A resilience-based prioritization scheme for water main rehabilitation

He Jin and Kalyan R. Piratla

ABSTRACT

Water supply infrastructure in the United States is one lifeline system that is in dire need of huge financial investments to counter pipeline deterioration while keeping up with increasing demands and reliability goals. With decreasing financial resources available to state and local governments, effective decision-making tools for pipeline prioritization are becoming an increasingly integral part of the water utility industry. A majority of existing prioritization frameworks are merely based on the likelihood of the failure of pipelines and the resulting consequences, with little consideration given to the utility's response time to a water pipeline failure. This paper presents a novel resilience-based framework for effective prioritization of water distribution pipelines. The novelty lies in estimating the utility's response time to a pipeline failure. The proposed framework is demonstrated on a section of a real water distribution network in a coastal city of the United States. The pipeline priority results obtained are also compared with those from a more traditional risk-based prioritization scheme, and a reasonably significant difference has been observed. While availability of quality data is a challenge, this study brings to attention the importance of response time to water pipeline failures and demonstrates the merits of incorporating it in a prioritization scheme.

Key words | decision-making tools, resilience, water distribution pipelines

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INTRODUCTION

There is a great dependability of modern urban societies on lifeline systems such as drinking water distribution networks (WDNs) for basic survival and economic prosperity. Therefore, reliability of supply both in terms of quantity and quality is one of the top priorities for any water utility. Supply interruptions could also impede firefighting capabilities, potentially resulting in loss of lives and property. The American Society for Civil Engineers (ASCE) in their latest infrastructure report card gave a near-failing 'D' grade for drinking water infrastructure (ASCE 2013). Our WDNs, currently in a deteriorated state, need huge investments that are beyond the capabilities of local municipalities and governments. For example, the estimated 20-year capital investment need for revamping deteriorated pipelines in the United States is about $334.8 billion (ASCE 2013). This poor state can be primarily attributed to the fact that a majority of pipelines have been in service for considerably longer than their intended use. Sub-optimal design techniques at the time of their installation combined with lack of adequate maintenance exacerbated this problem.

Due to the lack of economically feasible and reliable condition assessment techniques, a majority of pipelines are not adequately monitored in order to identify and fix the defects before they grow into catastrophic failures. With about 240,000 water main breaks reported annually in the USA, consequences of the current state of WDNs include decreased reliability, supply interruptions, and other societal inconveniences (ASCE 2013). These consequences could be prohibitively expensive, depending primarily on the size of the failed pipeline and its importance in the overall WDN functioning. For example, emergency repairs to large diameter water mains in critical locations have proven to be

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expensive compared to planned rehabilitation (ASCE 2013). Consequently, effective asset management and subsequent prioritization of critical pipelines for planned rehabilitation is a timely need for water utilities. This paper presents a novel prioritization framework for rehabilitation of critical pipelines. The novelty lies in the modeling of time taken to detect and repair failed pipelines. The proposed framework is demonstrated on a section of real WDN to highlight its advantages compared to the more traditional risk-based framework for rehabilitation prioritization.

PREVIOUS RESEARCH

Several researchers have proposed schemes in the past for rehabilitation prioritization of WDN pipelines based on their failure criticality (Moglia *et al.* 2006; Rogers & Grigg 2009; Studzinski & Pietrucha-Urbanik 2012; Grigg *et al.* 2013; Rahman *et al.* 2014; Yoo *et al.* 2014). Failure criticality in a majority of these past studies was evaluated based on the respective pipeline's condition and the estimated impact of its failure. As water pipelines age, they deteriorate due to the combination of several factors that include natural material degradation and subsequent loss of structural integrity, lack of proper maintenance, fatigue loading and subsequent localized damage, design defects or construction errors that weaken the system over time, adverse operating schedules, and adverse environments (Piratla *et al.* 2014). Pipeline condition upon investigation is usually translated into the probability of its failure. Impacts of water pipeline failures in some cases are felt only locally in the form of flooding of streets, damage to roads and traffic restrictions, and in other cases are system-wide in the form of supply interruptions, low pressures, and potential contamination. The aggregate failure impacts are usually represented using a normalized index. Approaches adopted in the literature for estimating failure probability and failure impacts are briefly reviewed in the following paragraphs.

Previous researchers employed different approaches for estimating the failure probability of water supply pipelines. Moglia *et al.* (2006) used a non-homogeneous Poisson process (NHPP) model by considering pipe length, size, type, age, operating pressure, and soil type as influential variables, and also modified this using the best linear unbiased predictor for better failure probability prediction. Rogers & Grigg (2009) used NHPP and multi-criteria decision analysis (MCDA) for estimating pipeline failure probability. Rogers & Grigg's (2009) NHPP model is based on pipe age, condition, and historical failure information, and was found to be applicable only to pipelines with three or more previous breaks. The MCDA model is based on the ratings given to several influential factors along with their respective user-assigned weights, and it was found to be applicable to pipelines with one or two previous breaks. Studzinski & Pietrucha-Urbanik (2012) estimated failure probability based on the ratio of average pipeline suspension time due to repair to the average operational time without a failure. Grigg *et al.* (2013) calculated the pipeline failure likelihood index using the weighted sum of ratings given to variables such as age, break rate, and service conditions (i.e., traffic load, pressure zone, and soil corrosivity), where weights are defined by the user. Rahman *et al.* (2014) proposed a probability failure score based on the remaining useful life of a pipeline, which is estimated by considering age, material, and failure history. Yoo *et al.* (2014) estimated failure probability using a probabilistic neural network (PNN) model based on pipeline deterioration rate, which was calculated by considering internal and external factors that influence pipeline failure. Internal factors included several pipeline attributes, failure history, failure type, water quality, and operating pressure. External factors included corrosion rate, backfilled soil type, and road width. In addition to the studies reviewed in this paper, there are several other published studies that evaluated failure probability of pipelines; however, a major limitation has been the availability of quality data that enhances the accuracy of the model output.

Previous researchers also employed different approaches for estimating the failure consequences of water supply pipelines. Moglia *et al.* (2006) estimated failure consequences based on the costs of pipeline renewal, valve insertions, pipeline repairs, supply interruption, and physical damages caused by failures. Berardi *et al.* (2008) estimated failure consequences based on direct costs of pipe replacement, risk of pipe breaks, system reliability, work allocation, and leakage reduction using the pressure-driven model for simulating the hydraulic performance of the system. These failure consequences are employed as objectives in a multi-objective genetic algorithm (MOGA) in order to identify a set of optimal pipeline replacement schemes. Berardi *et al.* (2009)

added a sixth objective, namely, preferential pipe selection, to their previous MOGA framework for rehabilitation decision-making in WDNs. Rogers & Grigg (2009) estimated monetary failure consequences based on economic, environmental, and social factors. Studzinski & Pietrucha-Urbanik (2012) estimated failure consequences as the ratio of volume of water not delivered to the required water volume. Grigg *et al.* (2013) used a weighted sum of the ratings given to repair cost, pipe size, and failure location, in which the weights are defined by the user. Rahman *et al.* (2014) used a degree of impact which is based on water service demand, number of critical consumers, density of customers, land use, traffic impact, pipe materials, and repair cost. Yoo *et al.* (2014) used a hydraulic importance formula, which was calculated as the ratio of delivered water to required water for both single and multiple pipeline failure scenarios. Although many researchers have presented approaches for assessing water main failure consequences, due to the difficulty associated with predicting the true failure impact in the form of interruption duration, notifications of interruptions, time and day of interruption, number of interruptions per year and the resulting environmental and societal costs, estimating failure consequences has been challenging and less accurate.

In summary, several studies in the past developed risk-based prioritization models for WDNs; however, many limitations led to over-simplification of risk calculations, especially while estimating the consequences. Not much consideration has been given to estimating the time taken by a water utility operator in responding to a pipeline failure. Clearly, failure consequences depend on how fast and efficiently a water utility operator responds. This paper proposes and demonstrates a modified risk assessment model, named as resilience assessment, which is based on pipeline failure probability, consequences, and restoration capability, which are separately estimated and integrated into one metric.

RESILIENCE-BASED PRIORITIZATION FRAMEWORK

Resilience has been defined in the literature in different ways: Woods (2005, 2006) defined it as the capability of a system to create foresight, to recognize, to anticipate, and to defend against the changing shape of risk before adverse consequences occur. Rose & Liao (2005) defined it as the inherent ability and adaptive responses of systems that enable them to avoid potential losses; O'Rourke (2007) defined it as the ability of a system to bounce or spring back into shape or position after being pressed or stretched. In this study, resilience in the context of WDNs is defined as the ability to resist failure and recover within minimum possible cost and time consequences. This definition is further explained using the life cycle illustration of a water main break presented in Figure 1.

The ability to resist failure without loss of functionality is a combined effect of the inherent system strength and the type and extent of stresses imposed upon it. For example, deterioration due to wall corrosion in metallic pipelines will degrade the structural capacity to perform under a variety of loads. Consequently, the failure probability will be higher in such pipelines, making them less resilient to failures. This ability to resist failures is expected to decrease with increased deterioration, which is a currently prevailing trend in the USA's WDN pipelines. As illustrated in Figure 1, if a pipeline fails at time 'T_F' due to its reduced ability to resist failures, overall system performance drops from its original performance (C_O) to performance in failed state (C_F). The extent of performance reduction (C_O-C_F) depends on the failure severity, the overall WDN's reliance on the failed pipeline, and the amount of redundancy available in the system. Once a failure is detected, the corresponding pipeline will be isolated at time 'T_D' for repair. At this time, the overall system performance changes from C_F to C_D, where C_D denotes WDN performance when the failed pipe is isolated for repair. Emergency crews are sent to repair the pipeline, after which full functionality (C_O) is recovered at time 'T_R.' The loss in WDN

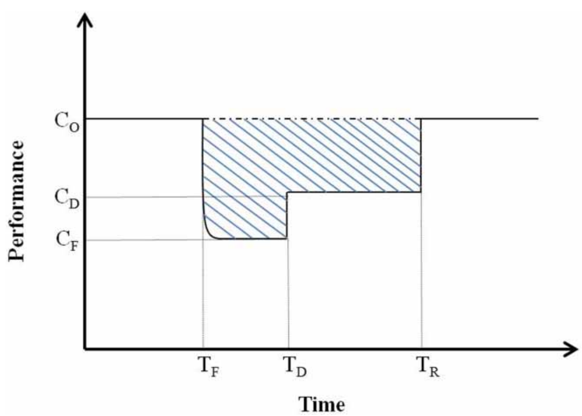

Figure 1 | Life cycle illustration of a water main break.

resilience for a given pipeline failure can be characterized by the hashed area in Figure 1, which is approximately equal to $[\{(C_O\text{-}C_F)*(T_D\text{-}T_F)\} + \{(C_O\text{-}C_D)*(T_R\text{-}T_D)\}]$.

In asset management, pipelines are monitored for their physical condition in order to evaluate probability of failure or expected remaining service life. Given the failure probability of a pipeline (P_j), the WDN resilience against that specific pipeline's failure (R_j) is calculated using Equation (1). A logarithmic function is proposed to quantify resilience in order to constrain its value between 0 and 1. The overall WDN resilience (R) is calculated using Equations (2)–(4).

$$R_j = 1 + \frac{1}{\log \frac{P_j*[(C_O - C_F)(T_D - T_F) + (C_O - C_D)(T_R - T_D)]_j}{10}} \tag{1}$$

$$R = \sum_{j=1}^{NS} R_j * \mathrm{W_j} \tag{2}$$

$$W_j = \frac{C'_j}{\sum_{j=1}^{NS} C'_j} \tag{3}$$

$$C'_j = \frac{\sum_{i=1}^{NN} Qr_i \; - \; \sum_{i=1}^{NN} Q_{i,j}}{\sum_{i=1}^{NN} Qr_i} \tag{4}$$

where R_j is the WDN resilience against failure of pipeline j; P_j is the failure probability of pipeline j; C_O is the original WDN performance before failure; C_F is the WDN performance immediately after the failure of pipeline j; C_D is the WDN performance when a failed pipeline is detected and isolated; T_F is the time of occurrence of failure; T_D is the time when a failed pipeline is detected and isolated; T_R is the time when a failed pipeline is repaired and re-commissioned into service; R is the overall WDN resilience; W_j is the relative importance of pipeline j in the WDN; NS is the number of pipelines in the WDN; C'_j is the effect on WDN performance when pipeline j is isolated; Qr_i is the required flow at node i of WDN; $Q_{i,j}$ is the actual flow supplied at node i when pipeline j is removed from the WDN; and NN is the total number of nodes in the WDN.

The pipelines are appropriately prioritized for rehabilitation or replacement based on the corresponding resilience values. The five parameters, namely, P_j, C_O-C_F, T_D-T_F, C_O-C_D, and T_R-T_D are modeled in this study in such a way that their values range between 0 and 1. The individual parametric models are further explained in the following sub-sections.

Failure probability

Physical mechanisms that lead to pipeline failure are often complex and not completely understood (Kleiner & Rajani 2001). Consequently, statistical models have been prominently used in the past for assessing trends in pipeline deterioration and estimating failure probability. Past failure and current condition data form the backbone of such statistical models. Multivariate regression analysis, PNNs, Markov and semi-Markov models are among several statistical modeling techniques that have been successfully applied for predicting deterioration of underground pipeline infrastructure (Micevski *et al.* 2002; Kleiner *et al.* 2006; Tran *et al.* 2006). The limitation of these models, however, is that they require high quality data, which may not be always available. Failure probability of a pipeline (P_j) is estimated in this study using a more tried and tested approach, presented in Equation (5) (Ciaponi *et al.* 2012):

$$P_j = \left[\prod_{j=1}^{NS} p(a)_j\right] * \frac{1 - p(a)_j}{p(a)_j} \tag{5}$$

where P_j is the probability that only pipeline j will fail; $p(a)_j$ is the probability that pipeline j is available and functional; and NS is the number of pipelines in the WDN.

Pipeline availability, $p(a)_j$, is 1 minus the failure probability, as shown in Equation (6). Failure probability of a pipeline is estimated using Equation (7) assuming that the failure rate follows a Poisson distribution (Yoo *et al.* 2013):

$$p(a)_j = 1 - \; p(f)_j \tag{6}$$

$$p(f) = 1 - e^{-\gamma L} \tag{7}$$

where $p(f)$ is the pipeline failure probability; γ is the prevailing break rate in number of failures/year/feet, which is estimated using historic failure data; and L is the pipeline length in feet (1 foot = 0.3048 m).

Failure consequences

Failure consequences are the losses incurred as a result of water pipeline failure. Depending on topology, design, redundancy, and demand patterns, failure consequences vary across a WDN. Consequences can be categorized into 'local impacts' and 'system-wide impacts.' Failure consequences of a large diameter pipeline that forms a critical link to a section of WDN could have system-wide impacts, rendering a significant portion of WDN dysfunctional. On the other hand, there will be some pipelines where failure will result in mere local impacts. System-wide consequences can be quantified by estimating the shortage of supply at all demand nodes in the WDN for a pipeline failure scenario. Consequences in the following two sequential stages of pipeline failure are separately estimated in this study: (a) from failure occurrence until the pipeline is isolated for repair (i.e., C_O-C_F in Figure 1) and (b) from pipeline isolation until it is repaired and re-commissioned (i.e., C_O-C_D in Figure 1).

Failure consequence in the first sequential stage is the reduction in system pressure due to energy loss from the failure. Only after the problem is detected and located is the pipeline isolated for repair by closing the isolation valves nearest to either side of the failure location.

In order to assess the failure consequence in this first stage (C_j), orifice flows at the center of pipelines are simulated in this study. Discharge through orifice nodes, calculated using Greely's formula shown in Equation (8), are used to estimate the resulting steady-state pressure heads at all the WDN nodes through integration of EPANET with the pressure-driven simulation model that is characterized by Equations (9)–(11) (Gupta & Bhave 1996). This integration is accomplished through the use of EPANET toolkit (Rossman 2000) in visual basic for applications interface of Microsoft Excel. The actual nodal flows in failed state ($Q_{i,j}$) are estimated using the following iterative steps: (1) nodal heads (H^{act}) are estimated using EPANET; (2) actual nodal demands (Q) are calculated based on the estimated H^{act} using Equations (9)–(11); (3) adjusted H^{act} is calculated for each node based on the calculated nodal demand (Q) using EPANET; and (4) convergence of H^{act} is checked and steps 2 and 3 are repeated until ΔH^{act} is negligibly small. Failure consequences from the resulting WDN node heads are calculated using Equation (12).

$$Q_0 = 30.394 * \mathrm{A} * \sqrt{\mathrm{H}} \tag{8}$$

where Q_0 is the orifice flow rate in gpm; A is the cross-sectional area of the break in square inches (1 inch = 25.4 mm), which is considered to be the same as the pipeline's cross-sectional area; and H is the node pressure in psi.

$$Q_{i,j} = \begin{cases} 0 & \text{if} \quad H_i^{act} < H_i^{\min} \\ Qr_i \times DSR & \text{if} \quad H_i^{\min} \le H_i^{act} \le H_i^{des} \\ Qr_i & \text{if} \quad H_i^{act} > H_i^{des} \end{cases} \tag{9}$$

where $Q_{i,j}$ is the actual flow supplied at node i when pipeline j has failed; Qr_i is the required flow at node i of the WDN; H^{min} is the minimum node head; H^{des} is the desired node head; H^{act} is the actual node head; DSR is a demand satisfaction ratio which denotes the percentage of satisfied demand (Bhave 1981; Germanopoulos 1985; Wagner *et al.* 1988; Fujiwara & Li 1998; Tucciarelli *et al.* 1999; Tanyimboh & Templeman 2010).

H_i^{des} and DSR can be calculated using Equations (10) and (11) (Gupta & Bhave 1996; Fujiwara & Li 1998):

$$H_i^{des} = H_i^{min} + K_i \left(Q_i^{req}\right)^n \tag{10}$$

$$DSR = \frac{\left(H_i^{act} - H_i^{min}\right)^2 \left(3H_i^{des} - 2H_i^{act} - H_i^{min}\right)}{\left(H_i^{des} - H_i^{min}\right)^3} \tag{11}$$

where $\mathrm{K_i}$ is an empirical resistance factor for node i, taken in this study as 0.1 $\mathrm{min^2/m^5}$ for all nodes; and n is an exponent which is taken as 2 in this study (Gupta & Bhave 1996).

$$C_j = \frac{\sum_{i=1}^{NN} Qr_i - \sum_{i=1}^{NN} Q_{i,j}}{\sum_{i=1}^{NN} Qr_i} \tag{12}$$

where C_j is the estimated failure consequence of pipeline j before it is isolated; and NN is the total number of nodes in the WDN. It should be noted that C_j is a metric that ranges between 0 and 1, and represents C_O-C_F in Figure 1.

Consequences of water pipeline failure in the second sequential stage include possible system-wide pressure reduction and supply outages. These consequences (C'_j) are estimated following the same procedure described for C_j using Equation (4), except there are no simulated orifice flows but instead failed pipelines are isolated using the same integrated EPANET and pressure-driven simulation model used for estimating $\mathrm{C_j}$. Similar to C_j, C'_j is a metric that ranges between 0 and 1, and represents C_O-C_D in Figure 1.

Response time

A water utility's response to a pipeline failure begins with detection, followed by repair. Pipeline failures could be detected from an unusual pressure drop at the supply source as well as at other locations in the WDN where pressure is continuously monitored. Otherwise, it is only realized when the effects are felt above the ground in the form of water flooding streets, sidewalks, or even houses. Upon realizing the presence of a failure and detecting its location, water utility crews isolate the failed component for repair work. Minimizing the time between the break occurrence and its isolation (i.e., T_D-T_F), referred to as detection time (*TD*) in this study, is critical because much energy is wasted through pressure loss in addition to significant amounts of water losses. Repair work begins after the failed section has been isolated. Emergency pipeline repairs could take a few hours to days depending on location, site access, failure severity, soil cover depth, pipe material, pipe diameter, surrounding utilities, and soil conditions. Minimizing the time between isolation of a failed section and completing the repair (i.e., T_R-T_D), referred to as repair time (*TR*) in this study, is also crucial because closing of a WDN section for repair may lead to supply outages at several critical locations in the WDN, in addition to traffic-related woes. Both *TD* and *TR* are estimated in this study to range between 0 and 1, and together they epitomize the response time of a water utility to pipeline failure.

Figure 2 illustrates the effect of response time on the resilience of WDNs against pipeline failures. It can be observed from Figure 2 that the system, after failing, is brought back to its original performance level by time 'T_{R1}' in Scenario 1, whereas it has taken more time, 'T_{R2}', in Scenario 2. It is clear that the loss of resilience in Scenario 2 is greater and can be attributed to the difference in the response time.

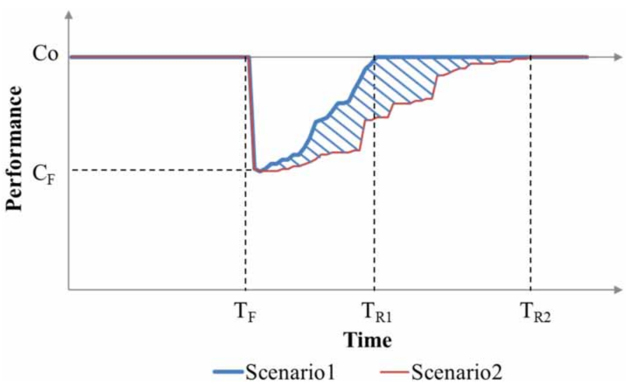

Figure 2 | Depiction of the effect of response time on WDN resilience.

Although there have been several previous studies on pipeline failures, a majority of them focused on leveraging past failure knowledge for predicting future failures. To the best knowledge of the authors, there is no evidence of previous attempts to model water utilities' response time to pipeline failures. A majority of previous studies on rehabilitation prioritization therefore implicitly made a contestable assumption that response time is uniform for all pipelines. In fact, the detection (*TD*) and repair (*TR*) times of failed pipelines depend on several factors that are identified in Figure 3. *TD* and *TR* parameters are estimated separately in this study using analytical hierarchy process (AHP), considering the factors identified in Figure 3.

As can be seen from Figure 3, detection time (*TD*) is considered to be dependent on four factors, namely, frequency (D_{11}) and type (D_{12}) of monitoring administered by the water utility, techniques used for precisely locating failures (D_{21}), and the expertise of inspecting field crews (D_{22}). Table 1 presents the criteria developed in this study for rating these four factors for a given pipeline on a scale of 0.1 to 1. The rating scale is chosen in such a way that *TD* when calculated will range between 0 and 1. Rating criteria for different categories of these four factors are devised, as shown in Table 1, based on the influence of individual categories on *TD*. For example, the frequency of monitoring (D_{11}) factor is classified into 'passive,' 'periodic,' and 'continuous' categories with corresponding ratings of 1, 0.55, and 0.1. The smaller the rating, the sooner a failure is detected. Passive monitoring refers to the practice where pipelines are not proactively monitored but only assessed upon a failure. Periodic monitoring refers to the practice where pipelines are monitored periodically (e.g., annually). Continuous monitoring refers to the practice where pipelines are continuously monitored, for example, using smart sensor networks that are embedded in WDNs. Continuous monitoring of WDNs will enable water utilities to detect failures as soon as they occur and, therefore, reduce the detection time. Similarly, periodic monitoring is better than passive monitoring. Passive, and periodic monitoring to some extent, are common practices followed by water utilities. It should be noted that ratings of 0.1, 0.55, and 1 are given to the D_{11} factor only based on the

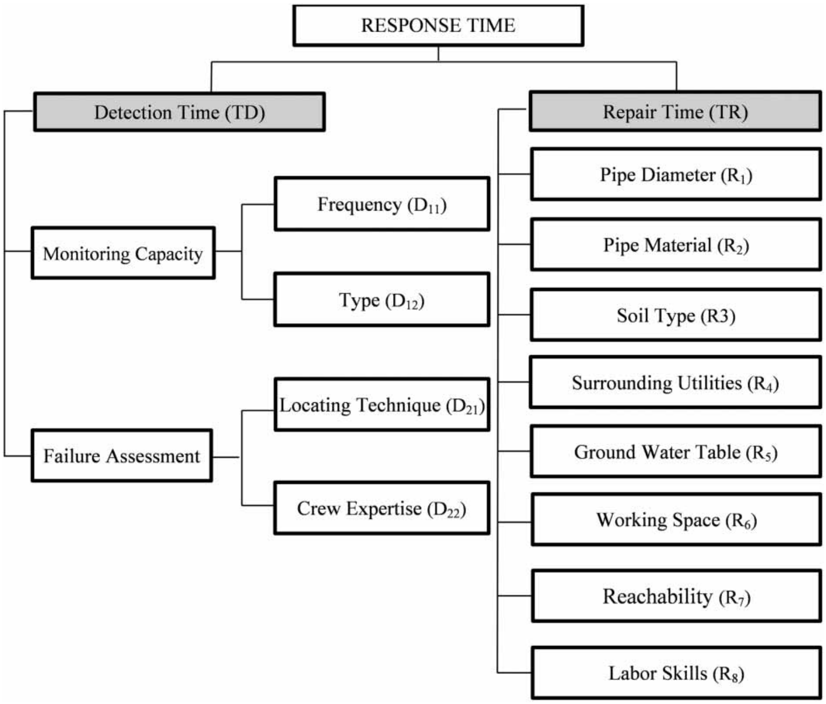

Figure 3 | Factors influencing response time to main breaks.

Table 1 | Proposed rules for rating detection time factors

Sub-time factors	Rating justifications	Rating	Explanations
Monitoring strategy	Frequency (D_{11})	1	Passive: Pipelines are inspected after any incidents
		0.55	Periodic: Pipelines are inspected periodically
		0.1	Continuous: Pipelines are continuously monitored
	Type (D_{12})	1	Non-mechanical inspection: Visual observations made after an incident
		0.55	Mechanical inspection: inspection done using temporary acoustic or other techniques usually after a suspicion
		0.1	Sensors: Robust embedded sensor networks
Failure assessment	Locating technique (D_{21})	1	Visual: Visual observation for failure locating and assessment
		0.55	*Ad hoc*: Hardware used for failure locating and assessment
		0.1	Online: Locating and assessing failures data from embedded sensing systems
	Crew expertise (D_{22})	1	1–3 years of experience
		0.55	3–6 years of experience
		0.1	6 or more years of experience

relative influence of different D_{11} categories on TD and not their absolute influence. Ratings based on their proportional absolute influence will require further empirical research in the future. Similarly, categories and corresponding rating criteria for the other three factors, namely, D_{12}, D_{21}, and D_{22}, are formulated and presented in Table 1.

As seen in Figure 3, repair time (TR) is considered to be dependent on several factors, such as pipeline diameter (R_1), pipeline material (R_2), type of soil (R_3), presence of surrounding utilities (R_4), ground water table (R_5), working space (R_6), reachability of the work site (R_7), and labor skills (R_8). Larger diameter pipelines are expected to take a longer time for repair than smaller diameter pipelines (Hartley 2013). R_1 is classified into three categories and ratings assigned accordingly, as shown in Table 2. Concrete pipes were reported to have taken more time for repair followed by metal pipes and then plastic pipes (Bueno 2010); rating criteria R_2 factor is accordingly formulated and presented in Table 2. Rating criteria for R_3, R_5, R_7, and R_8 factors are appropriately formulated based on evidence from the literature (Doloi *et al.* 2012; Weir & Cullen 2014), whereas rating criteria for R_4 and R_6 are intuitively formulated, as shown in Table 2.

Once all the factors that affect *TD* and *TR* of water pipeline failures were categorized and the respective rating criteria formulated, their relative influence on *TD* and *TR* was investigated using AHP based on survey responses of water utility professionals in the USA. A survey comprising 37 questions was sent to several water utility professionals (mostly public water utility operators) that are spread over the 50 states in the USA. The survey asked respondents to rate the pair-wise relative importance of all the factors that affect *TD* and *TR*, respectively. The following seven-point scale was used in the survey for pair-wise comparisons: (a) significantly less important – [importance ratio of 1/3], (b) less important – [1/2], (c) somewhat less important – [2/3], (d) equally important – [1], (e) somewhat more important – [1.5], (f) more important – [2], and (g) significantly more important – [3]. Forty responses were received from water utility professionals spread over 30 different states. All responses have been synthesized in order to calculate the average pair-wise comparison of the influence of different factors on *TD* and *TR*. Thereafter, relative weightings of all the factors were calculated using AHP, and presented in Figure 4. The sum of weightings will add up to 100% for each hierarchical level, as can be observed from Figure 4.

The calculated weightings of individual factors, along with their respective numerical ratings, are used to estimate *TD* and *TR* as per Equations (13) and (14):

$$TD_j = \left\{ \left[\sum_{i=1}^{2} (RD_{1i} * \mathrm{WD}_{1i}) \right] * \mathrm{WD}_1 + \left[\sum_{k=1}^{2} (RD_{2k} * \mathrm{WD}_{2k}) \right] * \mathrm{WD}_2 \right\} * \mathrm{WD} \quad (13)$$

Table 2 | Proposed rules for rating repair time factors

Rating justifications	Rating	Explanations
Pipe diameter (R_1)	1	>24 inches*
	0.55	>8 inches and ≤24 inches
	0.1	≤8 inches
Pipe material (R_2)	1	Concrete pipe
	0.55	Metal pipe
	0.1	Plastic pipe
Soil type (R_3)	1	Calcarenite
	0.55	Sandy and clay mixed facies
	0.1	Sandy facies
Surrounding utilities (R_4)	1	More than one surrounding utility located within a radius of three pipe diameters
	0.55	Only one surrounding utility is located within a radius of three pipe diameters
	0.1	No surrounding utility is located within a radius of three pipe diameters
Ground water table (R_5)	1	Ground water table is higher than the location of the failed pipe
	0.1	Ground water table is lower than the location of the failed pipe
Working space (R_6)	1	Freeway or arterial road
	0.55	Collector or local road
	0.1	Non-paved road
Reachability of work site (R_7)	1	It takes 2 or more hours to transport required labor, equipment, and materials to work site
	0.55	It takes between 1 and 2 hours to transport required labor, equipment, and materials to work site
	0.1	It takes less than 1 hour to transport required labor, equipment, and materials to work site
Labor skill (R_8)	1	0–1 years of experience
	0.55	1–5 years of experience
	0.1	5 or more years of experience

*1 inch = 25.4 mm.

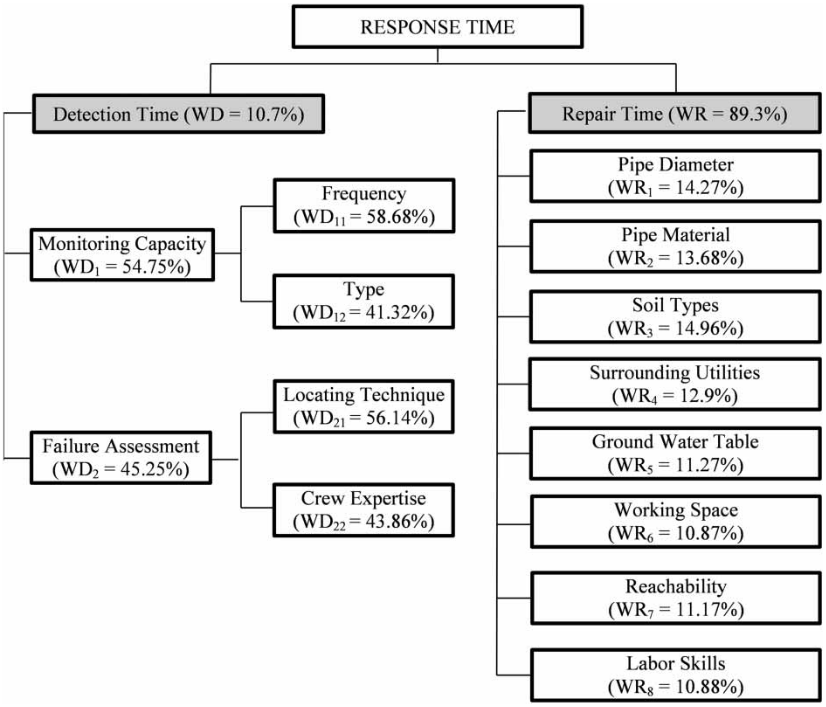

Figure 4 | Relative weightings for factors influencing response time to main breaks.

$$TR_j = \left[\sum_{m=1}^{8}(RR_m{*}\mathrm{WR_m})\right]{*}\mathrm{WR} \tag{14}$$

where RD_{1i} and RD_{2k} are ratings (i.e., 0.1, 0.55, or 1) given to factors that influence TD; RR_m is a rating given to factors that influence TR; WD and WR are weightings of TD and TR, respectively, as shown in Figure 4; WD_1, WD_2, WD_{1i}, and WD_{2k} are weightings of D_1, D_2, D_{1i}, and D_{2k} factors as shown in Figure 4; WR_m is a weighting of the R_m factor as shown in Figure 4.

Resilience-based prioritization

In order to rehabilitate pipelines, it is important to accurately prioritize them based on their criticality. In this paper, a resilience-based prioritization scheme is proposed in which criticality is assessed based on WDN resilience to each pipeline failing (R_j). R_j is calculated using Equation (15), which is a reformed version of Equation (1). Failure probability, consequences, and response time parameters used in Equation (15) are estimated using the formulations presented in the preceding paragraphs in this section:

$$R_j = 1 + \frac{1}{\log \frac{P_j{*}\left[\left(C_j{*}TD_j\right) + \left(C'_j{*}TR_j\right)\right]}{10}} \tag{15}$$

where R_j is the WDN resilience against failure of pipeline j; P_j is the failure probability of pipeline j; C_j is an estimated failure consequence of a pipeline before it is isolated for repair; C'_j is the estimated failure consequence of a pipeline after it is isolated for repair; TD_j is an indicator of the failure detection time of pipeline j; and TR_j is an indicator of the estimated repair time of pipeline j.

DEMONSTRATION OF THE PRIORITIZATION FRAMEWORK

The proposed resilience-based prioritization framework is demonstrated in this study using a slightly modified section of a large WDN that serves a coastal city in the USA. The

WDN section used for demonstration, hereafter referred to as CWDN, consists of 53 nodes and 72 pipelines with lengths ranging from 25 feet to 800 feet. The physical pipeline layout of CWDN was obtained in geographic information system (GIS) format from the public water utility that manages water supply in the region. Appropriate boundary conditions for CWDN are modeled by adding one pump connected to a reservoir, as shown in Figure 5. Figures 6–8 illustrate the distribution of pipe material, diameter, and soil type measured by length of CWDN pipelines, respectively. P_j is calculated using Equation (5) based on records of previous failures in CWDN, which are summarized in Table 3. A representative hydraulic model is developed for CWDN using EPANET, which is later integrated with the pressure-demand relationships characterized in Equations (9)–(11), for simulating failed states in order to assess the consequences (C_j and C'_j) as per Equations (4) and (12). The placement of isolation valves in CWDN has been taken into consideration while estimating the failure consequences. Of the total 72 CWDN pipelines, 63 are equipped with isolation valves that will enable their individual isolation for repair in case of a failure event. The isolation of the remaining nine pipelines would result in the closure of additional pipelines due to the way the isolation valves are placed. The estimated C_j of CWDN pipelines ranged from 0.27 to 1, whereas the upper limit of $C_j^{'}$ was 0.4.

Out of the 12 factors listed in Figure 3 that influence *TD* and *TR*, R_1, R_2, and R_3 are rated, as per Table 2, based on available GIS data for CWDN. Ratings for D_{11}, D_{12}, and D_{21} are considered to be dependent on pipe sizes, an assumption that is consistent with most common asset management practices. Pipes less than 24 inches in diameter are considered to be 'passively' monitored using 'visual' techniques for failure detection and location. Pipes with a diameter greater than 24 inches are considered to be 'periodically' monitored using ad hoc techniques for failure detection and location. R_5 was given a rating of 0.1 for all pipelines, as per Table 2, because the ground water level in the CWDN region is in the range of 5 to 15 feet (Walter 1971) and the typical soil cover depth for CWDN pipelines is only about 4 feet. R_6 and R_7 factors are rated, as per Table 2, based on road types and distances of respective pipelines from the water utility office location.

Due to the lack of available data, ratings for the remaining three factors, namely, D_{22}, R_4, and R_8, are simulated using the Monte Carlo technique. One hundred simulations were carried out using random ratings for these three factors (i.e., D_{22}, R_4, and R_8) and estimated ratings for the other

Figure 5 | CWDN test bed used for demonstration.

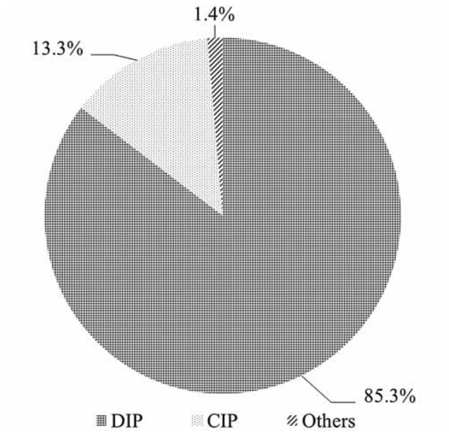

Figure 6 | Distribution of CWDN pipe material by length.

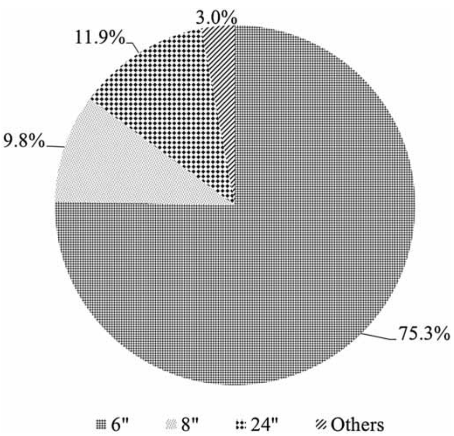

Figure 7 | Distribution of CWDN pipe diameter by length (1 inch = 25.4 mm).

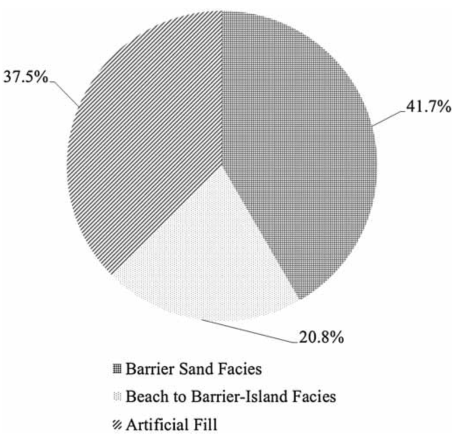

Figure 8 | Distribution of soil type in CWDN region by pipeline length.

Table 3 | Synthesis of past break data for CWDN pipelines

Type of pipe	Diameter (inches)*	Type of soil	Break rate (#/mi/year)
CIP	≤ 6	Artificial fill	0.12
		Beach to barrier-island facies	0.73
		Barrier sand facies	0.50
	8	Artificial fill	0.32
		Clayey sand and clay facies	26.40
		Barrier sand facies	0.34
	10	Barrier sand facies	0.74
	12	Artificial fill	1.75
		Beach to barrier-island facies	0.84
		Barrier sand facies	0.20
	16	Barrier sand facies	0.20
DIP	≤ 6	Artificial fill	0.26
		Beach to barrier-island Facies	0.81
		Barrier sand facies	0.19
	8	Artificial fill	0.20
		Beach to barrier-island facies	0.30
		Barrier sand facies	0.12
	10	Barrier sand facies	0.15
	12	Artificial fill	0.06
		Beach to barrier-island facies	0.33
		Barrier sand facies	0.02
	16	Artificial fill	0.13
		Beach to barrier-island facies	0.45
		Barrier sand facies	0.10
	24	Artificial fill	0.35
		Beach to barrier-island facies	1.28
		Barrier sand facies	0.15

*1 inch = 25.4 mm.

nine factors are discussed in the preceding paragraph. The resultant TD_j and TR_j are combined with P_j, C_j, and C'_j of the respective CWDN pipelines using Equation (15) to obtain resilience values (R_j) and subsequent priority rankings. The pipeline corresponding to the least CWDN resilience is given the highest priority for rehabilitation.

The calculated resilience of CWDN against singular failures of its pipelines varied from 0.76 to 0.86 over the 100 simulations. It turned out that the pipeline corresponding to the least resilience value has the highest values of estimated consequences (C_j and C'_j) and repair time (TR_j). The highest consequence is because the least resilient pipeline is a water main of 24-inch diameter. The highest repair time is due to the fact that this large diameter pipeline is buried within the freeway right-of-way, making it take a longer time to repair. Additionally, three specific pipelines stood out with significantly lower resilience values compared to others, which is mainly due to their higher failure consequences (C_j and C_j') and repair time (*TR*). These initial observations suggested that failure consequences may have greatly influenced resilience values. In order to evaluate the overall correlation between the individual parameters (i.e., P_j, C_j, C'_j, TD_j, and TR_j) and resilience (R_j), a pair-wise comparison metric *h(R, E)* is formulated, as shown in Equations (16)–(19), and used.

$$R_{i,j} = \begin{cases} i, & \text{if} \quad R_i < R_j \\ j, & \text{if} \quad R_i > R_j \\ i, & \text{if} \quad R_i = R_j \quad \text{and} \quad i \leq j \\ j, & \text{if} \quad R_i = R_j \quad \text{and} \quad i > j \end{cases} \tag{16}$$

$$E_{i,j} = \begin{cases} j, & \text{if} \quad E_i < E_j \\ i, & \text{if} \quad E_i > E_j \\ j, & \text{if} \quad E_i = E_j \quad \text{and} \quad i \leq j \\ i, & \text{if} \quad E_i = E_j \quad \text{and} \quad i > j \end{cases} \tag{17}$$

$$g(R_{i,j},\ E_{i,j}) = \begin{cases} 0, & \text{if} \quad R_{i,j} = E_{i,j} \\ 1, & \text{if} \quad R_{i,j} \neq E_{i,j} \\ 0, & \text{if} \quad i = j \end{cases} \tag{18}$$

$$h(R,\ E) = \frac{\sum_{i=1}^{l} \sum_{j=1}^{l} g(R_{i,j},\ E_{i,j})}{l*(1-1)} \times 100\% \tag{19}$$

where $R_{i,j}$ is the pair-wise comparison of CWDN resilience against failures of pipelines *i* and *j*; $E_{i,j}$ is the pair-wise comparison of different parameters (i.e., '*E*' can be P_j, C_j, C'_j, TD_j, or TR_j) for pipelines *i* and *j*; $g(R_{i,j}, E_{i,j})$ is a metric indicating the change in pair-wise comparison of pipelines *i* and *j* between resilience and any of the other parameters; *h(R, E)* is the percent change in pair-wise comparisons over all possible pairs of pipelines (i, j); *l* is the number of pipelines in the network.

The calculated *h(R, E)* for all possible combinations of resilience and other parameters is illustrated in Figure 9. It can be seen from Figure 9 that resilience had the greatest correlation with P_j, with only about 9% change in pair-wise pipeline priorities, followed by *TR* with about 42% change. Upon further investigation, it was observed that

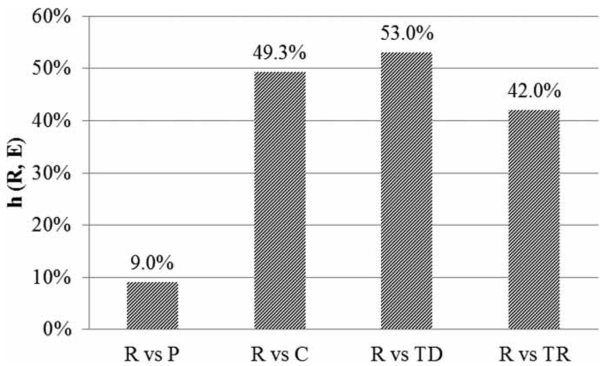

Figure 9 | Percent change in pair-wise relative rankings of resilience and other parameters.

higher correlation between R_j, and P_j is mainly due to the fact that several of the CWDN pipelines are smaller in diameter, which hints that their failure probability is greater and repair times shorter. The smaller variances of repair times are not sufficient to change the pair-wise priorities formed on the basis of failure probability. On the other hand, detection time can be seen to have the least correlation with resilience, as per Figure 9, which is due to its smaller variance across CWDN pipelines. The failure consequence post-isolation (*C*') was found to be negligible for 62 pipelines among the total of 72, because the actual node flow was close or equal to the required flow and as a result, *h(R, C')* was found to be close to zero.

The overall CWDN resilience calculated using Equation (2) is found to vary in a small range of 0.76 to 0.77 over the 100 simulations, with an average value of about 0.766.

COMPARING RISK- VS. RESILIENCE-BASED PRIORITIZATION

In this section, pipeline priorities based on resilience are compared with priorities obtained from a more traditional risk-based framework, where response time was not considered at all or at most considered as a constant, such as that presented by Studzinski & Pietrucha-Urbanik (2012), Kanta & Brumbelow (2013), Yoo *et al.* (2014), and Laucelli & Giustolisi (2014). The objective of this comparison is to evaluate the merits of considering response time in pipeline rehabilitation prioritization. Figure 10 illustrates the methodology employed for performing this comparative

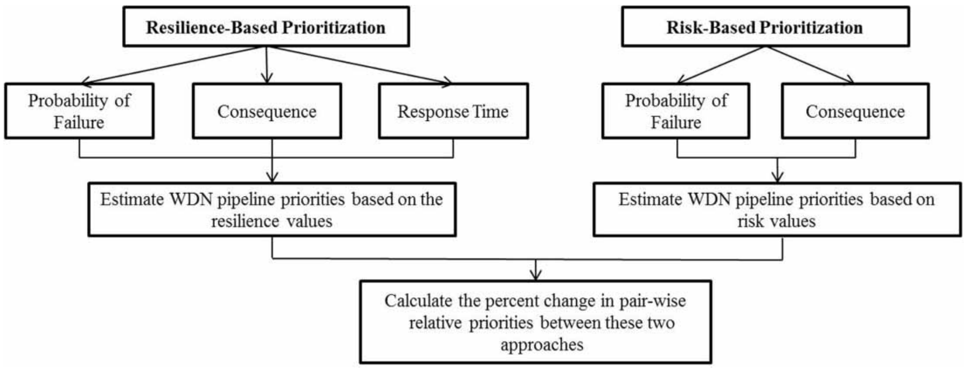

Figure 10 | Resilience- vs. risk-based prioritization comparison methodology.

analysis. In a risk-based approach, pipelines are prioritized based on failure risk calculated using Equation (20).

$$R'_j = P_j * C'_j \tag{20}$$

where P_j is the failure probability of pipeline j; and C'_j is the consequence of pipeline failure post its isolation for repair. Calculation procedures of P_j and C'_j are discussed in the section 'Resilience-based prioritization framework'.

For each of the 100 simulations performed for estimating *TD* and *TR*, CWDN pipelines are prioritized in the increasing order of system resilience against respective pipeline failures, resulting in 100 sets of priority rankings. CWDN pipelines are also prioritized using the risk-based approach based on Equation (20) to obtain one set of priority rankings. The 100 sets of priorities from the resilience-based approach are compared with priorities from the risk-based approach by employing the percent change metric *h (R, R')*, calculated using Equations (16)–(19). The overall percent change is in the range of 7.9 to 10.4%, with an average of about 9.2% over the 100 simulations. The observed percent change in pair-wise priorities from risk to resilience-based methods is, for the most part, due to the greater repair time (TR_j) of large diameter pipelines that are buried within the freeway right-of-way, compared to other pipelines. Although failure consequences of large diameter pipelines are significant, their failure probability is much less compared to several other pipelines in the CWDN. Consequently, the large diameter pipelines (four in number in CWDN's case) were found to be ranked between 10 and 25 in the risk-based approach, whereas they were ranked between 4 and 8 in the resilience-based approach. Twelve out of 100 simulations for resilience-based prioritization yielded a different pipeline for the most critical selection compared to the risk-based method, as can be seen from Figure 11. It was observed in those 12 simulations that greater values of detection (TD_j) and repair times (TR_j) made the difference. From these comparative analyses, it can be observed that both *TD* and *TR* affected the pipeline criticalities for rehabilitation prioritization. Similarly, the average percent change in pair-wise priorities for the top three, five, seven, and 10 critical pipelines from the risk-based method are about 15.3, 13.6, 13.2, and 16% compared to the resilience-based method, as illustrated in Figure 11. These changes too can be attributed to detection time (TD_j) in the case of several pipelines and repair time (TR_j) for large diameter pipelines that are buried within the freeway right-of-way. It can be seen from these results that consideration of detection and repair times as part of the resilience framework did have a reasonable impact on CWDN pipeline priorities.

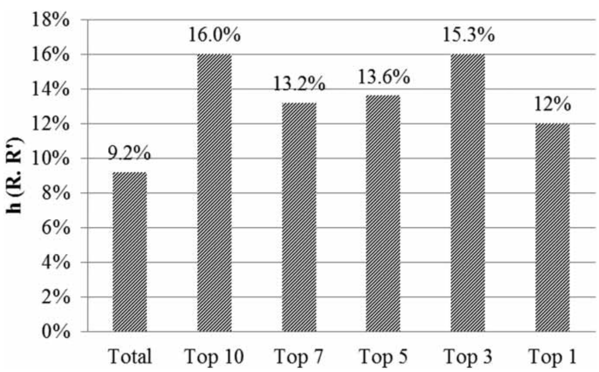

Figure 11 | Average percentage change in pair-wise priorities of CWDN's critical pipelines.

Upon further investigation of the results, it was observed that some time factors were largely uniform across CWDN, thereby contributing little to the variation in detection and repair times. For example, the criteria of *pipe size less than, equal to, or greater than 24 inches in diameter* influences four of the twelve time factors, namely D_{11}, D_{12}, D_{21}, and R_1, and it was observed that 85.1% of CWDN pipelines fall in the 'pipe size less than 24 inches' category. Similarly, 98.6, 100, 100, and 100% of CWDN pipelines fall in the 'metal' – (R_2), 'sandy facies' – (R_3), 'above ground water table' – (R_5), and 'less than one mile from water utility location' – (R_7) categories, respectively (1 mile = 1.609 km). CWDN is a small 72-pipeline section considered for demonstrating the proposed approach in this study, and it definitely lacks the kind of variation in pipe material, soil type, and accessibility that is usually observed in a typical large-scale WDN. Clearly, the percent change, $h\ (R, R')$, would have been greater in a large-scale WDN, thereby highlighting the greater significance of incorporating response time into prioritization schemes.

It is also suggested in this study that WDN resilience can be enhanced by not only improving the physical infrastructure but also the ability of a utility operator to respond quickly to a failed pipeline. The cost–benefit analyses of such improvements should be investigated in the future using a robust optimization algorithm.

CONCLUSIONS AND RECOMMENDATIONS

WDNs are currently in need of immediate attention in the form of technological innovation, financial resources, and planning and management tools. This study presents a resilience-based prioritization approach for pipeline rehabilitation planning. Resilience is quantified in this study as a combination of estimated failure probability, failure consequences, and failure response time. To the best knowledge of the authors, there have not been any previous studies that explicitly considered response time in the evaluation of pipeline failure risk. Utility response time is estimated in this study based on the outcomes of a survey on several factors that influence both failure detection and repair times. A section of a large WDN with about 4.35 miles of pipeline is used to demonstrate the proposed resilience-based prioritization approach. The WDN used for demonstration contained ductile iron and cast iron pipe materials for the most part, and has diameters ranging from 4 inches to 24 inches. WDN pipelines are prioritized in the increasing order of their resilience values, and the overall system resilience for the demonstrative WDN was calculated to be 0.766.

The results from the resilience-based prioritization framework are compared with those obtained from a more traditional risk-based approach to evaluate the merits of incorporating response time. A relative pair-wise comparison metric was employed for a meaningful comparison of pipeline priorities from resilience- and risk-based approaches. The comparison revealed that the average percent change in relative pipeline priorities for the top one, three, five, seven, and 10 critical pipelines from the risk-based approach are about 12, 15.3, 13.6, 13.2, and 16% when compared to the resilience-based approach. With an overall average percent change in pair-wise relative rankings of 9.2%, the comparison highlighted reasonably significant differences in pipeline priorities. This overall percent change is expected to be higher in the case of a large-scale WDN, highlighting the greater significance of incorporating response time into prioritization schemes. It needs to be further investigated as to what set of rehabilitation actions will result in the greatest increase in WDN resilience as defined in this study. An optimization algorithm subjected to budget constraints needs to be developed and used in the future for effective rehabilitation decision-making. A more practical way of rating the detection time and repair time factors may also be pursued in the future for enabling easier adoption of the proposed approach by water utilities.

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