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LIMITATIONS OF RELIABILITY INDICES ON PRACTICAL WATER DISTRIBUTION SYSTEM APPLICATIONS: BRIDGING THE GAP BETWEEN THEORY AND PRACTICE

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ABSTRACT: Water Distribution Systems (WDS) are critical components of physical infrastructure providing safe, clean water supply continuously to urban populations, economic activities, and the public health system. These systems must be reliable to endure growing demands, aging infrastructure, and environmental uncertainties. Several indices have been developed to measure WDS reliability, such as Resilience Index, Modified Resilience Index, Entropy Reliability Indicator, Minimum Surplus Head and Total Surplus Head. These indices usually provide information about system performance under predefined conditions; however, they fail to capture real-world complexities such as extreme demand fluctuations, cascading failures, and adaptive operational strategies. This paper reviews the existing indices of WDS reliability, emphasizing the strengths and limitations of each. While many of the indices assess the available surplus capacity, they oversimplify hydraulic behavior, ignore dynamic system responses, and lack adaptability to uncertainty conditions. Further, computational demands and discrepancies in reliability assessment methodologies render them impracticable when deployed on larger networks. Instead, recent advances such as machine learning, stochastic modeling, and graph-theoretic approaches are promising solutions that still require refinement to allow real-world applicability. To bridge the gap between theoretical assessment and practical application, a multi-objective approach should be considered, incorporating hydraulic, mechanical, topological, and water quality aspects. Real-time data collection, predictive analytics, and adaptive decision-making would enhance WDS reliability assessment and support resilient infrastructure development. This can enable informed decision-making that leads to optimal system performance, risk mitigation, and sustainability of WDS in the face of evolving challenges.

1. INTRODUCTION

Water distribution systems (WDS) play a crucial role in cities, ensuring a steady supply of clean and safe water to support growing populations and economic activities. These systems must operate reliably despite challenges such as fluctuating water demand, aging infrastructure, and external pressures like climate change. In engineering terms, reliability is defined as the probability that a system will perform its specific function under specific conditions for a specified period of time. Keeping WDSs dependable is essential for public health, economic stability, and urban resilience. However, as these systems become more complex and face increasing demands, assessing and improving their reliability has become a challenging task. To address this, a thorough review of current WDS reliability indices is herein conducted.

Researchers have developed various reliability metrics that use hydraulic modeling to evaluate system performance under predefined conditions, including the Resilience Index (RI) (Todini, 2000), the Modified Resilience Index (MRI) (Jayaram & Srinivasan, 2008), and the Entropy Reliability Indicator (ERI) (Awumah, et al., 1990). While these metrics work well for normal operating conditions, they often fail to capture the full complexity of real-world scenarios, such as extreme demand spikes or cascading failures. Because of this gap between theory and practice, some highly resilient designs may be overlooked in optimization efforts (Giustolisi & Savic, 2009). Additionally, the practical application of these metrics faces several hurdles, including high computational demands, limited flexibility in real-world settings, and a lack of agreement on the best evaluation methods. These limitations highlight the need for more advanced and comprehensive approaches to reliability assessment.

Systematic reviews have documented the evolution of WDN reliability research. Gunawan, et al. (2017) provided a comprehensive analysis of performance metrics, including reliability, resilience, redundancy, and robustness, to highlight the need for harmonized frameworks to effectively evaluate these interdependent properties. Candelieri, et al. (2020) also addressed the resilience of urban networked infrastructures, especially of WDNs, and emphasized the importance of both global connectivity measures and the role of individual components in maintaining system resilience. Sirsant, et al. (2023) comprehensively analyzed a total of 347 articles published between 2000 and 2022, identifying prevalent methodologies and stressing the need for standardizing assessment frameworks for WDN reliability research. Moreover, Lestakova and others (2024) performed critical review of different types of resilience metrics in existence, showing that many do not fully characterize the dynamic nature of WDSs. They called for the formulation of metrics that encompass both structure and function in consideration of resilience.
Although a great deal has been done, it remains challenging to standardize measuring tools that are fully representative of the complexity of real WDS operating in severe conditions and provide useful and actionable information for real systems. This paper, thus, reviews existing WDS reliability indices and assesses their strengths and limitations in the context of addressing practical challenges.

2. LITERATURE REVIEW

The earliest developed reliability indicators include but are not limited to; Resilience Index (RI), Modified Resilience Index (MRI), Entropy Reliability Indicator (ERI), Minimum Surplus Head (MSH), and Total Surplus Head (TSH). The Resilience Index (RI) which was introduced by Todini (2000) evaluates the capacity in handling disruptions by quantifying the excess power beyond the minimum required to meet demand. While RI provides a useful baseline for resilience assessment, it has notable limitations. Specifically, it does not fully account for system performance under extreme demand conditions, where the surplus power may be insufficient to maintain service levels (Tanyimboh, et al., 2011). This limitation suggests that RI may not adequately capture the complexities of system behavior during peak stress scenarios. To address some of the shortcomings of RI, the Modified Resilience Index (MRI) was developed by Jayaram & Srinivasan (2008). MRI expands on RI by incorporating the percentage of surplus power relative to the required power at individual nodes within the network. This node-specific approach aims to provide a more detailed understanding of resilience by considering local variations in demand and capacity. However, studies have shown that MRI is highly correlated with RI, limiting its added value (Tanyimboh, et al., 2011). The strong correlation indicates that MRI may not offer significant new insights beyond those provided by RI, questioning the necessity of its more complex calculations. Todini's RI takes values up to a maximum of 1.

The Entropy Reliability Indicator (ERI) presented by Tanyimboh & Templeman (1993) utilizes the concept of entropy to assess the WDS reliability. This concept was originally proposed by Awumah, et al. (1990). By evaluating how evenly flow is distributed, ERI provides insights into the redundancy and reliability of the system. A more uniform flow distribution is generally indicative of a more resilient network, as it suggests multiple pathways for service delivery. However, ERI has its limitations; it fails to capture the system's dynamic response to unforeseen disruptions (U.S. Environmental Protection Agency, 2014). While it reflects the static redundancy of the network, it does not account for how the system adapts or recovers when unexpected failures occur, limiting its effectiveness in comprehensive resilience assessment.

Minimum Surplus Head (MSH) and Total Surplus Head (TSH) are both indicators of excess capacity in a system, particularly hydraulic systems. MSH takes into account the minimum surplus head (pressure) at the most critical point in the network, while TSH is the sum of the surplus head across all nodes. They are both employed to ensure there is adequate pressure to meet demand under normal operating conditions. However, research indicates that neither MSH nor TSH is an effective system performance predictor under peak demand or failure scenarios (Moghaddam, et al., 2022). Their focus on surplus capacity under standard conditions means they may not accurately reflect the system's ability to cope with extraordinary stresses or component failures. Minimum Surplus Head (MSH) works for finding weak points in a network by calculating minimum excess pressure but is worst case focused, so investments can be wasted, and other weaknesses can be overlooked. MSH also does not consider redundancy in the network, so it will be less accurate for extremely looped networks where localized weakness is not an indicator of network resilience. At the same time, Total Surplus Head (TSH) adds up surplus pressure across all nodes, taking a system-wide snapshot of energy without considering spatial pressure distribution. High TSH can create pressure imbalances, high pumping expense, and inefficiencies, with excessive pumping creating leaks and pipe bursts. Moreover, TSH does not consider pipe failures, sometimes creating a false sense of security, such as in its New York City example, where it was stable despite severe transmission main failures.

One of the principal deficiencies of reliability indices of WDS is their oversimplification of hydraulic behavior. Most reliability indices such as RI established by Todini in 2000 and NRI established by Prasad & Park in 2004 are based on static conditions and fail to accommodate real-time demands, pressure oscillations, and operational constraints. Entropy-based methods, as first suggested by Awumah et al. in 1990, provide only a redundancy surrogate measure without addressing hydraulic performance in repeated cases of failure occurrences. Failure modes are not addressed adequately in other important issues either. Traditional reliability indices have the propensity to assign individual pipe failures while true failures consist of simultaneous pipe bursts, pump failure, or valve failures, as noted by Moghaddam et al. in 2022. Cascading failure effect, which has the tendency of greatly altering the hydraulic condition of the network, is poorly captured by most of the indices. Berardi et al. (2022) highlighted that the cascading failures have unexpected effects that traditional reliability indices fail to predict. Further, most models do not consider the impacts of adaptive actions, such as pressure management, reconfiguration of pumps, and emergency interconnections, that utilities implement in order to ensure serviceability. Zhuang et al. (2012) also observed that existing measures of reliability do not include dynamic control actions, which are an important aspect of enhancing resilience.

On the other hand, WDS reliability and resilience received considerable amount of attention from recent studies who created a variety of methods to assess and enhance the WDS performance during different type of failures. Table 1 provides a comparative analysis of recent advanced reliability assessment approaches used in WDS. This comparison make is clear there is no uniform measure, and no standard framework to quantify reliability in different studies, leading to inconsistency and making it difficult to compare different assessment methods directly. Model parameter uncertainty is a challenge in simulating reliability. Pipe roughness, nodal demands, and failure probabilities have uncertainties that are inadequately captured by deterministic reliability indices. Scenario limitations hinder comprehensive reliability analysis because the majority of existing models handle a subset of demand fluctuations and failure modes and ignore low-probability yet high-impact events such as extreme weather conditions or simultaneous pipe rupture (Moghaddam et al., 2020; Ostfeld, 2004). Monsef et al. (2019) suggested that stochastic models would be a better choice as they take into account the correlation between reliability indices and network behavior under uncertain operating conditions. However, they require large quantities of data, which may not always be available in practical applications.

Lestakova et al. (2024) stressed that system resilience should be tested against extreme events like natural disasters, extreme weather and armed conflict. Similarly, a study by Goodarzi et al. (2021) discussed the operational reliability of WDSs in catastrophic scenarios leading to mechanical failure such as natural or man-made disasters, severe weather or even old pipelines. They also considered hydraulic failures such as improper pump operations due to network demand fluctuation. In addition, Li et al. (2023) introduced a time-variant seismic resilience analysis model for WDSs, considering the effects of aging infrastructure and corrosion on pipeline performance during earthquakes. Another probabilistic approach was proposed by Waldrip, et al. (2016) who developed a maximum entropy method in the analysis of pipe networks, that accommodates variability in flow rates and enhanced predictive capacity. Pandey and Srinivas (2024) also noted that adding the dimension of sustainability to reliability analysis adds another complexity, and it is not easy to derive one reliability measure that can be applied to all states of the network.

However, simulating reliability under various uncertain scenarios and for large networks creates a significant computational demand, which remains a hindrance in the implementation of reliability indices in real cases. Reliability calculation through Monte Carlo simulations, as used by Dini et al. (2021), is computationally demanding, and so it is not viable for big networks. As such, surrogate reliability indices are often employed, though they involve drastic approximations that can lead to misleading appraisals. In addition, real-time decision-making requires fast and efficient computation of reliability indices, but existing indices are too complex to be utilized dynamically. Wang & Zhu (2021) noted that data-driven or machine learning-based approaches are required for enhancing real-time predictive reliability analysis. Also, EPANET Based Benchmark Analysis by Nair and Meyyappan (2024) assessed effect of pipe diameters on reliability, which would give an insight into system performance and possible failure zones. It is somehow limited in that it is mostly confined to benchmark datasets and maintenance issues are not extensively explored. Additionally, Valis et al. in 2022 developed a State Space Model which utilizes time-series data to project long-term fail patterns and seasonal variations. Unfortunately, it requires extensive historical data for a case which effectively limits its applicability in a wide sense.

On the other hand, the graph-theoretic Framework by Herrera et al. in 2016 considers resilience through network topology and redundancy without hydraulic simulations, thus making it very efficient with respect to large networks but is missing real-time hydraulic data and some detailed flow properties. To deal with this, an integrated reliability assessment model was presented by Azhar et al. (2022) which integrates mechanical and hydraulic reliabilities using minimum-cut-set analysis and pressure-dependent demand analysis. This model is an excellent tool for identification of components that are most likely to fail but does not consider water quality nor provide strong predictive modeling capabilities. Sousa and others (2024) suggested a new index with a novel concept of pressure surplus threshold, thus making the characterization of more realistic pressure limits from the viewpoint of operational management and emphasizing crucial network characteristics in the assessment of reliability. The use of graph theory has become more widespread in the analysis of WDS reliability. Pagano, et al. (2019) compared global resilience analyses with graph theory approaches, indicating that network resilience metrics can pinpoint crucial components of such a network. Their research shows a huge advantage of integrating topological analysis with hydraulic modeling in comprehensively understanding the network resilience. Likewise, Pagano, et al. (2022) outlined a systematic approach to the identification of critical pipes whose failure would significantly impede the network resilience by developing a pipe ranking approach based on various graph theory metrics.

Avoiding the computational demands of large real WDSs, many reliability indices are only verified on small example networks. Farahmandfar & Piratla (2017) noted that real world performance of indices, where limitations of operation and sensor measurements are considered, is not much researched. Additionally, existing indexes focus mainly on network-scale performance and exclude consideration of consumer-scale reliability perception. Jeong & Kang (2020) explained that water quality reliability, including chlorine decay reliability and contamination potential threats, is usually not included in hydraulic reliability indexes to provide a more comprehensive assessment.

Table 1: Comparative Analysis of Recent Reliability Analysis Studies.

Author, Name	Equation/Approach	Reliability Type	Demand Uncertainty Consideration	Pipe Failure Consideration	Pump Failure Consideration	Tank Operation Consideration	Valve Operation Consideration	Simulating Uncertainty Via.	Brief Summary
Huang et a. (2025)	RI, NRI, Extended NRI formulas (NRI2u and NRI2uk), which integrate pipe diameter uniformity and node degree.	Mechanical	Yes, by evaluating resilience under different demands	Yes, single pipe and multi-pipe scenarios	No	No	Yes, follows N-rule for valve placement.	Monte Carlo Simulation	Proposes two novel energy-based surrogate measures (NRI2u and NRI2uk) to evaluate and improve WDS resilience
Pandey & Srinivas (2024)	Integrated Sustainability Index (ISI), Criticality Index (CI)	Hydraulic, Topological	Yes, first-order reliability method to quantify uncertainty associated with networks ability to meet minimum pressure requirements.	No	No	No	Not explicitly mentioned	Not specified	Introduces an Integrated Sustainability Index (ISI) to assess WDS resilience.
Sousa et al. (2024)	Extended resilience index including network features	Hydraulic, Quality	Yes, includes pressure surplus threshold	Yes, considers redundancy in network topology	No	Yes, evaluates tank operation	No	Statistical analysis	Proposes an enhanced resilience index incorporating redundancy, uniformity, and pressure surplus to improve reliability assessment.
Nair & Meyyappan (2024)	Durability assessment using EPANET	Hydraulic	No	Yes, through pipe dia. Variations	Yes, affects system performance	No	Yes, valves and hydrants included	Not specified	Uses EPANET for durability assessment of water distribution networks.
Berardi et al. (2022)	Path/connectivity-based approach for mechanical reliability	Mechanical	No	Yes, through topological changes	Yes, through pump and pressure variations	Yes, includes tank level monitoring	Yes, considers valve operation impact	Hydraulic modeling	Proposes a path/connectivity-based approach for mechanical reliability analysis.
Moghaddam et al. (2022)	Hydraulic reliability indices under pipe failure	Hydraulic	No	Yes, RI under pipe failure conditions	No	No	No	Genetic Algorithm Optimization	Evaluates hydraulic reliability indices under pipe failure conditions.
Azhar et al. (2022)	Integrated reliability assessment model	Hydraulic, Mechanical	Yes, includes pressure-dependent demand analysis	Yes, historical pipe failures	Yes, integrates mechanical and hydraulic conditions	Yes, evaluates tank and pressure systems	Yes, considers valve conditions	Minimum-cut-set Theory	Develops an integrated reliability assessment model combining mechanical and hydraulic conditions.
Valis et al. (2022)	State-space models for reliability prediction	Hydraulic	No	Yes, based on long-term failure rates	No	No	No	Time-series modeling	Uses state-space models to predict and assess water distribution reliability.
Pagano, et al. (2022)	Pipe ranking using Bayesian Belief Networks	Topological	No	Yes, evaluates pipe failures in resilience ranking	No	No	No	Bayesian Belief Networks	Develops a Bayesian Belief Network-based ranking method for assessing critical pipes in WDN resilience analysis.
Dini et al. (2021)	Monte Carlo Simulation (MCS) for stochastic reliability	Hydraulic	Yes, considers pipe roughness, diameter, and nodal demand	No	No	No	No	Monte Carlo Simulation	Utilizes Monte Carlo Simulation (MCS) for stochastic reliability evaluation.
Wang & Zhu (2021)	Fuzzy Set Theory for reliability analysis	Hydraulic, Quality	Yes, considers uncertain demand and roughness coefficients	No	No	No	No	Fuzzy Set Theory	Employs fuzzy set theory for reliability assessment of water distribution networks.
Tanyimboh et al. (2020)	Discussion on Deficiency of Reliability Indicators	Hydraulic, Topological	Yes, mentions variations in nodal demands	Yes, critiques lack of probabilistic failure models	No	No	No	Pressure-driven Analysis	Critiques deficiencies in traditional reliability indicators for WDS.

Table 1 Continued.

Author, Name	Equation/Approach	Reliability Type	Demand Uncertainty Consideration	Pipe Failure Consideration	Pump Failure Consideration	Tank Operation Consideration	Valve Operation Consideration	Simulating Uncertainty Via.	Brief Summary
Jeong & Kang (2020)	Comparative Analysis of Reliability Indices	Hydraulic, Mechanical, Topological	Yes, analyzed using different water demand scenarios	Yes, considered through various failure conditions	No	No	No	Multi-criteria Decision Analysis (MCDA)	Conducts a comparative analysis of reliability indices and hydraulic measures.
Monsef et al. (2019)	Stochastic method based on correlation with reliability indexes	Hydraulic, Mechanical	Yes, examined through surplus head metrics	Yes, evaluated under pipe burst conditions	No	No	No	Stochastic analysis	Applies stochastic correlation methods to analyze reliability indicators.
Pagano, et al. (2019)	Graph Theory & Global Resilience Analysis	Topological	No	Yes, assesses pipe failures using topological metrics	No	No	No	Graph Theory Analysis	Compares Graph Theory and Global Resilience Analysis for assessing WDN resilience, focusing on topological metrics.
Farahmandfar & Piratla (2017)	Comparison of Topological vs Flow-Based Seismic Resilience Metrics	Mechanical	No	Yes, through mech. pipeline failure probabilities	No	No	No	Seismic Simulation	Compares topological and flow-based seismic resilience metrics for pipeline systems.
Herrera et al. (2016)	Graph-Theoretic Framework for Resilience	Topological	No	Yes, network redundancy	No	Yes, includes impact of tanks	No	Graph Theory	Applies graph-theoretic methods to evaluate resilience in sectorized water networks.
Atkinson et al. (2014)	Todini resilience index and entropy for WDS	Hydraulic, Mechanical	Yes, examined through multi-objective optimization	Yes, resilience index evaluates pipe failure impact	Yes, considered in mechanical reliability	Yes, analyzed in network configurations	Yes, impact on mechanical reliability	Optimization-based	Compares Todini resilience index and entropy for water distribution system reliability.
Zhuang et al. (2012)	Monte Carlo Simulation for Adaptive Pump Operation	Hydraulic	Yes, considers demand fluctuations	Yes, includes pipe break simulations	Yes, considers pump outage scenarios	Yes, includes tank level adjustments	Yes, considers valve operations	Monte Carlo Simulation	Implements Monte Carlo Simulation for adaptive pump operation under failures.
Tanyimboh, et al., 2011)	Hydraulic reliability equation	Hydraulic	Yes, considers demand variations	Yes, considers pipe failure probability	Yes, considers pump failure probability	No	No	Monte Carlo Simulation	Evaluates hydraulic reliability using a statistical entropy-based approach, comparing surrogate reliability measures.
Jayaram & Srinivasan (2008)	Performance-based reliability with life cycle costing	Hydraulic, Mechanical	Yes, considers demand as probabilistic variable	Yes, probabilistic pipe failure model	Yes, probabilistic pump failure model	No	No	Monte Carlo, First-order Reliability Method	Proposes a life cycle costing approach for optimal water network design, incorporating reliability and maintenance considerations.
Todini (2000)	Resilience index based on available power	Hydraulic	Yes, considers demand uncertainty via surplus energy	Yes, considers pipe failures implicitly	Yes, considers pump failures indirectly	Yes, considers storage capacity	Yes, considers valve operation	Heuristic Optimization	Introduces resilience index as a measure of hydraulic reliability, considering redundancy and energy surplus in looped networks.
Tanyimboh & Templeman (1993)	Maximum entropy flow method	Hydraulic, Topological	Yes, considers entropy-based demand distribution	Yes, incorporates pipe failures in entropy calculations	No	No	No	Entropy-based modeling	Introduces a maximum entropy approach to flow distribution in networks, aiming to enhance reliability through optimal redundancy.

Another challenge is the discrepancy between theoretical reliability indexes and regulations and utility constraints. Water utilities operate under some regulatory schemes that may vary from the assumptions made in theoretical models of reliability. Tanyimboh et al. (2020) have noted that cost limitations normally restrict the adoption of solutions suggested by theoretical models so that cost-conscious reliability assessment models are required. Besides, the increasing diversity in climatic conditions and urbanization patterns adds additional uncertainty to reliability indices, and thus more robust structures taking these changing conditions into consideration need to be established. Lastly, Atkinson et al. (2014) compared Todini's RI with entropy. The study highlighted that while high-entropy networks improve mechanical reliability, they tend to be costly and may lead to water quality issues. On the other hand, resilience-based designs are more cost-effective but do not fully capture the interconnectedness of the network.

One of the latest WDS reliability studies by Huang et al. (2025) introduced new surrogate resilience measures that are computationally efficient and accont factors like node degree and pipe diameter uniformity. However, they focus only on mechanical reliability. Although decisions on WDS design and operations should consider all aspects of reliability, i.e. hydraulic, topological, mechanical and quality, none of the indices yet consider a holistic reliability assessment. Thus, and integrated approach is needed for the practical evaluation and improvement of WDS reliability.

3. CONCLUSIONS

To bridge the gap between theory and practice, multi-objective reliability assessment approaches should be developed focusing on hydraulic, mechanical, topological, and water quality parameters. These can leverage existing quantitative modeling approaches, as well as advanced computational tools, including machine learning to achieve better accuracy and efficiency in reliability assessment. To ensure these approaches can be implemented in practice and are useful, real data sets should be collected and used for testing. Data collected through IoT can support these advances and enhance the predictive capability of reliability indices, as suggested by Berardi et al. (2022). Additionally, reliability should be assessed against a variety of scenarios and case studies so as to heighten their validity and effectiveness on real systems. In addition to day-to-day demand variations and potential infrastructure failures, future uncertainty related to climate change should also be considered. Moreover, incorporating user-oriented reliability issues, e.g., interruptions in service and consumer satisfaction, can lead to more practical evaluations. An integrated WDS reliability framework can allow decision-makers to predict and control system vulnerabilities more holistically against increasing demands, climate change, and aging infrastructure. This will enable the water distribution sector to build, operate and maintain more reliable systems, to not only ensure service continuity, but also manage resources and protect the public health.

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