pressures at the Average Zone Point should be calculated as 24-hour averages values; night pressures at the Average Zone Point are usually referred to as AZNPs (average zone night pressures) and are essential in component analysis of night flow data.

To obtain average pressures for whole systems, calculate the weighted average value of pressure, preferably using number of service connections in each Zone as the weighting factor. Where Network Analysis models are available, this calculation can be based on node point data.

CONCLUSIONS

The concept of 'Unavoidable' or 'Technical Minimum' Losses has been recognised by practitioners for many years, but simple 'losses per km of mains' estimates have been of little practical use, for reasons which are now well understood. The publication of the IWA Water Losses Task Force's system-specific equation for UARL (based on component analysis, using clearly stated auditable principles) has been a significant advance for practical leakage analysis and management.

Because allowance is made for 3 key system-specific parameters – length of mains, number of connections, location of customer meters and average operating pressure – the UARL and ILI approach is more soundly based than previous traditional performance indicators for management of Real Losses in distribution systems. Separating the substantial influence of pressure from the 'infrastructure' factors has introduced clarity to the technical analysis without much additional effort. The approach can be, and is being, used for International, National, and 'within system' comparisons.

Some circumstances have been identified where the UARL formula and ILI approach may not be strictly applicable for performance comparisons. These are systems with fewer than 5000 service connections, density of connections less than 20 per km of mains, or average pressure less than 25 metres.

Nationally recognised leaders in leakage management (Appendix C) have been able to reduce Real Losses close to (but not significantly below) their predicted UARL - giving ILIs close to 1.0, for a wide range of system characteristics. This shows that the UARL formula does reasonably predict 'how low you can go' with Real Losses in systems with diverse characteristics, provided there is sufficient economic or local motivation, and well-managed infrastructure in good condition.

The combination of UARL/ILI, and the IWA standard water balance with 95% confidence limits, offers a new and practical tool for rapid evaluation of opportunities and best options for further leakage management.

Acknowledgements

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Appendix A: Component Analysis to Calculate Unavoidable Annual Real Losses

Mains: assumed new burst frequency 13/100 km mains/year at 50m pressure

- 95% of events reported, 5% unreported
- Reported mains leaks average 864 m^3 loss each (12 m^3/hr for 3 days, or equivalent)
- So loss/km/year from reported mains leaks = 864 x 13 x 0.95/100 = **107** m^3/km/year
- Unreported mains leaks average 7200 m^3 loss each (6 m^3/hr for 50 days, or equivalent)
- So loss/km/year from unreported mains leaks = 7200x 13 x 0.05/100 = **47** m^3/km/year
- Background leakage: 20 l/km/hour for 365 days = **175** m^3/km/year

Total for mains at 50m pressure = **329** m^3/km/year

Service Connections: assumed new leak frequency 5/1000 connections/year at 50m pressure

- Data split into 'main to property line' (3/1000 conns/year at 50m pressure) and 'after property line' (2/1000 conns/year, for 15m average length of unmetered underground private pipe)
- 75% of events reported, 25% unreported
- Assumed flow rate for all new leaks is 1.6 m3/hr at 50m pressure

Service Connections, Main to property line

- Reported leaks (main to property line) average 307 m^3 loss each (1.6 m^3/hr for 8 days)
- So loss/conn/year from these reported leaks = (307 x 3 x 0.75)/1000 = **0.7** m^3/conn/year
- Unreported leaks (main to property line) average 3840 m^3 loss each (1.6 m^3/hr for 100 days)
- So loss/conn/year from these unreported leaks = (3840 x 3 x 0.25)/1000 = **2.9** m^3/conn/year
- Background leakage (main to property line) =1.25 l/conn/hr for 365 days = **11.0** m^3/conn/year

Total for service connections, main to property line = **14.6** m^3/conn/year

Service Connections, private underground pipe between property line and meter

- Reported leaks (15m private pipe) average 346 m^3 loss each (1.6 m^3/hr for 9 days)
- So loss/conn/year from these reported leaks = (346 x 2 x 0.75)/15 = **35** m^3/km/year
- Unreported leaks (15m private pipe) average 3878 m^3 loss each (1.6 m^3/hr for 101 days)
- So loss/conn/year from these unreported leaks = (3878 x 2 x 0.25)/15 = **129** m^3/km/year
- Background leakage = 0.5 l/conn/hr for 15m/connection for 365 days = **292** m^3/km/year

Total for 15m private pipe, property line to customer meters = **456** m^3/km/year

Table A1: Summary of Unavoidable Annual Real Losses Component Analysis at 50m pressure

Infrastructure Component	Background Leakage	Reported Leaks	Unreported Leaks	Total	Units
Mains	175	107	47	329	M^3/km mains/yr
Service Connections, mains to property line	11.0	0.7	2.9	14.6	M3/service connection /yr
Underground pipe, where customer meter is located after property line	292	35	129	456	M3/km of pipe/ year

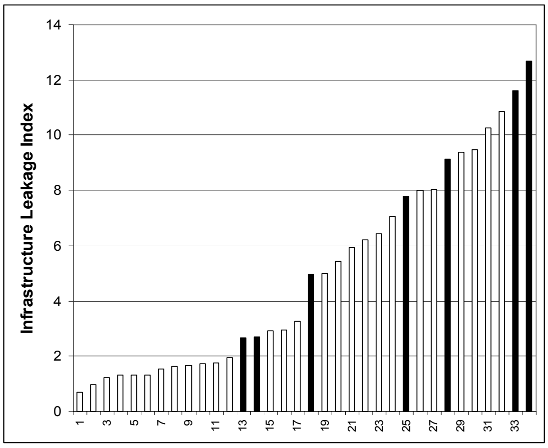
In Table 4 of Lambert et al (1999), the above figures were multiplied by 1000 (to convert to litres), divided by 365 (to convert to average daily values) and divided by 50 metres (to present the figures 'per litre per day per metre of pressure', assuming a linear pressure:leakage relationship). These are shown Table A2 below.

Table A2: Summary of Unavoidable Annual Real Losses Components in AQUA Paper Format

Infrastructure Component	Background Leakage	Reported Leaks	Unreported Leaks	Total	Units
Mains	9.6	5.8	2.6	18.0	l/km mains/day/ metre of pressure
Service Connections, mains to property line	0.60	0.04	0.16	0.80	l/service conn/ day/m. pressure
Underground pipe, where customer meter is located after property line	16.0	1.9	7.1	25.0	l/km of pipe/ day/ metre of pressure

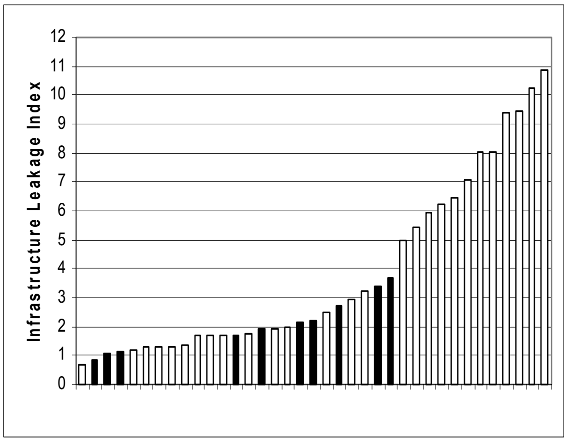
Appendix B: Some National ILI Data for North America, Australia and South Africa

Figure B1: Seven North American Systems, compared to the IWA International Data Set
Source of data: Lambert et al (2000b)



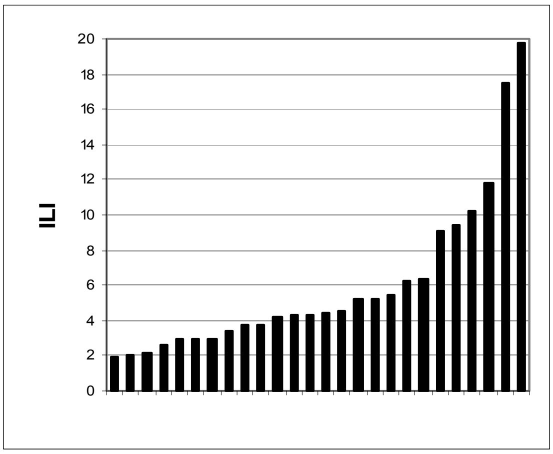
Infrastructure Leakage Index 2.7 to 12.7
(average 7.4)
Density of Connections 25 to 91/km of mains
(average 54/km of mains)
Customer meters 0 to 8 metres after property line
(average Lp = 4 metres)
Operating Pressure 39 to 60 metres
(average 50 metres)
Non-Revenue Water 15.3 to 33.5%
(average 24%)

Figure B2: Ten Australian Urban Systems compared to the IWA International Data Set
Source of data: Carpenter et al (2002)



Infrastructure Leakage Index 0.9 to 3.7
(average 2.1)
Density of Connections 28 to 69/km of mains
(average 47/km of mains)
Customer meters at property line
(average Lp = 0 metres)
Operating Pressure 35 to 72 metres
(average 49 metres)
Non-Revenue Water 9.5 to 22%
(average 14%)

Figure B3: Twenty-six South African Systems
Source of Data: McKenzie et al (2002)



Infrastructure Leakage Index 1.9 to 19.8
(average 6.0)
Density of Connections 22 to 111/km of mains
(average 53/km of mains)
Customer meters at property line
(average Lp = 0 metres)
Operating Pressure 30 to 75 metres
(average 48.4 metres)
Non-Revenue Water 8% to 52%
(average 24.2%)

Note: Systems with fewer than 5000 service connections, or density of connections less than 20 per km, or pressure less than 25 metres, were removed from the South African data set prior to this analysis

Appendix C: Some Water Utilities with Infrastructure Leakage Index values of 1.5 or less

System, country and year	Density of Connections/ km of mains	Distance from property line to customer meter	Average pressure	UARL	CARL	ILI = CARL/ UARL	NRW% of system input volume
		Metres	metres	l/conn/d	l/conn/d		%
WML, Netherlands, 1997	55.5	3	35	42	29	0.70	5.3
Ecowater, New Zealand, 2000/01	46.5	0	54	64	60	0.94	11.0
Central Area Halifax, Canada, 2001/02	50.6	7.5	54.9	73.7	75	1.01	8.0
Yarra Valley Water Australia, 2000/01	62	0	72	78.5	87	1.10	12.8
South-East Water, Australia, 2000/01	53.9	0	54.3	61.6	69	1.11	9.9
JWU, West Bank Palestine, 1996	27.9	0	86	124	146	1.17	22.7
Singapore, 1997	38.0	10	40	61	74	1.21	4.9
Wide Bay Water, Australia 2000/01	27.1	0	65	95.1	116	1.22	14.0
South-West Water, England, Distribution Losses 2001/02	48.4	0*	58	67.5	90.8	1.34	21.1
Southern Water, England, Distribution Losses 2001/02	72.2	0*	46.2	48.5	72.3	1.49	13.8

* These are distribution losses up to the property line; estimates are also available for real losses on metered and unmetered private pipes after the property line (Office of Water Services, 2001)

Notes:

1. All of the above Utilities have well-sectorised networks, with sector inflows continuously monitored by SCADA systems or permanent data loggers.
2. Systems where all customers have roof tanks (JWU) typically experience much higher levels of apparent losses (due to customer meter under-registration) than systems with direct pressure.
3. 95% confidence limits, calculated for Real Losses volume and ILI etc for several of the above systems, are typically in the range +/- 20% to 35%
4. The IWA ‘best practice’ recognises that NRW% - a simple Financial Performance Indicator - is not a reliable indicator of efficiency of management of real losses from distribution systems. Comparison of the two right-hand columns in the above table provides additional confirmation of this. The correlation coefficient between ILI and % NRW in the original (1999) AQUA data set was only 0.17.

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