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Evaluating the performance of water distribution network deterioration using customer-oriented performance indices

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ABSTRACT

Water distribution networks (WDNs) are an essential urban infrastructure, with their performance directly influencing societal well-being. Our study applied to a real network model that employs a 24-h simulation with 1-h time steps and evaluates the impact of leaks and loss in the pipe cross-sectional area on WDN hydraulic performance as experienced by end users. Adhering to a UK utility's 20-m head pressure requirement as the water main benchmark, we present two new customer-oriented performance indices (CPIs) centred on network reliability and pressure deficit severity. The new CPIs adeptly quantify network performance degradation due to pipe deterioration. This degradation translates directly to a poor customer experience, highlighting the potential for these CPIs to pinpoint areas of the network where performance levels are compromised. Furthermore, the CPIs identify individual pipes within the network where defects would severely impact network performance and the sets of pipes which, when simultaneously experiencing defects, would lead to a more severe loss in network performance. Results show that the CPIs capture relatively small performance declines and identify sensitive pipes impacting network performance, providing insights for optimised inspection and maintenance intervention to provide better customer service.

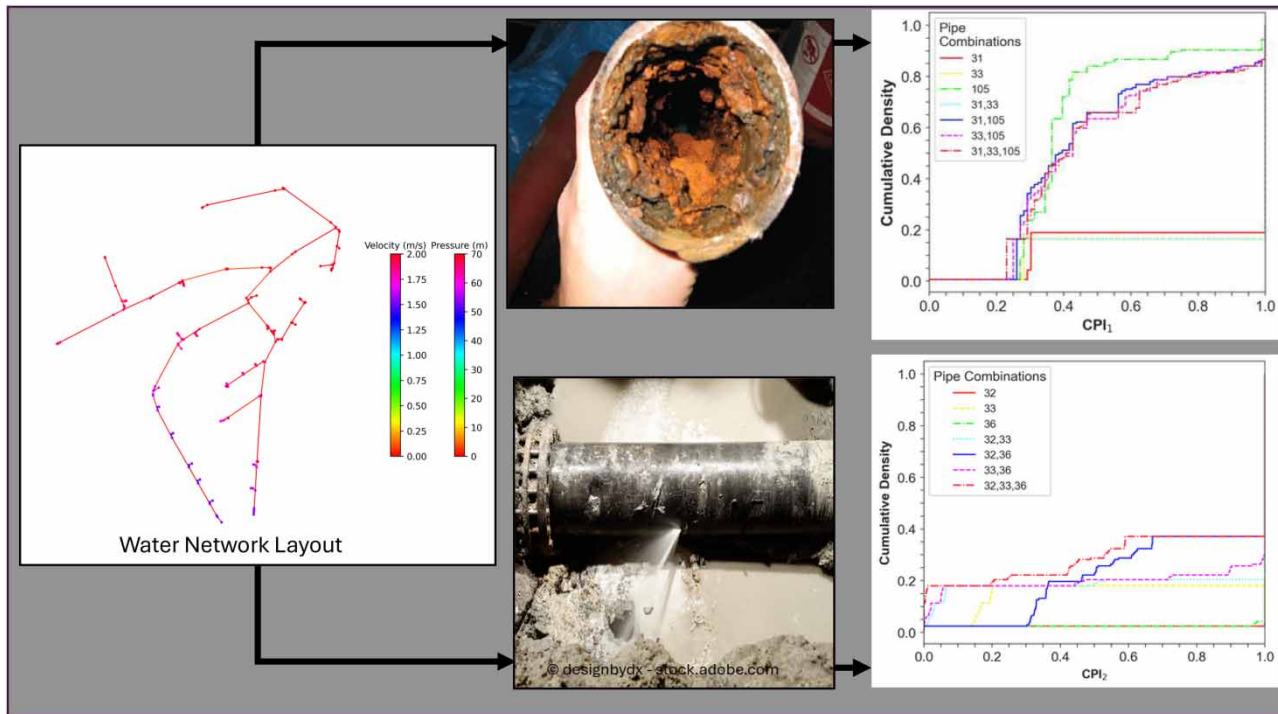
Key words: customer-oriented performance indices, pipe deterioration, pressure deficit, water distribution network

HIGHLIGHTS

- Novel customer performance indices (CPIs) to evaluate water network's performance.
- The study employs minimum pressure over time requirements as a reflection of customer experience.
- Findings show how pipe leaks and cross-sectional area loss in different areas of the network impact customer experience.
- CPIs can guide targeted inspections for improved network performance and customer experience.

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GRAPHICAL ABSTRACT



INTRODUCTION

Water distribution networks (WDNs) are essential for delivering potable water to urban and rural populations, and their efficient operation is critical to ensuring reliable service and maintaining consumer satisfaction. However, ageing WDNs are susceptible to defects which can significantly impair hydraulic performance, increase operational costs, and diminish customer satisfaction (Boxall *et al.* 2004; Almandoz *et al.* 2005; Farley & Trow 2005; Aminu Beshir *et al.* 2024). To mitigate these challenges and maintain reliable service, utilities must employ effective inspection, maintenance, and rehabilitation strategies, addressing defects that impact hydraulic performance to avoid disruptions (Parvizsedghy *et al.* 2017; D'Ercole *et al.* 2018).

Incorporating customer-centric variables into performance assessments of water utilities has gained momentum over the past two decades. Since 1999, when water companies in England and Wales introduced the overall performance assessment (OPA) framework, there has been a shift towards evaluating service quality from the consumer's perspective. Picazo-Tadeo *et al.* (2008) note that Saal & Parker (2001) were among the first to include customer satisfaction in the performance measurement of water utilities, laying the foundation for more comprehensive frameworks that balance technical efficiency with consumer expectations.

Building on this foundation, Sala-Garrido *et al.* (2021) integrated customer-related performance indicators (PIs), such as service interruptions and complaints, into the 'benefit of the doubt' composite indicator framework. This approach provides a more holistic evaluation of water service quality, incorporating technical and customer-focused metrics. The WUSQI and the benefit of the doubt indicators effectively assess water utility performance from a customer-centred standpoint by evaluating customer contacts and service interruptions, planned or unplanned. However, they lack the granularity to identify specific issues within the utility's network. A method that evaluates performance directly from the utility's network, linking customer satisfaction to hydraulic parameters, would provide valuable insights into utility quality of service. This approach would enhance customer satisfaction by informing proactive decisions for effective network management.

In a related study, Mocholi-Arce *et al.* (2021) emphasised the importance of variables like water leakage and bursts per kilometre as key indicators of water utility productivity. Reducing such incidents enhances operational efficiency and significantly improves customer satisfaction. Furthermore, Duarte *et al.* (2009) introduced the global index of service quality

(GISEQ), integrating various PIs related to customer satisfaction and service reliability, further demonstrating the industry's growing recognition of the need for customer-oriented performance assessments.

The increasing importance of customer experience to water utilities has led to the demand for more customer-centric approaches for evaluating performance. Assessing the performance of WDNs requires balancing utility-driven objectives such as operational efficiency and equitable water distribution with the needs and expectations of customers, who prioritise affordability, reliable supply, and minimal service interruptions (Naamani & Sana 2021).

Traditional PIs for evaluating utility services or their networks are often selected based on ease of calculation, availability of data, or even local traditions rather than their technical suitability for meaningful comparisons across the systems. This approach can produce indicators that merely create a positive impression of performance rather than reflecting the level of service. As a result, important insights into operational inefficiencies may be missed, undermining efforts to improve water management (Cheong 1991). The proper basis for selecting PIs should focus on those that offer the most rational technical basis for comparison, ensuring that performance assessments are accurate and actionable. Similarly, Kwietniewski (2004) models water distribution system (WDS) reliability using a system-wide pressure performance index, focusing on fault states and overall system probabilities. While this highlights the likelihood of events occurring, it overlooks the need for detailed, node-specific analysis, such as how faults in particular pipes or areas of the network impact pressure variations at WDS nodes, directly affecting customer service in the network.

To address these challenges, utilities and regulators have consistently developed new performance assessment tools and improved existing performance methodologies to help balance operational goals with customer satisfaction. These tools, used during both the design and operational phases of WDN management, establish benchmarks for supply reliability, pressure management, and overall service quality (Ofwat 2005). Cardoso *et al.* (2004) identified two primary methods for evaluating water supply system performance: PIs and technical performance assessment. International organisations, such as the International Water Association (IWA), the Office of Water Services (Ofwat), and the International Benchmarking Network (IBNET), have developed specific PIs to measure the reliability of water services provided by utilities quantitatively. These indicators focus on crucial aspects such as the frequency and duration of supply interruptions, pressure levels in distribution systems, leakage rates, and customer complaints (Ofwat 2005; Van den Berg & Danilenko 2010; Alegre *et al.* 2016).

For instance, Ofwat uses metrics like the percentage of customers experiencing supply interruptions lasting more than 3 h, as well as the average duration of interruptions per year. Similarly, IWA has created a set of key performance indicators (KPIs) that assess water loss (using the infrastructure leakage index), supply continuity, and system responsiveness to disruptions. IBNET's benchmarking framework also includes indicators that measure both physical losses in the system and the responsiveness to customer complaints about service reliability. These standardised PIs provide a clear, data-driven framework that helps utilities benchmark their service quality, identify areas for improvement, and compare their performance with global best practices. Water utilities can ensure they meet regulatory standards by applying these indicators while enhancing service reliability and customer satisfaction. These indicators help benchmark and improve utility service quality but are reactive, averaged for network regions, and lack the granularity to inform pipe-level operations and maintenance within the utility network.

Technical performance assessment tools typically focus on system hydraulics, using parameters such as pressure, velocity, and flow rate to evaluate performance. Alegre & Coelho (1995) introduced technical performance indices (TPIs) that assess hydraulic performance based on nodal pressure heads. Other studies, such as those by Todini (2000) and Prasad & Park (2004), have used resilience indices to measure WDN performance, incorporating factors such as nodal demand and hydraulic heads. Yazdani & Jeffrey (2012) proposed a topological performance index to quantify water distribution systems' redundancy and structural robustness. Tanyimboh & Sheahan (2002) developed an optimised WDN layout using the entropy index to improve WDN performance. Although entropy, topography, and resilience metrics are known to inform WDN design decisions, they are limited mainly by their focus on network connectivity, redundancy, and the ability to restore operation after a disruption without considering the customer experience. While entropy, topography, and resilience metrics ensure alternative flow paths and system recovery, they do not guarantee that the pre-disruption service levels are maintained after the failure event (Knoeri *et al.* 2016). Consequently, they fall short of evaluating performance from a customer-centric perspective, which requires ensuring that water supply meets demand at the desired service levels consistently.

The growing emphasis on customer-centric performance evaluation offers a more comprehensive perspective on WDN performance. By integrating customer-focused metrics with traditional technical evaluations while maintaining service reliability, utilities can better align system operations with customer expectations. This holistic approach enhances operational efficiency and improves customer satisfaction, particularly in ageing networks prone to service disruptions.

In this context, the study introduces a novel approach to evaluating WDN performance by focusing on pipe-level analysis using customer-oriented performance indices (CPIs), prioritising maintaining minimum pressure levels to meet user demand. Unlike broader utility-level assessments, this method allows for identifying specific pipes critical to maintaining network performance. By examining how leaks and reductions in pipe cross-sectional areas impact hydraulic performance, the method pinpoints vulnerable pipes that pose a risk to service quality. This granularity enables utilities to optimise operations and maintenance, allowing for targeted repairs and proactive inspection strategies. Ultimately, this approach mitigates service disruptions, enhances operational efficiency, and ensures reliable water delivery, significantly improving customer satisfaction by addressing issues at their source.

METHODS

We proposed CPIs that assess service levels using time-series pressure data. The study employed WNTR-EPANET (Rossman 2000; Klise *et al.* 2017), considering it is open source and has existing Python libraries, which enable efficient implementation of the deterioration scenarios and automate the simulation process. The simulation was performed by setting the demand model to pressure-dependent demand (PDD), which produces realistic hydraulic simulation results during disruptive events in WDNs (Rossman 2000). Nodal pressure time-series results from the simulation are applied to compute the CPIs.

Establishing a system-wide pressure threshold is valuable for monitoring network operation and performance. In England and Wales, utilities must maintain a minimum pressure of 10 m while providing 9 litres of water per minute at the customer tap of primary use, according to Ofwat (2005), this is often interpreted as a static pressure of 17 m in the street. Shin *et al.* (2018) emphasised that increasing system pressure is a common strategy to ensure resilience against hydraulic disruptions, which can significantly enhance the ability of a water distribution system to meet pressure and flow requirements even during disruption. For instance, Yorkshire Water, a water utility in England, often designs its WDNs with 20 m pressure heads. This study adopted Yorkshire Water's (2020), and common across the UK, minimum water main pressure of 20 m head outside all properties, but other thresholds can be used.

Development of proposed CPIs

This study simulated a case study network for 24 h with a 15-min timestep, considering the minimum required pressure (P) of 20 m at node j to meet user demand. A CPI of 1.0 for node j indicates that node j receives pressure higher or equal to the minimum pressure requirement throughout the simulation period. The following conditions for developing the CPIs were introduced in Equation (1):

$$\begin{cases} \text{If } P_j \geq 20 \text{ m, CPI} = 1 \\ \text{If } P_j < 20 \text{ m, CPI} \neq 1 \end{cases} \quad (1)$$

CPI₁ measures the WDN's reliability in meeting the 20-m pressure threshold. CPI₁ considers the pressure deficits in network nodes throughout the 24-h simulation period. A pressure deficit period is defined as a period during which the pressure at node j goes below 20 m. The CPI₁ for node j (denoted as CPI_{1,j}) is calculated as one minus the ratio of the summed duration of all pressure deficit periods at node j to the total simulation time (T_s), this can be written as:

$$\text{CPI}_{1,j} = 1 - \frac{\sum_{i=1}^n T_{i,j}}{T_s} \quad (2)$$

CPI₂ investigates the WDN's performance based on the severity of pressure deficit over time compared with the 20-m pressure threshold. It measures this severity by considering the area under the curve of pressure deficit over time. CPI₂ for node j (denoted as CPI_{2,j}) is calculated as one minus the ratio of the summed area of the period of all pressure deficit ($A_{i,j}$) at node j to the product of the pressure threshold of 20 m head and the total simulation time (T_s) and denoted as A_s .

Where $A_S = 20T_s$ serving as a reference area, this can be written as:

$$\text{CPI}_{2,j} = 1 - \frac{\sum_{i=1}^n A_{i,j}}{A_S} \quad (3)$$

The overall network performance denoted as CPI_{Net} is computed as the average CPI of the nodes in the network. This is calculated based on the total number of nodes, N , in the network, as shown in Equation (4):

$$\text{CPI}_{\text{Net}} = \frac{1}{N} \sum_{j=1}^N \text{CPI}_j \quad (4)$$

Scenario 1: Impact of 5% leak diameter proportional to pipe diameter

In this scenario, the impact of pipe leaks on the WDN performance was assessed using CPIs. Leak sizes of 5% of each pipe's manufacturer diameter D_0 were applied based on a study by [Yu et al. \(2019\)](#). The leak diameter D_{leak} for each pipe was determined using Equation (5) was then used to calculate the leak area in Equation (6). The leak area was normalised as a ratio of the leak area to the original pipe area, as shown in Equation (8). This normalisation process captured the relative change in leak size across varying pipe diameters in the network, allowing for a standardised comparison of leak areas across different pipes and a more comprehensive system performance analysis.

$$D_{\text{leak}} = 5\% \times D_0 \quad (5)$$

$$A_{\text{leak}} = \pi \left(\frac{D_{\text{leak}}}{2} \right)^2 \quad (6)$$

$$A_0 = \pi \left(\frac{D_0}{2} \right)^2 \quad (7)$$

$$\text{Normalised leak area} = \frac{A_{\text{leak}}}{A_0} \quad (8)$$

Leak discharge was modelled using the emitter settings feature in [Rossman \(2000\)](#). The process involved splitting the pipe, creating an artificial node along the pipe, and applying an emitter at that node to simulate a pressure-driven discharge as given in Equation (9):

$$Q_{\text{leak}} = K_{\text{leak}} \cdot P^\beta \quad (9)$$

where K_{leak} is the emitter coefficient that represents the size of the leak (related to the leak area), P is the pressure at the leaking node since it is modelled by breaking a pipe length and introducing it at the joint where the leak is applied, and β is the pressure exponent, set to 0.5 in this study, assuming a leak from an orifice as turbulent flow.

Scenario 2: Loss in the cross-sectional area of pipes by 80%

This scenario considered individual pipes experiencing a loss in cross-sectional area and their respective impact on the network performance based on the CPIs. The reduction in diameter was quantified as an 80% loss in the pipe diameter based on findings from [Rathnayaka \(2016\)](#). Given D_0 as the original diameter of the pipe, the effective diameter was computed using Equation (10) factoring in the pipe roughness to the deteriorated diameter at 80% was derived from Equation (11).

In this scenario, loss of pipe capacity was simulated based on a study by [Boxall et al. \(2004\)](#), which identified reduced pipe diameter and roughness as notable determinants when estimating the impact of deterioration in WDN models. To account for the impact of roughness and pipe diameter reduction, the diameter of pipes in the case study was adjusted using the formula:

$$\text{For original state: } D_{\text{effective}} = [D_0 - 2(K_0)] \quad (10)$$

where K_0 represents the roughness of the pipe in the calibrated case study network and D_0 is the inner diameter of the pipe.

$$D_{\text{Loss in diameter}} = 80\% \times D_{\text{effective}} \quad (11)$$

The roughness and diameter reduction adjustment were applied selectively to the pipes tested in each simulation cycle, rather than uniformly across the entire network, to provide a precise and localised assessment of hydraulics. Factoring the roughness into the diameter adjustment using Equation (10), the model analysis captured the effect of increased flow resistance caused by pipe surface degradation and the corresponding reduction in cross-sectional area.

Performance levels and estimation of proportions nodes operating within each performance level

The CPIs are classified into five levels based on the WDN's ability to maintain the minimum required pressure. 0–0.2 indicates a severe impact, 0.2–0.4 indicates a significant impact, 0.4–0.6 corresponds to a moderate impact, 0.6–0.8 reflects a minor impact, and 0.8–0.999 represents a slight impact. All CPI values under 1 indicate some level of pressure deficit. Furthermore, we used the cumulative distribution function (CDF) methodology to evaluate the CPI distribution across all impact levels and clarify the impact trend at nodes. In this case, the CDF sorted the CPI values at nodes for each pipe or combination, starting from zero, and plots the cumulative proportion of nodes affected. It enabled a clear comparison of how single pipe or their combinations contribute to performance degradation, with the stepwise progression highlighting the extent and range of nodal impacts across the network.

Case study water distribution network

Figure 1 presents a typical UK DMA (District Meter Area) comprising 175 pipes, with pipe lengths ranging from 0.7 to 165 m and diameters varying between 32 and 200 mm. The hydraulic properties of the network are characterised by

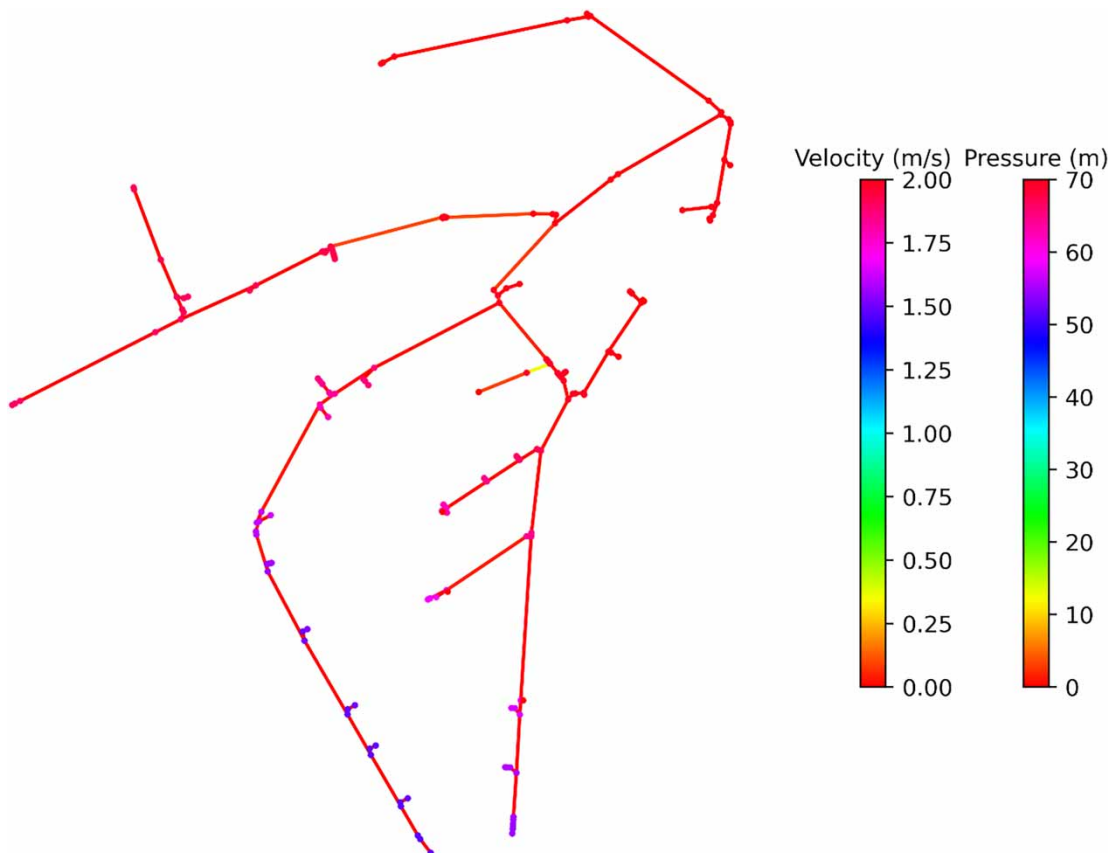


Figure 1 | Case study network: pressure at nodes and velocity in pipes at 9:00 AM.

Hazen-Williams C-factors, which span from 44 to 150, reflecting the varied roughness of different pipe materials within the network. This WDN was an operational DMA (subsequently changed due to wide-scale system reconfigurations), making it available for research but representative and, hence, suitable for assessing hydraulic performance under varying operational conditions. Initially, all 167 nodes within the network exhibit a CPI of 1 with pressures higher than 50 m, indicating that the nodes' pressure meets the required 20 m standard throughout the simulation period.

The network's demand patterns demonstrate typical diurnal patterns over 24 h, with distinct peaks during early morning hours, fluctuations throughout midday and evening, and lowest demand at night. This dynamic demand profile is vital for demonstrating the CPI's ability to capture hydraulic performance changes in the network if defective.

RESULTS AND DISCUSSION

This section presents the results and discusses how pipe defects impact WDN performance using the proposed CPIs. Initially, individual pipes had either the scenario 1 or scenario 2 defect applied. The network was simulated using the PDD simulation approach to evaluate the impact of individual defects on the network's performance. The CPIs are analysed with a CDF, heatmap, and scatter plots to assess the distribution of CPIs and the number of nodes impacted with service disruption across the network corresponding to each pipe defect. Furthermore, the overall network performance was assessed, and the pipes were ranked according to their sensitivity to network performance. Pipes selected from this ranking are used to demonstrate the effects of multiple simultaneous defects on WDN performance.

Results from scenario 1

Impact of individual pipe leak on WDN performance

Figure 2 presents the CDF plots for the CPIs across the network, showing the impact of a 5% leak size proportional to each pipe's diameter, where each pipe is simulated with a leak one at a time, and this process is repeated for all pipes in the network.

The results in Figure 2 reveal that 83 pipes caused at least one node to have severe periods of pressure deficits lasting between 19.2 and 24 h, as represented in the 0–0.2 CPI region of the CDF. The heatmap in Supplementary Appendix A1 provides a visual representation of the network's sensitive pipes for this defect scenario, resulting in a severe period of pressure deficit with CPI_1 values between 0 and 0.2, indicated in red corresponding to the Node IDs.

From Supplementary Appendix A2, Pipes 31, 32, and 33 rank as the top three, each affecting 34 nodes with severe periods of pressure deficit, as highlighted by the circled Pipe IDs. This suggests that if any of these pipes experience a 5% leak proportional to their diameter, up to 20% of the network's nodes could face pressure deficits lasting for 19.2 h or beyond. For instance, Supplementary Appendices A1 and A2 show that Pipe IDs 1–54 caused severe periods of pressure deficits in downstream nodes, mainly those farthest from the water source; considering the network configuration as a branched network, leaks in upstream pipes result in reduced pressure at dependent downstream nodes due to limited alternative supply paths.

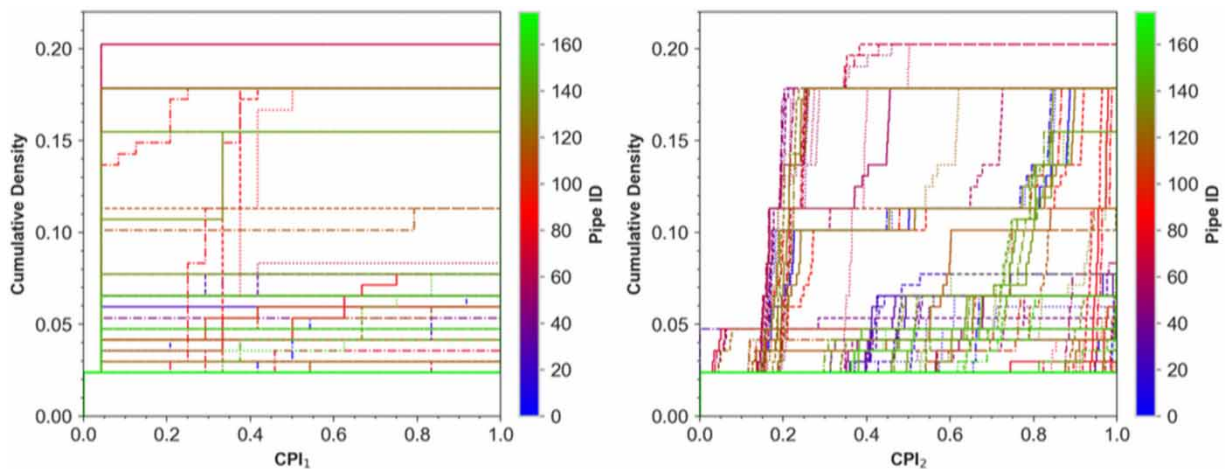


Figure 2 | Nodal CPI distributions based on 5% leak.

Furthermore, from Supplementary Appendix A2, based on the number of nodes impacted per level of impact, Pipes 26, 28, and 29 come at the top of the ranking for pipes resulting in significant periods of pressure deficits if they experience leakage, and affected 26, 5, and 21 nodes, respectively. This means that for Pipes 26, 28, and 29 to experience a leak of the size considered in this analysis, 15, 13, and 8% of nodes in the network are at risk of significant non-compliance with the performance objective of the study. Therefore, customers served by these nodes would likely experience service disruption between 19.2 and 14.4 h a day.

Additionally, the results show that 2–7% of nodes in the network experienced moderate pressure deficits lasting between 9.6 and 14.4 h, with CPI_1 values of 0.4–0.6, most notably impacted by Pipes 28, 29, and 139, which affected 11, 7, and 5 nodes, respectively. CPI_1 offers comprehensive insight by identifying specific pipes responsible for performance decline by not only evaluating the number of nodes with pressure drops, as in Klise *et al.* (2017) but also quantifying varying levels of pressure deficit durations across the network. As a normalised index over the entire network operational period, CPI_1 enables more detailed comparisons across pipes, providing a clearer understanding of system performance over time. This data-driven approach enhances network management by targeting sensitive pipes and enabling timely interventions, ultimately improving customer service quality.

Figure 2 for CPI_2 complements the CPI_1 analysis by capturing the duration and intensity of pressure deficits. The results indicate that while some pipes may have caused severe period pressure deficits at specific nodes, as demonstrated by CPI_1 , CPI_2 reveals that the deficits' intensity could be minor or slight. The trend is most evident for Pipe IDs 9–16, where Supplementary Appendix A1 shows that Node IDs 6–9 experienced a severe impact based on CPI_1 , but CPI_2 indicates only minor to moderate impacts, suggesting that while the pressure deficit lasted for an extended period, its severity remained low.

When these observations are analysed against the Ofwat PI, a limitation in the Ofwat performance standard becomes apparent. The Ofwat (2018) performance measures service interruption as any event where pressure falls below 3 m for more than 3 h at the point where water leaves the water mains and enters the customer's property. This definition fails to account for prolonged pressure deficits at nodes that maintain pressure equal to or above 3 m and vice versa. Although this may shield utilities from compensation claims under the Guaranteed Standards Scheme (GSS), it ignores customers served by Node IDs 5–9 who have faced poor service for 19.2 h, regardless of the intensity of the pressure drop being minor. The problem is compounded when these nodes service critical infrastructures such as hospitals and schools, where even minor pressure reductions over an extended period can have significant consequences.

The CPIs in this study bridged the gap by offering a nuanced understanding of network performance, capturing the minor intensity and severe duration deficit events that conventional indicators like Ofwat's might overlook. Furthermore, the analysis indicates a localised impact across the network, such that most pipes severely impact nodes within their section of the network. This is expected, as the case study network is fully branched, with only one supply route to downstream nodes, meaning that when an upstream pipe fails, nodes relying on this pipe for supply could face service disruption. Nodes severely impacted with lower CPI values signal non-compliance with the study's performance standards, which would negatively impact customer satisfaction within those nodes.

The overview of the results demonstrates the ability of the CPIs to guide decision-making for inspection and maintenance for the case study network by pinpointing sets of pipes, those in the category of Pipes 32, 33, and 36, resulting in widespread, prolonged severe pressure deficit with potential high intensity of pressure. Additionally, the performance grading into different levels can serve as a further guide for prioritising pipe inspection and maintenance, focusing on high-risk pipes that influence the service of critical customers.

Overall network performance and ranking pipes in order of their impact

Regarding the overall network performance, CPI_{Net} across all performance levels, the CPIs of all nodes in the network are averaged for each pipe leak, one at a time, focusing primarily on $CPI_{2,Net}$, since it factors in both the duration and severity of pressure deficit. Pipes are ranked based on their sensitivity using $CPI_{2,Net}$. This process provides additional insight into the network-wide performance instead of relying entirely on those pipes impacting the highest number of nodes and causing the most extended period of pressure deficit, which could be biased in some cases, mainly when a pipe impacts more nodes with less severity for an extended period and vice versa.

Figure 3 displays that $CPI_{2,Net}$ values ranged between 0.85 and 0.95 across all pipes tested with leak one at a time, indicating performance degradation. The previous analysis for CPI_1 showed that when assessing the number of nodes impacted and the

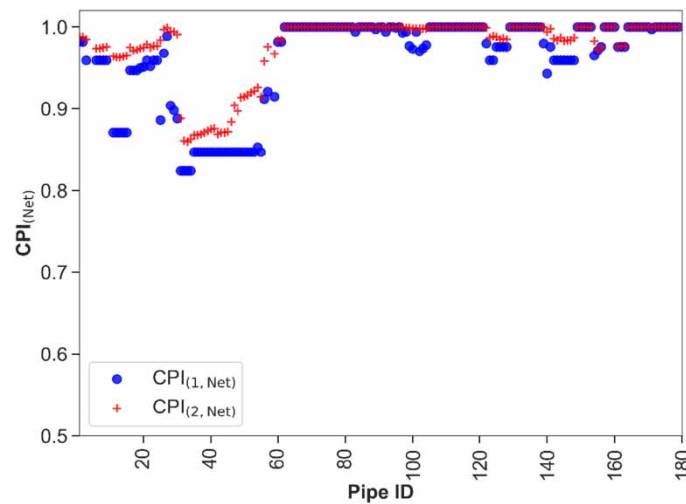


Figure 3 | Overall network performance CPI_{Net} based on 5% leak diameter to pipe diameter.

duration of pressure deficits, Pipes 31, 32, and 33 were the top contributors of severe duration pressure deficits. These pipes are located at critical sections of the network and serve as only a supply path from the water source to the downstream nodes in their sections of the network, as shown in [Figure 4](#). However, when evaluated from the perspective of overall network performance using the $CPI_{2,Net}$, Pipe 36 resulted in lower $CPI_{2,Net}$ than Pipe 31, demonstrating a more widespread severity of pressure deficit across the network for the same leak size.

Going forward, in the demonstration of multiple simultaneous defect scenarios, the analysis will consider Pipes 32, 33, and 36, which had the lowest $CPI_{2,Net}$.

Impact of simultaneous multiple leak defects on WDN performance

The density plots in [Figure 5](#) show CPI_1 and CPI_2 assessment of the impact of simultaneous multiple leaks occurrence in Pipes 32, 33, and 36, identified as the most sensitive to the network's performance (under the size of leak considered in this study) based on $CPI_{2,Net}$. [Table 1](#) further demonstrates the proportions of nodes within different performance levels.

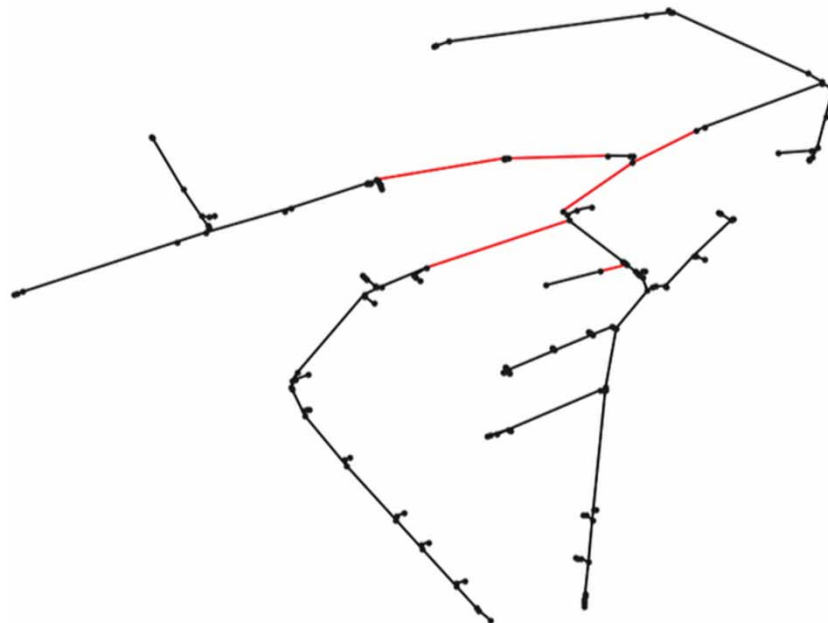


Figure 4 | Identified pipe locations used in the analysis.

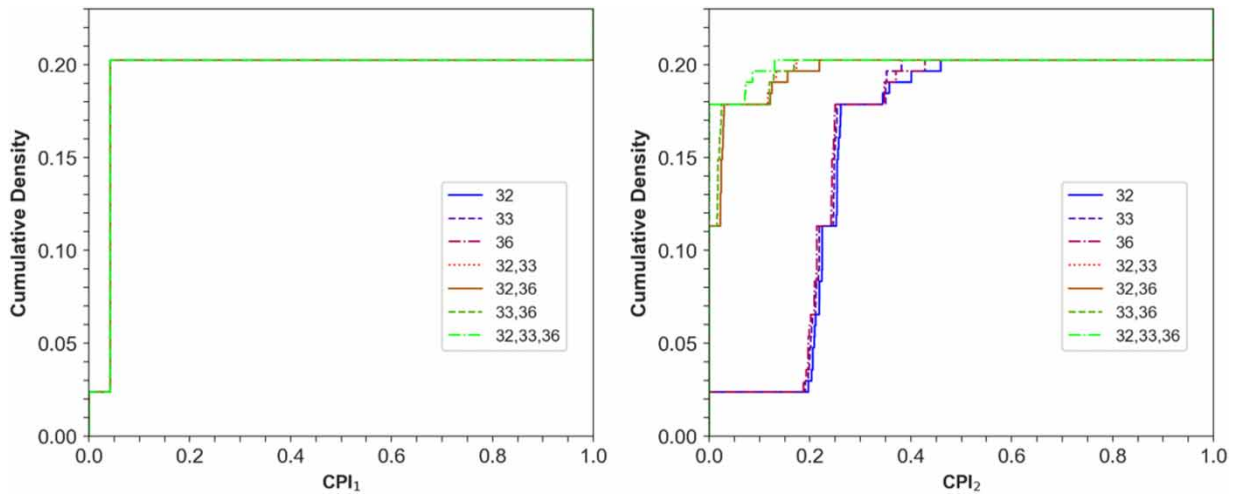


Figure 5 | Nodal CPI distributions of simultaneous multiple leak events.

Table 1 | Proportions of performance levels for multiple pipes simultaneously experiencing a leak

		<i>CPI₁</i>					
		Severe Impact (%)	Significant Impact (%)	Moderate Impact (%)	Minor Impact (%)	Slight Impact (%)	No Impact (%)
. Pipe Combinations		0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-0.999	1.0
32		20.4	0	0	0	0	79.6
33		20.4	0	0	0	0	79.6
36		20.4	0	0	0	0	79.6
32,33		20.4	0	0	0	0	79.6
32,36		20.4	0	0	0	0	79.6
33,36		20.4	0	0	0	0	79.6
32,33,36		20.4	0	0	0	0	79.6

		<i>CPI₂</i>					
		Severe Impact (%)	Significant Impact (%)	Moderate Impact (%)	Minor Impact (%)	Slight Impact (%)	No Impact (%)
Pipe Combinations		0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-0.999	1.0
32		3	16.2	1.2	0	0	79.6
33		4.8	15.6	0	0	0	79.6
36		6	13.8	0.6	0	0	79.6
32,33		20.4	0	0	0	0	79.6
32,36		19.8	0.6	0	0	0	79.6
33,36		20.4	0	0	0	0	79.6
32,33,36		20.4	0	0	0	0	79.6

From Table 1 for CPI_1 , the data shows that even when multiple pipes experienced leaks simultaneously, the duration of pressure deficit remained constant compared with single pipe events. This suggests that the network's response remains relatively stable under compounded pipe failures, likely due to the PDD (Rossman 2000) simulator used in the analysis, which redistributed the demand and mitigated the impact of additional pipe failures. The PDD simulation ensures that the system can manage pressure deficits without significantly extending the duration of disruptions, even when multiple pipes fail. Overall, for all scenarios, 20% of nodes in the network experienced a severe duration of pressure deficit lasting 19.2–24 h, while approximately 80% of the network nodes were not impacted.

The CPI_2 data trends from Table 1 exhibit multiplicative and non-linear effects across pipe combinations. For individual pipes, 3–6% of nodes in the network experienced severe deficits below the 20 m pressure threshold. However, when these pipes are combined, the severe impact increases. For instance, the combination of Pipes 32 and 33 severely impacts 20.4% of the network's nodes, while the combination of Pipes 32 and 36 produces a severe impact on 19.8%. These numbers indicate a multiplicative effect due to the system's rapid escalation in pressure deficits below the required pressure to meet customer water demand.

The data also highlight the non-linear behaviour of the pressure deficit. Combinations 32, 33 and 33, 36 exhibit a 20.4% severe impact of pressure deficit, with no moderate or minor impacts recorded in the 0.4–0.8 CPI range. This lack of intermediate impact suggests that any of the three pipes simultaneously experience a leak of the size considered for the analysis, the system experienced a sharp, immediate jump to severe pressure deficits, bypassing lower levels of impact. In contrast, individual pipes still show some distribution across moderate and significant impacts, with Pipe 32 contributing 16.2% in the 0.2–0.4 range and Pipe 36 showing 13.8%. This further supports the observation that combinations of pipe failures trigger a multiplicative escalation in severity rather than following a linear or additive pattern. The multiplicative pressure deficits could be attributed to the branched network configuration, which lacks the resilience to maintain consistent pressure levels, causing significant localised drops despite the PDD simulator's attempt to redistribute pressure across the network, as observed in the CPI_1 in Table 1.

Results from scenario 2

Impact of loss in cross-sectional area of pipes on WDN performance

Figure 6 presents the CDF plots for the $CPIs$ across the network, showing the impact of 80% loss in the cross-sectional area of each pipe simulated one at a time. This process is repeated for all pipes in the network. In Figure 6, the result shows that out of 175 pipes in the network, only eight resulted in widespread performance decline across the network, and pipes that did not impact the network performance are not displayed in the graph.

Furthermore, in Supplementary Appendices B1 and B2 and Figure 6 for CPI_1 , the result demonstrates that Pipe 105 stands out as the susceptible to the network performance for this defect condition, with 70% of the network's nodes experiencing a significant period of pressure deficit lasting 19.2–14.4 h and 14% experiencing a moderate period of pressure deficit lasting 14.4–9.6 h. While 7.7% of nodes felt no impact of the defect in Pipe 105, 4.2% experienced a slight period of pressure deficit

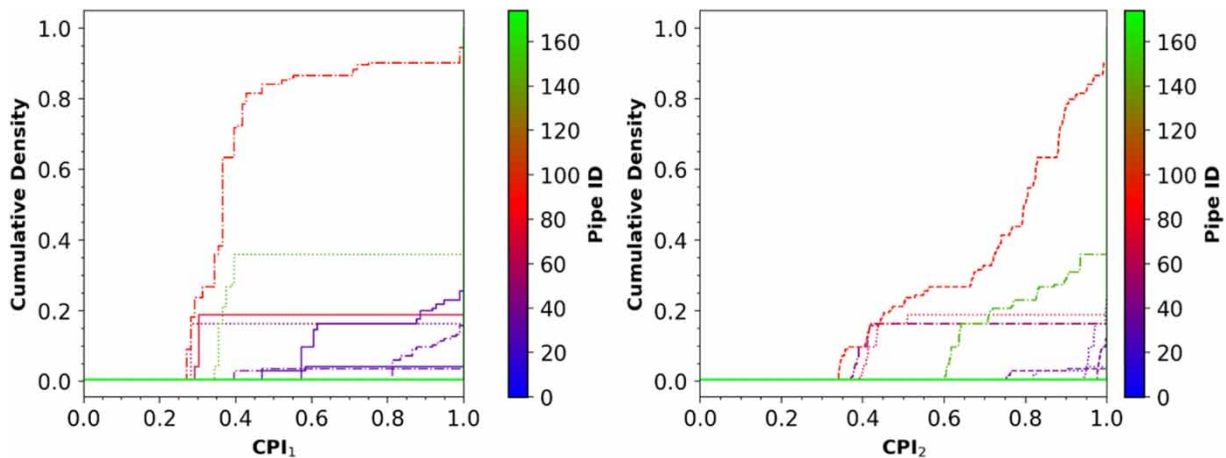


Figure 6 | Nodal CPI distributions are based on an 80% loss in the pipe cross-sectional area.

lasting up to 4.8 h. Another 3.6 and 2.3% of the nodes experienced minor periods of pressure deficit lasting between 9.6 and 4.8 h.

Additionally, Pipe 32 results in a 35% significant duration of pressure deficit, while Pipes 31 and 33 show 18 and 15.6% of the network's nodes experiencing a moderate duration of pressure drop. Pipe 66 displays a balanced distribution of pressure issues with 16% moderate impact, 4% minor impact, and 5.4% slight impact, pointing to a moderately vulnerable section in the network. On the other hand, Pipes 154 and 155 demonstrate some resilience to the defect condition, with 94 and 95% of nodes not being impacted. Pipe 80, however, shows some impact, particularly in the minor and slight duration of pressure deficits noticed at 10 and 5.4% of the network's nodes, respectively. The CDF plot visually supports these findings, with Pipe 105 showing a steep rise in its curve, confirming its significant pressure deficits. At the same time, Pipes 31, 32, 33, and 66 have more gradual curves, reflecting their mixed impact across the network.

In Figure 6 and Supplementary Appendix B2 for CPI_2 , the results demonstrate that Pipes 31, 33, and 105 are the three most sensitive pipes among the eight pipes, resulting in a significant intensity of pressure deficit at 3, 9, and 9% of the network's nodes, respectively. For instance, Node IDs 135–153 experienced minor intensity of pressure deficit, as shown in Supplementary Appendix B1 for CPI_2 if compared to CPI_1 for Pipe 105, the result indicates that these nodes experienced a significant duration of pressure deficit. This is also the case of Pipe 68 being replaced by Pipe 33 in the ranks of the three most sensitive pipes, as indicated by the CPI_1 . The results indicate that while a node could experience a significant period of pressure deficit, the severity of the pressure deficit below the pressure required could be minor.

Pipe 105 appears the most sensitive for this scenario due to its position close to the water source and as a critical water supply path in the network, as shown in Figure 6 and Supplementary Appendices B1 and B2. It shows high susceptibility across all impact levels, from severe to slight, and results in the lowest percentage of no impact. It indicates significant periods and severity of non-compliance and poor customer service across the network due to pressure deficits below the 20 m threshold.

Impact of loss in cross-sectional area of pipes on WDN overall performance

Figure 7 for $CPI_{2,Net}$ confirms that most pipes did not impact the network's performance, considering the $CPI_{2,Net}$ values clustering around 1.0. However, a few pipes have $CPI_{2,Net}$ values around 0.74–0.98, marking them as sensitive to the overall network performance. Ranking the pipes in order of their sensitivity, Pipes 31, 33, and 105 exhibit the lowest $CPI_{2,Net}$, and are ranked as the three most sensitive.

Impact of loss in the cross-sectional area of selected pipes on WDN nodal performance

The density plots in Figure 8 and Table 1 show the distribution of CPI_1 and CPI_2 across the network when the three most sensitive Pipes 31, 33, and 105, simultaneously lose 80% of their capacity. The simulation is performed for all possible

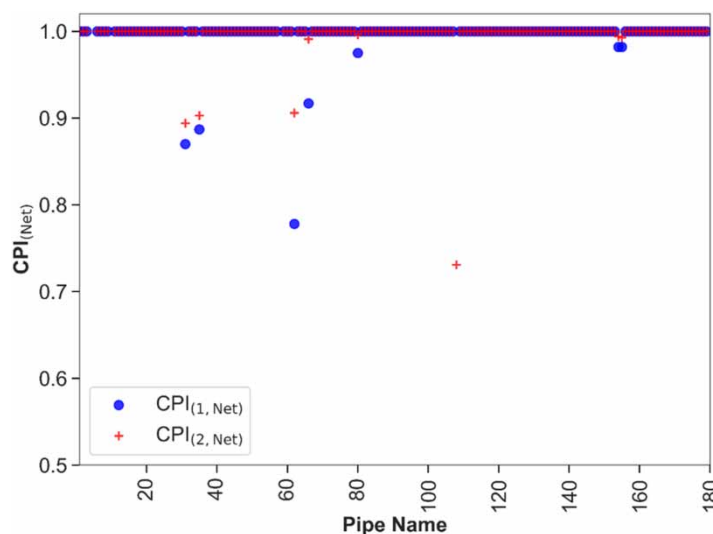


Figure 7 | Overall network performance based on an 80% loss in the cross-sectional area of pipes.

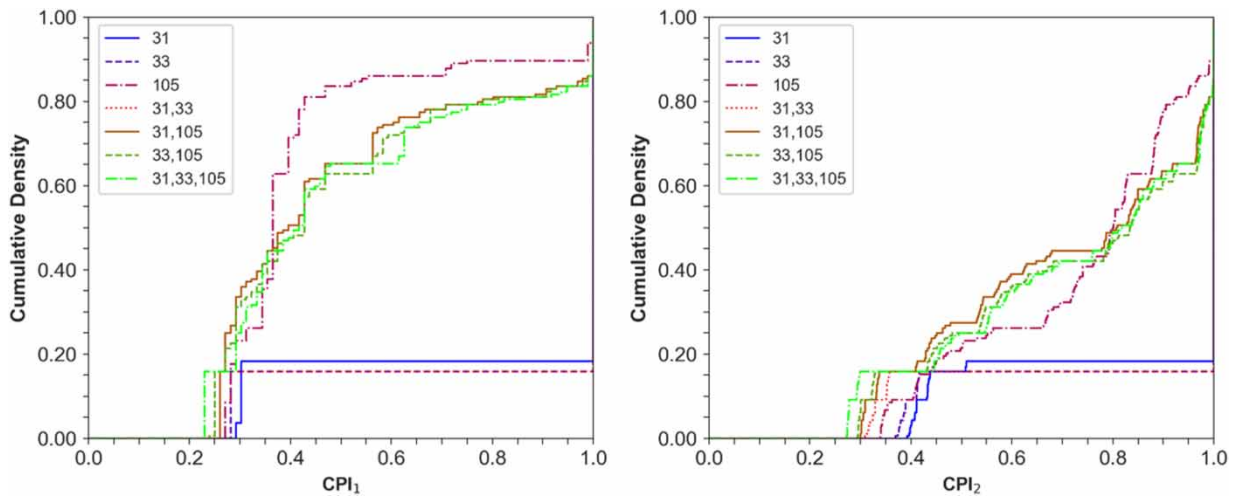


Figure 8 | Nodal CPI distributions of simultaneous 80% loss in the diameter of critical pipes.

combinations involving the three pipes, one at a time. Table 2 shows the proportion of network nodes within the different performance levels.

Table 2 for CPI_1 shows that the combination of Pipes 31 and 33 results in 15.6% of the nodes experiencing a significant duration of pressure deficit, and 84.4% felt no impact, similar to the single pipe event of Pipe 33. This shows a linear or additive behaviour, where multiple pipe failure hydraulic impact on the network is not higher than their pipe impact due to pressure balancing in the network. This suggests some level of resilience due to the PDD simulation method. However, when Pipe 105 is combined with either Pipe 31 or Pipe 33, the impact is evident across the network, demonstrating a multiplicative effect. For instance, the combination of Pipes 31 and 105 results in 52.1 and 23.4% of nodes experiencing significant and moderate periods of pressure deficit, respectively, while 13.1% of nodes felt no impact of the defect in these two pipes, losing 80% of their flow capacity, simultaneously. Similarly, the combination of Pipes 33 and 105 resulted in approximately the same behaviour.

This multiplicative behaviour underscores Pipe 105's dominant role in the network. Its combination with other pipes compounds the hydraulic load on the network, causing the PDD simulator to balance the pressure in the system by forcing demand nodes to lower the demands, as seen across the impact levels for multiple pipe combinations against single pipe events. Notwithstanding, the CPIs identified Pipe 105 as the most critical pipe among all three based on the defect condition due to its proximity to the water source and service to a large network area, as shown in Figure 4.

Finally, from Table 2 and Figure 8 for CPI_1 , combining all three Pipes, 31, 33, and 105, introduces a non-linear effect. While the significant impact is felt at 52.1% of the nodes, the proportion of nodes impacted with a moderate period of pressure deficit decreased to 17.4%, and the percentages of nodes experiencing minor and slight durations of pressure deficit increased to 10.7 and 6.6%, respectively. Compared with Pipe 105 alone, this reduction in the significant impact level is also attributed to the PDD simulator, which redistributes the pressure deficits across the network when they lose their capacity simultaneously. By spreading the pressure deficits more evenly, the period of pressure deficit across the network reduces at some nodes, especially those closer to the water source, as seen in the proportions of nodes transitioning from the significant impact level to the moderate, minor, and slight ranges. This is evident in the no impact range for Pipe 105 compared with all three pipes' combinations, showing 13.1% of nodes with no impact for all three pipes as against 7.7% for Pipe 105 alone. This means that nodes whose pressure was close to the 20 m required pressure transitioned to having pressure equal to or greater than the minimum required pressure. The redistribution by the PDD simulator prevents the network from experiencing catastrophic failure by balancing the pressure loss across a wider area.

The data from Table 2 and Figure 8 for CPI_2 reveals several deeper insights into the behaviour of the network under pipe failure scenarios, particularly concerning the distribution of pressure deficits and how the network responds to individual and combined pipe cross-sectional area losses. A clear trend shows that Pipe 105 plays a dominant role in creating pressure

Table 2 | Proportions of performance levels for multiple pipes simultaneously experiencing loss in cross-sectional area

<i>CPI₁</i>						
Pipe Combinations	Severe Impact (%) 0-0.2	Significant Impact (%) 0.2-0.4	Moderate Impact (%) 0.4-0.6	Minor Impact (%) 0.6-0.8	Slight Impact (%) 0.8-0.999	No Impact (%) 1.0
31	0	18	0	0	0	82
33	0	15.6	0	0	0	84.4
105	0	70.1	14.4	3.6	4.2	7.7
31,33	0	15.6	0	0	0	84.4
31,105	0	52.1	23.4	6	5.4	13.1
33,105	0	52.1	24	5.3	5.4	13.2
31,33,105	0	52.1	17.4	10.7	6.6	13.2
<i>CPI₂</i>						
Pipe Combinations	Severe Impact (%) 0-0.2	Significant Impact (%) 0.2-0.4	Moderate Impact (%) 0.4-0.6	Minor Impact (%) 0.6-0.8	Slight Impact (%) 0.8-0.999	No Impact (%) 1.0
31	0	3	17.4	0	0	79.6
33	0	9	9	0	0	82
105	0	9	16.8	22.8	39.4	12.0
31,33	0	18	0	0	0	82
31,105	0	18	23.2	10.2	33.5	15.1
33,105	0	18	19.8	10.2	36.5	15.5
31,33,105	0	18	18.6	13.8	34.1	15.5

deficits by affecting a large portion of the network and, when combined with other pipes, forces the system to readjust to the impact of failure.

As stated earlier, the PDD simulator is crucial in understanding why Pipe 105's impact is pervasive. The PDD spreads pressure deficits across the network when multiple pipe failures stress the system. As a result, in combinations involving Pipe 105, we see a dilution of the severe impact into the moderate, minor, and slight impact categories rather than a concentration of severe impacts. This redistribution helps explain why the moderate and slight impacts increase in combined failures, particularly in combinations involving Pipe 105, as the PDD attempts to keep pressure within acceptable limits at more nodes. However, this redistribution also highlights the system's limitations. While it may prevent catastrophic pressure failures at a small portion of the network, it also leads to widespread suboptimal performance, as seen in moderate and significant impact ranges for combinations involving Pipe 105.

Another critical insight is that Pipes 31 and 33, when combined without Pipe 105, exhibit a linear response, where their impacts do not result in more deficits if compared with their individual impact. This suggests that the network can maintain its resilience relatively well when these pipes face an 80% loss in their flow capacity. However, when Pipe 105 is introduced, even in combinations with Pipes 31 and 33, a non-linear effect across the network as well as multiplicative in the minor and slight impact range, where the impacts are spread across more nodes, with the CDF curves in Figure 8 for CPI_2 reflecting a

more gradual rise. This suggests that Pipe 105 significantly disrupts the pressure equilibrium in the network, reducing the network's capacity to maintain service to a large portion of nodes.

CONCLUSION

This research evaluates the performance of deteriorated WDNs using CPIs, which relate to a water utility's benchmark for maintaining a minimum pressure of 20 m head. The study introduces two CPIs: CPI_1 measures the duration of pressure deficits below the threshold, while CPI_2 assesses the severity of these deficits by capturing the area under the pressure deficit curve over time. The indices effectively identify minor performance drops and highlight sensitive pipes that could cause pressure drops below the minimum required to supply user water demand. They also pinpoint areas of the network vulnerable to non-compliance with the study's performance objective.

Our analysis reveals that when pipes are simulated with defects one at a time, the overall network performance still maintains reasonable performance with CPI_{Net} values around 0.95 indicate slight pressure deficits in a large proportion of the network's nodes, with few nodes severely impacted by a high magnitude of pressure deficit for an extended period, as indicated by the CPI_1 and CPI_2 . Additionally, a small proportion of nodes experience a minor to slight magnitude of pressure deficit for a minor to slight period. Furthermore, when two or more pipes have deteriorated simultaneously, CPIs capture the changes in the network performance for these events relative to the performance standard established for the study.

The method used in the study provides us with information on sets of pipes in the network that require periodic inspection to ensure optimal network performance and reduce cascading failure. These findings underscore the necessity for regular and targeted inspections of specific pipes to reduce the network's vulnerability to the defect conditions analysed in this study, guaranteeing adequate network performance while ensuring satisfactory customer service. The methodology demonstrates that CPIs offer a customer-centred understanding of network performance and illustrate the value of a data-driven approach to network management. While the indices can capture slight pressure deficits, they can be adapted for any organisation, region, or country with specific minimum pressure standards.

FUTURE RECOMMENDATIONS

The impacts of leaks and capacity loss at the branched network nodes could be more complex in a looped network with alternative supply paths and built-in resilience. The results observed in this study are likely due to the dendritic nature of the network, where a single supply route limits the network's resilience. In contrast, a looped network may involve more complex interactions, as reduced pipe diameter results in higher head loss, causing flow redirection through alternative paths, therefore maintaining the service levels. Additionally, the assumption of regular defect shapes for all pipes may not reflect the actual deterioration mechanisms in pipes of different materials, as irregular defects like localised corrosion, cracks, and pitting can have varying hydraulic impacts (De Marchis & Milici 2019). Therefore, to enhance the accuracy of future performance assessments using the CPIs, we will consider various defect types and sizes and apply the methodology to a looped network with hydraulic resilience, providing a more detailed evaluation of how defects influence pressure loss and network performance.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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