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Water loss management in Europe: perceptions, drivers, responses/strategies, and results

Peter van Thienen [a,*], David Bernhard Steffelbauer [b,c] and Ina Vertommen [a]

[a] KWR Water Research Institute, Groningenhaven 7, 3433 PE, Nieuwegein The Netherlands
[b] KWB Kompetenzzentrum Wasser Berlin gGmbH, Grunewaldstr.61-62, Berlin 10825, Germany
[c] Indigo Water FlexCo, Höhenweg 13c, Seiersberg-Pirka 8054, Austria
*Corresponding author. E-mail: peter.van.thienen@kwrwater.nl

PvT, 0000-0001-5528-845X; DBS, 0000-0003-2137-985X; IV, 0000-0002-0897-1309

ABSTRACT

Despite global efforts to reduce non-revenue water (NRW), average levels remain at 30% worldwide and 25% in European countries. This paper investigates whether these persistent water losses stem primarily from uncontrollable environmental factors or from management practices. Through two rounds of questionnaires with water utilities across multiple countries and exploratory data analysis of data on 120 utilities, the research examines geographical conditions, utility characteristics, and water loss reduction strategies. Findings reveal that geographical conditions significantly impact Infrastructure Leakage Index (ILI) levels across Europe, suggesting that these factors should be considered when setting reduction targets. Also, a clear progression exists from low-resource measures implemented by high-ILI utilities to sophisticated technologies adopted by low-ILI utilities. While underinvestment likely contributes to high water losses, limited network investment data prevented a comprehensive analysis. The study recommends that the EU drinking water directive should account for utility size, establish measurement standards, encourage partnerships between large and small utilities, and include smaller utilities in reporting requirements. Additionally, incorporating economic metrics and investment data for pipe rehabilitation and digital technologies would enhance understanding of effective water loss reduction strategies. Comprehensive, standardized data collection could catalyze innovations to reduce 'unavoidable' losses and significantly decrease overall water losses across Europe.

Key words: digitalization, external factors, NRW reduction strategies, unavoidable losses, water loss

HIGHLIGHTS

- European water losses average 25%, raising questions about environmental factors vs. management practices as primary causes.
- Geographical conditions significantly impact water loss levels and should be considered when setting reduction targets.
- Smaller utilities often have higher losses and represent significant potential for EU-wide water reduction.
- Clear progression exists from basic measures in high-loss utilities to advanced technologies in low-loss utilities.
- Standardized data collection is crucial for understanding water loss patterns and developing effective solutions.

INTRODUCTION

Non-revenue water (NRW), the difference between the volume of water distributed and the amount billed to customers, is approximately 120 billion m^3 of water each year (Kingdom *et al.* 2006). The majority of NRW stems from physical losses (Kingdom *et al.* 2006), with undetected leaks in water pipes being the main reason, at least in developed countries. Despite efforts to decrease NRW, the global average remains at 30% (Liemberger & Wyatt 2019). This issue is not confined to less economically developed countries. In fact, the average NRW level in European countries is 25%, according to EurEau (2021). These high NRW levels pose a significant challenge in terms of energy and resource efficiency, particularly considering factors like population growth, urbanization, and the impact of climate change on water availability. The European Union (EU) has introduced a directive to minimize water loss (Directive (EU) 2020/2184), which now requires large water utilities ($\geq$1,000 m^3/day or $\geq$50,000 people) to report water losses in EU member states, using either the Infrastructure Leakage Index (ILI) or another appropriate method. Based on EU-wide reported figures, the EU will establish a threshold value for water losses. The drinking water directive will then require member states to create action plans for effective leakage reduction. This requirement will pressure utilities with high levels of NRW to reduce their losses.

Over the past decades, we have built up a reasonable understanding of pipe failure mechanisms and the behavior of leaks. However, the question remains: why are water losses so high and why do they vary across countries, and even within the same country? Could these losses, to some degree, be attributed to environmental factors beyond operators' control – such as soil conditions, topography, or climate? For instance, leaks in sandy ground may infiltrate and become less easily visible on the surface (Barton *et al.* 2022). Additionally, since leakage rates depend on pressure, areas with significant elevation changes experience greater water losses through pipe leaks and faulty joints (Santonastaso *et al.* 2020). Moreover, seasonal temperature swings between cold winters and warm summers stress pipes, leading to more breaks during seasonal transitions. Given these natural constraints, should we penalize utilities and countries that face these unfavorable environmental conditions? Or should the leakage reduction requirements reflect these conditions?

But more factors may be at play. Chronic underinvestment in infrastructure maintenance has resulted in aging networks, while leak detection efforts remain insufficient. The key question is whether utilities should proactively increase their rehabilitation spending or simply allocate existing funds in a more reactive way to address leakage.

Finally, digitalization may offer a solution – combining sensors, data, and algorithms through hydraulic modeling, data analysis, AI, and digital twins can create valuable opportunities to identify, understand, and resolve water loss problems (Sarni *et al.* 2019). However, widespread adoption of digital solutions for water loss management remains incomplete (Daniel *et al.* 2023). These promising technologies require high-quality data and dense sensor networks, which means they have initially been implemented mainly as research prototypes or proof-of-concept projects at innovative, early-adopter utilities that were willing and able to invest, but are becoming more mainstream now (Daniel *et al.* 2023).

This paper seeks to answer these questions by sharing insights gathered from interviews with water utilities across various countries about their water losses and water loss management strategies. It also includes an exploratory data analysis to identify possible factors affecting leakage levels in different countries, regions, and utilities.

METHODS

Questionnaires

In order to understand the present situation, conditions, and their context for European water utilities, a questionnaire was developed in an iterative manner among the authors generally following best practices as described in, e.g., Krosnick & Presser (2010). It was sent out to water companies throughout Europe, examining factors affecting water losses through five main sections: (i) pipe network characteristics, (ii) water loss assessment methods, (iii) pipe renewal and network rehabilitation strategies, (iv) sensors and available data for active leakage control, and (v) perceived trade-offs between pipe rehabilitation, repair, and leak management. The response rate was 37% (11/30). We note that the number of participants is clearly insufficient to be a representative sample of the European drinking water sector (e.g., for a 90% confidence level, that would require 67 participants out of a population of 15,200 utilities in the EU (Statista 2025), using Cochran's (1977) sample size estimate). The objective in this paper is not to provide this representative overview, but to tentatively identify relations between parameters for the subpopulation represented by the sample.

In the pipe network characteristics section, we collected data about utility size through three metrics: network length, number of customers served, and daily water volume provided. This information enables comparison between utilities and helps determine whether larger utilities implement more advanced water loss prevention processes. We also gathered data about pipe material distribution, as leakage patterns depend on the interaction between network pressure, pipe materials, and typical failure modes (holes, cracks) (Cassa *et al.* 2010; Fuchs-Hanusch *et al.* 2016). The survey included questions about pipe age since deterioration increases with time, and older pipes fail more frequently. Therefore, research indicates that age is the strongest predictor of failure risk (Dawood *et al.* 2022).

In the water losses section, we assessed utilities' loss magnitude and measurement methods for comparative analysis. We tracked whether losses were decreasing – suggesting successful reduction efforts – or increasing, which might indicate ongoing challenges and growing awareness. We explored their motivations for reducing water losses, examining whether internal pressures or external forces (regulators, government bodies, or public opinion) drove their reduction initiatives, and documented their current loss reduction measures.

The final three sections – pipe renewal, sensors, and trade-offs – focused on evaluating the balance between pipe rehabilitation and smart water management for leakage reduction. These sections address the four principal methods of interventions to reduce real water losses: (i) pipeline and asset management, (ii) pressure management, (iii) speed and quality of repairs, and (iv) active leakage control (Farley & Trow 2003). While pipeline and asset management involve conventional rehabilitation and pipe renewal (Section 3), eventually supported by digital asset management tools, the other components utilize smart water technologies, including sensors, computer models, and automated alert systems (Section 4). In Section 5, we examined utilities' strategic preferences between proactive network rehabilitation to prevent failures and reactive 'firefighting' approaches that focus on swift leak detection, localization, and repairs with the help of smart water technologies and digitalization.

An initial analysis of the answers that were obtained from the participating water utilities inspired us to formulate a series of follow-up questions, which were sent to the utilities that responded to the first questionnaire. Most questions related to changes in policies over the past decades and geographical characteristics. The full list of questions is provided in the Supplementary material. The response rate to this second round was 73% (8/11). Companies were anonymized for privacy reasons. Table 1 summarizes the ID-code for each water utility, the country of origin, their estimated ILI values, if they answered the follow-up questionnaire, and their approximate size in terms of customers served and network length.

Table 1 | Water utilities that answered the questionnaire, identified by a company ID, corresponding country of origin, ILI, approximate number of customers served, and network size

ID	Country	ILI	Follow-Up	~ Customers (x1000)	~ Network Size (km)
1	Netherlands	0.32		> 1000	> 10000
2	Netherlands	0.38	X	> 1000	> 5000
3	Netherlands	0.43	X	> 500	> 2500
4	Netherlands	0.49	X	> 1000	> 25000
5	Germany	0.7	X	> 1000	> 5000
6	Belgium	1.23	X	> 1000	>25000
7	Portugal	1.55		< 100	~ 1000
8	Cyprus	2.59		> 100	~ 1000
9	Switzerland	3.58	X	> 250	~ 1000
10	Norway	4.48	X	> 250	~ 1000
11	Greece	5.25	X	> 500	> 2500

Note: Companies that answered both questionnaires are indicated by 'X'.

Data gathering and analysis

Additional data, including topography, soil types, water loss, investment data, rates, water demand, and availability, were gathered to give more context to the answers provided to the questionnaires.

Soil types – which affect the ease of leak detection, as leaks surface quickly in sandy soils, and are therefore easier to see, while these remain hidden longer in permeable soils – were obtained by studying the supply areas of the contributing water utilities in the Soil Atlas of Europe (European Soil Bureau Network European Commission 2005). The topography of a supply area significantly affects pressure variations in drinking water distribution systems. Higher elevations experience lower pressures, while lower areas face increased pressure loads – leading to higher risks of pipe failures and greater leakage flow through existing cracks/faults in pipes. Hence, their topography range was determined using Google Maps for the supply areas. In an extension of some of the analyses presented below, ILI numbers were obtained or estimated for an additional 119 European utilities from their websites and annual reports, and predominant soil types and elevation differences in their supply areas were collected as described above. The ILI is a performance indicator of real (physical) water loss from the supply network of water distribution systems, calculated as the fraction between the current annual real losses (CARL) and the unavoidable annual real losses (UARL) as follows: ILI = CARL/UARL with UARL = (18 × Lm + 0.80 × Nc + 25 × Lp) × P, in which Lm is the main length (km), Nc is the number of service connections, Lp is the total length of underground pipe (street edge to customer meters), and P is the operating pressure (meters) (Lambert *et al.* 1999). It is commonly interpreted to be a more meaningful indicator of water loss rate than others because it focuses on physical losses and corrects for operating pressure, and as such, is suitable for the purposes of this paper.

Water loss data for the participating water companies have been reported by the companies themselves, in varying forms. We have transformed these into ILI factors wherever necessary, sometimes making assumptions about operating pressures (i.e., 30 m) and mean service pipe length (i.e., 20 m). On a national level, we have used water loss and investment level numbers as compiled by EurEau (2017, 2021). Utilities are categorized by the ILI level in the following way: ILI < 1, 1 ≤ ILI < 3, ILI ≥ 3, which is both reflective of best-performing, common, and most challenged utilities, and provides a somewhat even spread among the participating utilities.

RESULTS

Company and network characterization

Network length and connections

Figure 1 shows the number of connections and the mean network pipe length per connection plotted with estimated ILI values. All parameters cover a significant range between the 96 utilities that are included in the diagrams (note that not all utilities from the additional dataset were included in this analysis, absent relevant data). Very high-ILI values (>5) are observed for all but the largest (>1 million connections) utilities. Apart from this observation, no clear trends emerge.

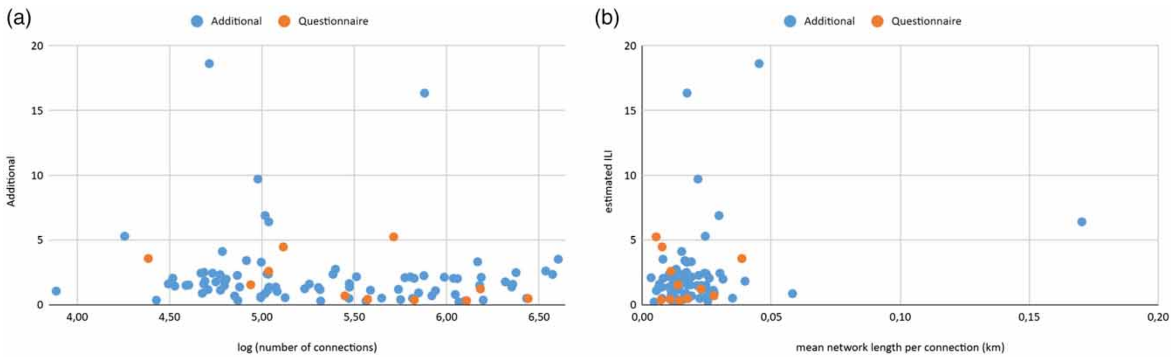

Figure 1 | Estimated ILI plotted against (a) number of connections and (b) mean network pipe length per connection for the utilities that participated in the questionnaire and the additional dataset.

Used materials

Figure 2 shows the composition, in terms of materials, of the pipe networks of the contributing water utilities, ranked from low to high estimated ILI (depicted on the *x*-axis labeling as the number next to the IDs in brackets). A number of observations can be made. The first is that some distinct groups can be indicated. Utilities 1, 2, 4, 6, and to some extent 11 are quite similar in the sense that polyvinyl chloride (PVC) is their main material, followed by asbestos cement (AC) (except for 2 and 4) and, in varying proportions, steel, polyethylene (PE), cast iron, and other materials. The second group is made up of utilities 5, 9, and 10, which have ductile iron as one of their major constituents, together with cast iron, and other materials in smaller proportions. The third group is basically 'the rest', i.e., 3, 7, and 8, and very heterogeneous.

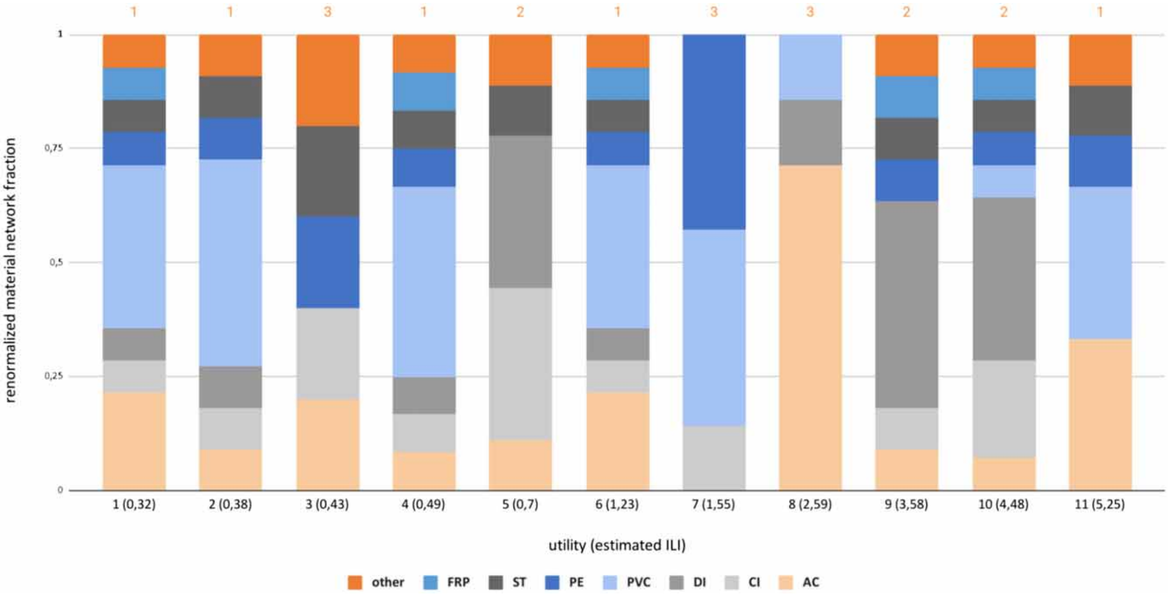

Figure 2 | Approximate network material composition for all contributing water utilities, ranked from low to high estimated ILI, with the material category number indicated above each bar (see the main text).

The second observation is that there is a wide variation of estimated ILI numbers, not just over the entire population, but also within the relatively homogeneous first (0.32–5.25) and second (0.7–4.48) groups. This observation supports the notion that it is not the materials *per se* that determine network leakage rates. Note that specific pipe materials were preferentially used in certain periods, so materials can also reflect pipe age. Our observation suggests local conditions (soil, topography, etc.) and treatment of the material (pressure management, maintenance, transients, etc.) are more important. We do, however, see that the two companies with the highest percentage of AC in their networks are among those with the highest ILIs.

Water loss and soil type

It has been recognized for a long time that soil type can both influence the frequency of bursts in pipes and also the speed with which leaks become visible at the surface (Lambert *et al.* 1999). Serafeim *et al.* (2024) discuss, in addition to soil corrosiveness and groundwater levels, the role of soil subsidence, relaxation, and instability in combination with the presence of angular/sharp fragments that may result in significant point pressures on pipe walls that may lead to crack formation.

Table 2 gives an overview of primary soil types in the provision areas of the contributing water utilities in relation to the estimated ILI values for these utilities. We must note that, of course, the number of observations

Table 2 | Overview of primary soil type occurrences for three estimated ILI classes

	D	P	L	O	B	J	X	I
ILI<1	20%	40%	0%	20%	0%	20%	0%	0%
1<ILI<3	0%	33%	33%	0%	33%	33%	33%	0%
ILI>3	0%	0%	0%	0%	67%	33%	0%	33%

B	Cambisol	Soil that is only moderately developed on account of limited age or rejuvenation of the soil material
D	Albeluvisol	Acid soil with a bleached horizon penetrating a clay accumulation horizon
I	Lithic leptosol	Shallow soil over hard rock or gravelly material
J	Fluvisol	Young soil in alluvial (floodplain), lacustrine (lake) and marine deposits
L	Luvisol	Soil with a subsurface horizon of high activity clay accumulation and high base saturation
O	Histosol	Dark soil with high accumulation of partially decomposed organic matter generally developed in wet or cold conditions
P	Podzol	Acid soil with a bleached horizon underlain by an accumulation of organic matter, aluminium and iron
X	Calcisol	Soil with significant accumulation of secondary calcium carbonates, generally developed in dry areas

Note that most of the contributing utilities have multiple soil types in their areas. Soil types are taken from maps in the Soil Atlas of Europe (European Soil Bureau Network European Commission 2005); soil type descriptions are copied from this source.

is too limited to draw statistically significant conclusions. However, a clear trend is visible, particularly on the right-hand side of the table. We observe that the highest ILI values only occur in areas where the primary soil type is X (calcisol), I (leptosol), B (cambisol), and J (fluvisol). Fluvisols occur in the supply area of 7 of the 11 contributing utilities, in all ILI categories (see the left-hand side of the table), and consist of (unconsolidated) sediment layers. Leptosols are shallow and overlaying hard or gravelly material; calcisols may also contain hard calcrete layers (European Soil Bureau Network European Commission 2005), suggesting that the presence of hard/rocky material in the soil plays a role in high leakage rates. This correlation between soil type and ILI deserves a more comprehensive investigation.

This indicative result inspired a more elaborate data gathering and analysis, in which the ILI was collected or estimated for 119 European utilities, and primary soil types were ascertained. Table 3 shows outcomes of a two-sample Kolmogorov–Smirnov test on sampled probability densities for estimated ILI for different soil types compared with each other. This shows which combinations might have the same probability density distributions or not (full analysis in the Supplementary material). The latter case presents statistically significantly different ILI distributions (≠ in Table 4). This analysis shows Luvisols (L in the table), Cambisols (B), and in particular Leptosols (I), as well as disturbed (urban) soil having statistically significantly higher ILI values compared with Podzols (P). Leptosols also show a significantly higher ILI than Luvisols (L) and Fluvisols (J). As such, they may be interpreted to present more challenging conditions for water utilities. These results are similar to those in Table 3, from a completely independent source, confirming with greater statistical significance the initial indication found in our initial analysis. Note that the number of samples is small (9–10) for Fluvisol, Leptosol, and Town and borderline intermediate for Podzol (18) and Cambisol (23), reducing statistical significance for these cases. Therefore, these results should be considered exploratory rather than conclusive.

Table 3 | Results of two-sample Kolmogorov–Smirnov test on sampled probability densities for estimated ILI for different soil types compared with each other

	P (Podzol)	J (Fluvisol)	L (Luvisol)	B (Cambisol)	I (Leptosol)	town
P (Podzol)			≠	≠	≠	≠
J (Fluvisol)					≠	
L (Luvisol)	≠				≠	
B (Cambisol)	≠					
I (Leptosol)	≠	≠	≠			
town	≠					

Note: Combinations with significantly different ILI statistics are marked. For the full analysis, see the Supplementary material.

Table 4 | Estimated water loss levels (ILI) in relation to topography of the supply area

	flat	intermediate	rough
ILI<1	45%	0%	0%
1<ILI<3	0%	27%	0%
ILI>3	0%	9%	18%

Note: Flat: $<$200 m elevation difference between the lowest and highest points of the supply area; intermediate: 200–500 m, rough: $>$500 m.

Water loss and topography

Strong variations in elevation will result in strong variations in pressure in a pipe system, which may contribute to the generation of leaks and bursts. Also, higher pressures result in higher loss rates for the same leak size (Van Zyl

& Malde 2017). Pressure variations are often mitigated through pressure zoning. Table 4 shows that the lowest ILI numbers in the current investigation occur exclusively for those utilities that operate in a flat topography supply area, and that the highest ILI numbers occur exclusively in those areas with intermediate or rough terrain. Note that, in particular, the highest points in the supply areas are not necessarily (or in most cases likely) covered by the pipe network. The total variation of elevation within a supply area is, however, considered to be a proxy for the variation within the network.

Again, this indicative result inspired a more elaborate data gathering and analysis, in which the ILI was collected or estimated for 119 European utilities, and maximum elevation differences within supply areas were ascertained. Results of a two-sample Kolmogorov–Smirnov test are shown in Table 5. This demonstrates that supply areas with elevation differences of 0–200 m are statistically significantly different (i.e., have lower ILI values) from those with 200–500 m and those with 500 + m. 200–500 and 500+ are not different. This supports the conclusion that can be provisionally drawn from Table 4, again with a completely independent data source.

Table 5 | Results of a two-sample Kolmogorov–Smirnov test comparing the observed probability densities for ILI in three elevation difference classes

	0-200 m	200-500 m	500+ m
0-200 m		≠	≠
200-500 m	≠		
500+ m	≠		

Note: Combinations with significantly different ILI statistics are marked. For the full analysis, see the Supplementary material.

Current practice

Evolution of rehabilitation rate

Table 6 gives an overview of self-reported rehabilitation rate evolutions as a function of ILI class. The majority of contributing water utilities either have a stable or increasing rehabilitation rate. There is no clear relation to the actual ILI. An explanation for this could be that utilities that are currently rehabilitating considerably introduce stress to the pipe network stemming from repairs, hence, in the short term, there might be more leakage, but in the long run, as the network ages will be lower the water loss rates are expected to go down. An alternative or additional explanation could be that the economics behind the rehabilitation can be very complex and political, so the utilities with ILI higher than 3 might not get the financial resources to rehabilitate. We note that we are merely showing the directions of change here, whereas it is the absolute level of rehabilitation that matters.

Table 6 | Self-reported rehabilitation rate evolution as a function of estimated ILI for the 11 contributing water utilities

	going up	stable	going down	count
ILI<1	40%	60%	0%	5
1<=ILI<3	100%	0%	0%	3
ILI>=3	0%	67%	33%	3

Water loss reduction strategies

Table 7 gives an overview of reported strategies that are applied by the participating utilities to reduce water losses. A clear progression can be seen from low-resource measures (awareness, pressure management – these can be considered low-hanging fruits) that are seen mostly at high-ILI utilities toward high-resource measures such as district metered areas (DMAs) and smart meters that are seen exclusively with the mid- and low-ILI utilities.

Table 7 | Applied water loss reduction strategies at the participating water utilities, as a function of estimated ILI

	Awareness	Pressure management	Active leak detection & fixing	DMAs	Smart meters	count
ILI<1	0%	0%	20%	60%	40%	5
1<=ILI<3	0%	67%	67%	100%	33%	3
ILI>=3	33%	33%	67%	0%	0%	3

Note: Percentages apply within ILI categories.

Pressure management is a tool that is used more by water utilities that have a higher ILI, which makes sense, as it may be, depending on network topology and local topography, an effective way to reduce water losses with relatively little effort (Rupiper *et al.* 2022).

Active leak detection and fixing is reported by 2 out of 3 companies that are in the highest ILI category (3 and above). These networks are clearly in most need of a proactive/reactive approach to leakages because of their relatively high rate of occurrence.

DMAs are applied by utilities in the low-mid ILI categories. Smart meters, on the other hand, are mostly applied by water utilities that have low ILIs. This can be interpreted in three ways: (i) the lower pressure on the utility to respond to urgent repair needs (either because of prior investments in leakage management or because of favorable conditions) may leave more means available for investments that may be expected to give insights and/or contribute to water loss reduction on the longer run, either because the utility is specifically aiming to further reduce losses, or for other reasons, such as a digitalization strategy; (ii) water utilities with low ILIs may focus more on finding the smaller leaks that are harder to identify and localize, therefore requiring a finer-grained network of sensors, for example through pressure sensors on smart meters, or putting more focus on leak detection on the customer premises; (iii) these more labor and capital intensive measures have resulted in the low-ILI values that are observed. However, we need to observe that these utilities have had relatively low-ILI levels for several decades, before introducing more advanced NRW management approaches.

We note that the five utilities in the ILI < 1 category all have relatively flat topographies and soft soils (unconsolidated sediments) that may pose lower risks for pipe damage and make it easier to reach pipes. These conditions may strongly influence the level of unavoidable losses. Note that our calculation of ILI in the analysis above uses the same approach to UARL for all utilities without taking into account the environmental conditions (except for the average pressure). Below, we investigate if these conditions may provide a partial explanation for the observed low-ILI values.

The implementation of these strategies, as reported by the utilities, includes the following aspects:

DMAs	Subdivision of network into smaller working areas; increased the number of flow meters in their network; more insight into the areas with higher NRW, which was used to prioritize the pipeline replacement strategy/timeline.
Active leakage control	Leak detection and prediction software; monitoring of leak repair times to proactively manage leaks.
Pressure management	Striking a balance between minimizing leakage risk and maintaining adequate pressure to meet customer needs.
Pipe replacement	Condition-based approach; focus on rehabilitating and renewing the pipes in their drinking water supply network; change of material for drinking water pipes, in particular gray cast iron pipes to coated ductile iron; frequent use of PE and other plastic pipes during pipe rehabilitation; all these approaches are reported to have contributed (strongly) to NRW reduction.
Software	With low leakage levels, utilities struggle in making (positive) business cases to invest in software; failure registration initially using self-built tools, but later transitioning to commercial software; systematic application of software not until a strategic decision to do so was made; comprehensive statistical data on the operation and monitoring of drinking water system demonstrate the positive influence of prioritized rehabilitation on levels of NRW; Geographical Information Systems (GIS)

	significantly supported NRW reduction and facilitates the deployment of the hydraulic model for urban water supply; software enables the utility to estimate the avoidable leakage and helps prioritize efforts to reduce leakage in the system.
Additional measures	A better policy to minimize water theft; a more efficient and prompt mechanism for leak detection and repair; replacing conventional water meters with digital ones; round-the-clock duty for their leakage detection team, resulting in reduced leak localization time.

The policies outlined in the above reflect diverse approaches taken by different companies in deciding between rehabilitating or fixing network segments. While all companies begin with the common step of fixing network issues, the decision criteria for transitioning to rehabilitation vary. Some companies prioritize factors like the number of failures, material type, and consequence severity, while others focus on parameters such as age, length, and the number of breaks. The criteria for selecting segments for rehabilitation also differ, with some companies considering the risk to maintaining the customer minutes lost Key Performance Indicator (KPI) (the average number of minutes a customer experiences a loss of water supply due to interruptions), while others rely on specific factors like age, length, and historical leak data, or simply and pragmatically go along with third parties when the pavement is already opened anyway, e.g., for sewer rehabilitation. The approach to replacing existing pipes during the fixing process may vary, with differences in when and why pipes are replaced. Additional considerations, including network age, fault types, resource requirements, NRW levels, and location-specific factors like cost and workload, contribute to the overall decision-making process. Various analytical methods are employed, ranging from evaluating damage frequency data to categorizing damage reasons and monitoring network pressure variations. These variations in policies underscore how companies adopt tailored strategies based on their unique operational contexts, priorities, and goals in managing network infrastructure.

Incentives and drivers

Incentives and their origins

An overview of self-reported incentives for water companies to reduce water loss is provided in Table 8. Standing out is the internally motivated incentive of reducing the costs of lost water production. To a lesser degree, water companies also want, as a policy, to reduce damages to third-party property and recognize the need to reduce water shortages. The 'other' category includes incentives such as government-imposed limits on groundwater abstraction, costs of repairs, and the assertion that this helps postpone investments that would otherwise be needed to meet growing water demand.

Table 8 | Incentives for water loss reduction (columns) and the origins of these incentives (rows), as reported by the contributing water utilities

ORIGINS	Water shortages	Damages to 3d party property	Costs of lost water production	Other
company policy	45%	55%	91%	27%
regulator	9%	0%	0%	0%
government	9%	0%	0%	18%
public (perception)	9%	36%	0%	9%
other	27%	9%	9%	45%

Perceptions of water shortage

The perception of water shortage varies per country. The answers to our questionnaire give an illuminating overview of perceptions on water shortage in the countries of the participating utilities.

In the Netherlands, water utilities believe that the population does not perceive water scarcity as a current or urgent issue, and even if they are aware, they may not always act on it. The water utilities, on the other hand, do perceive water scarcity as a problem and are worried about the effects of climate change and population growth on the demand for water and the limited availability of fresh water sources – both in terms of quantity and quality. Perceptions vary in view of different sources: utilities that source from river bank groundwater are less affected by droughts than companies that use groundwater. Permits for groundwater are not expected to be enlarged by the government (considering, for instance, environmental reasons), which limits the availability of water that the utilities can treat and distribute.

In Belgium, water shortage is perceived as a relevant issue, particularly in the Flanders area. High population density, industrial activity, and agriculture contribute to water demand. The Belgian government actively raises awareness about water scarcity, leading most users to be conscious of their water usage.

Mainland Greece generally does not face water shortage issues due to its mountainous terrain and abundant natural surface and groundwater resources. However, some islands experience intense water stress due to freshwater scarcity or salination. Public awareness about water conservation varies, with island areas more attuned to the issue than other regions where old habits persist. Sustainable use of water is promoted by several organizations; however, this does not seem sufficient to influence how the population uses water.

The Swiss water utility has multiple and varied sources to abstract water, and is, in terms of quantity, not worried about water availability. The water utility is, however, worried about the quality of their sources, due to groundwater pollution by chlorothalonil metabolites and per- and polyfluoroalkyl substances (PFAS). In Switzerland, public awareness of water conservation needs is high: the public is aware and acting on it. The utility carries out annual awareness campaigns on water conservation, and annual per capita water consumption has decreased by 36% in 30 years (as a consequence, water sales decreased by 17%). It is pointed out that in 1992, the utility switched from flat-rate billing to water retail billing.

In Norway, the interviewed utility experiences brief dry periods, due to minimal rainfall or cold weather, approximately every decade. During these periods, the water utility has limited inflow into its reservoirs and takes several measures to cope with this. The utility proactively notifies customers, urging water conservation by taking shorter showers and avoiding activities like watering gardens. Flow meters are mandatory for commercial buildings in the city. The relatively few residential water meters result in less customer awareness about their water use. The utility claims to implement rules to prevent excessive consumption.

Perception of conditions leading to water loss

The collected data relates water losses to soil type and topography. The interviewed water utilities also have a perception of different conditions that might affect leakage levels in their supply area. They report differences in elevation/topography, soil type, history, and integration of local networks, the condition of the network, and weather conditions (correlation between water demand and leakages) as the primary circumstances affecting water loss.

Infrastructure investments

Investment history and water loss evolution on a national level

It is often difficult to obtain a history of investments in water distribution networks. This was also the case with the water utilities that participated in this study. Nevertheless, one might intuit that the present-day failure rate (or its proxy: water loss) is in part the result of the integrated investment history in the network, in particular the part that relates to network maintenance, repair, and rehabilitation. Absent data at the level of individual water utilities, we have analyzed national data reported by EurEau (2017, 2021); their 2009 report did not contain the aspects relevant for this analysis. The results of this analysis are presented in Figure 3. There is no strong correlation between the investment rate in 2017 (a), the investment rate in 2021 (b), or the change in the investment rate between 2017 and 2021 (c), on the one hand, and changes in the leakage rate over the same time period, on the other hand, in the sense of convincing R^2 values. However, a weak negative correlation is consistently observed. Strangely, this trend is stronger when looking at the 2021 investment rate than when looking at the 2017 rate. This suggests that there might be a relatively quick payoff of these investments.

Also, high investment rates mostly correlate with mild increases to mild decreases in water loss, and stronger increases in water loss rates are only observed for those countries that have relatively low investment rates. Nevertheless, some countries, such as Malta and Finland, manage to achieve water loss reductions even with relatively low investment rates.

However, the absence of a clear water loss change signal at increased investment rates suggests that either investments in the infrastructure generally do not pay off on short timescales in terms of water loss reduction

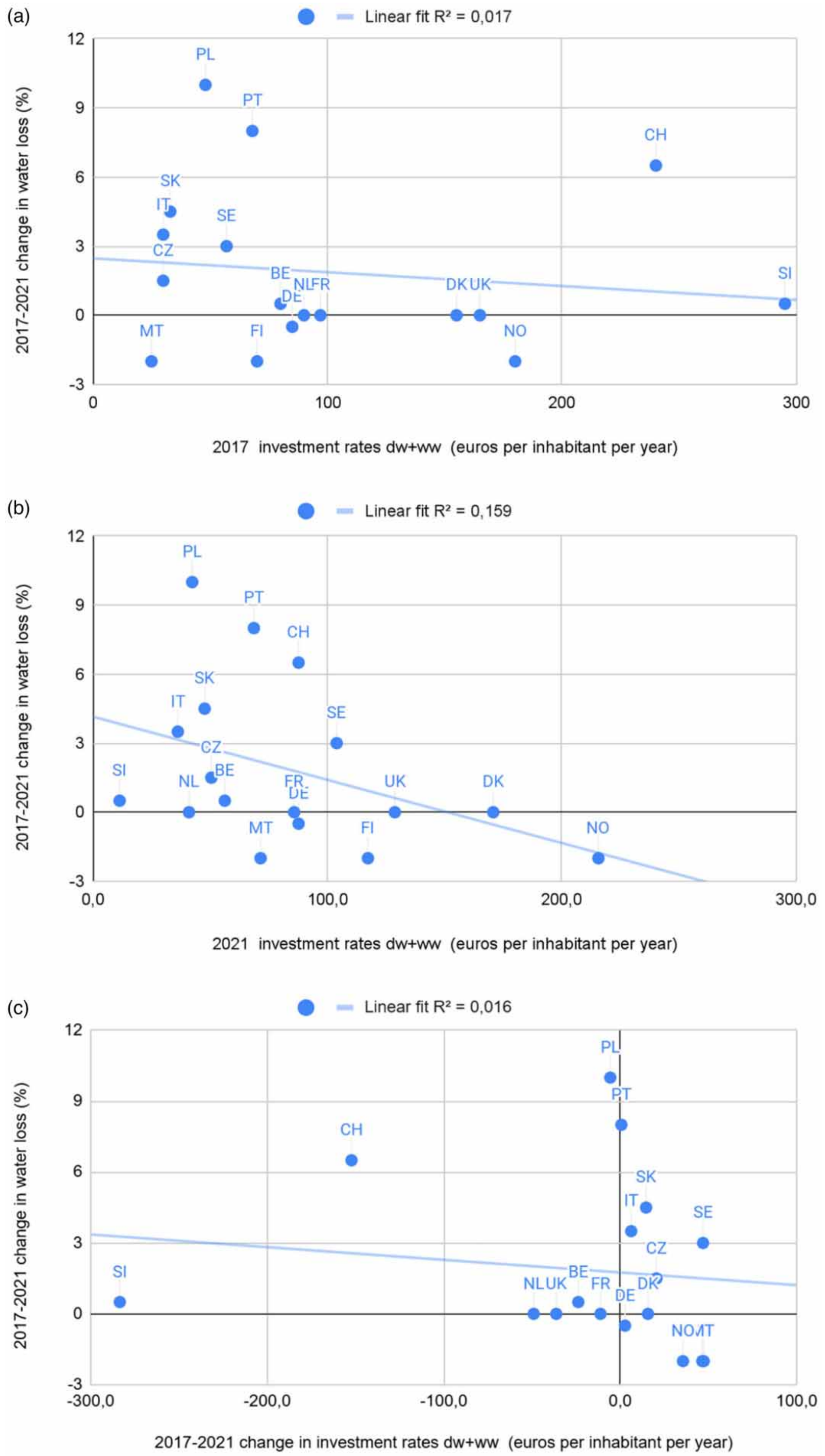

Figure 3 | Correlations between (changes in) investment rates (inflation-corrected) and loss rates for 17 European countries. (a) 2017–2021 changes in water losses as a function of 2017 absolute investment rates in drinking and wastewater infrastructure per inhabitant per year; (b) 2017–2021 changes in water losses as a function of 2021 absolute investment rates in drinking and wastewater infrastructure per inhabitant per year; (c) changes in water loss rates reported between 2017 and 2021 changes in vs. investment rates (in both drinking and wastewater infrastructure). Data from EurEau (2017, 2021).

(contrasting with our earlier interpretation), or that other parameters are more determining for the evolution of water loss rates. We must note, however, that the picture painted by Figure 3 may have been clouded by investments in wastewater infrastructure that logically do not (significantly) affect drinking water losses and/or other confounding factors that were not included in our analysis, such as a potential co-occurrence of investment in both digital leakage control techniques and infrastructure renewal.

Infrastructure investments on a utility level

Investments in assets and infrastructure are expected to have a significant impact on the performance of the distribution networks and leakage levels. Means of investment vary between water utilities.

Detailed numbers are not available for most utilities; four of the participating utilities did manage to find and share relative investment rates in expansion and three in rehabilitation for the period since 1980. Their reported relative numbers are shown in Figure 4. Whereas network expansion investment evolutions vary between companies (Figure 4(a)), a consistent increase in investment in rehabilitation can be observed for the past decade (Figure 4(b)). No clear correlation between either investment history (Figure 4(a)) or mean relative investment level since 1980 (Figure 4(c)) and current ILI levels can be seen with only four datapoints. Figure 4(d) does show that the highest ILI value is associated with the highest mean investment rate since 2002, compared with present-day investment levels, which is likely reflecting efforts to combat this high water loss number. Note that absolute investment rates, which would make the comparison more meaningful, are not known to the authors. We point out that the small number of observations is limiting the statistical significance of this observation.

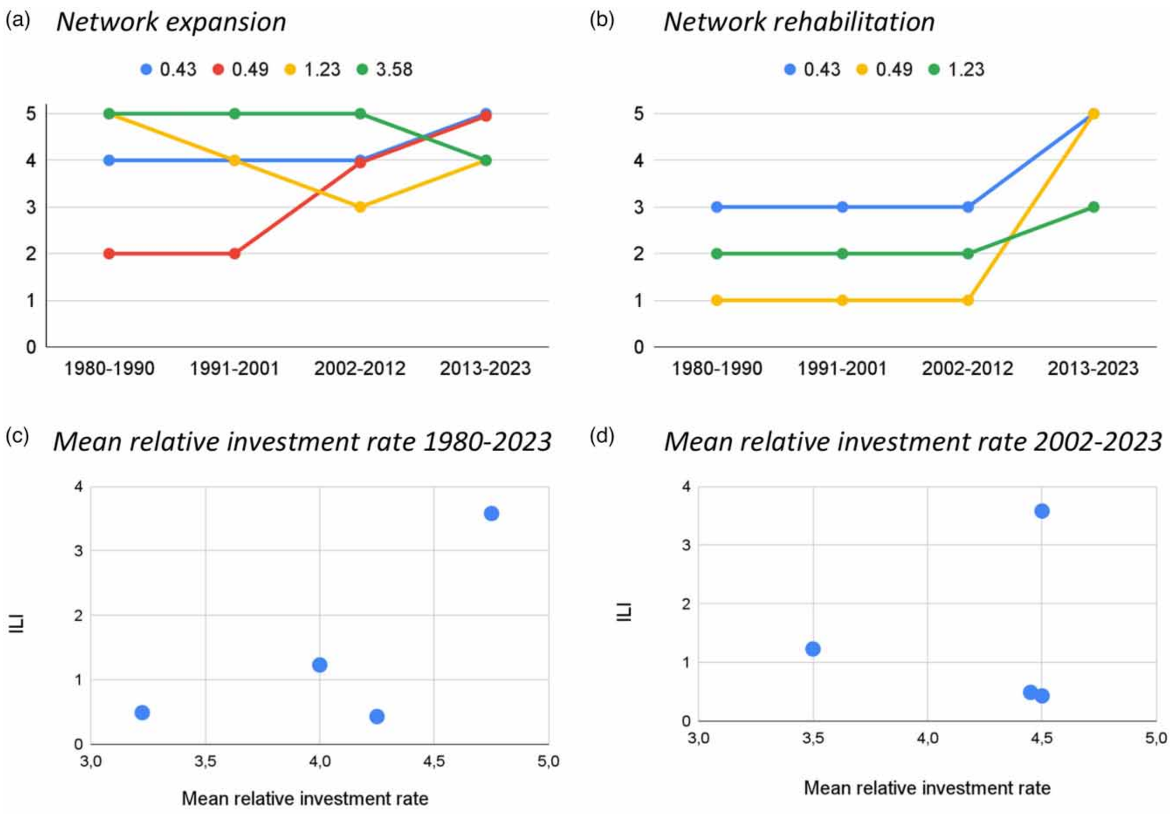

Figure 4 | Evolution in investments in network expansion for four utilities (a) and in network rehabilitation for three (b). The legend indicates current ILI values for these utilities. Levels indicate the investment levels: 1 = no investments, 2 = less than half of the current investment, 3 = less than the current investment, 4 = comparable to the current investment, 5 = more than the current level of investment.

DISCUSSION

Favorable vs. challenging conditions

In their overview of parameters affecting pipe failure, Barton *et al.* (2019) include soil hazards, with a particular reference to shrink-swell behavior of clays and differential settlement, as well as internal pressure (and its variations). The effects of pressure on leakage and pressure management as a mitigation strategy have been known for a long time (Van Zyl & Clayton 2007; Adedeji *et al.* 2018).

Our results, which are on a higher abstraction level of supply area water loss rather than failure of individual pipes, are consistent with these findings to some degree. We find that Luvisols, 'with a subsurface horizon of high activity clay accumulation and high base saturation', are associated with a higher ILI than Podzols. However, the same is true for Cambisols, which are moderately developed soils that generally do not have clay, and in particular Leptosols (shallow soil over hard rock or gravelly material). In the latter two cases, differential settlement seems a less likely mechanism, and we may speculate that the presence of rocky material may contribute to higher leakage rates.

Our results suggest that some geographical conditions are favorable for maintaining low water loss levels, in particular, limited variations in elevation and forgiving soil type. The consequences of both types of conditions can, however, be mitigated by technological means, i.e., pressure management and adequate preparation of pipe sand beds, respectively. The results from our analysis suggest that neither mitigation measures has been fully implemented with the utilities that were part of our investigation.

We must also acknowledge that there may be a co-occurrence of unfavorable topography, soil types, and/or aged infrastructure, which would make it more difficult to isolate causal relations. The co-occurrence is confirmed for unfavorable topography and soil types (see the Supplementary material), but unknown for infrastructure condition.

Rehabilitation or digitalization?

Although it may be 'obvious' to many that smart water solutions are necessary, unavoidable, and beneficial, there are several reasons to look into this issue more deeply. First, there appears to be a significant technology push from the digital solutions market. Second, some argue that smart water poses a so-called moral hazard in that the implicit belief that technological solutions can always be found would blind us to the underlying transgressions of planetary boundaries (Hartley & Kuecker 2020). Third, smart water implementations require significant investment – money that could instead be spent on pipes to improve network performance and customer service levels. However, utilities lack sufficient data and studies to guide their decision-making on whether to invest in new technology or focus on infrastructure rehabilitation to reduce losses. The potential of digital technologies for water loss reduction is often described, and deployment of digital technologies to address leakage is progressing relatively quickly (Daniel *et al.* 2023 and references therein), but studies that balance costs and benefits remain rare. And fourth, a too strong dependency on digital technology for the basic functioning of a water supply system poses a risk, either with respect to cybersecurity issues or for operation under changing circumstances if there is no human-operable fallback option (Savić 2022; Van Thienen *et al.* 2023).

With respect to the benefits of digitalization and smart water technologies vs. rehabilitation on reducing water losses, our results tell a sobering story. We do need to emphasize that the number of participants in our investigation was relatively small, which affects the statistical significance of the numerical analysis. With this caveat in mind, we observe that:

- Some utilities have managed to maintain low leakage rates for decades, even before the advent of smart water solutions.
- There appears to be no strong correlation between network material composition and leakage rates.
- There does appear to be a correlation between geographical factors (topography and soil type) and leakage rates.

A potentially important missing factor from this evaluation is the maintenance history of the networks (Malm *et al.* 2012). Unfortunately, information about this seems to be difficult to obtain.

What can we carefully conclude from this? First, it does not require digital water solutions to maintain the prime condition of a network if the geographical conditions are favorable. In these cases, there is a real need for understanding how much further improvement of the system is possible by implementing digital water solutions.

Ahopelto & Vahala (2020) performed a cost-benefit analysis on three investment-based leakage reduction strategies – district metering, pressure reduction, and pipe renovations. Their main conclusion is that 'water loss management might not be directly cost-beneficial to utilities operating with moderate leakage levels'. Half of the 92 Finnish utilities that these authors studied had very low-ILI values; the other half had up to 5.2. Contrary to Ahopelto & Vahala (2020), Rupiper *et al.* (2022) concluded that water loss reduction is economically efficient in many cases, based on an analysis of 882 US utilities.

Perception and true development

The perception of water utilities regarding network integrity and water loss, the measures they implement to address these issues, and the actual evolution of network performance show both alignment and discrepancies. Water utilities perceive water scarcity and network conditions as critical drivers for action, with their primary motivation being the reduction of costs associated with lost water production. To combat water losses, utilities generally recognize the importance of rehabilitation and proactive measures, such as active leak detection, pressure management, and the use of smart meters. Indeed, Lee *et al.* (2024) noted a historical progression from reactive to proactive asset management policies and the progressive development and introduction of advanced data-driven decision-making. Within the population of utilities that participated in this study, the choice between these strategies seems to be based on the level of leakage affecting the water utility: utilities in higher ILI categories prioritize reactive measures, such as pressure management, active leak detection, and repair, while those with lower ILIs invest in more advanced technologies, like smart meters and pressure sensors. These technologies provide insights into network performance and condition, enabling consistent monitoring and contributing to long-term leakage reduction. Additionally, pipe rehabilitation and replacement are perceived by some utilities as highly effective, particularly when a condition-based strategy is employed, prioritizing the replacement of pipes in poor condition.

However, the reported rehabilitation rates and investment strategies do not always align clearly with actual water loss reductions. On a country level, we observe that high investment rates per inhabitant mostly correlate with mild increases to mild decreases in water loss over a 4-year period (2017–2021), whereas stronger increases in water loss rates are only observed for those countries that have relatively low investment rates. Nevertheless, some countries manage to achieve water loss reductions even with relatively low investment rates. Note that these numbers on a national level include investments in both drinking water and wastewater infrastructure, which may muddle their actual contributions to water loss reduction. This suggests that while utilities are taking meaningful steps to improve network integrity, short-term stress from repairs may temporarily increase leakage, with long-term benefits taking more time to materialize. The weak correlation between investment rates and water loss reduction further underscores the complexity of the issue. External factors, such as soil type, topography, and the specific characteristics of the infrastructure, play a significant role in shaping outcomes, as acknowledged by the utilities themselves.

Overall, while utilities' perceptions and actions align with the goal of reducing water loss, the actual results are influenced by a complex interplay of factors. This highlights the need for nuanced, context-specific approaches that account for both immediate challenges and long-term network performance.

Size of utilities

Larger utilities are perceived to benefit from economies of scale, though studies on this question show conflicting results (Ferro *et al.* 2011; Klien & Michaud 2019). Economies of scale would allow them to allocate more substantial budgets for infrastructure rehabilitation and maintenance. These financial resources would enable them to replace aging pipes and assets before they fail catastrophically, significantly reducing water losses over time. In any case, larger utilities can more easily afford to employ dedicated staff specifically trained to detect, locate, and repair leaks on a regular basis. These specialized teams utilize advanced technologies such as acoustic leak detection, hydraulic measurement data (flow and pressure), and in combination with hydraulic modeling and smart metering to identify non-visible leaks before they escalate into major issues. Furthermore, larger organizations generally implement more sophisticated management systems and processes. They often adopt comprehensive water loss management strategies with clear performance indicators and regular auditing procedures. These structured approaches favor preventive methods instead of reactive ones, allowing them to address potential problems before significant water loss occurs. The combination of superior financial resources, specialized staff, advanced technologies, and robust management practices typically results in lower overall water loss rates for larger utilities compared with their smaller counterparts, as we have also seen in our interviews.

Use of ILI in EU regulations and possible improvements

The EU Drinking Water Directive 2020/2184 mandates large water utilities to report losses using ILI or another appropriate method, set threshold values, and requires member states to develop leakage reduction plans, putting pressure on utilities with high NRW. Considering the results of our interview campaign as well as the exploratory data analysis on water losses, there are several critical points raised with this approach.

First, despite its widespread adoption, the ILI has notable limitations: lack of standardization and inconsistent calculation methods between utilities, as there is considerable flexibility within the input parameters that can be adjusted to favor utilities; dependence on data that is not universally available (e.g., pressure data); failure to account for regional factors like water scarcity or energy costs; implementation barriers for smaller utilities with limited resources; and the potential to obscure significant losses when presented without proper context – the ILI might mask substantial water losses in absolute terms or their economic impact. However, developing a more appropriate and easy-to-use indicator remains a scientific challenge that has persisted for decades.

Second, small utilities (serving under 50,000 people) should also be included in water loss management initiatives despite the EU Directive's focus on larger providers. These smaller systems experience higher percentage losses due to aging infrastructure and limited resources, yet can benefit significantly from targeted interventions. They serve a substantial portion of the population, particularly in rural areas, where reducing water loss could yield meaningful operational savings and lower water costs. Basic improvements in these systems often produce proportionally greater benefits than in larger systems with existing measures. Including smaller utilities would provide a more complete picture of water loss across the EU and ensure conservation efforts benefit all citizens. Additionally, successful strategies from larger systems can be adapted and scaled appropriately for smaller systems.

Third, our research shows that geographical factors like minimal elevation changes and favorable soil conditions make it easier to maintain low water loss levels. This prompts an ethical question: should utilities facing challenging geographical conditions be held to identical standards as those in optimal environments? A more equitable approach would include contextual evaluations that acknowledge unique challenges, relative improvement metrics rather than absolute targets, and targeted support instead of penalties for utilities in difficult environments. This approach would also recognize progress despite adverse conditions and implement regulatory frameworks that balance accountability with fairness. While geographical challenges should not excuse inaction, performance standards should recognize factors beyond utilities' control. A nuanced approach would focus on continuous improvement within context rather than imposing universal standards that might unfairly disadvantage utilities facing inherent geographical challenges.

Many utilities worldwide show an ILI lower than 1, meaning that their real losses are lower than what is considered unavoidable in the ILI framework. This illustrates that our understanding of what is unavoidable needs to be updated.

In any case, it is beneficial to first measure leakage levels in a standardized way as suggested by the EU, and then mitigate water losses through a combination of preventive rehabilitation, robust management practices, and smart water technologies. Particular attention should be given to providing more support or incentives for smaller utilities and those facing geographical challenges.

Low-hanging fruits vs. long-term water loss management

In the results of our questionnaire, we observed a clear progression from low-resource measures (awareness, pressure management) that are seen mostly at high-ILI utilities toward high-resource measures such as DMAs and smart meters that are seen exclusively with the mid- and low-ILI utilities.

Awareness and pressure management are obvious low-hanging fruits that may contribute considerably to water loss reduction, but they can address the water loss issue to some degree – they will not result in fixing leaks. Additionally, more resource-intensive measures are needed for that, including active leakage management and repairs, DMA sectorization, and smart metering. The latter measures are mostly seen with lower ILI utilities. This can be interpreted in three ways: (i) because more means are available for investments that may be expected to give insights and/or contribute to water loss reduction on the longer run, (ii) because water utilities with low ILIs may have a more explicit focus on finding the smaller leaks that are harder to identify and localize, therefore requiring a finer-grained network of sensors, for example through pressure sensors on smart meters, or (iii) because these more labor and capital intensive measures have resulted in the low-ILI values that are observed. We stress that the utilities concerned in our study have shown low leakage levels for decades, before the introduction of DMAs and smart water solutions.

Further research

Several of the results and insights gained from our data analysis would be strengthened by a larger supporting dataset. Foremost, it would be interesting to gather more investment history data for more utilities and expand the analysis presented in this paper. Also, the moment of introduction of digital techniques should be considered in these analyses. Finally, for a better understanding of the relation between investment levels and network performance in terms of water loss, detailed economic data and broader datasets are necessary to further study and substantiate our initial findings.

CONCLUSIONS

This work explores two main perspectives on NRW levels: whether water losses are primarily influenced by environmental factors beyond utility control (such as soil conditions, topography, climate, and pressure variations), or whether utilities can fully control their water losses through management and technological factors – including infrastructure investment, maintenance practices, and digital solutions. This distinction is particularly relevant to the EU Directive 2020/2184, which requires large water utilities to report water losses and establishes threshold values that may trigger mandatory action plans for leakage reduction by member states with high loss levels. Our research – comprising two rounds of questionnaires with 11 water utilities from 8 countries in the first round and 8 utilities from 6 countries in the second, along with exploratory data analysis of 119 utilities from publicly available data – yielded several important conclusions and recommendations for the EU drinking water directive:

- Favorable and challenging geographical conditions are reflected in ILI levels throughout Europe. These conditions should be considered when prescribing leakage reduction targets and comparing utility performances, particularly when comparing leakage levels among different countries.
- The EU directive should consider utility size and economies of scale in water loss reduction. It should set measurement standards and encourage large-small utility partnerships, while including smaller utilities in reporting requirements since they often face higher losses and, in sum, represent significant potential for EU-wide water loss reduction.
- A clear progression exists from low-resource measures applied mostly by high-ILI utilities to high-resource measures used exclusively by mid- and low-ILI utilities. This progression is especially significant regarding sensors and smart water technologies.
- Limited network investment data prevented analysis of its impact on leakage levels, though underinvestment likely contributes significantly. We propose including investment data for pipe rehabilitation and digital technologies in EU Directive reporting to assess which investments best reduce water losses.
- Limited reliable data currently constrains our understanding of the causes of high water loss. The EU directive presents a valuable opportunity to collect standardized water loss data across Europe. This data collection could be strengthened by incorporating economic metrics and extending reporting requirements to smaller utilities – while considering the varying governance structures among EU countries. Such comprehensive information would help utilities, researchers, policy makers, and technology providers better understand water loss patterns and their driving factors, potentially catalyzing innovations that could reduce currently 'unavoidable' losses and significantly decrease overall water losses.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

P.T. and I.V. declare no conflicts of interest. While this paper advocates for the inclusion of smaller utilities in EU water loss management initiatives, we acknowledge a potential conflict of interest as one of the authors (D.B.S.) transitioned during writing this paper from a research group leader of a non-profit research center to a CEO of Indigo Water FlexCo, a company providing digital water management solutions to utilities. To maintain transparency and scientific integrity:

- All arguments presented are supported by peer-reviewed research and objective data from multiple sources.
- Co-authors include independent researchers from research institutions to ensure balanced perspectives.
- The methodology and conclusions have undergone rigorous peer review.

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