Assessment of metrics for resilient design of water distribution networks

Kalyan R. Piratla and Samuel T. Ariaratnam

ABSTRACT

Water distribution networks (WDNs) play a crucial role in the well-being of human populations and economic prosperity. It is essential that they cope with abnormal operating conditions and recover functionality quickly. Traditionally, WDNs are designed using cost and reliability objectives, but there is a lack of consensus on the definition and quantification of reliability which typically is a computationally intense process. Subsequently, various reliability-like metrics, called resilience indices, have been developed and demonstrated in the design of WDNs. Few studies exist that thoroughly evaluate the performance of the previously developed resilience metrics. This paper investigates three resilience metrics by evaluating their performance on three benchmark WDNs for several simulated mechanical failure states. The metrics studied are: (a) resilience index, (b) network resilience index (NRI), and (c) modified resilience index (MRI). The metric MRI performed better overall but NRI produced cheaper designs that performed better in the case of WDN-I. It is recommended that a better metric that incorporates different dimensions of resilience, such as robustness and redundancy, should be developed in the future.

Key words | failure state analysis, optimization, resilience, water distribution networks

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INTRODUCTION

Water distribution networks (WDNs) play a vital role in the survival of human populations and economic growth. It is therefore essential that WDNs function continuously in the face of both exogenous and endogenous risks that threaten to have devastating consequences. Exogenous risks include but are not limited to landslides or seismic ground movements, traffic loading, buoyancy uplift, intrusions, and soil erosion while endogenous risks include material degradation and pressure surges. A majority of our WDNs are in a deteriorated state thus reducing their ability to cope with these threatening risks. Consequently, there have been about 240,000 water main failures annually in the USA (ASCE 2013).

WDN components such as pipes, tanks, and pumps are typically designed to meet flow and pressure requirements at consumption points while maintaining sufficient service reliability. Reliability can be understood as a risk management approach where the system is designed to handle certain known risks using probabilistic risk analysis techniques. The ability to manage abnormal hydraulic loading in terms of pressure surges and demand variation is termed 'hydraulic' reliability, whereas the ability to manage mechanical component failures is termed 'mechanical' reliability. The specific way of quantifying reliability has varied over time and there is not one approach that comprehensively quantified both hydraulic and mechanical reliabilities of WDNs. Reliability evaluation is a computationally complex process due to the need for the simulation of various known failed scenarios for performance evaluation. In addition, reliability can only assess system performance for known risks and does not address unforeseeable risks.

To address the limitations of reliability, the concept of resilience has been pursued in order to ensure minimal

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loss in system performance when faced with known and unknown risks. Resilience denotes the ability of the system to withstand complete disruption and recover within reasonable time and cost consequences. Resilience is an evolving science and therefore there are no universally accepted metrics to quantify it. There are three resilience metrics that were proposed for WDNs in the past but there has not been a thorough study evaluating these metrics. This paper measures the relative performance of the three identified resilience metrics in dealing with the same set of WDN failures, and evaluates the metrics for use in the design of Greenfield WDNs and expansion of existing systems. The results will help decision-makers in choosing an appropriate metric to guide the design of their WDNs.

PREVIOUS RESEARCH

A continuous supply of water is more important during times of calamities and, consequently, for the past few years, there has been a strong focus on the concept of resilience in the context of infrastructure systems. While the concept of resilience is better understood generally, there is a strong need for a quantifiable metric that water utilities and design engineers can incorporate into the design and maintenance of water supply systems. There have been three such resilience metrics developed for water supply systems.

Todini (2000) presented the resilience index (RI) metric as an alternative to network reliability, and it is characterized as the amount of buffer energy available in the network that can be lost when there is a greater demand or a pipe failure. His formulation of resilience was based on the fact that an increase in demand or pipe failures lead to higher internal energy losses. A positive resilience value for a given network implies that there is surplus amount of energy supplied either by using greater capacity pumps or elevated reservoirs, both of which will cost more. Consequently, there is a trade-off between cost and resilience as is the case with reliability and it is the designer who selects the best fit for any given scenario. Advantages of RI are that it is independent of the type of failure and it also does not require the simulation of various failure states as in the case of reliability, thereby significantly reducing the computational time. Todini's RI (or index of resilience, I_r) is calculated using Equations (1) and (2):

$$\begin{aligned}\text{RI } or\ I_r &= 1 - \left(\frac{P_{\text{tot}} - \gamma \sum_{i=1}^{n_n} q_i{*}h_i}{P_{\text{tot}} - \gamma \sum_{i=1}^{n_n} q_i{*}h_i{*}}\right)\\ &= \frac{\sum_{i=1}^{n_n} q_i{*}(h_i - h_i{*})}{\sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p}\left(\frac{P_j}{\gamma}\right) - \sum_{i=1}^{n_n} q_i{*}h_i{*}}\end{aligned} \qquad (1)$$

$$P_{\text{tot}} = \gamma \sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p} P_j \qquad (2)$$

where $q_i{*}$ = demand at node i; h_i = actual node head in no-failure condition; $h_i{*}$ = minimum node head; P_{tot} = total available power at the entrance in the WDN; γ = specific weight of water; Q_k = discharge from reservoir k; H_k = reservoir head; n_r = number of reservoirs; P_j = power supplied to the network by the jth pump; n_p = number of pumps.

Prasad & Park (2004) argued that Todini's RI may work well for the case of increased demands but not for pipe outages. Their argument seems logical when RI is applied on branched networks in which failure of upstream pipes will have severe downstream impacts no matter how high the RI value is. Subsequently, they extended Todini's metric by adding the effect of reliable loops and proposed a network resilience index (NRI). Reliable loops are ensured when pipes connected to a node are not of varying diameters. Using the same notation used for RI, NRI is calculated using Equations (3) and (4).

$$\text{NRI} = I_n = \frac{\sum_{i=1}^{n_n} C_i q_i (h_i - h_i{*})}{\left[\sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_{pu}}\left(\frac{P_j}{\gamma}\right)\right] - \sum_{i=1}^{nn} q_i h_i{*}} \qquad (3)$$

$$C_i = \frac{\sum_{l=1}^{n_{p_i}} D_l}{n\,p_i \times \max\{D_l\}} \qquad (4)$$

where C_i = node uniformity coefficient; n_{pi} = number of pipes connected to node i; D_l = diameter of pipe l.

Jayaram & Srinivasan (2008) argued that Todini's RI may not be appropriate when multiple sources are present in the network. Their argument is based on the fact that discharge from reservoirs is not independent of pipe diameters and therefore the denominator in Todini's RI may increase when a larger portion of network demand is met by a reservoir that is at a greater elevation head. The additional power added to the network will likely increase the energy surplus in the network resulting in an increase in the numerator of RI (Equation (1)). As a result of the increase in both numerator and denominator, RI value may not increase despite the increase of energy surplus in the network. Consequently, Jayaram & Srinivasan modified Todini's RI as shown in Equation (5):

$$\mathrm{MRI} = \frac{\sum_{i=1}^{n_n} q_i(h_i - h_i*)}{\sum_{i=1}^{n_n} q_i h_i*} \times 100 \tag{5}$$

Raad *et al.* (2010) first attempted to evaluate four surrogate reliability measures that include an entropy measure, mixed reliability metric in addition to RI and NRI as considered in this paper. They designed three benchmark WDNs using the four chosen reliability surrogate metrics as co-objectives along with cost, and then tested the Pareto-optimal solution sets for their performance under both hydraulic and mechanical failure scenarios. They used a pressure-driven analysis approach for evaluating system performance in various failure states. One limitation of their study is the fact that they have taken the average of all considered failure scenarios without accounting for their respective probabilities. They have also considered only single pipe-failure scenarios for performance evaluations. Our WDNs are in a deteriorated state and, therefore, we may not continue to assume that the failure probability of more than one pipe at any time is negligible.

Banos *et al.* (2011) evaluated the performance of the three resilience metrics considered in this research, but only for demand variations. Their approach is similar to that of Raad *et al.* except that they have considered the network feasibility in any failed scenario as a binary variable. In other words, a failed state in their performance evaluation approach is either feasible or unfeasible depending on whether all the nodal pressures are met or not. This may not be accurate in reality as there would still be some flow at the demand node even if the actual pressure is less than the minimum required, as long as it is positive. Our study extends both these studies by evaluating the three chosen resilience metrics for their performance in several simulated single- and double-pipe-failure scenarios by also considering their associated failure probabilities.

RESEARCH METHODOLOGY

Figure 1 illustrates the methodology of the research presented in this paper. Three popular benchmark networks, named in this research as WDN-I, WDN-II, and WDN-III, are used for evaluating the performance of the three chosen resilience metrics. Figures 2–4 show the layouts of the WDNs initially presented by Alperovits & Shamir (1977), Gessler (1985), and Morgan & Goulter (1985), respectively. Each of the chosen WDNs is initially designed for pipe sizes using cost and each of the resilience metrics as objectives using the multi-objective WDN optimization model developed by Piratla & Ariaratnam (2013a). The optimization model was developed using a tool called GANetXL which is linked with EPANET for pressure constraint checking (Savic *et al.* 2011). Several other applications of GANetXL in water-related optimization studies can be found in the literature (Deepthi *et al.* 2009; Piratla & Ariaratnam 2012; Farmani *et al.* 2012). Sorted Pareto-optimal solution sets for each WDN and for each resilience-metric are obtained from the optimization task. The system performance in each of the failed states (j) for each of the Pareto-solution (i) is then evaluated using a proposed risk metric. An overall risk index is calculated for each pair of WDN and resilience metric in order to compare the performance of the resilience metrics. EPANET toolkit is extensively used for this intense computational simulation exercise in conjunction with visual basic for applications (VBA) in Microsoft Excel. Each of the tasks in Figure 1 is further explained in the following sections of this paper.

DESIGN OF WDNS USING RESILIENCE AND COST OBJECTIVES

Each of the resilience metrics is used as an objective along with cost to obtain the Pareto-optimal solution set of pipe sizes for each of the WDNs–I, II, and III. The networks are designed for pipe diameters keeping all other variables constant; those variables such as pipeline length, nodal elevation and demand, and pressure requirements are taken from the original formulations of these WDNs. Pipe cost data along with the set of diameters considered for pipe size variables are also taken from the original

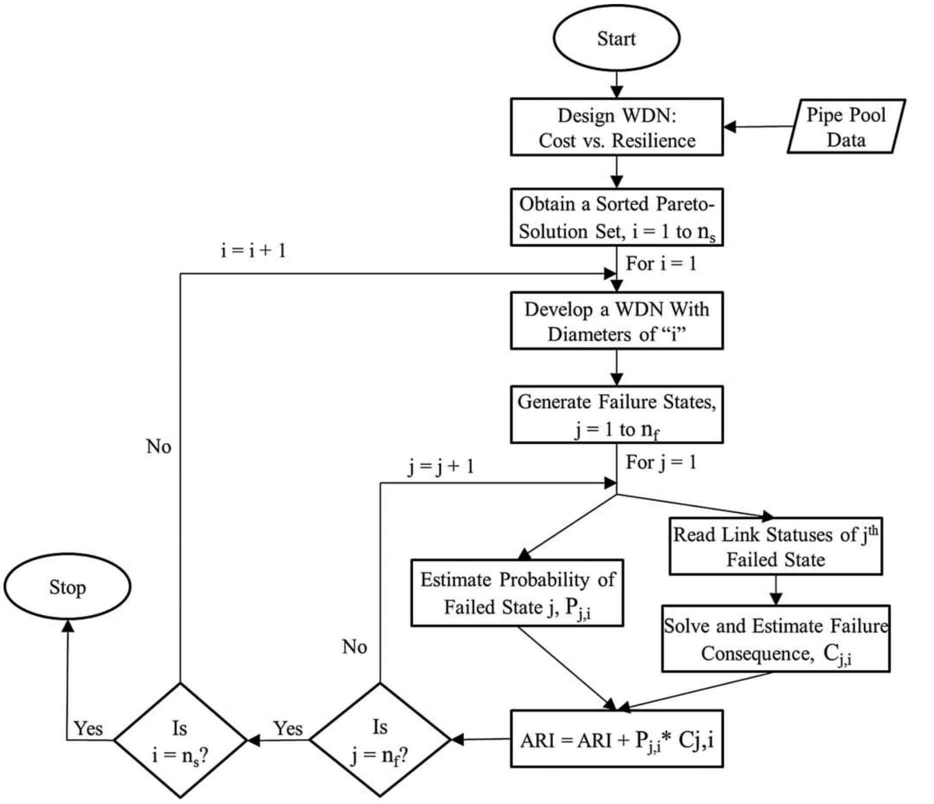

Figure 1 | Flowchart illustrating the logic for investigating the efficient resilience metric.

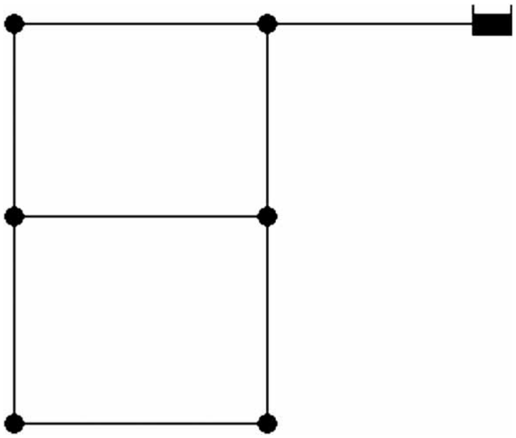

Figure 2 | Layout of WDN-I.

formulations to ensure validity of the model (Alperovits & Shamir 1977; Gessler 1985; Morgan & Goulter 1985). The optimization framework for the design process is as follows:

Objective-1: minimize $\text{cost} = \sum_{j=1}^{n_l} C_{D_j} \times L_j$

where C_{Dj} = cost per unit length of pipe of diameter D_j (\$/m); L_j = length of pipe (m) j; n_l = number of links.

Objective-2: maximize resilience = RI or NRI or MRI
Constraints: $h_i \geq h_i{}^*$ ($\forall$ node i)

where h_i = actual pressure head in no-failure condition; $h_i{}^*$ = minimum pressure head.

The WDNs were initially designed for pipe diameters using cost alone as the objective to validate the optimization model. The results tallied with the optimal diameter sets obtained for these networks in the literature. The optimization model is then used for designing the three networks using each of the three resilience metrics making a total of nine different optimization problems, as shown in Table 1. The optimization algorithm is run several times for each of the nine problems with different sets of crossover and mutation rates in order to obtain the Pareto-optimal fronts that are illustrated in Figures 5–7. The performance of the Pareto-optimal solution sets are further analyzed to evaluate the relative efficiency of resilience metrics in producing reliable design alternatives.

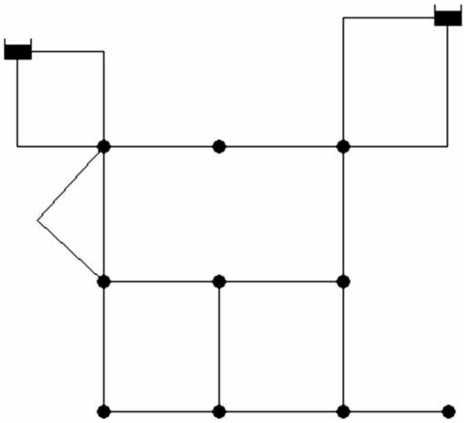

Figure 3 | Layout of WDN-II.

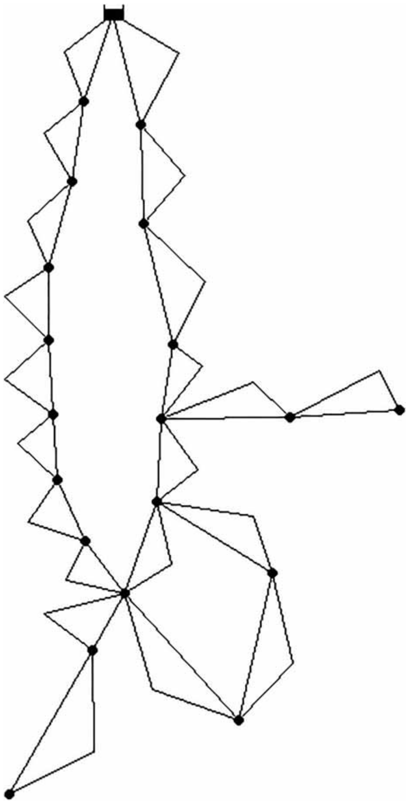

Figure 4 | Layout of WDN-III.

PERFORMANCE ANALYSIS OF WDNS IN FAILED STATES

As illustrated in Figure 1, for each Pareto-optimal solution (i), various failure states ($j = 1$ to n_f) are simulated by accounting for all possible single and double pipe break scenarios. A VBA code is written in Microsoft Excel for developing a matrix with statuses of all the network links in all the failure scenarios. Link statuses in each failure state are communicated to the hydraulic model and it is solved using the EPANET toolkit which enables making changes to network parameters without needing to rebuild the whole network as a new input file. The network performance is evaluated in each of the failed scenarios based on the nodal head data obtained from running the hydraulic simulation. For any failed scenario, there are no consequences if all the nodes are met with the required pressure head.

Table 1 | Formulations for resilient design

System	Formulation #	Objectives
WDN-I	1	Cost and RI
	2	Cost and NRI
	3	Cost and MRI
WDN-II	1	Cost and RI
	2	Cost and NRI
	3	Cost and MRI
WDN-III	1	Cost and RI
	2	Cost and NRI
	3	Cost and MRI

A statistical performance measure called average risk index (ARI) is defined and used in this research to analyze the results. Risk is defined as the probability of failure multiplied by its consequence. ARI incorporates the probability of the simulated failure states in a manner similar to the minimum cut-set method proposed by Su *et al.* (1987). ARI is estimated using Equations (6)–(12). An indicator average percentage of unfeasible scenarios (APUS) was used by Banos *et al.* (2011) for analyzing system performance for simulated hydraulic failures. APUS does not include the failure probability $P_{j,i}$ in its formulation and it appears to objectively classify any pressure deficit as a failure. The performance of WDNs in terms of APUS is also presented in this paper.

$$\mathrm{ARI}_i = \frac{1}{f}\sum_{j=1}^{f} P_{j,i} \times C_{j,i} \tag{6}$$

$$\mathrm{ARI} = \frac{1}{f \times m}\sum_{i=1}^{m}\sum_{j=1}^{f} P_{j,i} \times C_{j,i} \tag{7}$$

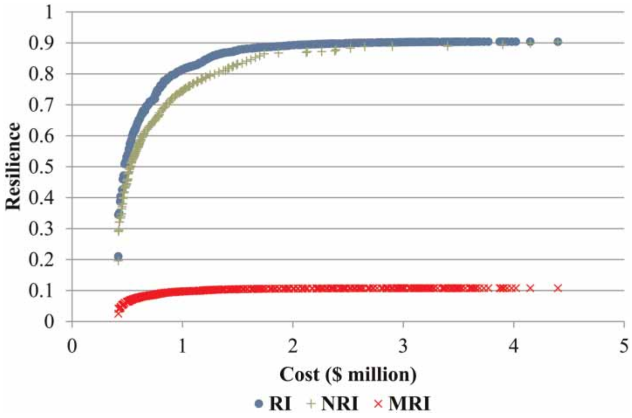

Figure 5 | Pareto-optimal solutions for WDN-I considering RI, NRI, and MRI indices (adapted from Piratla & Ariaratnam (2013b)).

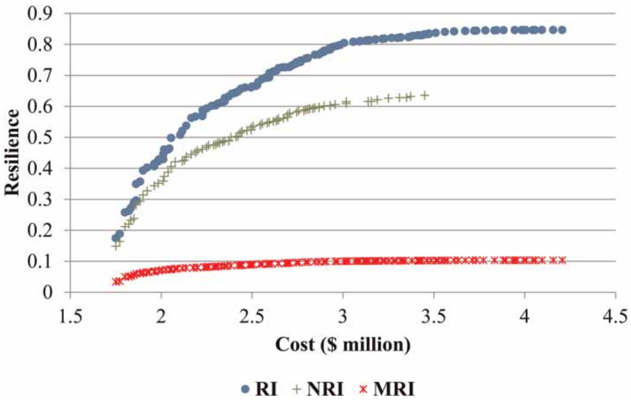

Figure 6 | Pareto-optimal solutions for WDN-II considering RI, NRI, and MRI indices.

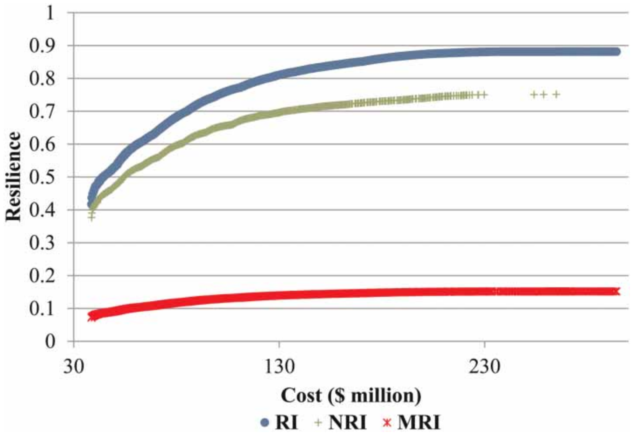

Figure 7 | Pareto-optimal solutions for WDN-III considering RI, NRI, and MRI indices (adapted from Piratla & Ariaratnam (2013b)).

$$C_{j,i} = \sum_{p=1}^{n} H_{p,j,i} \times \frac{Q_p}{\sum Q_p} \tag{8}$$

$$H_{p,j,i} = \begin{cases} 1, \ h_{p,j,i} \leq 0 \\ 1 - \dfrac{\sqrt{h_{p,j,i}}}{\sqrt{h'_p}}, \ h_{p,j,i} - h'_p \leq 0 \ \& \ h_{p,j,i} \geq 0 \\ 0, \ h_{p,j,i} - h'_p \geq 0 \end{cases} \tag{9}$$

where ARI_i = average risk index for a Pareto-solution i; ARI = average risk index for all the Pareto-solutions; m = number of Pareto-solutions for a WDN; j = failed state number; f = number of failure states (all single and double pipe breaks); p = node number; n = number of nodes in a given WDN; Q_p = demand at node p; $P_{j,i}$ = probability of realizing a failure state j in a Pareto-solution i; $C_{j,i}$ = consequence of failed state j for Pareto-solution i; $H_{p,j,i}$ = flow deficit factor due to pressure deficit; $h_{p,j,i}$ = actual head at node p in failure state j; $h_p^{'}$ = minimum required head at node p.

The risk (ARI) as defined in Equations (6)–(9) is measured by taking into account the failure consequence which is as a function of both pressure head deficit and flow. A majority of the water network simulation models such as EPANET use demand-driven analysis (DDA) for calculating nodal heads and flows. In DDA, it is just assumed that nodes are served with required demand irrespective of the pressure. Consequently, in a pipe failure state, DDA-based simulation models produce extremely low pressures indicating that the network is not able to cope with the demands. There were studies in the past that presented pressure-driven models to address this challenge but there are reported difficulties in terms of calibration, and absence of robust methods for computational solutions. The consequence ($C_{j,i}$) of a failed state in this research is estimated based on the summation of flow deficit normalized in such a way that $C_{j,i}$ can take a maximum value of 1. Flow deficit at each node is estimated using a flow deficit factor as shown in Equation (9). If the observed nodal pressure in a failed state is only marginally less than the required, the consequences may not be that significant (i.e., $H_{j,p,i}$ will be closer to zero). The consequence function presented in Equation (9) is used to capture the actual consequence of pressure deficit rather than objectively classifying the consequence as 'failure' or 'not failure' based on the ability to meet the minimum required nodal pressures.

The probability of having a failure state is taken as the product of probabilities of failing components in that particular state:

$$P_j = \prod_{l} P_l \tag{10}$$

where P_l = failure probability of the broken link l in failure state j. Failure probability of a pipe link is estimated using Poisson probability distribution as suggested by Goulter & Coals (1986):

$$P_l = 1 - e^{-\beta_l} \tag{11}$$

where P_l = probability of failure for link l; β_l = expected number of failures per year for pipe l ($= r_l \times L_l$); r_l = break rate per year per unit length; L_l = length of pipe l.

There have been various studies in the past that have attempted to develop water main break prediction models. Water pipes deteriorate over time, and with added stresses from the external and internal environment, they tend to fail. It is quite difficult to understand and model the physical mechanisms that lead to a pipe failure (Kleiner & Rajani 2001). Subsequently, various statistical models were derived in the past to predict water pipeline deterioration. A complete review of the body of work in water pipeline deterioration is well documented (Kleiner & Rajani 2001). It is generally accepted that water pipelines exhibit lower failure rates in the early phase of their lifecycle, and also that larger diameter pipes break less frequently than smaller diameter pipes. There has been a set of models in the past that separately estimated pipe failure probability for smaller diameter ($\leq 6''$ or 150 mm) and larger diameter pipes ($\geq 8''$ or 200 mm) using different deterioration schemes (Andreou 1986; Marks *et al.* 1987; Li & Haimes 1992). While it is recognized that employment of a two-phased (early phase and toward-the-end phase) model may produce better failure probabilities, lack of data currently limits its usage. Owing to the use of benchmark networks in this research and the subsequent lack of real field data, a simpler break prediction model is employed by using break rates presented in the literature for various pipe diameters. Shamir & Howard (1979) conducted a regression analysis to obtain a break prediction model that relates break rate to the exponent of the pipe's age. Their model (Equation (12)) is used to estimate r_l in Equation (11) considering a 20-year time period (t-t_0) and a break growth rate (A) of 0.05:

$$N(t) = N(t_0)e^{A(t-t_0)} \tag{12}$$

where t = time in years; t_0 = base year for the analysis; $N(t_0)$ = number of breaks per unit length of pipe in year t_0 (presented in Table 2); $N(t)$ = number of breaks per mile length of pipe in year t; A = growth rate coefficient (1/year) which was estimated to range from 0.01 to 0.15. The break rate data presented in Table 2 are adapted from the literature (Neelakantan *et al.* 2008). Break rates for diameters greater than 609.6 mm are appropriately extrapolated in this study.

The performance of each WDN for various failure states in terms of ARI and APUS is presented in Table 3. The usage of resilience metrics in the design process is expected to improve the performance of the networks in failed states. Subsequently, correlation between resilience metrics and performance metrics for all the Pareto-solutions is estimated using linear regression modeling approach similar to that conducted in Raad *et al.* (2010). The performance analysis of WDNs is a computationally intensive process as the algorithm needs to analyze the performance of the WDN in each failed state of each Pareto-solution. The number of hydraulic calculations exceeded one million in the case of WDN-III

Table 2 | Pipe break rate data

Diameter (mm)	Break rate (breaks/yr/km)	Diameter (mm)	Break rate (breaks/yr/km)
25.4	1.3	1,219.2	0.0095
50.8	1.05	1,524	0.009
76.2	0.81	1,828.8	0.0085
101.6	0.58	2,133.6	0.008
152.4	0.41	2,438.4	0.0075
203.2	0.25	2,743.2	0.007
254	0.15	3,048	0.0065
304.8	0.1	3,352.8	0.006
355.6	0.08	3,657.6	0.0055
406.4	0.06	3,962.4	0.005
457.2	0.05	4,267.2	0.0045
508	0.04	4,572	0.004
558.8	0.03	4,876.8	0.0035
609.6	0.02	5,181.6	0.003
914.4	0.01		

Table 3 | Results from the investigation of efficient RI

Network	Metric	ARI	Correlation (R) - metric vs. ARI	APUS	Correlation (R) - metric vs. APUS
WDN-I	RI	1.284%	−0.904	76.93%	−0.563
	NRI	1.476%	−0.897	71.81%*	−0.954
	MRI	1.211%*	−0.909	77.24%	−0.566
WDN-II	RI	2.655%	−0.978	66.74%	−0.976
	NRI	3.370%	−0.969	68.46%	−0.976
	MRI	2.612%*	−0.962	65.58%*	−0.971
WDN-III	RI	0.0154%	−0.965	55.68%	−0.932
	NRI	0.0208%	−0.977	63.13%	−0.915
	MRI	0.0153%*	−0.964	55.62%*	−0.932

*Best metric indication for each scenario.

which is still a relatively smaller network. The average computational time for this analysis was found to be 0.0463 seconds for a single hydraulic run on an Intel i7 3.4 GHz processor. Figures 8–10 illustrate the performance of the metrics shown on an ARI vs. Cost graph for the three WDNs.

ANALYSIS AND DISCUSSION

Table 3 presents the performance of RI, NRI, and modified resilience index (MRI) in terms of both ARI and APUS for each of the WDNs in various failed states. It can be seen that NRI performed better for WDN-I when APUS is considered as the performance metric. There is also a strong correlation between NRI and APUS that suggests a potential linear relationship in the case of WDN-I. MRI performed better in the cases of WDN-II and WDN-III with strong correlation with APUS. The drawback of basing the performance analysis on APUS is that it does not account for the probability of having a failed state. If the performance of a Pareto-solution in a given failed state is unfeasible but the probability of having such a failed state is much less, then the ability of the network to perform satisfactorily in that failed state may not be a concern. Subsequently, a new performance metric (ARI) is developed by incorporating the probability of failed state in addition to the performance in failed state.

It can be seen from Table 3 that MRI performed marginally better overall than RI for all the WDNs when ARI is considered as the performance metric. There is also a reasonable correlation between MRI and ARI for all the WDNs. Figures 8–10 illustrate the performance of the WDNs for the three resilience metrics studied in this research. NRI is generally expected to perform better overall due to its formulation aimed at producing reliable loops and greater redundancy to counter pipe failures. Such a trend is clearly observed in the case of WDN-I, as can be seen from Figure 8, but is not noticed in the cases of WDN-II and WDN-III. It can be observed from Figure 8 that NRI is able to produce cheaper solutions with better (i.e., low) ARI values compared to RI and MRI. For example, NRI is able to obtain a solution for WDN-I that costs $1 million which resulted in an ARI value of about 0.6%. To obtain a similar ARI value using RI and MRI, it costs at least $1.77 and $2.11 million, according to Figure 8. The solution that resulted in $1 million cost and an NRI value of 0.7443 from the design of WDN-I when NRI is used as the resilience metric is S_1 (in mm)$_=${558.8, 406.4, 508, 355.6, 508, 406.4, 355.6, and 355.6}. The RI value for the solution S_1 is calculated as 0.79744. It is understood that solution S_1 is not obtained from the design of WDN-I when RI is used as the resilience metric because there is a better solution S_2 (in mm) = {558.8, 508, 508, 304.8, 406.4, 25.4, 406.4, and 355.6} that resulted in a greater RI value of 0.79961 at a cheaper cost of $932,000. Subsequently, solution S_1 was dominated by better solutions, such as S_2 in the genetic algorithm non-dominated sorting. The problem with S_2 is that it included a pipe diameter value of 25.4 mm for link-6 in WDN-I. Such a small diameter for a water pipeline leads to greater probability of failure, and the fact that link-6 is connected to node-6 which has the highest demand of 330 m^3/hr resulted in a greater ARI value in the case of WDN-I. Such a trend for NRI is not observed in WDN-II and WDN-III.

Although MRI seems to have fared well overall, NRI found significantly cheaper solutions at a better ARI value in the case of WDN-I. It may be incorrect to conclude from

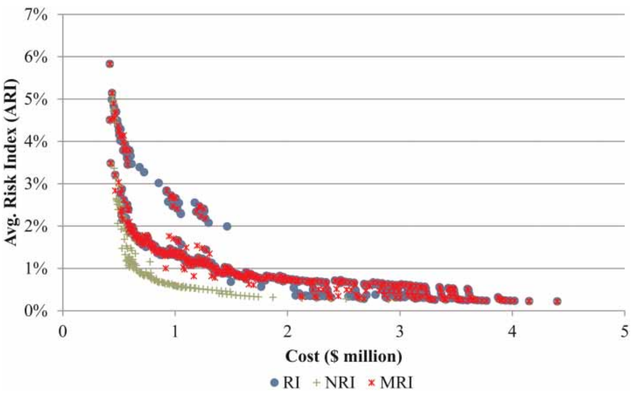

Figure 8 | The performance of the resilience metrics vs. cost for WDN-I.

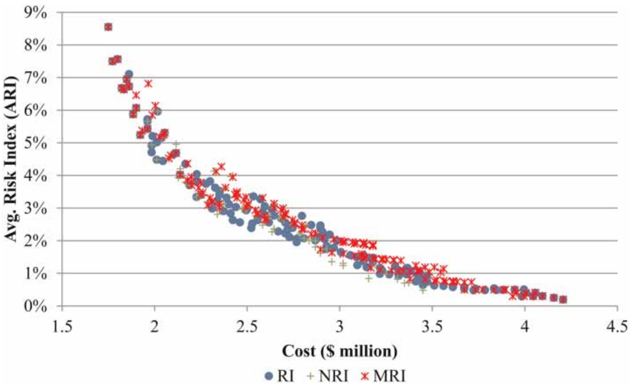

Figure 9 | The performance of the resilience metrics vs. cost for WDN-II.

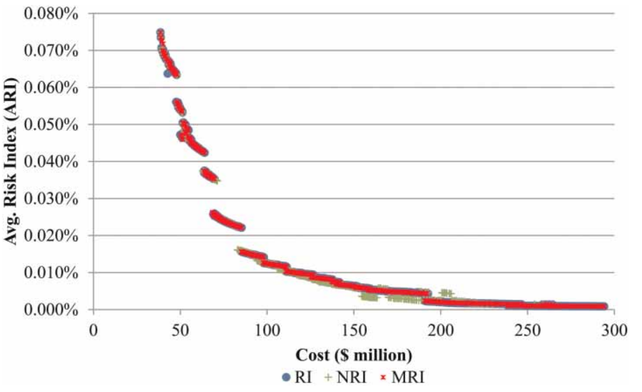

Figure 10 | The performance of the resilience metrics vs. cost for WDN-III.

this research that either MRI or NRI is the best metric to quantify resilience. Theoretically, neither of the resilience metrics considered could be accurate in quantifying the true resilience of water distribution networks. Resilience is defined in *Webster's Unabridged Dictionary* as 'the ability to bounce or spring back into shape, position, etc. after being pressed or stretched.' There are varying definitions of the word 'resilience' but they all indicate the ability to resist and recover after distress. Bruneau *et al.* (2003) characterized resilience using four qualities: (a) robustness, (b) redundancy, (c) resourcefulness, and (d) rapidity. All three metrics evaluated in this research truly considered only redundancy in terms of providing sufficient buffer energy for internal dissipation or path redundancy in the case of failures. An increase in RI, NRI, or MRI will definitely increase the ability of the system to resist complete disruption, but there are also other ways of improving resilience. For example, incorporating pipe deterioration characteristics based on material, diameter, and historical experiences, and compensating for it using other measures such as additional local redundancy around that particular pipe can be beneficial. In addition, vulnerabilities in the region can also be identified and reliability-like analysis could be included in the resilience framework to make the resilience quantification even more comprehensive. If the resilience metrics were to be applied for the design of expansion of existing WDNs, condition ratings of system components can be incorporated into resilience quantification. Subsequently, a new resilience metric may be developed in the future considering the aforementioned recommendations.

CONCLUSIONS AND RECOMMENDATIONS

Three resilience metrics were evaluated in this paper by assessing their performance on three benchmark WDNs in producing designs that are able to cope with failures. The resilience metrics were used as objectives along with cost in the design of WDNs to produce a set of non-dominant solutions for pipe diameters. The Pareto-optimal solutions obtained were scrutinized to evaluate the system's performance under various failure conditions. Using DDA-based EPANET (and its toolkit) with a computational algorithm, the performance of designed WDNs was evaluated in both single and double pipe failure states. The probabilities of realizing the simulated failed states were incorporated into the performance analysis for an accurate estimate of the failure risk. The performance is evaluated similarly to that of risk wherein failure probability is multiplied with failure consequences. For a given design solution and a given failed state, a hydraulic simulation was run to understand the nodal pressures and actual flows. If the pressures are greater than the minimum required, then that given solution is feasible in that given failed state or else a failure consequence was assigned. An indicator called the ARI was defined and used to assess the performance of all Pareto-solutions in all failed states.

The results revealed that MRI performed marginally better in all the three WDNs. However, NRI produced cheaper solutions at a better ARI value in the case of WDN-I. The results are not conclusive enough to select either of the metrics as a favorite for quantifying true resilience of water distribution networks. It is possible that none of the three metrics accurately quantify the true resilience of a WDN and there is a need for a better metric that incorporates robustness aspects into a resilience framework.

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