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From advanced hydraulic modelling to performance indicator for the efficiency of investments in leakage management of pressurized water systems

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ABSTRACT

Introduction: The digital transition is meant as the review of processes using digital technologies and strategies to increase efficiency based on a simpler collection of representative data. The process of interest here is the leakage management in systems distributing water.
Objective: To develop a novel key performance indicator (KPI) for leakage management considering the needs of ongoing digital transition in the water sector, which is opening a new era in the management of drinking water infrastructures.
Methodology: The novel KPI, named Asset Management Support Indicator, is developed starting from advanced hydraulic modelling and the physical laws governing leakage outflows, in order to be physically based and rational for increasing the efficiency of leakage management activities using representative process data.
Results: The Asset Management Support Indicator supports effective leakage management strategies by driving towards efficiency, as discussed and demonstrated using several real case studies.
Conclusion: The novel indicator is consistent with the digital transition perspective and current need of increasing the efficiency of water utilities, and it is also suitable to be adopted by water authorities to benchmark their performances, because it overcomes the weaknesses of traditional KPIs.

1. Introduction

The digital transition is meant as the review of processes using products based on digital technologies, i.e., hardware, and novel digital strategies, i.e., software, to increase efficiency. The simpler, more accessible, and representative collection and evaluation of data related to processes is the knowledge base to provide useful information for efficiency.

In 2020, the global pandemic highlighted the importance of preparedness and resilience of critical infrastructures to cope with extreme events, worsened by the increasing water demand worldwide and the impacts of climate change. In the aftermath of pandemic, recovery initiatives witnessed an unprecedented allocation of resources towards drinking water infrastructures (DWIs), to make their management more efficient and sustainable through the implementation of digitalization.

The aim is to direct digitalization investments to increase the *rationality* of DWI management, i.e., to make management activities *replicable, scalable,* and *flexible* (*adaptable* to the inherent uncertainty of DWI management) from the operational (short term) to the strategic (long term) horizon, to achieve *efficiency* and *effectiveness.*

DWIs encompass both water transmission (WTS) and distribution (WDS) systems. The former are generally characterized by long pipelines with large diameters and few or no connections to customers, while the latter comprise shorter pipelines with smaller diameters and numerous customer connections. WTSs provide the transfer of substantial water volumes to consumption centres (towns or cities). WDSs, also called Water Distribution Networks (WDNs) because of their networked structure, transfer water to end users.

Around the world, many DWIs are severely affected by significant volumes of water losses. whose reduction is an emerging issue to make the management of DWIs efficient and sustainable from socio-economic and environmental perspectives, also considering the impact of climate

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change on water resources (Liemberger and Wyatt, 2019). Furthermore, it was proved that high leakage rates are related to increased rates of pipe breaks (Girard and Stewart, 2007), thus exposing communities in urbanized areas to major impacts in terms of service interruptions and reliability of WDNs.

Real water losses from pipes are diffuse leakage outflows caused by the combined effect of infrastructure deterioration and pressure (Lambert, 1994; Farley and Trow, 2003) according to the Torricelli's law. The main leakage management activities are pressure control, active leakage detection and pipes replacement. Diffuse leakage outflows along pipes and customer connections, also named background leakages, are caused by the natural process of deterioration, increasing over time, due to several external and internal factors as detailed in (Kleiner and Rajani, 2001). The system monitoring, which breaks up the WDNs in District Metered Areas (DMAs) (Farley and Trow, 2003), is an effective way to manage water losses coping with the complexity of such water systems.

Water Performance Indicators (WPIs) aim to measure the effectiveness in managing DWIs (Alegre et al., 2016) and delivering safe, reliable, and affordable water services to customers. The concept behind WPIs is to incorporate the outcomes of DWI planning and maintenance, including physical, economic, operational, and service quality factors. Their purpose is to assess the impacts of planning and maintenance activities and to make a cross-comparison with benchmarks of similar water utilities (Liemberger, 2002; Seago et al., 2005). Nonetheless, in recent years WPIs have been used also to target investments for water loss management.

This paper develops and discusses a novel WPI for leakage management named Asset Management Support Indicator (AMSI), which is characterized by several novelties:

- It is developed starting from the advanced hydraulic modelling of pressurized water systems; therefore, it is physically based and not empirical.
- It is consistent with the two leakage models of the technical-scientific literature, the Power model (Germanopoulos, 1985) and the Fixed Area and Variable Area Discharge (FAVAD) model (May 1994; Van Zyl and Cassa, 2014).
- It meets the needs of DWI digitalization by allowing the use of data collection and hydraulic modelling to rationally and efficiently direct investments.
- It is easy to calculate from daily water balance and mean pressure provided by the hydraulic model of the system under analysis.
- It is scalable, for example at the scale of DMAs as well as at consumption centre scale, and allows driving decisions about the technical activities, e.g., pressure control versus pipes replacement to reduce leakages.
- It is a synthetic and rational indicator linked to hydraulic simulation that can be used to optimize leak management activities as an efficiency driver completely consistent with the benchmarking needs of water utilities. Furthermore, it can be used for *ex ante* and *ex post* evaluations for the design of activities at a tactical and strategic time horizons.

Finally, the comparisons of AMSI with the water loss percentage indicator, widely used across several European countries (WAREG, 2023), and the Infrastructure Leakage Indicator (ILI) are reported in the case studies to clarify the different approaches.

2. Advanced hydraulic modelling and leakages at pipe level

The mathematical model for steady-state hydraulic analysis of a pressurized water pipeline system, composed of n_p pipes with unknown flow rates, n_n nodes with unknown heads and n_0 nodes with known heads, is expressed by two sets of equations of momentum and mass balance at pipes and nodes, respectively, as follows:

$$\begin{aligned} &\mathbf{A}_{pp}\mathbf{Q}_p + \mathbf{A}_{pn}\mathbf{H}_n = -\mathbf{A}_{p0}\mathbf{H}_0 \\ &\mathbf{A}_{np}\mathbf{Q}_p - \mathbf{d}_n(\mathbf{H}_n) = \mathbf{0}_n \end{aligned} \tag{1}$$

where $\mathbf{A}_{pp}$=[n_p, n_p] is a diagonal matrix with elements based on the pipes resistance; $\mathbf{Q}_p$=[n_p, 1] is a column vector of unknown pipes flow rates; $\mathbf{H}_n$=[n_n, 1] is a column vector of unknown nodal heads; $\mathbf{H}_0$=[n_0, 1] is a column vector of known nodal heads; $\mathbf{0}_n$=[n_n, 1] is a column vector of null values; $\mathbf{d}_n$=[n_n, 1] is a column vector of nodal water flows; $\mathbf{A}_{pn}=\mathbf{A}_{np}^T$ and $\mathbf{A}_{p0}$ are the topological incidence sub-matrices of size [n_p, n_n] and [n_p, n_0], respectively, derived from the general topological matrix $\bar{\mathbf{A}}_{pn}$=[$\mathbf{A}_{pn}$ ¦ $\mathbf{A}_{p0}$] of size [n_p, n_n+ n_0].

The hydraulic model in (1) is the general form for pressure-driven analysis (PDA) (Giustolisi et al., 2008; Giustolisi and Walski, 2012) meaning that the hydraulic status of the water system, $\mathbf{Q}_p$ and $\mathbf{H}_n$, is driven by pressure dependency of nodal demands, $\mathbf{d}_n$. This is a more general assumption than demand-driven analysis (DDA) assuming the priors about $\mathbf{d}_n$ (Giustolisi and Walski, 2012). Note that $\mathbf{d}_n$ represents the summation of different components of demands as for example customer and leakage ones (Giustolisi and Walski, 2012).

The system in (1) is non-linear with respect to both momentum and mass balance equations whose status variables, $\mathbf{Q}_p$ and $\mathbf{H}_n$, and boundary conditions are the representative values for the assumed steady-state timestep, Δt, depending on the analysis purpose.

To the work, it is relevant to explicit the meaning of steady-state assumption with respect to the demand components and status variables. The hydraulic model in (1) can be explained as follows:

$$\begin{aligned} &\mathbf{A}_{pp}\mathbf{Q}_p(t,\Delta t) + \mathbf{A}_{pn}\mathbf{H}_n(t,\Delta t) && = && -\mathbf{A}_{p0}\mathbf{H}_0(t,\Delta t) \\ &\mathbf{A}_{np}\mathbf{Q}_p(t,\Delta t) - \mathbf{d}_n^{mean}(t,\mathbf{H}_n(t,\Delta t)) && = && \mathbf{0}_n \\ &\mathbf{d}_n^{mean}(\mathbf{H}_n(t,\Delta t)) = \frac{\int_t^{t+\Delta t}\mathbf{d}_n(\mathbf{H}_n(t,\Delta t))}{\Delta t} = \frac{\mathbf{V}_n(\mathbf{H}_n(t,\Delta t))}{\Delta t} \end{aligned} \tag{2}$$

where $\mathbf{d}_n^{mean}$ is then the mean value of each nodal demand component during the time interval (t, t+Δt), Δt is the hydraulic timestep representative of the model and $\mathbf{V}_n$=[n_n, 1] is a column vector of the related volumes.

Consistently, the status variables $\mathbf{Q}_p$ and $\mathbf{H}_n$ do not represent instantaneous values but, in good technical approximation, the mean values over (t, t+Δt) as follows:

$$\begin{aligned} \mathbf{H}_n^{mean}(t,\Delta t) &= \frac{\int_t^{t+\Delta t}\mathbf{H}_n(t,t+\Delta t)}{\Delta t} \\ \mathbf{Q}_p^{mean}(t,\Delta t) &= \frac{\int_t^{t+\Delta t}\mathbf{Q}_p(t,t+\Delta t)}{\Delta t} \end{aligned} \tag{3}$$

Giustolisi et al. (2008), introduced the leakage model component, using the hydraulic analysis at pipe level, as follows:

$$\mathbf{d}_{p-leak}^{mean}\left(\mathbf{P}_p^{mean}(t,\Delta t)\right) = \begin{cases} \beta_k\cdot\left(P_k^{mean}(t,\Delta t)\right)^{\alpha_k}\cdot L_k & \text{Power model} \\ \left[\beta_k\cdot\sqrt{P_k^{mean}(t,\Delta t)} + M_k\cdot\left(P_k^{mean}(t,\Delta t)\right)^{1.5}\right]\cdot L_k & \text{FAVAD model} \end{cases} \tag{4}$$

where $\mathbf{d}_{p\text{-}leak}$=[$n_p$, 1] is, consistently with the previous discussion, a column vector of the mean pipe outflows due to leakages, which can be modelled using the mean pressures at pipe level (P_k^{mean}) contained in the column vector $\mathbf{P}_p$ =[n_p, 1], and L_k is the length of the kth pipe. Eq. (4) reports two leakage models to calculate $\mathbf{d}_{p\text{-}leak}$: (1) the Power model (Germanopoulos, 1985) and (2) the Fixed Area and Variable Area Discharge (FAVAD) model (May, 1994; Van Zyl and Cassa, 2014). The former is empirical, the latter is physically based on experimental demonstrations (Van Zyl and Cassa, 2014). Note that, when applied to hydraulic modelling of pressurized networks, the leakage models in Eq. (4) must be considered as conceptual, i.e., following the empirically (Power) or physically based (FAVAD) equation structure, and not punctual. In other words, the structure of the models is consistent with the phenomenology (empirical or physically based) at the single leak level but, because the background leaks are unknown as position, size, and number, they are modelled referring to the mean pressure on the pipes. Consequently, β_k can be considered as the deterioration factor related to the main and service connection pipes, M_k refers to the materials which characterize the increase in the size of the orifices (unknown as position and size because labelled as background) along the asset due to pressure (Van Zyl and Cassa, 2014; Van Zyl et al., 2017) and α_k is an empirical parameter to be calibrated or prior assumed. Therefore, the advanced hydraulic modelling, as reported in Giustolisi et al. (2008), calculates the single pipe outflow due to leakages using one of the models of Eq. (4), which are pressure-driven demands due to water losses to be summed to the demand of customers and any other water outflow, as reported in Giustolisi & Walski (2012). The pressure P_k^{mean} is, then, the mean pressure of each pipe calculated as average value of the two pressures at its ending nodes during the search of the solution of the modelling equations in (2) for the single steady state snapshot, (t, $t+\Delta t$), using the modified global gradient algorithm reported in Giustolisi et al. (2008). Finally, the pressures at nodes are the unknown variables that are calculated from unknown nodal heads of the system (2).

Note that the FAVAD model can be written as follows:

$$\begin{aligned}
&\mathbf{d}_{p-leak}^{mean}\left(\mathbf{P}_p^{mean}(t,\Delta t)\right)=\beta_k\cdot\left(P_k^{mean}(t,\Delta t)\right)^{\alpha_k\left(P_k^{mean}(t,\Delta t)\right)}\cdot L_k\\
&LN_k\left(M_k,\beta_k,P_k^{mean}(t,\Delta t)\right)=\frac{M_k}{\beta_k}P_k^{mean}(t,\Delta t);\quad \alpha_k\left(M_k,\beta_k,P_k^{mean}(t,\Delta t)\right)=\frac{1.5\cdot LN_k+0.5}{LN_k+1}
\end{aligned}\tag{5}$$

where the leakage number LN_k (Van Zyl and Cassa, 2014) allows to make explicit that α_k depends on material and pressure.

The pressure-dependant leakages at pipe level should be transformed to nodal outflows for the hydraulic modelling purpose of the system (2) as follows (Giustolisi et al., 2008):

$$\mathbf{d}_{n-leak}^{mean}\left(t,\Delta t,\mathbf{P}_p^{mean}(t,\Delta t)\right)=\frac{1}{2}\left|\mathbf{A}_{np}\right|\times\mathbf{d}_{p-leak}^{mean}\left(t,\Delta t,\mathbf{P}_p^{mean}(t,\Delta t)\right)\tag{6}$$

The advanced hydraulic model approach is then based on the background leakage model representing at pipe level the pressure-dependant outflows based on the empirical Power or the physical based FAVAD models.

The purpose of the model is to assess pressure-driven leakages at pipe level based on mean pressure and length of main pipes, which are the relevant information available during hydraulic modelling. Reminding that background leakages are unknown as position, size, and number, it is reported a practical approach to calculate the leakages at pipe level depending on an overall deterioration factor and a phenomenological model, empirical (Germanopoulos, 1985) or physically based (May, 1994; Van Zyl and Cassa, 2014).

To explicit the contribution of the service connections to the leakages without explicitly considering them in hydraulic modelling, it is possible to use the total length of mains and service connections for L_k, and the mean pressure at the main pipes remains representative without impairing the technical/practical perspective.

More in general, the leakage propensity of each single pipe can be used, for example, by assigning β_k based on a prior model representing the propensity of pipes to burst as function of pipe age, diameter, number of connections to properties, etc. (Berardi and Giustolisi, 2021). In the future the collection of data fostered by the digital transformation could enable discovering network specific burst model (Savic et al., 2009).

3. AMSI, asset management support indicator

The DWIs distribute volumes of water to customers, therefore, their functioning is conditioned by the daily life cycle of human beings, since the planetary revolution around the Earth's Sun has such cadence in the night-day succession. Such daily life cycle is quite stable, albeit with some differences between holidays, weekdays, summer, winter, etc. For this reason, it is correct to analyse the DWIs based on the daily operating cycle, considering the operational differences and the boundary conditions that determine their functioning.

Therefore, starting from Eqs. (4) and (5), where the leakage outflow is in cubic meters per second, and transforming it in cubic meters per day and length of pipe in kilometres, the mean density of water losses of the kth pipe from t to $t+\Delta t$, $\mathrm{D}_{k\text{-}leak}$ (m^3/d/km), can be written as follows:

$$\mathrm{D}_{k-leak}=8.6\cdot10^7\cdot\beta_k\cdot\left(P_k^{mean}(t,\Delta t)\right)^{\alpha_k\left(P_k^{mean}(t,\Delta t)\right)}\tag{7}$$

Considering the daily operative cycle,

$$\mathrm{D}_{k-leak}=8.6\cdot10^7\cdot\frac{\beta_k}{N}\cdot\sum_{t=1}^{N}\left(P_k^{mean}(t,\Delta t)\right)^{\alpha_k\left(P_k^{mean}(t,\Delta t)\right)}\tag{8}$$

where N is the number of steady state snapshot of the daily hydraulic simulation.

Eq. (8) allows writing,

$$\begin{aligned}
&\mathrm{AMSI}_{k-leak}=\frac{D_{k-leak}}{\left(P_{k-ref}\right)^{\alpha_{k-ref}}}=8.6\cdot10^7\cdot\beta_k\\
&P_{k-ref}=\frac{\sum_{t=1}^{N}P_k^{mean}(t,\Delta t)}{N}
\end{aligned}\tag{9}$$

where $P_{k\text{-}ref}$ is the reference pressure of the kth pipe, in meters of water column, which is assumed as the mean pressure over the N simulations of the operative cycle. Consequently, considering Eqs. (8) and (9), $\alpha_{k\text{-}ref}$, the reference exponent of the kth pipe, can be computed as follows:

$$\begin{aligned}
&\sum_{i=1}^{N}N^{-1}\beta_k\cdot\left(P_k^{mean}(t,\Delta t)\right)^{\alpha_k\left(P_k^{mean}(t,\Delta t)\right)}=\beta_k\cdot\left(P_{k-ref}\right)^{\alpha_{k-ref}}\Rightarrow\\
&\Rightarrow\alpha_{k-ref}=\frac{\log\left[\sum_{t=1}^{N}N^{-1}\left(P_k^{mean}(t,\Delta t)\right)^{\alpha_k\left(P_k^{mean}(t,\Delta t)\right)}\right]}{\log\left(P_{k-ref}\right)}
\end{aligned}\tag{10}$$

$\mathrm{AMSI}_{k\text{-}leak}$ of Eq. (9) is the Asset Management Support Indicator for the kth pipe, which represents a scaled deterioration indicator consistent with advanced hydraulic modelling. It is developed not to change with pressure variation, e.g., in consequence of a control activity, and allows to support investments as discussed later in the document. $\mathrm{AMSI}_{k\text{-}leak}$ indicates the density of water losses of a pipe, $D_{k\text{-}leak}$ (m^3/d/km), for the unit reference pressure.

AMSI can be scaled up from the *k*th pipe to any *s*th portion of the pressurized water system, e.g., DMA or consumption centre including *m* pipes, as follows:

$$\mathrm{AMSI}_s = \frac{\mathrm{D}_{s-leak}}{\left(P_{s-ref}\right)^{\alpha_{s-ref}}} = 8.6\cdot10^7\cdot\beta_{s-leak}$$
$$\mathrm{D}_{s-leak} = 8.6\cdot10^7\cdot\frac{\sum_{k=1}^{m}\beta_k\cdot\left(P_{k-ref}\right)^{\alpha_{k-ref}}\cdot L_k}{L_s} \tag{11}$$

where $\mathrm{D}_{s\text{-}leak}$ is the mean density of water loss indicator of the *s*th portion of the system (m^3/d/km), L_s is the length of the system and $\beta_{s\text{-}leak}$ is its deterioration factor.

$P_{s\text{-}ref}$ and $\alpha_{s\text{-}ref}$ are the reference pressure and leakage model exponent, respectively, of the system under analysis; they are assumed as the mean values of $P_{k\text{-}ref}$ and $\alpha_{k\text{-}ref}$ over the *m* pipes weighted by their lengths:

$$P_{s-ref} = \frac{\sum_{k=1}^{m} P_{k-ref}\cdot L_k}{L_s} \qquad \alpha_{s-ref} = \frac{\sum_{k=1}^{m}\alpha_{k-ref}\cdot L_k}{L_s} \tag{12}$$

For technical purposes, $\alpha_{s\text{-}ref}$ can be at first approximated to the unit value in the range of pressure variation and material of typical WDSs (Van Zyl and Cassa, 2014; Schwaller et al., 2015; Van Zyl and Malde, 2017). Note that although based on hydraulic modelling, the value of $P_{s\text{-}ref}$ can be also approximated by representative pressure measurements.

AMSI_s is then the daily volume of leakages per kilometre of the system pipelines and per unit reference pressure; it characterizes the system deterioration allowing to support the decision about the activities of leakage management, i.e., pipes replacement and active leakage detection versus pressure control.

$\beta_{s\text{-}leak}$ can be related to the asset internal factors such as pipes age, material and diameter, number of connections to properties, etc., through β_k of each pipe and external factors such as pressure level, effects of fatigue (e.g., pressure variation due to unsteady flow or pressure control; traffic; etc.), environment, climate, etc., as reported in Kleiner & Rajani (2001). This is relevant because data collection of today digitalization can allow machine-learning to assess the dependence which can increase the support to the leakage management actions. Note that the indicator of Eq. (11), AMSI_s, i.e., $\beta_{s\text{-}leak}$, depends on $\alpha_{s\text{-}ref}$ and $P_{s\text{-}ref}$, in addition to β_k. Assuming $\alpha_{s\text{-}ref} = 1$ for simplicity, without impairing the generality of the discussion, it is possible to write:

$$\mathrm{AMSI}_s = 8.6\cdot10^7\cdot\beta_{s-leak} = \frac{\sum_{k=1}^{m}\mathrm{AMSI}_k\cdot P_{k-ref}\cdot L_k}{\sum_{k=1}^{m}P_{k-ref}\cdot L_k}$$
$$\mathrm{AMSI}_s > \mathrm{AMSI}_k \quad \overset{P_{k-ref}-\Delta P}{\overbrace{\Rightarrow}} \quad \mathrm{AMSI}_{s-new} < \mathrm{AMSI}_s \tag{13}$$
$$\mathrm{AMSI}_s < \mathrm{AMSI}_k \quad \overset{P_{k-ref}+\Delta P}{\overbrace{\Rightarrow}} \quad \mathrm{AMSI}_{s-new} > \mathrm{AMSI}_s$$

The structure of Eq. (13) states that AMSI_s decreases if any of AMSI_k decreases due to the pipe replacement or the active leakage detection activity. The two relationships of Eqs. (13) are demonstrated in the supplementary material.

It is of interest to note that AMSI_s decreases if $\mathrm{AMSI}_s < \mathrm{AMSI}_k$ and the pressure decreases, $P_{k\text{-}ref} - \Delta P$, while it increases if $\mathrm{AMSI}_s > \mathrm{AMSI}_k$ and pressure increases, $P_{k\text{-}ref} + \Delta P$. This is a relevant occurrence because it provides to AMSI the capability to evaluate the benefit of pressure control activities and benchmarking them, for example, with respect to pipes replacement. To explain the finding in Eq. (13), Table 1 reports six subsystems having different values of AMSI_s, which are reported in the fourth row, corresponding to different $\beta_{s\text{-}leak}$ and $P_{s\text{-}ref}$. Note that they correspond to different $\mathrm{D}_{s\text{-}leak}$. Therefore, the indicator for the entire system AMSI_{all} composed of six subsystems can be written as follows:

$$\mathrm{AMSI}_{all} = \frac{\sum_{s=1}^{6}\mathrm{AMSI}_s\cdot P_{s-ref}\cdot L_s}{\sum_{s=1}^{m}P_{s-ref}\cdot L_s} = \frac{\sum_{s=1}^{6}\mathrm{D}_{s-leak}\cdot L_s}{\sum_{s=1}^{m}P_{s-ref}\cdot L_s} = \frac{\mathrm{D}_{all-leak}}{P_{all-ref}} \tag{14}$$

where $\mathrm{D}_{all\text{-}leak}$ and $P_{all\text{-}ref}$ are the density of the water losses and the reference pressure, respectively, both calculated as the mean value weighted by the lengths, L_s. It was assumed that a pressure decrease of 20 m was performed in each subsystem separately, i.e. one by one. The seventh row of Table 1 reports the values of the indicator for the entire system, $\mathrm{AMSI}_{all\text{-}new}$, after pressure decrease into each subsystem separately; the original values of $P_{s\text{-}ref}$ are reported in the sixth row of Table 1. The case study was built to have AMSI_{all} of Eq. (14) equal to the value in bold of the third system, i.e. when pressure decreases in the third subsystem only $\mathrm{AMSI}_{all} = \mathrm{AMSI}_{all\text{-}new} = 0.856348$. Then, the seventh row of Table 1 reports in *italic* the values of AMSI $_{all\text{-}new}$ decreased with respect to the AMSI_{all} in ***italic-bold*** the increased and in **bold** the one unchanged. Note that the example in Table 1 shows and numerically demonstrates that Eq. (13) allows to drive pressure management towards the subsystems having AMSI_s higher than AMSI_{all}. This is a highly valuable feature of the novel indicator.

In other words, the structure of AMSI penalizes the pressure control in the less deteriorated subsystems (number 4 or 6 of Table 1) when AMSI is scaled to represent all of them with a single indicator. Thus, when AMSI is scaled up, although the pressure and leakage outflow are reduced looking at the single subsystems 4 or 6, the reduction of pressure prevails with respect to the reduction of leakages. Note that, as extreme case, we can think of at a subsystem without leakage outflow ($\beta_{s\text{-}leak} = 0$); the pressure control reduces the reference pressure of that

Table 1
Application of Eq. (13) to direct pressure control investments.

	1	2	3	4	5	6
$P_{s\text{-}ref}\cdot L_s$	$1.05\cdot10^{4}$	$3.00\cdot10^{3}$	$1.25\cdot10^{3}$	$9.00\cdot10^{3}$	$4.55\cdot10^{3}$	$8.00\cdot10^{3}$
$\beta_{s\text{-}leak}\cdot L_s$	$1.74\cdot10^{-6}$	$6.37\cdot10^{-7}$	$2.48\cdot10^{-7}$	$9.72\cdot10^{-7}$	$1.96\cdot10^{-6}$	$1.16\cdot10^{-6}$
L_s	150	50	25	120	130	200
AMSI_s	1	1.1	**0.856348**	0.7	1.3	0.5
$\beta_{s\text{-}leak}$	$1.16\cdot10^{-8}$	$1.27\cdot10^{-8}$	$9.91\cdot10^{-9}$	$8.10\cdot10^{-9}$	$1.50\cdot10^{-8}$	$5.79\cdot10^{-9}$
$P_{s\text{-}ref}$	70	60	50	75	35	40
$\mathrm{AMSI}_{all\text{-}new}$	*0.843406*	*0.849446*	**0.856348**	***0.867417***	*0.822120*	***0.900478***

subsystem and consequently of the six subsystems $P_{all\text{-}ref}$, while $D_{all\text{-}leak}$ does not change and $\text{AMSI}_{all\text{-}new}$, see Eq. (13), increases. This is a relevant feature of AMSI that can be used to direct the efficiency of investments for pressure control with respect to DMAs, also, i.e., indicating the pressure control for the most deteriorated areas.

An alternative definition of the indicator in Eq. (14) could be to define AMSI_{all} as the mean value of AMSI_{s} weighted by the subsystem lengths. This makes not explicit the dependence of the indicator on system pressure and then on pressure management. However, it is preferable the first definition because of the features just reported. Finally, a simple example of AMSI relevance is here reported. Three consumption centres are characterized by a rather high density of water losses $D_{s\text{-}leak} = 50$ m^3/d/km, with quite different reference pressure $P_{s\text{-}ref} = 25$, 100 and 50 m. Assuming $\alpha_{s\text{-}ref} = 1$, we got respectively AMSI = 2, 0.5 and 1.

Here AMSI provides insights about the reason of the high-water loss density, $D_{s\text{-}leak} = 50$ m^3/d/km, offering guidelines for asset management as follows: (1) in the first centre ($P_{s\text{-}ref} = 25$ m), water losses depend mostly on system deterioration, consequently, it needs of prioritized plans for pipes replacement along with the implementation of active leakage detection actions; (2) in the second centre ($P_{s\text{-}ref} = 100$ m), high water losses depend on high system pressure level, thus, the priority actions are related to pressure control actions; and (3) in the third town, water losses depend on both system pressure and pipeline deterioration, then, a combination of the approaches previously exposed is recommended to address the issue effectively.

The next section reports in detail the analysis of AMSI with respect to capability of supporting decision on the efficiency of the type of investment for leakage management.

4. AMSI for the rationality of investment path decisions

The aim of this section is to demonstrate the capability of AMSI to support the rationality of investments for pipes replacement and active leakage detection versus pressure control to reduce the density of water losses. The term “system” is used here to refer to a portion of the pressurized water system under analysis. Starting from Eq. (11) and reminding that AMSI is developed to have a small and technically negligible change with the pressure variation being a scaled deterioration factor of the system, the Fig. 1 shows $D_{s\text{-}leak}$ versus $P_{s\text{-}ref}$ for several values of AMSI, from 0.2 to 5 assuming $\alpha_{s\text{-}ref} = 1$. Fig. 1 shows the relevance of AMSI reporting $D_{s\text{-}leak}$ both in m^3/d/km and in L/s/km.

To better understand the values of AMSI, it is important to note that $D_{s\text{-}leak} = 125$ m^3/d/km corresponds to a flow of about 1.45 L/s/km, therefore a huge value of the linear leakage outflow considering that it is a mean value of the system. Fig. 1 shows that $D_{s\text{-}leak} = 125$ m^3/d/km is reached with $P_{s\text{-}ref} = \{100;\ 50;\ 25\}$m for AMSI = {1.25, 2.5, 5}, respectively, corresponding to $\beta_{s\text{-}leak} = \{1.45;\ 2.89;\ 5.79\}\cdot 10^{-8}$. On the contrary, AMSI lower than 1, {0.8, 0.4, 0.2} in the diagram, corresponds to $\beta_{s\text{-}leak} = \{1.31;\ 4.63;\ 9.26\}\cdot 10^{-9}$ and linear leakage outflow of about {40; 18; 10} m^3/d/km at $P_{s\text{-}ref} = 50$ m. Therefore, it is possible to state that AMSI lower and higher than the unit approximately divides, respectively, non-deteriorated and deteriorated systems, the former requiring pressure control versus the latter requiring pipes replacement.

Note that in practice the values of β_k at pipe level, a reference for those characterizing a portion of the system, spans in the range $[10^{-9};\ 10^{-7}]$ corresponding to new pipes and very much deteriorated ones, respectively.

Fig. 1 reports eight arrows from (1) to (8) representing different investment paths to explain the support that AMSI can provide to leakage management. Furthermore, for explanatory purposes, two possible levels of “compatible mean pressure” of the system at 40 m and 25 m are indicated in the diagram. The compatible mean pressure is a relevant concept to understand the actual unavoidable density of water losses of the system. In fact, WDNs are quite different as management history, terrain altimetry, building heights, presence of local private tanks with pumping, minimum pressure required by service charters, etc. Therefore, each consumption centre and DMA may be characterized by the lowest mean pressure that can be compatible with the minimum pressure required for a correct service to customers.

The actual unavoidable density of water losses of the system is specific of each system and determines the minimum density of water losses

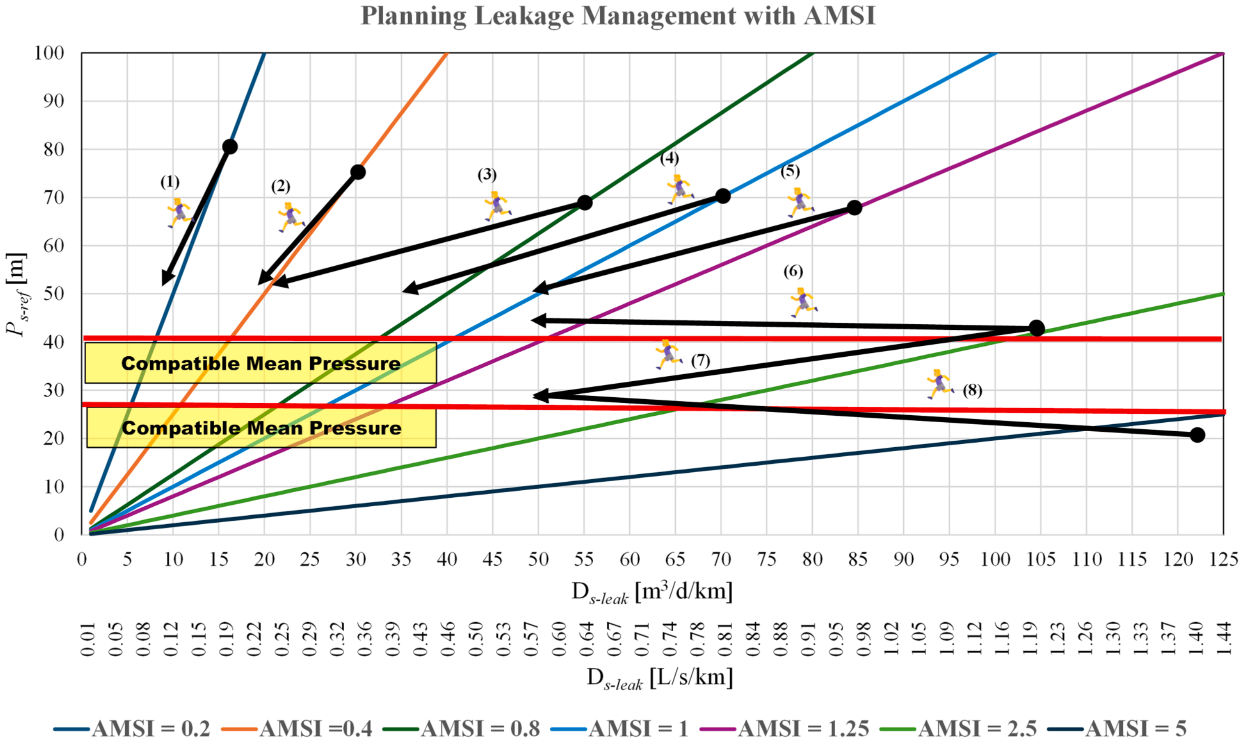

Fig. 1. Diagram to support investments for leakage management. Arrows from (1) to (8) are investment paths.

that can be reached at the actual AMSI, according to the following equation:

$$\mathrm{D}_{s-leak}^{P-un} = \mathrm{AMSI}_s \left(P_{s-ref}^{\min}\right)^{\alpha_{s-ref}} \tag{15}$$

where $\mathrm{D}^{P\text{-}un}$ is the minimum, unavoidable, density of water losses at constant AMSI, due to the system deterioration associated to P^{min}, i.e., the minimum reference pressure, which is the lowest mean pressure that can be compatible with the minimum pressure required for a correct service to customers. For example, a system characterized by AMSI = 1 can reach $\mathrm{D}^{P\text{-}un} = 40$ or 25 m^3/d/km depending on $P^{min} = 40$ or 25 m, respectively, as reported in Fig. 1.

Thus, the novel indicator together with the evaluation of the minimum reference pressure for the specific system allows calculating the unavoidable daily water loss depending on the specific consumption centre and DMA. In addition, after pipes replacement and/or active leakage detection activities, the system deterioration decreases with lower values of AMSI and $\beta_{s\text{-}leak}$; therefore, the model calibration allows calculating the new AMSI and the new unavoidable density of water losses, $\mathrm{D}^{P\text{-}un}$. For example, in Fig. 1, if AMSI decreases to 0.8, $\mathrm{D}^{P\text{-}un}$ decreases from about 32 to 20 m^3/d/km if the compatible mean pressure changes from 40 or 25 m. Hence, the strategy based on AMSI allows calculating the unavoidable water loss of the system by means of monitoring data and model calibration, before and after the activities of pipes replacement and/or active leakage detection. This fact supports the quality of investments because of the *ex-ante* and *ex-post* possibility to evaluate in a rational way the effect of works. Furthermore, if the reference pressure can be reduced with technical actions, it is possible to assess the benefit using the simple Eq. (15). Amongst the eight arrows from (1) to (8) in Fig. 1, arrows (1) and (2) represent the investment paths in non-deteriorated systems, AMSI = 0.2 and 0.4, where the density of water losses is generally low, and the pressure control activity is the best cost/benefit investment path to reduce $\mathrm{D}_{s\text{-}leak}$ and with a minor reduction of AMSI. Note that the possibility of reducing water losses, in absolute value, is not high in such systems and, as reported in the previous section (Table 1), the pressure control in the most deteriorated areas decreases AMSI that, for this reason, also directs pressure control.

Arrows (3), (4) and (5) represent investment paths in systems characterized by medium deterioration and high pressure in the examples. The arrows represent the paths of pressure control with reduction of the $P_{s\text{-}ref}$, associated to the reduction of AMSI due to pipes replacement and/or active leakage detection activities. The margin of water loss reduction is here relevant with both pressure control and pipes replacement activities and then, the cost/benefit ratio is generally low.

Arrows (6), (7) and (8) represent investment paths in systems characterized by high deterioration. They are also generally distinguished by a low pressure because of the deterioration itself, i.e., hydraulically speaking because of the high value of the linear leakage outflow as shown in Fig. 1. The investment path is here constrained by the technical situation and the pressure control is not applicable, unless there are pressure reduction margins with respect to the compatible mean pressure, as for arrow (7). Then, pipe replacement plans and/or active leakage detection are required to decrease AMSI, and although these activities are more expensive and riskier (also more uncertain) than pressure control, they represent the only possible choice to reduce water losses.

The investment path of the arrow (7) shows the possibility to reduce pressure along with AMSI. It depends on the starting level of reference pressure with respect to the compatible one. Finally, the path (8) shows the case of a system where pipes replacement allows to increase the reference pressure which starts below the minimum level for a correct service. Note that, in the case of pipes replacement and/or active leakage detection, pressure level will increase as AMSI is decreasing, but it may be adjusted through pressure control.

Fig. 2 reports the same diagram of Fig. 1 assuming $\alpha = 1.1$ and 0.9, respectively. The two diagrams show that the AMSI constant curves in these cases are not straight lines, since they follow the assumed exponents, but the previous discussion still applies.

The calculation of the unavoidable density of water losses and the evaluation its reduction change because of the exponent, which can be calibrated with advanced hydraulic modelling and monitoring data of today digital transition.

4.1. Synthetic indicators to benchmark

Fig. 1, or the equivalent Fig. 2, and Eq. (13) allow defining two indices of efficiency as follows:

$$\begin{aligned} \mathrm{PLI} &= \frac{\mathrm{D}_{s-leak}}{\mathrm{D}_{s-leak}^{P-un}\left(\mathrm{AMSI}, P_{s-ref}^{\min}, \alpha_{s-ref}\right)} = \frac{\mathrm{D}_{s-leak}}{\mathrm{AMSI}\left(P_{s-ref}^{\min}\right)^{\alpha_{s-ref}}} \\ \mathrm{DLI} &= \frac{\mathrm{D}_{s-leak}^{\beta-un}\left(\mathrm{AMSI}_{budget}, P_{s-ref}^{\min}, \alpha_{s-ref}\right)}{\mathrm{D}_{s-leak}^{P-un}\left(\mathrm{AMSI}, P_{s-ref}^{\min}, \alpha_{s-ref}\right)} = \frac{\mathrm{AMSI}_{budget}}{\mathrm{AMSI}} \end{aligned} \tag{16}$$

where the $\mathrm{D}^{P\text{-}un}$ and $\mathrm{D}^{\beta\text{-}un}$ are, respectively, the minimum density of water losses reachable with pressure management and with the reduction of the deterioration by pipes replacement and leakage detection activities once reached the compatible pressure.

PLI is the dimensionless Pressure Leakage Indicator to benchmark systems with respect to pressure management, while DLI is the dimensionless Deterioration Leakage Indicator to benchmark systems with respect to pipe replacement investments.

The former is greater than unit by definition and the latter is lower than unit depending on the AMSI_{budget}, which is the reachable value of the deterioration based on available investment for pipe replacement plans. Therefore, DLI could be multiplied by investment budget to make it an efficiency indicator of pipe replacement plans.

Finally, it is relevant to note that AMSI, PLI and DLI are developed using a unique strategy and theory, which makes them consistent and robust from both the scientific and technical standpoints.

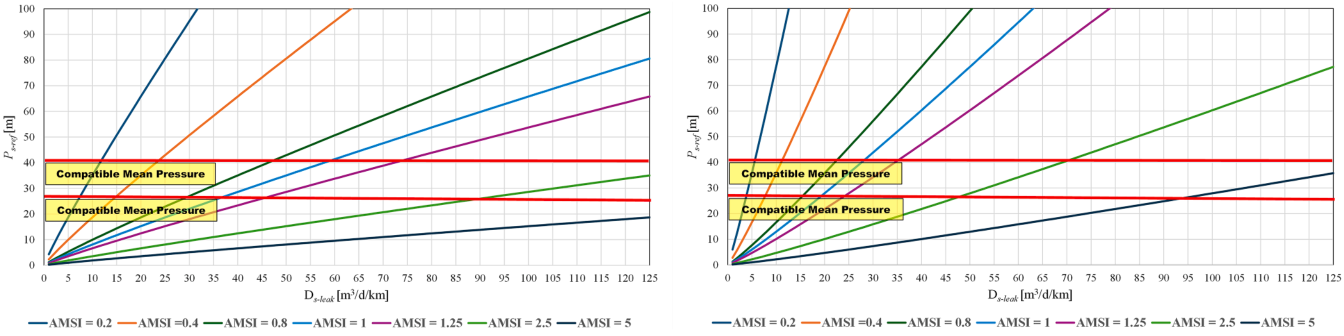

Fig. 2. Diagram to support investments for leakage management; upper $\alpha = 1.1$ (left) and lower $\alpha = 0.9$ (right).

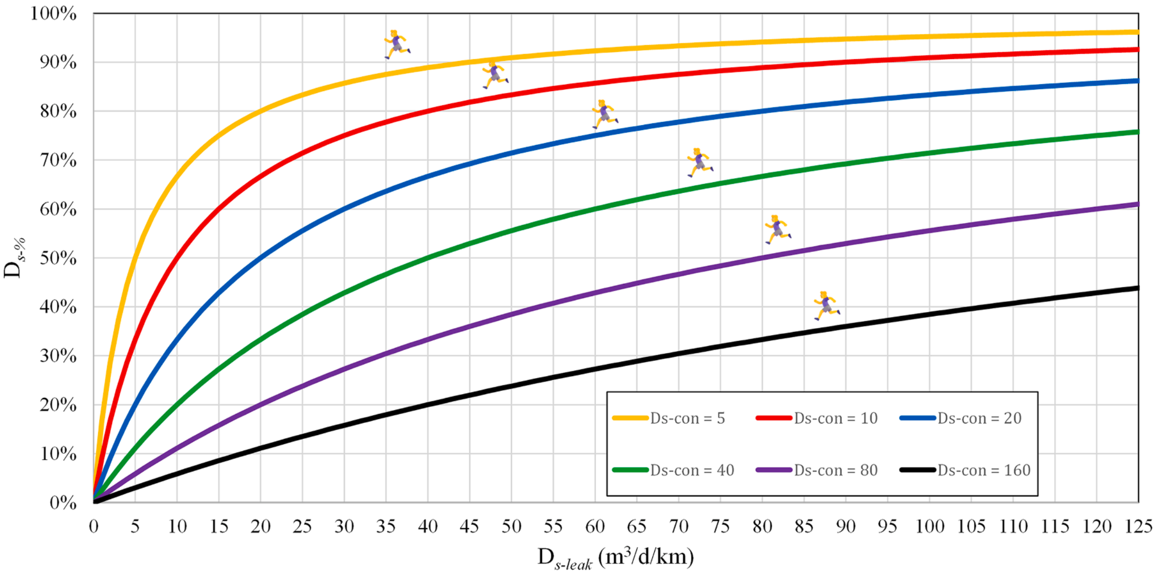

Fig. 3. Diagram to support investments for leakage management using percentage of water loss.

5. The percentage of water loss to direct investments

It is here reported a brief discussion on the percentage water loss indicator with the density of water losses as driver for investments. The percentage water loss indicator, $D_{s-\%}$, may be expressed as follows:

$$D_{s-\%} = 100\cdot\frac{W_{s-leak}}{W_{s-leak}+W_{s-con}} = 100\cdot\frac{D_{s-leak}}{D_{s-leak}+D_{s-con}} \tag{17}$$

where W_{s-con} is the daily water consumption and W_{s-leak} is the daily water loss, both expressed in m^3/d, D_{s-con} is the density of consumption and D_{s-leak} the density of water losses, both expressed in m^3/d/km. Fig. 3 reports the diagram of D_{s-leak} versus $D_{s-\%}$ for different levels of consumption D_{s-con}.

In Fig. 3 the persons running on the curve at constant D_{s-con} represents the investment to reduce D_{s-leak} moving towards the left with respect to *x*-axis. The position of the person represents the starting point as D_{s-leak} and $D_{s-\%}$, e.g., one for each level D_{s-con}.

Note that we can assume, in first approximation, that D_{s-con} does not vary much because the density of consumption is specific of a consumption centre, being mostly dependant on population density and the number of connections to properties. Furthermore, the values of D_{s-con} reported in Fig. 3 are realistic. In fact, low urbanized centres can have values close or lower than 5 m^3/d/km and D_{s-con} can be easily greater than 80 m^3/d/km in urbanized towns and greater than 200 m^3/d/km in big towns. At DMA level D_{s-con} could be null or very low that is one of the reasons of non-scalability of the percentage indicator being much dependant on consumption of the system under analysis.

Fig. 3 shows that if the strategy of the leakage reduction, and thus the selection of investments is directed by $D_{s-\%}$, the results can be misleading. It is the case, for instance, of system with $D_{s-con} = 5\div10$ m^3/d/km, in which low values of D_{s-leak} (say less than 20 m^3/d/km) are associated to high values of $D_{s-\%}$, with scarce possibility of reducing the latter indicator. Then, the investments reducing the lowest D_{s-leak} will not produce the most efficient leakage reduction option. In addition, the investments for lower D_{s-cons} cannot be evaluated through the $D_{s-\%}$ because the curve remains flat and falls, depending on the level of D_{s-con}, for very low values of D_{s-leak} that, to be reached, might require huge investments, not justified in terms of volume of water losses reduction. Furthermore, the diagram in Fig. 3 cannot support the decision on the kind of investments because the pressure of the system does not play an explicit role as driver, as the reference pressure and the level of AMSI in the previous section. Note that in different real consumption centres, and even more at DMA level, the variability D_{s-con} is relevant, and the same water utility usually manages centres where D_{s-con} may easily span from 5 to 100 m^3/d/km.

The reason of the weakness of $D_{s-\%}$ as driver of investments depends on the structure of Eq. (17), where D_{s-leak}, that is the target variable to be reduced, is both at the denominator and numerator; furthermore D_{s-con} plays a relevant role being at the denominator. In fact, a common strategy of water utilities is to reduce consumptions through information and education of customers. In addition, smart metering is expected to reduce D_{s-cons} since it will increase the awareness of user consumption.

Thus, the leakage reduction investment plans directed by $D_{s-\%}$ have the intrinsic paradox that, while trying to reduce D_{s-leak}, the decrease of D_{s-con} might result into constant or increased $D_{s-\%}$, as from Eq. (17).

6. Discussion on ILI and AMSI

For the sake of completeness, it is here reported a discussion on AMSI and Infrastructure Leakage Indicator (ILI), originally formulated on empirical basis (Lambert et al., 1999; Lambert and McKenzie, 2002). From Eqs. (11) and, for example, the EU Directives and Regulations (IWA, 2022), AMSI and ILI formulations are the following,

$$\begin{aligned} \mathrm{AMSI} &= \frac{D_{s-leak}}{\left(P_{s-ref}\right)^{\alpha_{s-ref}}} = \frac{W_{s-leak}}{\left(P_{s-ref}\right)^{\alpha_{s-ref}}\cdot L_s} \\ \mathrm{ILI} &= \frac{\mathrm{CARL}}{\mathrm{UARL}} = \frac{W_{year-leak}}{P_s\cdot(6.57\cdot L_m + 9.13\cdot L_c + 0.257\cdot N_c)} \end{aligned} \tag{18}$$

where CARL ($=W_{year-leak}$) is the Current Annual Real Losses volume (m^3/year) and UARL is defined as the Unavoidable Annual Real Losses volume (m^3/year). W_{s-leak} has the same physical meaning of CARL, but it is defined at the daily scale.

UARL is given using an empirical formulation based on system pressure P_s (m), length of the mains and service connections to properties, L_m and L_c, respectively (km), and the number of connections, N_c. Note that for AMSI L_s might include both L_m and L_c as previously reported.

The comparison of AMSI and ILI shows the different genesis of the indicators. Lambert (1999) introduced ILI in a different technical condition, when data collection was weak and hydraulic modelling was mainly devoted to pipe sizing or fire protection verifications. In fact, ILI is based on water volumes in m^3/year, although it can be calculated at the daily scale by dividing UARL by 365 and using a daily volume of water losses. This way the P_s of ILI can be defined similarly to $P_{s\text{-}ref}$ of AMSI, although the original definition was not clear.

Therefore, the difference between ILI and AMSI resides in the denominators. The following equations report them for the sake of clarity in the following discussion.

$$\begin{aligned} &\text{AMSI} \Rightarrow \left(P_{s-ref}\right)^{\alpha_{s-ref}} \cdot \left(L_m + L_c\right) \\ &\text{ILI} \Rightarrow P_{s-ref} \cdot \left(a \cdot L_m + b \cdot L_c + c \cdot N_c\right) \end{aligned} \tag{19}$$

Note that it is preferable to report *a*, *b*, and *c* instead of specific constant values of UARL because they depend on the scale of analysis and units to compute UARL.

Apart from the accommodation to the daily scale and the definition of the pressure for ILI, Eq. (18) shows that it is empirical and needs of the number of connections as independent variable. In addition, it assumes leakages linear with pressure and, consequently, it provides unrealistic values if α_k at pipe level is different from unit.

Furthermore, as showed in the previous paragraphs, since AMSI is mainly related to the deterioration of the portion of the system under analysis, after pipes replacement the new model calibration reflects its change and the new values of AMSI can be prior evaluated, via advanced hydraulic modelling, considering the new β_k of the replaced pipes. This way the unavoidable density of water losses of the system can be prior predicted as well, and post assessed.

ILI changes with pipes replacement and/or active leakage detection activities can be predicted via advanced hydraulic modelling, CARL changes, while UARL changes cannot be predicted if the assumption $P_s = P_{s\text{-}ref}$ is not adopted.

In addition, the unavoidable density of water losses in AMSI depends on the "compatible mean pressure" of the system, as shown in the previous section, but this is not the case of ILI. UARL depends only on the geometric characteristics of the WDN, but not on the material, which is instead considered in AMSI, being $\alpha_{s\text{-}ref}$ derived from model calibration, as from the studies of Van Zyl & Cassa (2014). Also, the presence of the number of connections, N_c, in UARL does not allow the scalability of ILI because when their number is low ILI increases too much. In fact, for a proper application of ILI a minimum number of connections is usually recommended, as in the EU Directives and Regulations (IWA, 2022).

Overall, the comparison between ILI and AMSI proves the reasons of the rationality of the latter, provided that it is calculated through monitoring data of systems and advanced model calibration. In this way, AMSI allows the rational evaluation of investment paths at any scale of the water system, which can be coherently integrated in different portions of the water systems managed by the water utility, both *ex-ante* and *ex-post*. This is relevant for an indicator that is expected to be consistent with today digital transition, considering the need of making progressively more efficient the process of leakage management.

However, ILI is used for benchmarking pressurized water systems. In fact, it is used by some national authorities to compare different water utilities or by water utilities to compare the efficiency of different WDNs to address investments for leakage reduction.

7. Using AMSI at DMA and consumption centres level in real WDNs

The case studies aim at demonstrating and discussing the novel indicator AMSI. A single real Apulian consumption centre, the WDN of San Marzano, is used to discuss AMSI and other indicators at the DMA scale. Furthermore, other twelve Apulian consumption centres, characterized by different levels of water losses, are useful to show synthetic results after and before optimal design of DMAs and pressure control. All the WDN hydraulic models were calibrated using real data and the advanced hydraulic analysis including the leakage model, as previously reported. Each model was calibrated using the pipes propensity to leak (Berardi and Giustolisi, 2021) as proportional to the number of connections to properties and inverse of the diameter, while data on pipe age were not available. Real measurements of five days (winter and summer weekdays and weekend days plus the new year day) were used in the calibration procedure. It identified the demand patterns and calibrated pipes β_k using an optimization procedure (Laucelli et al., 2023). Afterwards, the optimal DMA design (Laucelli et al., 2017) was applied at each WDN.

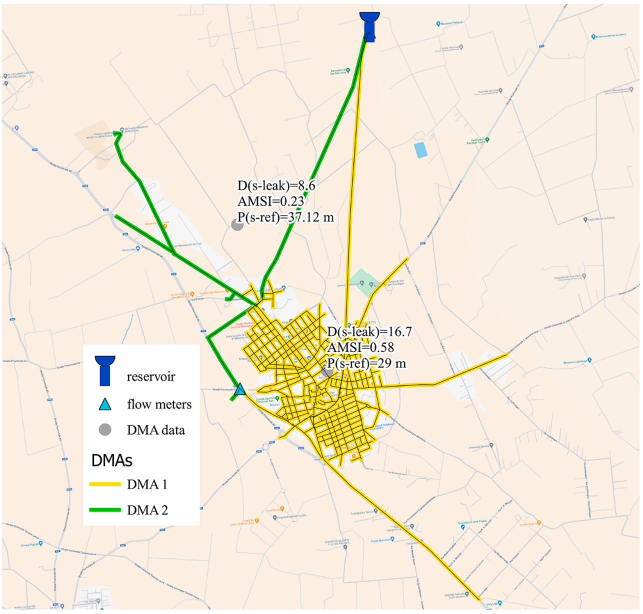

Fig. 4. Layout WDS of San Marzano. Calibrated model and original DMAs.

7.1. Single consumption centre and DMAs

San Marzano is a town served by a WDN of about 51.5 km in length with one source of water; its layout is reported in Fig. 4. The WDN serves 3286 properties with 2714 connections. The WDN was originally divided into two DMAs by one internal flow meter and two others close to the single source of water (reservoir) along the two sub-urban mains departing from it.

Table 2 reports the relevant data of each DMA and of the entire WDN. Note that the pipe length was increased by a factor of 1.22 to account for the length of connections.

The value of AMSI of the entire system is rather low because the density of water losses, $D_{s\text{-}leak}$, is low with respect to the mean pressure, $P_{s\text{-}ref}$. At DMA level AMSI indicates that the most deteriorated system is DMA #1 which serves the downtown, as reported in Fig. 4. Note that the percentage indicator, $D_{s\text{-}\%}$, is rather high both for the entire system and the single DMAs being low the density of consumption, $D_{s\text{-}con}$. DMA #2 has a huge value of the $D_{s\text{-}\%}$ (= 90.74%) because the transmission pipes supply water to an industrial area with a very low $D_{s\text{-}con}$ (= 0.88 m^3/d/km). It is noteworthy that ILI gives a different picture of the leakage entity because at DMA level it is very affected by the number of connections in the definition of UARL. Note that, based on EU Directives and Regulations (IWA, 2022), the ILI category is "very high" for both the DMAs and the entire system.

Fig. 5 reports the WDN of San Marzano optimally divided into nine DMAs, and Table 3 reports the relevant data in each row along the entire WDN.

Table 3 shows that the percentage water loss, $D_{s\text{-}\%}$, is a very weak indicator at DMA level because of its dependence on $D_{s\text{-}con}$. Note that for two DMAs (seventh and eighth) it is equal to 100% because it is null $D_{s\text{-}con}$, since districts that correspond to internal transmission pipelines have no connections to properties. AMSI values, instead, indicate the most deteriorated DMAs. It is worth to remind that the deterioration factor is at pipe level (AMSI_k) while at system level AMSI integrates the

Table 2
Centre of San Marzano. Relevant data and indicators of calibrated model.

DMA	L_s [m]	N_c [-]	$P_{s\text{-}ref}$ [m]	$W_{s\text{-}leak}$ [m^3/d]	$W_{s\text{-}con}$ [m^3/d]	$D_{s\text{-}leak}$ [m^3/d/km]	$D_{s\text{-}leak}$ [L/s/km]	$D_{s\text{-}\%}$ [%]	AMSI	ILI	$D_{s\text{-}con}$ [m^3/d/km]	UARL
1	54,362	2702	29.00	908	907	16.70	0.19	50.03	0.576	10.64	16.68	31,140
2	8557	12	37.12	74	8	8.60	0.10	90.74	0.232	11.45	0.88	2348
WDN	62,919	2714	30.10	982	914	15.60	0.18	51.78	0.518	10.47	14.53	34,231

$W_{s\text{-}con}$ = daily volume of consumption; $D_{s\text{-}con}$ = daily density of consumption; $D_{s\text{-}\%}$ = percentage of water loss.

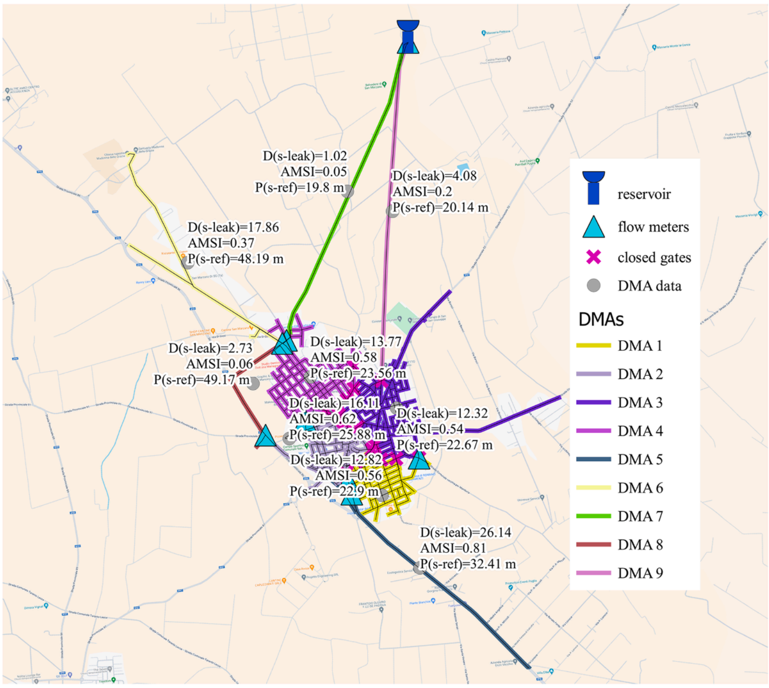

Fig. 5. DMAs after design: relevant data and indicators.

Table 3
Centre of San Marzano. Relevant data and indicators after DMA design.

DMA	L_s [m]	N_c [-]	$P_{s\text{-}ref}$ [m]	$W_{s\text{-}leak}$ [m^3/d]	$W_{s\text{-}con}$ [m^3/d]	$D_{s\text{-}leak}$ [m^3/d/km]	$D_{s\text{-}leak}$ [L/s/km]	$D_{s\text{-}\%}$ [%]	AMSI	ILI	$D_{s\text{-}con}$ [m^3/d/km]	UARL
1	8687	508	22.90	111	176	12.82	0.15	38.69	0.560	9.28	20.31	4376
2	9821	687	25.88	158	194	16.11	0.19	44.95	0.623	9.11	19.73	6339
3	15,440	717	22.67	190	267	12.32	0.14	41.60	0.543	10.48	17.29	6622
4	13,628	766	23.56	188	259	13.77	0.16	42.00	0.585	9.96	19.02	6877
5	3192	20	32.41	83	8	26.14	0.30	91.59	0.807	34.09	2.40	894
6	3693	12	48.19	66	8	17.86	0.21	89.77	0.371	17.20	2.04	1399
7	3433	0	19.80	3	0	1.02	0.01	100.00	0.051	2.67	0.00	478
8	1431	0	49.17	4	0	2.73	0.03	100.00	0.055	2.88	0.00	495
9	3594	4	20.14	15	3	4.08	0.05	84.03	0.203	10.11	0.78	530
WDN	62,919	2714	25.69	819	914	13.02	0.15	47.25	0.507	10.23	14.53	29,213

$W_{s\text{-}con}$ = daily volume of consumption; $D_{s\text{-}con}$ = daily density of consumption; $D_{s\text{-}\%}$ = percentage of water loss.

effect of the pressure distribution and pipes deterioration; this means that AMSI is a factor of proportionality between density of water losses and pressure effect on leakages consistently to the findings of Van Zyl et al. (2014). In fact, the optimal DMA design (Laucelli et al., 2017) determines the position of closed gates versus the flow measurement, thus reconfiguring the flow paths in the hydraulic network and causing pressure decrease in the most deteriorated areas. Therefore, the overall AMSI for the original system is equal to 0.518 (third row of Table 2) while it becomes 0.507 after optimal DMA design (tenth row of Table 3), which is consistent with the finding and discussion based on Table 1. About ILI, the category of DMAs following the values in Table 3 is "very high" for seven DMAs; it is "moderate" for the two DMAs (seventh and eighth) with very low $D_{s\text{-}\%}$ because UARL depends on the number of connections, which is null in such DMAs. Therefore, in general, ILI is not scalable because the number of connections is included in the definition of UARL. This is a drawback like the density of consumption ($D_{s\text{-}cons}$) in the definition of the percentage indicator ($D_{s\text{-}\%}$). The real weakness of ILI is in the empirical definition of UARL, which is not scalable unless specific sets of constants (*a, b,* and *c* in Eq. (19)) are defined for each system or portion of the system, but this would be in contrast with the idea of UARL itself. Finally, it is useful to show AMSI versus ILI in Fig. 6 to clarify that the similar structure does not mean similar results due to the relevant technical-scientific differences between the two indicators.

It is trivial to mention that a pipe rehabilitation plan reduces the

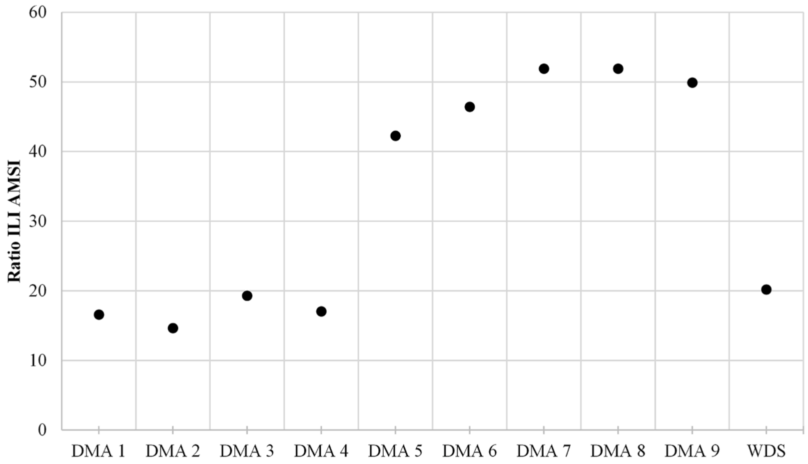

Fig. 6. Ratio ILI-AMSI for the DMAs and entire network.

Table 4
Apulian centres. Relevant data and indicators of calibrated model.

WDN	L_s [m]	N_c [-]	$P_{s\text{-}ref}$ [m]	$W_{s\text{-}leak}$ [m^3/d]	$W_{s\text{-}con}$ [m^3/d]	$D_{s\text{-}leak}$ [m^3/d/km]	$D_{s\text{-}leak}$ [L/s/km]	$D_{s\text{-}\%}$ [%]	AMSI	ILI	$D_{s\text{-}con}$ [m^3/d/km]	UARL
1	66,466	4773	41.90	4314	4728	64.90	0.75	47.71	1.549	22.18	71.13	70,980
2	49,739	2312	34.10	1677	1420	33.72	0.39	54.16	0.989	19.02	28.55	32,188
3	103,102	7936	22.00	3915	4349	37.97	0.44	47.37	1.726	23.50	42.18	60,820
4	112,045	5324	17.60	9238	3893	82.45	0.95	70.35	4.685	88.85	34.75	37,948
5	48,214	3194	40.30	2111	1041	43.79	0.51	66.98	1.087	16.49	21.59	46,743
6	35,148	2385	64.60	2248	764	63.95	0.74	74.63	0.990	14.76	21.74	55,562
7	120,841	8123	54.40	3862	3916	31.96	0.37	49.66	0.588	8.82	32.41	159,790
8	73,127	4808	28.40	1957	2416	26.76	0.31	44.75	0.942	14.37	33.04	49,696
9	38,198	3305	43.80	170	1562	4.46	0.05	9.83	0.102	1.27	40.89	48,968
10	33,208	1619	23.00	486	558	14.63	0.17	46.55	0.636	11.87	16.80	14,941
11	229,214	14,525	25.30	4217	6738	18.40	0.21	38.50	0.727	11.38	29.40	135,220
12	101,467	3149	56.40	1686	1847	16.61	0.19	47.72	0.295	7.16	18.20	85,885

$W_{s\text{-}con}$ = daily volume of consumption; $D_{s\text{-}con}$ = daily density of consumption; $D_{s\text{-}\%}$ = percentage of water loss.

Table 5
Apulian centres. Relevant data and indicators after DMA design.

WDN	L_s [m]	N_c [-]	$P_{s\text{-}ref}$ [m]	$W_{s\text{-}leak}$ [m^3/d]	$W_{s\text{-}con}$ [m^3/d]	$D_{s\text{-}leak}$ [m^3/d/km]	$D_{s\text{-}leak}$ [L/s/km]	$D_{s\text{-}\%}$ [%]	AMSI	ILI	$D_{s\text{-}con}$ [m^3/d/km]	UARL
1	66,466	4773	21.70	1992	4728	29.97	0.35	29.65	1.381	19.78	71.13	36,760
2	49,739	2312	17.40	830	1420	13.68	0.16	36.89	0.959	18.45	23.40	16,424
3	103,102	7936	20.60	3454	4349	27.46	0.32	44.27	1.626	22.14	34.57	56,949
4	112,045	5324	14.80	7539	3893	55.16	0.64	65.95	4.547	86.24	28.48	31,911
5	48,214	3194	17.50	865	1041	14.71	0.17	45.39	1.025	15.56	17.70	20,298
6	35,148	2385	20.40	641	764	14.94	0.17	45.61	0.894	13.33	17.82	17,546
7	120,841	8123	35.50	2550	3916	17.30	0.20	39.44	0.594	8.93	26.56	104,275
8	73,127	4808	23.80	1470	2416	16.48	0.19	37.83	0.845	12.88	27.08	41,647
9	38,198	3305	25.70	103	1562	2.21	0.03	6.19	0.105	1.31	33.52	28,732
10	33,208	1619	18.00	385	558	9.50	0.11	40.83	0.644	12.02	13.77	11,693
11	229,214	14,525	20.30	3322	6738	11.88	0.14	33.02	0.714	11.18	24.10	108,497
12	101,467	3149	42.50	1336	1847	10.79	0.12	41.97	0.310	7.53	14.92	64,718

$W_{s\text{-}con}$ = daily volume of consumption; $D_{s\text{-}con}$ = daily density of consumption; $D_{s\text{-}\%}$ = percentage of water loss.

AMSI of the DMA where the pipes are replaced while the hydraulic calculation are useful to assess the new pressure status and water losses in the entire hydraulic system. i.e., all the DMAs. In fact, the adverse effect of replacing pipes is the increase of pressure due to increase of the conductivity of the replaced pipes and decrease of their leakage outflows.

About the compatible mean pressure, it could be calculated assuming pressure reduction valves controlled by the critical points that guarantee the minimum pressure into the system over time driven by the demand patterns.

7.2. Results of optimal DMA and pressure control designs

We here show and discuss AMSI applied in a real design activity performed on twelve WDNs.

Tables 4 and 5 report the parameters and indicators computed before and after pressure control activities, respectively. Results are also shown in Fig. 7 in the same plot layout of Fig. 1. For the sake of simplicity, but without impairing the generality of the discussion, the graph shows a single compatible mean pressure of about 15 m for all the centres, although it varies by a few metres. The low value of the compatible pressure is due to the presence of private tanks with pumping providing pressure to the buildings, which is a technical characteristic of

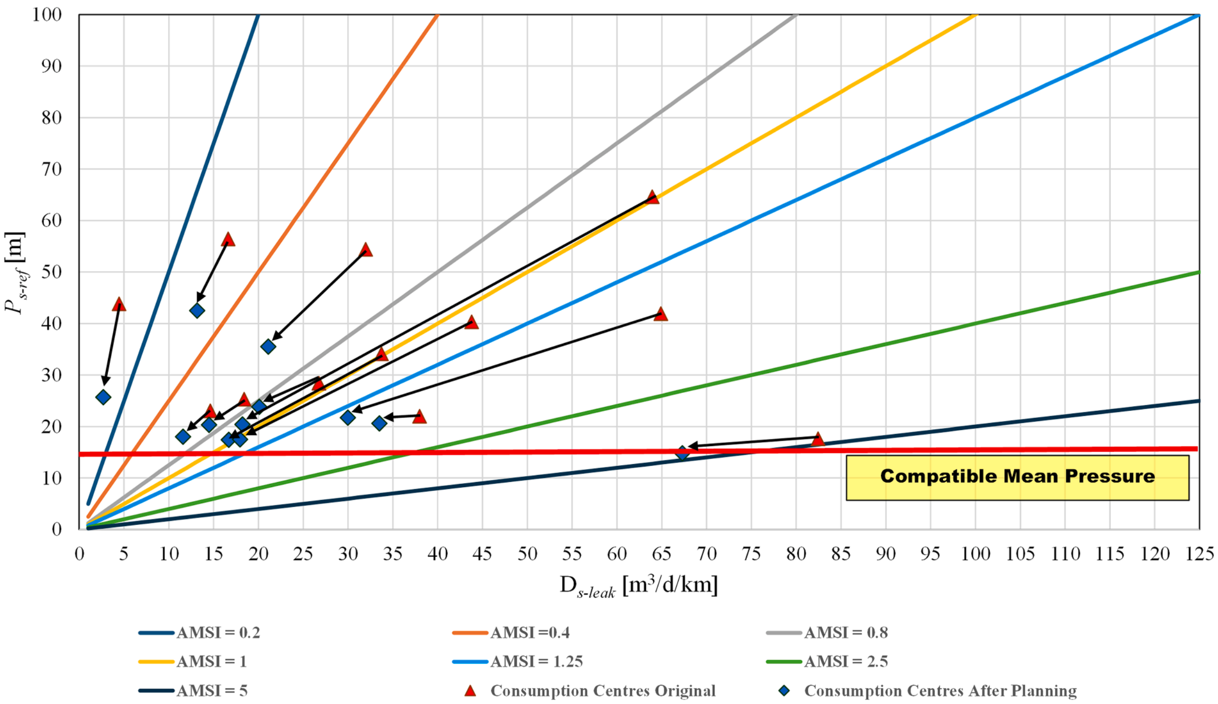

Fig. 7. Twelve WDNs after and before planning DMA and pressure control.

mediterranean areas.

In Fig. 7, the AMSI values (red indicators) show that three WDNs are more deteriorated than the others, considering that a high density of water losses, $D_{s\text{-}leak}$, corresponds to low pressure. Four WDNs exhibit AMSI close to unit and five lower than 0.8, the less deteriorated. Note that $D_{s\text{-}leak}$ does not explain by itself whether the main reason of water losses is pipeline deterioration or pressure. The blue indicators in Fig. 7 show that leakage management yields a significant reduction of $D_{s\text{-}leak}$ in all WDNs.

Note that in four WDNs (seventh, ninth, tenth and twelfth) AMSI results slightly increased, which indicates that the reduction of pressure, although reducing water losses, does not happen in most deteriorated portions of the network. This is because the initial value of $D_{s\text{-}leak}$ was low for the ninth, tenth and twelfth WDNs, while for the seventh one the pressure control was quite constrained by its altimetry.

Anyway, this aspect of AMSI deserves a specific study, which is out of the scopes of this work, about the characteristics of optimal DMAs and pressure control designs to reduce AMSI, i.e., to achieve pressure

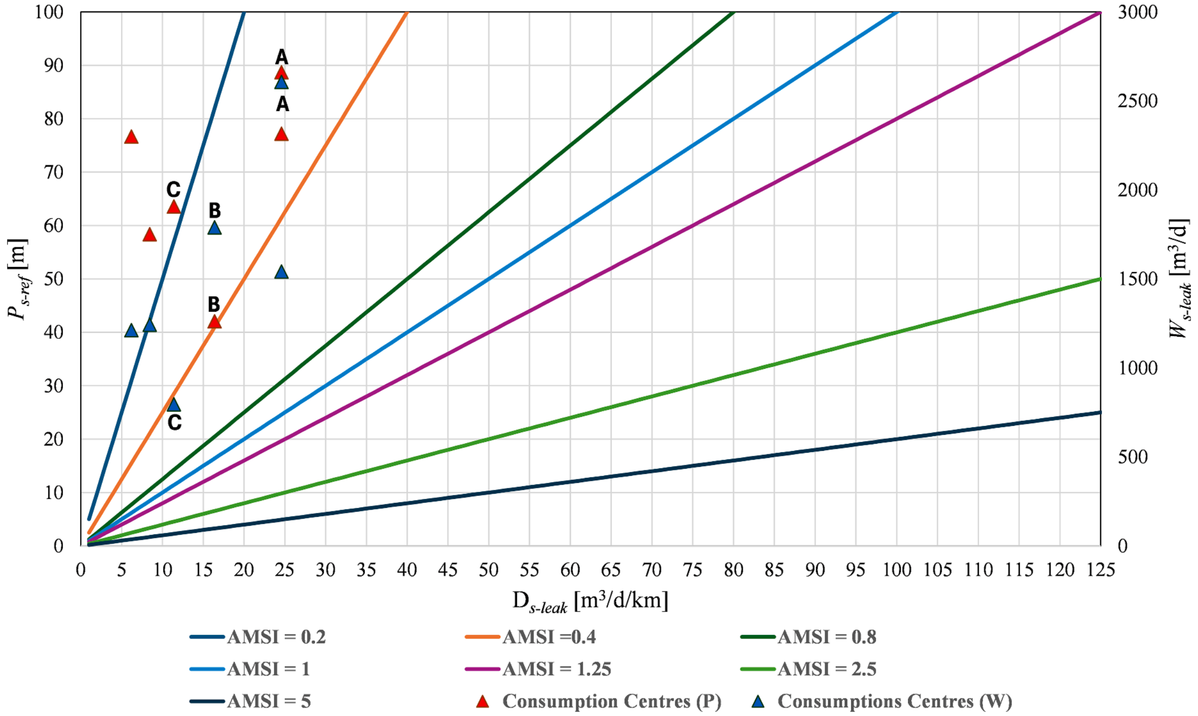

Fig. 8. Representation of AMSI value for three real Italian networks (red triangles); blue triangles refer to the water loss volumes $W_{s\text{-}leak}$ (on the y-axis on the right).

reduction in the most deteriorated portions of the hydraulic system, as reported in the example and discussion of Table 1.

Note that for the most deteriorated WDN, the fourth in Tables 4 and 5, AMSI was reduced from 4.68 to 4.54 with optimal DMA and pressure control activities, through a pressure reduction valve with the set point at a critical node. This implementation increases the effectiveness in reducing pressure and leakage outflows in the most deteriorated parts of the hydraulic system over time; therefore, $D_{s\text{-}leak}$ is reduced although the mean pressure is not much decreased. To explain the last occurrence from hydraulic perspective, note that leakage management activities tend to equalize the pressure over time and in the different zones of the network. Furthermore, Tables 5 and Fig. 7 ($D_{s\text{-}leak}$ remains high although decreases from 82.45 to 55.16) show that: in the most deteriorated WDNs, the pressure control is not the “final” solution to reduce leakages; and the only solution is to decrease AMSI, i.e. to have strategic investments for the replacement of the most deteriorated pipes where the pressure is higher.

Finally, note that ILI is classified “very high” for ten WDNs, “low” for the ninth WDN and “high” for the twelfth one, before planning leakage management. Therefore, also in this case, the classification does not vary after planning.

7.3. Directing investments path for leakage reduction on different WDNs

For water utilities that manage many WDNs, pursuing the efficiency of investments means to select the consumption centres where actions should be undertaken first, to achieve the maximum reduction of leakages. Therefore, in this condition the approach outlined here and based on the AMSI evaluation can be useful to support such decisions.

Fig. 8 shows, in the same layout as Fig. 1, the AMSI value for three real Italian networks (red triangles). To represent the useful characteristics of the analysed networks, these are also indicated with blue triangles which refer, on the *y*-axis on the right, to the water loss volumes $W_{s\text{-}leak}$.

The analysed networks are representative of three possible conditions in which a WDN can be before possible investments by the water utility to reduce water losses. They are characterized by low AMSI values (below 0.5), meaning that water losses are mainly due to high pressure regime rather than asset deterioration; in addition, the linear density of water losses is also low (below 25 $m^3/d/km$).

The WDN “A” shows the highest water loss volume (above 2600 m^3/day), with the highest reference pressure (about 88 m) and density of water losses of about 24 $m^3/d/km$. This means that water losses are mostly due to high pressures in the network, with a minimum responsibility of pipes deterioration. Consequently, the primary investment to reduce losses should be directed towards pressure control. Further reduction in losses could be achieved by replacing the most deteriorated pipes, but this should only be assessed after pressure control has been implemented.

The WDN “B” has an AMSI value of 0.4, with a linear density of water losses of about 16 $m^3/d/km$; this means that the reference pressure (around 40 m) is the lowest amongst the analysed networks. This network does not have significant water losses, nor a particularly high reference pressure, which indicates that water losses are due to both pressure and deterioration. Therefore, in this case, once the mean compatible pressure is reached, further leakage reduction requires investments for pipe replacement and active leakage detection, which could be higher than case A.

Finally, the WDN “C” shows the lowest AMSI value (about 0.2). This is because water losses (daily and linear) are very low, and the reference pressure is quite high (about 60 m). This means that the low water losses are due exclusively to pressure, with pipes in good condition. Even by reducing the pressure, we would have low margins for recovering losses, also because these are already very low. Therefore, the water utility may assign a lower priority of action to this system.

8. Conclusions

Water loss reduction is the main asset management goal of the water utilities worldwide. Leakages represent the “health” of the asset and are dependant on both pipeline deterioration and pressure conditions. Therefore, the definition and application of a suitable key performance indicator for water loss management is relevant both to address the priority of the actions to be undertaken and to evaluate their results. The digital transformation has the aim of making efficient the processes using digital tools and strategies by means of collecting representative data. Therefore, a proper and rational water loss indicator can today benefit from those data with the result of more efficient asset management and leakage control.

The novel Asset Management Support Indicator, AMSI, presented herein is conceived to direct the rational allocation of investments to reduce water losses in water supply and distribution systems. It is consistent with advanced hydraulic modelling, exploits field data collection and uses the main findings of the studies about leakage modelling so far. It is also physically based and take advantage from the opportunities of the current digital transition in the water sector. Through some real case studies, the paper demonstrates that AMSI is applicable from the large scale of a entire WDN to the small scale of a single DMA, allowing to identify and select the most efficient technical activities for leakage reduction in relation to the initial conditions.

In addition, since AMSI is based on the description of the physical system, it provides a synthetic and rational indicator that captures the integrated effects of pipeline deterioration and pressure. This feature, in turn, makes the minimization of AMSI an effective objective to drive optimal leakage management planning, at different time horizons. From this perspective, even decisions relating to asset management actions for irrigation networks under pressure, following calibration of the relevant hydraulic simulation models, could be supported by the AMSI evaluation, also because it is independent of consumptions.

Hence, this novel indicator holds the features to be consistent with the current need of water utilities, and it is also suitable to be adopted by water authorities to benchmark their performances.

CRediT authorship contribution statement

O. Giustolisi: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **G. Mazzolani:** Writing – review & editing, Validation, Supervision, Conceptualization. **L. Berardi:** Writing – review & editing, Validation, Methodology. **D.B. Laucelli:** Writing – review & editing, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The models used in the study are not available because considered sensitive by water utilities. All data generated by analyses during this study are included in this published article.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.121765.

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