Water Loss Assessment on Transmission Mains

Joerg Koelbl*, Daniel Zipperer**

* Blue Networks e.U., Roemerstrasse 18, A-8430 Leibnitz/Kaindorf, Austria, koelbl@bluenetworks.at

** aquabench GmbH, Frankfurter Str. 520, 51145 Köln, Germany, d.zipperer@aquabench.de

Keywords: Performance indicator, water loss, transmission mains

Introduction

For assessing water losses in water distribution systems, there are suitable performance indicators available, which allow the consideration of the relevant structural network parameters. However, for bulk systems, respectively transmission mains, so far no such performance indicators and assessment scheme exists.

Experiences in Africa show, that system managers assess water losses on transmission mains often in percentages of system input volume (SIV). This practice is unsuitable from a technical point of view. Further, in most cases no differentiation between real and apparent losses is applied and only the values for non-revenue water (NRW) expressed as a percentage of SIV are analysed. In Europe often losses per km of pipe are used.

The preferred performance indicator for distribution systems (compare Lambert & Hirner, 2000), the Infrastructure Leakage Index (ILI), is based on a reference value, the unavoidable annual real losses (UARL). The UARL originates from a dataset that included numerous distribution networks with miscellaneous pipe materials and diameters. For transmission pipes, the situation is different. In most cases, pipe material and diameters are rather homogenous, maybe with little variations along the pipeline corridor due to hydraulic requirements. Thus, each transmission network has its very own characteristic regarding pipe material, couplings and diameters. Due to this, and thanks to the fact that transmission mains only have an insufficient number of connections (off-takes), the UARL is seen as an unsuitable reference for the comparison of losses from different bulk systems. For example, it is not meaningful to compare water losses of a 1,000 mm reinforced concrete pipe with those of a 500 mm ductile iron pipe. The German water loss guidelines DVGW W 392 and the Austrian OVGW W 63 (2009) do not provide suitable concepts for standardised assessments of losses on transmission mains, and neither does any other guideline worldwide.

This paper aims to describe the findings from analyses of water losses on transmission mains using data from Germany, Austria and Kenya. It tries to elaborate the challenges in comparing water losses of different bulk systems. Further, it considers aspects of pipeline inspection and leak control as well as leak repair. The paper does not provide a final and conclusive suggestion of an assessment scheme for transmission mains, but it ought to lay the foundations for further discussion on this vital topic. The authors anticipate that additional inputs from water loss experts and experiences from other countries may enable the development of a performance indicator, similar to the ILI for distribution networks, but specifically for transmission mains.

Characteristics of NRW Components on Transmission Mains

The IWA water balance (see Table 1) is the standard methodology for assessing volumes of real and apparent losses. This scheme is applicable for both, transmission and distribution systems.

While the accuracy of the required water balance data is always challenging, particularly for transmissions systems, it is necessary to consider that water loss components, in general, are much smaller than the system input volume (SIV). Thus, inaccuracies of SIV have a significant impact on the accuracy, especially to the real component.

Table 1: IWA Water Balance (Alegre et al. 2017, amended)

System Input Volume	Authorised Consumption	Billed Authorised Consumption	Billed Metered Consumption	Revenue Water
			Billed Unmetered Consumption	
		Unbilled Authorised Consumption	Unbilled Metered Consumption	Non-Revenue Water
			Unbilled Unmetered Consumption	
	Water Losses	Apparent Losses	Unauthorised Consumption	
			Metering Inaccuracies and Data Handling Errors	
		Real Losses	Leakage on Raw Water Mains and Treatment Plants (if applicable)	
			Leakage on Transmission and/or Distribution Mains	
			Leakage and Overflows at Transmission and/or Distribution Storage Tanks	
			Leakage on Service Connections up to the Measurement Point	

Characteristics of NRW components on transmission mains vary between high income and low and Low and Middle Income (LAMI) countries.

While Unbilled Authorised Consumption (UAC) is usually low in high-income countries, real and apparent water loss components are the main components of NRW on transmission mains. Real losses occur during bursts, which usually have a short runtime as they are detected quickly, but also they arise from small leaks on connections (off-takes) and couplings which often have a long runtime as they are detected only by routine leak detection campaigns.

Of utmost importance is the apparent losses component that includes metering inaccuracies. The Apparent Loss Guidance Notes (Vermersch et al. 2016) recommend an adapted water balance, where apparent loss only include customer metering (respectively off-take metering) errors and which considers system input metering errors as part of the SIV component of the water balance. However, as the participating utilities did not assess errors in SIV metering in detail, all water balance data calculated for this study following the standard IWA water balance. Thus, all metering inaccuracies were allocated to the apparent loss component.

In LAMI countries real and apparent loss components are usually more extensive than in high-income countries, and the characteristics of these components are different. For example, the authors observed while working on loss reduction projects in East Africa that leaks often have long run times. For some leaks that are difficult to repair run times of several years are not uncommon. Further vandalism by people and in national parks due to wildlife is a big issue that leads to higher real loss volumes.

Apparent loss components also have another character in LAMI countries, where illegal consumption at all kind of accessible points such as off-takes, washouts and air valves are an issue. Metering inaccuracies are usually also higher since field assessment often show that meters do not work correctly. Not uncommonly, it is necessary to estimate flows thanks to utterly inoperable metering systems.

Metering Challenges of Transmission Systems

System Input and Section Meters

As water losses in comparison to the SIV represent only a small proportion, errors in SIV metering, respectively section metering, have a significant impact on the accuracy of calculated water loss volumes. In general, electromagnetic flow meters (full-bore or insertion) or ultrasonic meters are the best available technology for system input metering. Errors of such meters are usually within the range of +/- 1-2% or less (compare Table 2).

Table 2: Indicative Examples of Metering Accuracy (World Bank Institute, 2007, in Farley et al. 2010, amended)

Equipment/Method	Approximate Accuracy Range
Electromagnetic Flow Meters	< 0.15 – 0.5 %
Ultrasonic Flow Meters	0.5 – 1 %
Insertion Probes	≥ 2 %
Mechanical Meters	1.0 – 2 %
Venturi Meters	0.5 – 3 %
Measurement Weirs in open channels	10 – 50 %
Volume calculated with pump curves	10 – 50 %

Note: Actual meter accuracy will depend on many factors (like flow profile, calibration, meter installation, maintenance) and must be verified case by case.

Often SIV and section meters are not calibrated regularly due to various reasons. While large diameter meters are difficult to calibrate, system input meters are often also located in remote areas, which makes their calibration costly. Thus, many transmission system managers do not pay sufficient attention to this issue at the expense of inaccurate SIV measurements to result in inaccurate real and apparent loss calculation.

Off-Take Metering

In general, the number of off-takes (hand-over points to distribution or other transmission systems) is limited in high-income countries, and off-takes meters are of larger diameter.

In LAMI countries many off-takes (often with a small diameter) along transmission mains are more common than in high-income countries.

Potential Metering Errors

Since the number of both, system input and off-take meters, in transmission systems is much lower than in distribution systems, systematic measurement errors of individual meters have a more substantial impact due to statistical reasons. Not uncommonly water loss calculations in systems with low real losses result in negative real loss values, which is implausible.

Two datasets of high-income countries used for this analysis show negative water losses as metered system input volumes are less than billed water consumptions (one value is about -2.8% of the SIV, another is about -1.3% of SIV). Unfortunately, it was not possible to evaluate if this results from inaccuracies of system input meters or meters at off-takes or even a combination of both. Therefore, these negative losses were allocated to the apparent loss component.

Another fact is, that metering errors could be in the range of water losses on transmission mains or even higher in well-managed systems which are in excellent condition. This fact means that tremendous effort needs to be spent to ensure accurate metering, while the benefit for bulk suppliers frequently do not seem to be worth investing in accurate metering as water losses on transmission systems are often low.

Active Leakage Control on Transmission Systems

Without going into too much detail about the available leak detection methodologies for transmission mains, it is necessary to stress some issues to be able to understand the role of network inspection and active leakage control in transmission systems.

In general, monitoring for large bursts is easy because drops in pressure and reduced flows will indicate a burst. However, small leakages are difficult to identify on transmission mains. It may only be possible to identify small leaks by routine inspections of the transmission mains that possibly will require specific leak detection methodologies. Correlation is often not possible on transmission mains due to missing connection points to the pipe. Thus, besides visual inspections, especially geophones, in-pipe methodologies, as well as gas-methodologies are applied. These technologies require adequate expertise. Thus, they are costly which is a hindrance for many water utilities.

Origin of the dataset and selected Key PIs

To analyse the level of water loss among bulk water suppliers a set comprising water loss data from twenty utilities – sixteen from Germany, three from Kenya, and one Austrian – was utilised. The annual benchmarking program for bulk suppliers in Germany contributed data of several German utilities. Further, additional Austrian and Kenyan data were derived directly from some utilities or collected during contracted work. Most of the data are from 2016, but some datasets hold data from 2011, 2014, or 2015.

With these data, the authors calculated several standard performance indicators for NRW, apparent and real losses. In addition to this, we tested a new performance indicator to account for the influence of larger mains diameters on water loss levels and also the more widespread diameters distribution in transmission systems.

Table 3: Selected Key PIs

Domain	Type	Unit	Description
Non-Revenue Water	Financial	%	The proportion of Non-Revenue Water as a percentage of system input volume
Apparent Losses	Operational	%	The Proportion of Apparent Losses as a percentage of system input volume
Real Losses	Operational	$m^3/km/a$	Annual real losses per km mains
Real Losses	Operational	$m^3/m^2/a$	Annual real losses per lateral surface area

Non-Revenue Water

Numerous authors have argued in the available literature on water losses that the traditional ‘percentage by volume’ indicator for the various components of the water balance can be very misleading as differences and changes in the volume of consumption strongly influence them (e.g. Merks et al. 2017). However, provided that the ‘percentage by volume’ indicator account for the complete volume of non-revenue water, it is a quick way to derive at a reasonable ballpark figure that indicates the level of water loss from a revenue point of view. Thus, we used ‘NRW percentage by volume’ as the starting point of our analysis.

Apparent Losses

Apparent losses are one of the components that may be critically affecting utility performance regarding the level of water loss, notably if it lacks an appropriate meter management policy. However, while utility management may tackle meter handling errors and inaccuracies with a suitable policy, water theft and illegal use also involve a cultural and social perspective. Compared to leakage management and control there is still less research in components of apparent losses, and subsequently, up to now, there is no well-accepted indicator for apparent losses available. For this study, we thus used the 'percentage by volume' indicator to analyse the level of apparent losses.

Real Losses per Mains Length

Real losses are usually either expressed to the number of service connections of the supply system under study or over the mains length. Since leakage component analyses in water distribution systems across the world have shown that the most significant proportion of physical losses occur on services connections, including the connecting point to the main, the denominator with the best range of applicability for real losses is the number of service connections. However, for transmission systems, this does not apply as there are only a few 'service connections' (off-takes). Therefore, we used the mains length as this denominator is recommended as an alternative in the literature (Alegre *et al.*, 2017).

Real Losses per Lateral Surface

Various factors are affecting the level of water loss in supply systems, of which the mains length is only one aspect that is important. Compared to distribution systems, transmission networks usually consist of pipes that are larger in diameter. At the same time, the distribution of diameters can be more widespread. As the network structure (of which the existing pipe diameters are one aspect) is another factor that affects the level of water loss we used the lateral surface area of the mains as an alternative denominator that accounts for both, mains length and the embedded diameters. Unfortunately, the available data set provided the mains length for the diameters only in four classes:

- DN ≤ 100
- 100 < DN ≤ 300
- 300 < DN ≤ 600
- DN > 600

Consequently, it was only possible to use an average diameter for each of the classes. Thus, it is necessary to take the presented results for this indicator with a grain of salt. Nevertheless, we argue that this may be an interesting indicator for transmission systems. Just like any other available water loss indicator it only partly considers the various factors affecting the level of water loss, but it may provide some advantages compared to a pure longitudinal denominator while still being very easy to digest.

Results of Data Analyses

Non-Revenue Water

To get a feeling about the level of water loss we first looked at the Non-Revenue Water per system volume (Figure 1). Not surprisingly, the calculated values of the three Kenyan utilities pull away from their German and Austrian peers. There is a factor of 2.7 between the maximum NRW value of the European bulk suppliers and the minimum value in the Kenyan peer group. Also – not to our surprise – the diagram indicates that it is meaningful to expect NRW values in transmission systems to be much lower than those of distribution systems. It is even possible to argue that for the average German or Austrian bulk supplier NRW levels are neglectable – at least from a revenue point of view. For more than half of the included utilities in this study the NRW level is below one percent of the corresponding system input volume.

In addition to this, the diagram also shows negative NRW values for two bulk suppliers. These values arise due to a combination of a relatively large volume which is supplied using a relatively short and well-maintained transmission system to which only a few larger municipal customers are connected. These circumstances cause an under-registration of production and transmission input meters combined with an over-registration of customer meters (off-takes). Since the law in Germany requires utilities to replace or calibrate meters used for invoicing every six years (every five years in Austria), it is safe to assume that all metering inaccuracies are within the accepted range. Thanks to a lacking homogenization of measuring errors caused by the low number of connected customers those bulk suppliers are in the favourable circumstance to be legally able to invoice a higher volume than they have produced initially.

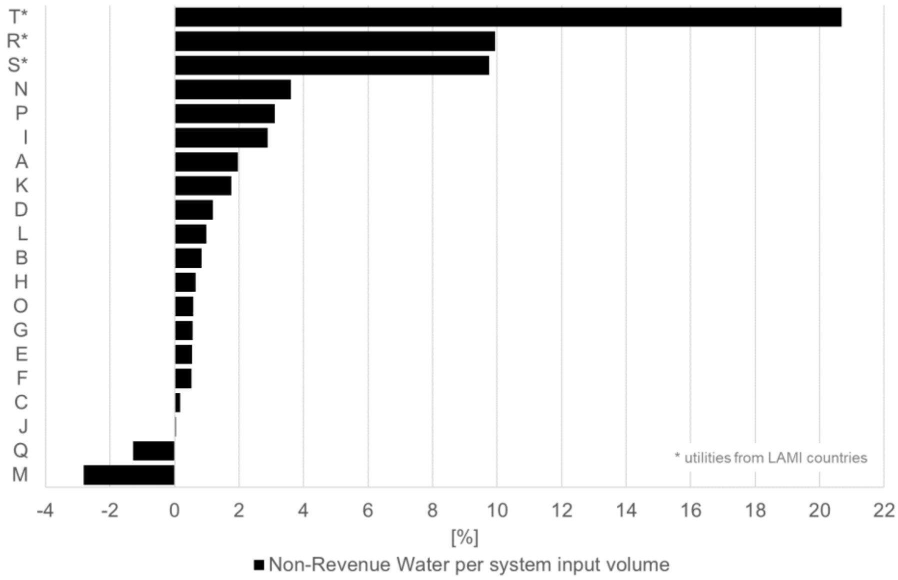

Figure 1: Non-Revenue Water per system input volume

Apparent Losses

Figure 2 shows the apparent losses per system input volume. Again, there is a factor of 2.7 between the maximum value of the European peer group and the minimum value of the Kenyan bulk suppliers. Apart from utility Q, it is safe to assume that the calculated values for all utilities, European and non-European, are based on fewer sound estimates of their apparent loss volume. Utility Q is the only utility with a negative NRW level that has no mains failures. Using the recommended standard steps for calculating the water balance given in the IWA 'Best Practice' Manual (Alegre et al., 2017), it is possible to allocate the entire negative difference between billed (and unbilled) authorised consumption and system input volume to the apparent losses as a whole. To the contrarian, utility M did have a few mains failures in the reference period. Consequently, it is necessary to conclude that its annual water balance must show some volume of real losses despite its negative overall NRW level. However, in this case, it is not possible to complete the IWA water balance with the recommended standard steps further than calculating the difference between system input volume and authorised consumption.

Even further, also the other calculated values for apparent losses may not be reasonably accurate. While the current German (DVGW, 2017) and Austrian (OVGW, 2009) water loss guidelines demand to restrict the application of apparent losses to a maximum of 0.5% of the system input volume, strictly speaking, this empirical value only applies to distribution systems. Currently, there is no such rule of thumb known for transmission systems. Even if there were a rule available, this would not apply to the Kenyan utilities. In this study, their level of apparent losses is roughly estimated to be equal (S, T) to their volume of real losses or around 50% of it (R).

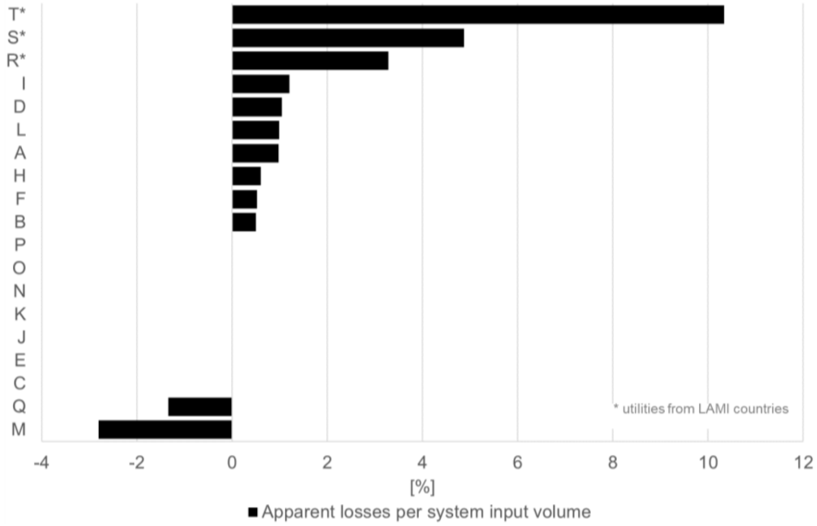

Figure 2: Apparent losses per system input volume

Real Losses per Mains Length

The previous version of the German water loss guidelines (DVGW, 2003) provided an evaluation scheme in which for a given supply system with a service connection density of fewer than 20 connections per km the below reference values were valid.

Table 4: Water loss reference values

	m³/km/h	m³/km/a
low	< 0,05	< 438
medium	0,05 – 0,10	438 - 876
high	> 0,10	> 876

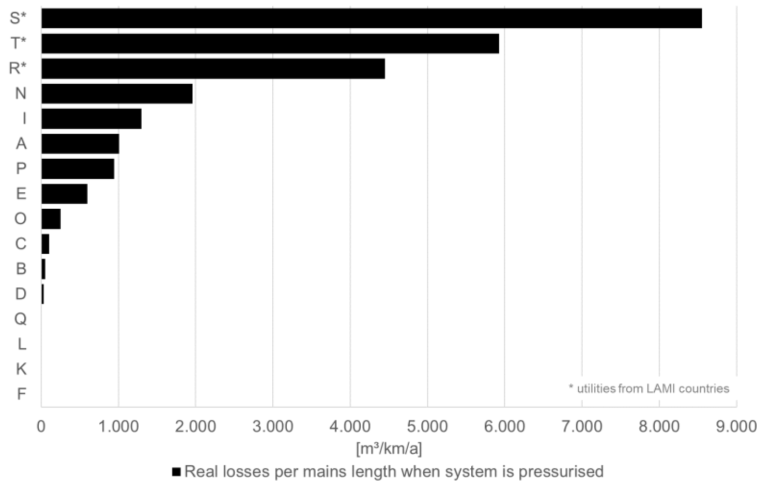

Figure 3: Real losses per mains length

Although the guidelines recently received an update due to which they now lack the above reference values, it is still interesting to compare them to the calculated values of real loses per mains length of the data set. Based on the reference values, more than a third of the transmission systems in Figure 3 would fall within the category of high water losses, including the three Kenyan utilities. However, strictly speaking, the evaluation scheme was developed using data from distribution systems (Weimer, 2001), and thus, it was not meant to evaluate transmission systems based on them. Nevertheless, it is not so far off to expect reference values for transmission systems to be even lower than those of distribution systems with a low service connection density. Unfortunately, to our knowledge, there is currently no such classification scheme for transmission systems available.

Real Losses per Lateral Surface

The denominator of this indicator considers the mains length, but at the same time, it combines it with the pipe diameter to a unit area. In our literature research, we did not find any evidence that such an indicator was used to evaluate water losses, and subsequently, we cannot draw from experience.

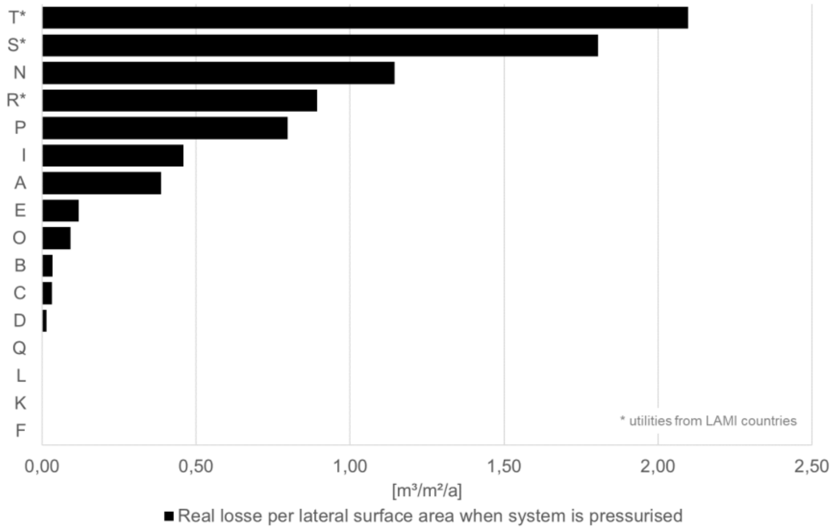

Figure 4: Real losses per lateral surface area

What we found interesting in Figure 4 is that compared to Figure 3, the order of the utilities does slightly change. Now, to our surprise, one of the Kenyan utilities is within the range of the European values, although still with a comparatively high value.

Table 5: Change of the relative position within the peer group

utility	F	K	L	Q	D	B	C	O	E	P	A	I	N	R	T	S
m³/km/a	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
m³/m²/a	1	2	3	4	5	7	6	8	9	12	10	11	14	13	16	15
count	0	0	0	0	0	-1	1	0	0	-2	1	1	-1	1	-1	1

The denominator favours utilities with a higher fraction of larger pipe diameters while it is less fortunate for bulk suppliers with smaller pipe diameters.

Additionally, we plotted the calculated level of this indicator against some explanatory factors. From these, the network inspection rate suggested having the most obvious influence. Figure 5 in which the radius of the circle is equivalent to the level of the real losses per lateral surface area illustrates this. Utilities B, C, and D that inspect their complete network at least once per year seem to have lower losses than their peers who investigate lesser parts of their transmission system (or who do not schedule an inspection at all).

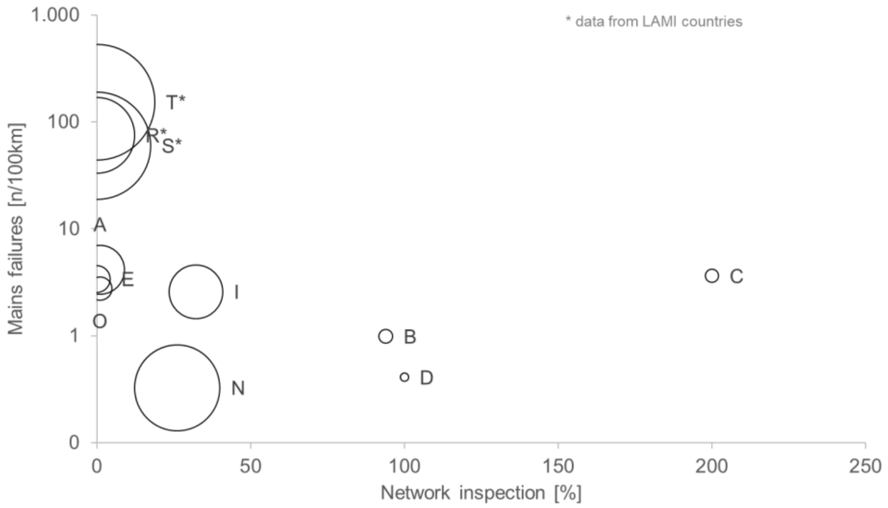

Figure 5: Network inspection rate and mains failures plotted against real losses per lateral surface area

Conclusions and Outlook

When preparing this paper, it was more or less clear that it will be unlikely being able to present a well-founded recommendation for one specific performance indicator with a suitable classification scheme for water losses on transmission mains. Even if assessing water losses on transmission systems looks easier than in distribution systems, it is getting tricky when it goes into the details. Every transmission system has its unique characteristic regarding structural parameters such as diameter, pipe material, type of couplings, and operating pressure to name just a few aspects.

The preferred performance indicators for assessing water losses on transmission systems mainly depends on the purpose of the analysis:

- For technical purposes, the percentage of system input volume is not meaningful. Unfortunately, this indicator is still widely used – for all types of water supply systems.
- For internal monitoring of water losses from one reference period to the next, losses per mains length (m^3/km/h or m^3/km/d or m^3/km/a) are suitable.
- Comparisons between transmission systems, benchmarking and loss assessments are challenging as every transmission system has specific characteristics. How meaningful is a comparison of losses per mains length when diameters, material and pressure are entirely different? Thus, these frame conditions need to be considered accordingly, which is not trivial.
- The performance indicator 'Real Losses per lateral surface' appears suitable for comparisons of differently sized transmission mains as it compensates differences in diameter. Nevertheless, it does not consider the average operation pressure and other parameters such as the off-take (connection) density.

What could be an ideal performance indicator for benchmarking and water loss assessment of transmission systems? Is it possible to create something like an 'ILI for transmission systems'? Such an idea seems feasible, and it would be beneficial to have a standardised performance indicator for transmission systems. Table 6 provides an overview which parameters are necessary to consider in a formula (similar to the ILI) and which parameters may be more suitable to use as explanatory factors.

Table 6: Parameters influencing water losses on transmission mains

Parameter	Included in the calculation	Considered as an explanatory factor
Pipe material	no	yes
Length of transmission mains	yes	possible
Pipe diameter (inner lateral surface)	possible	possible
Off-takes per km	possible	possible
Pressure	yes	possible
Pipe age	no	yes
Number of armatures (e.g. gate valves, air-valves, hydrants etc.)	possible	possible
Network inspection, monitoring	no	yes
Failure rates	no	yes
Country classifications by income level (LAMIC and non-LAMIC)	no	yes

By taking the ILI for water distribution systems as a blueprint, it is possible to draft a similar formula structure of an indicator for real losses on transmission mains in which the denominator represents the corresponding UARL:

$$\text{TLI} = \frac{Real\ loss\ volume\ [m^3]}{(a \times \sum_{i=1}^{i=n} 2 \times \pi \times r_n \times l_n + b \times N_{offtake} + c \times N_{armatures}) \times P}$$

TLI	*Transmission Mains Leakage Index*
a, b, c	*Coefficients, to be determined empirically, eventually different coefficients for high income and LAMI countries suitable*
r_n	*Inner pipe radius of pipe section n*
l_n	*Length of pipe section n*
$N_{offtake}$	*Number of off-takes along transmission main*
$N_{armatures}$	*Number of armatures along transmission main (gate valves, air valves, PRVs, hydrants, etc.)*
P	*Weighted average operation pressure* $\sum_{i=1}^{i=n} \frac{l_1\ x\ P_1 + l_2\ x\ P_2 + \cdots + l_n\ x\ P_n}{l_1 + l_2 + \cdots + l_n}$

Of course, such a performance indicator would require a more extensive data set for thorough testing the formula and determine the included coefficients empirically. We suggest establishing a working group, which collects standardised data from different countries and different frame conditions and carries out the analysis.

Almost twenty years after the creation of the ILI for distribution systems, and after its widespread adoption, it is about time to develop a similar indicator for transmission systems.

References

Alegre H., et al. (2017) Performance Indicators for Water Supply Services. IWA Manual of Best Practice, 3rd Edition. ISBN 9781780406336

DVGW - Guideline W 392 (2003) Network inspection and water losses – activities, procedures and assessment. – DVGW, Bonn, Germany.

DVGW - Guideline W 392 (2017) Water losses in distribution networks – Assessment, monitoring, classification, water balance, performance indicators. DVGW, Bonn, Germany.

Farley M., G. Wyeth, Z. Bin Md. Ghazali, A. Istandar and S. Singh (2010): The Manager’s Non-Revenue Water Handbook for Africa: A Guide to Understanding Water Losses. Edited by USAID – The World Bank Institute.

Lambert, A. and W. Hirner (2000) Losses from water supply systems: Standard terminology and recommended performance measures. IWA Blue Pages, London.

Merks C., Shepherd M., Fantozzi M. and A. Lambert (2017): NRW as a % of System Input Volume just doesn’t work! PI 2017 Conference of the IWA benchmarking and performance assessment group in Vienna, Austria, May 15-17 2017, Presentation.

OVGW W 63 (2009) Water losses in water supply systems – Assessment, evaluation and measures for water loss reduction. OVGW, Vienna, Austria.

Vermersch, M., F. Carteado, A. Rizzo, E. Johnson, F. Arregui and A. Lambert (2016): Guidance Notes on Apparent Losses and Water Loss Reduction Planning.

Weimer D. (2001): German National Report - Water Loss Management and Techniques. Report to IWA World Water Congress, Berlin, October 2001.