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Assessment of Resilience of Water Distribution Network against Seismic Hazards for Maintenance Planning

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Abstract: It is essential that water distribution networks (WDNs) remain performing undeviatingly following constrained to natural hazards, and it is considered vital in terms of seismic hazards, to keep maintaining structural integrity. Several studies on past earthquakes occurred in Vancouver, BC, have prompted notable destruction to WDNs, interpreting them as a potential reason for loss and damage from structural and economic perspective. Based on the behavior of underground water distribution pipelines, this paper suggests a method to quantify resiliency as easy-to-use metrics to improve the performance of water distribution network subjected to earthquakes. In cities like Vancouver, WDNs are prone to seismic hazards and are subject to regular refurbishment and repair. Following such circumstances, early evaluation of existing network's seismic structural resilience is essential to carry out strategic planning for maintenance and replacement works. In this paper, resilience index is produced for the WDN of the study area (an extensive network consisting of 62,293 links) considering three scenarios of earthquakes ranging between MMI 7 to MMI 10 (very strong to severe). These scenarios are formed using empirical data of past earthquakes, which includes ground motion and break rates of lifelines and the estimated peak ground acceleration (PGA). All the neighborhoods in the study area are ranked from most resilient to least resilient based on index metrics. Maintenance scenarios for the least resilient neighborhood due to the extreme exposure of the event have been produced as maintenance map to improve the resiliency of the system, integrated with the geographical location using software ArcGIS. To build a practical and feasible replacement strategy, 10 maintenance planning with network map is created showing an increase ranges from 0.8% to 41.52% in the total resiliency of the network and an estimated 15.17% to 89.96% increase of the invulnerability in the network mains. Taking cost as a vital limiting agent in the replacement of WDNs, afterward, evaluation of robust replacement alternatives are performed to find out maintenance planning strategy.

1. Introduction [3] [6]

Water distribution networks (WDNs) transfer water from reservoirs to industrial, commercial, and residential users throughout complex pipe arrangements. Following a hazard incident, it is helpful that WSNs remain to perform adequately to aid rescue and recovery processes. Past quakes in Canada including Charlevoix–Kamouraska, Quebec (Magnitude:7.9Mw, 1663), Vancouver, British Columbia (Magnitude: 7.2 Mw, 1918), Queen Charlotte Islands, BC (Mag. 7.0Mw, 1929), Baffin Bay (Mag. 7.7Mw, 1933), Vancouver Island, BC (Mag. 7.5Mw,1946),Central Canada (Mag.. 5.0 Mw, 2010) West of Vancouver Island, BC (Mag. 6.1Mw, 2012), Haida Gwaii (Mag. 6.3Mw, non-destructive Tsunami and aftershock of 7.8 earthquakes 2012), Yukon (Mag. 6.0 Mw, 2014), West of Vancouver Island, BC (Mag. 6.5Mw, 2014), and Stikine Region, British

Columbia (Mag. 6.3 Mw, doublet earthquake, 2017) have caused severe damages to WDNs, revealing their vulnerabilities (Natural Resources Canada). For example, according to Bent, A. L. (2002), the Baffin Bay earthquake is known as the largest of northern Arctic Circle Bent, A. L. (2002). The Vancouver Island earthquake, 1918 took place at 4 centimeters (1.6 in) per year (Cassidy et. Al. 1988) that caused a damaged wharf in Ucluelet along with a lighthouse at Estevan that experienced a severe shaking that made a crack through an entire length of the 33-meter steel-reinforced concrete tower. Also, the glass lens was found completely shattered, declaring the lighthouse inoperable. Another earthquake occurred on January 26, 1700 – estimated M9, Cascadia Subduction Zone, off British Columbia which is described in oral history as one of the biggest shock that damaged a village located at Pachena Bay on the west coast of the island and left no survivors and the shaking reportedly destroyed houses and infrastructures of the Cowichan Lake region in south-central Vancouver Island (Natural Resources Canada). In 1949, an earthquake in Haida, Gwaii, British Columbia, was observed in the distant north as the Yukon Territory and as notably south as Oregon, U.S. Damage was considered low due to the scattered type of population distribution. Nevertheless, on Haida Gwaii, chimneys fell, and on the mainland, windows were reported shattered, and buildings were swayed. In all of the incidents, water distribution system failures were observed, and WDN failure triggered severe direct and indirect structural and monetary losses to the subject (Natural Resources Canada)

As per the latest infrastructure report card presented by the American Society of Civil Engineers (ASCE), water supply infrastructure performances obtains a grade D in the North America region, mentioning about old age and absence of funding as primary challenges (ASCE 2013). This capacity to withstand stresses is frequently associated with the concept of the resilience of a system considering the infrastructure susceptibility. Observing all these past incidents of seismic attacks, resilience is accepted as a significant concern throughout the planning and operation of WDNs, along with the maintenance and rehabilitation outlining (Piratla, K. R. 2015).

Despite some prior research on the interpretation and quantification of infrastructure resilience, real-world utilization of this concept on large WDNs are inadequate to find. There are very few previous frameworks of WDNs that have included all dimensions of infrastructure resilience into a readily applicable metric formulation. To inscribe these shortcomings, this paper integrates a new resilience metric and manifests its use in selecting cost-effective maintenance approaches for making WDNs further resilient to seismic hazards.

2. Literature Review

The idea of resilience has attained importance in numerous disciplines such as psychology, science, ecology, climate, economics, urban planning, and disaster management. Disaster management investigation in recent years has frequently focused on advancing the goal of reaching disaster- resilient cities. As a move towards this intention, Bruneau et al. (2003), introduced a conceptual framework to determine the resilience of communities in which they portrayed resilience as a union of four infrastructural attributes, particularly robustness, redundancy, resourcefulness, and rapidity.

Different former studies have directed on quantifying and improving the resilience of the built environment facing natural and anthropogenic risks, among which some mainly focused on WDNs. Those prior bits of knowledge on WDN resilience are shortly interpreted in this section by classifying them into hazard-independent (or random breakdowns) and seismic hazard-related studies.

2.1 WSN Resilience against Random Failures

Investigations concentrating on arbitrary failures portrayed resilience as a systemic attribute that is independent of any specific risk. Some of these researches quantified resilience as a degree of additional capacity usable in the system to repay for the damage of a physical component. For example, Todini (2000) established a resilience metric as a measure of extra power in the system and showed its use in the design of WDNs. Prasad and Park (2004) continued working on Todini’s metric by consolidating the consequence of reliable loops in extension to surplus power in determining network resilience index. Jayaram and Srinivasan (2008) recommended a remodeled resilience metric, which notionally masters the drawback of

Todini's (2000) resilience metric when assessing networks with multiple reservoirs. These three flow-based metrics were formed to help control the design of new WDNs, and therefore, may not be appropriate for rehabilitation outlining of already existing WDNs.

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Another approach of identifying resilience against arbitrary breakdowns is to represent resilience as the antonym of system vulnerability and measuring by estimating vulnerability for different attacks. [Base paper] Studies regarding this method generally relied on composite graph theory-based network models that imitate real infrastructures, wherein the WDN is drawn as a set of nodes (i.e., reservoirs, tanks, or demand locations) which are joined by links (i.e., pipelines), and resilience is subjected to the function of link and node connectivity. For example, Kessler et al. (1990) used two metrics of link and node connectivity to measure the least number of attacks or breakdowns required to separate a group of nodes from their source. Yazdani and Jeffrey (2010) proposed another graph theory-based metrics and conducted thorough resilience investigation of a few benchmark WDNs corresponding to random and targeted attacks. Yazdani et al. (2011) employed the identical kind of metrics to explore network extension approaches and showed their application on the WDN of Kumasi, Ghana. Although graph theory-based metrics drastically decrease the computational period of resilience analysis, there are no sufficient studies where element failure likelihoods are placidly integrated with the graph theory metrics that consolidates with the magnitude of the individual event for easy applicability to system-level considering seismic activities.

2.2 Resilience against Seismic Failures

Bruneau et al. (2003) idealized seismic resilience as the capacity of both mechanical and social arrangements to endure seismic forces and survive with resulting consequences. They exhibited computable metrics of WDN resilience corresponding to decreased failure probabilities, lessened consequences, and reduced time to recovery. Chang and Shinozuka (2004) adopted this idea of resilience metrics and described their usefulness helping to mitigate the seismic consequences of a WDN in Memphis, TN. Some other thoughts regarding seismic resilience proposed the term of seismic risk discuss use of frameworks and associated reliability (Fragiadakis et al. 2013; Fragiadakis and Christodoulou 2014) to the risk.

Numerous other investigations approached by appraising the losses to commercial and residential water consumers of one of the prime water distribution systems of the San Francisco Bay Area from two inherent earthquakes. One is of a 7.9-moment magnitude (MW) quake on the San Andreas Fault and the other one of a 7.1MW earthquake on the Hayward Fault. Romero et al. (2010) exhibited the outputs of an inclusive simulation operation offered to determine the Los Angeles WDN functionality to an earthquake of magnitude 7.8 MW on the San Andreas Fault. Although there have been some former researches that endeavored to quantify the seismic resilience of WDNs, very few are offered with an easy and practical resilience enumerating method along with a computational frame to serve decision makers in system-level, facility suppliers in the operational-level and contributes to the capital advancement planning.

3. Demonstration of Study Area

The metric defined by Eq. (1) is utilized to quantify seismic resilience of the WDN allocating the Vancouver region of British Columbia, Canada. The Vancouver water distribution network hereafter mentioned to as VWDN is represented in Figure: 1, is a notably extensive network spread over a 114.97 km2 (44.39 sq. mi) of land to serve about 631,486 consumers (Water Utility Report, Vancouver 2017). Of the 1,488 km of water mains in the City, transmission mains, larger than 300 mm in diameter, account for ~5.0% of the total system length. In this study, water distribution lines accounting for rest 95% of the system length (about 1414 km) was considered and out of this 1414 km, an estimation of seismic resilience is carried out for total 1391.5 km of length with available data on pipeline properties and location.

VWDN consists of 62,293 individual pipe links and the pipelines range in diameters from 20 mm to 300 mm and are made of different materials such as cast iron pipe (CIP); ductile iron pipe (DIP); Copper, Poly-Vinyl Chloride (PVC), High-density Polyethylene (HDPE), and Galvanized Steel, as illustrated in Figure: 2. Earlier breakage information of VWDN pipelines is employed to designate the current health of the system. In West Vancouver CIP installed since 1951 has undergone a significant number of breaks during a period of 26 years (from 1983 to 2008). The pipelines have undergone between 9 and 16 breaks/km which is comparable to one break in every 1.5 to 2.5 years. Additionally, pipes established in specific years, such as 1955 and 1963, is reported to experience an exceptionally high number of breaks/km (District of West Vancouver Water Infrastructure Long Range Capital Renewal Forecast, 2010). However, in 2017, units acknowledged and responded to 100 water main breaks in West Vancouver (Water Utility Report, Vancouver 2017).

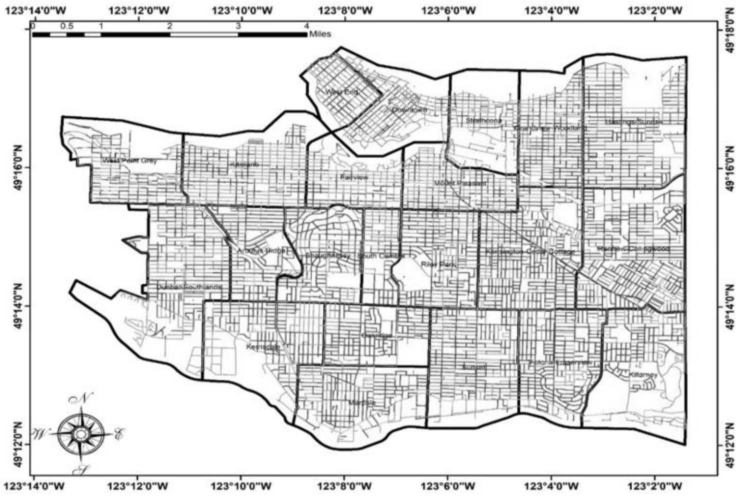

Figure: 1. Layout of the water supply network in the Vancouver, BC

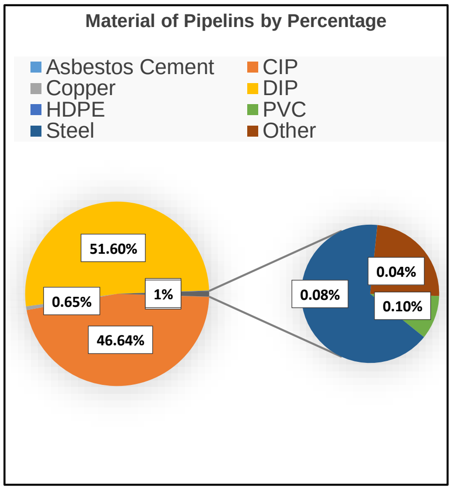

Figure: 2. Percentage distribution of supply pipe by material

4. Methodology for Estimating and Enhancing Seismic Resilience

A readily useful resilience metric for WDNs has been offered in this study. This metric unites robustness due to specific hazard with the redundancy dimensions corresponding to the system. The recommended metric can be readily applied for quantifying and magnifying the resilience of water distribution system with nominal computing demand.

The suggested resilience metric quantifies pipeline reinforcement as strengthening the resiliency in the conventional node-link formulation. The quantified degree is calculated as the sum of expected resilience of all the connected links. The magnitude of the specific hazard is scored as a weight to each link of the distribution network and later multiplied with the likelihood of the failure to find expected risk to prioritize pipelines with higher vulnerability. Finally, the weighted and modified node-degree method is formulated with a normalized value of resilience, perceived as an index number. The following expected risk:

[1] Expected Risk, E (W) = $\sum_{i=1}^{N_i} W_i . Pf_i$

Where, W_i = magnitude of vulnerability and Pf_i = the likelihood of failure which leads to expected risk E (W) and following resilience metric:

[2] Expected Resiliency, E (R) = 1 - $\frac{\sum_{i=1}^{N_n} W_i . Pf_i}{\sum_{i=1}^{n} J_i}$

Where E(R) is denoted as the expected resiliency, N_n = total number of links; Pf_i = failure probability of link J_i. The lower boundary of R is 0.0, which is found when Pf_i is obtained 1 for all pipelines in the network. The theoretical upper limit of E (R) will be maximum which is 1, when Pf_i is 0 for all links in the WDN, and the value is expected to be less than 1 for the most of the observations depending on the intensity of the hazard (Yazdani and Jeffrey 2011). This metric can be incorporated into both the robustness and redundancy aspect of a resilience framework.

Robustness of a pipeline in a distribution network is the capacity to resist strains. A seismic attack of notable magnitude can even fail a pipeline in a fully working state issuing from structural and materialistic flaws. A pipe deteriorated by decay or other reason may somewhat lose its initial strength to resist stress, becoming more weak to low or moderate seismic loading. The probability of failure Pf_i, therefore, is subject to the pipeline's environmental status and physical condition. However, its value intensifies with the magnitude and energy dissipation the seismic hazard it is subjected to. For a given earthquake scenario, Pfj can be calculated depending on various attributes such as diameter, length, material properties, and historical information utilizing empirical data regarding past seismic failures. Pipeline unavailability during the hazard, which is an index for robustness used in Eq. (3), can be calculated as Pf_i.

Redundancy is considered as system's capability to recompense for the loss of an element attributable to failure. A WDN can be portrayed as a spatially distributed network graph with nodes (i.e., reservoir, source or demand locations) and joining links (i.e., distribution and transmitting pipelines). A profoundly looped pattern will function better compared to a branched network arrangement when a system is subjected to seismic loading or other type of stress concentration. The methodology discussed in this study can also be extended to improve Redundancy, as a measure of node degree, to find substitute routes for distribution of water considering new installment of distribution links. Though most WDNs contains various types of elements (e.g., nodes, valves, reservoir tanks, pumps, and lifelines), the concentration of this study is based on the resilience of pipelines alone considering their dominant majority in the constitution of the network in terms of the number and also to obtain a simplified mathematical approach that will be applicable for both small and large domain in network distribution.

4.1 Estimation of Pipeline Fragility

Pipeline fragility is estimated in this method based on the concepts shown in the American Lifelines Alliance guidelines (ALA 2001, 2005). The damage algorithms recommended by Grigoriu et al [Grigoriu, O'Rourke, Khater] were used by ALA 2001. Pf_i is computed considering a Poisson probability distribution of the expected failures denoted as (Piratla and Ariaratnam 2011; Fragiadakis and Christodoulou 2014)

[3] Failure Probability, Pf_i = 1 - $e^{-n_i.L_i}$

Where Pf_i = probability that a pipeline will have complete failure, n_i = the mean break rate for the pipeline J_i (number of breaks/km/yr.); and L_i= the length of the pipe J_i in km (1 km = 3,281 ft.). To obtain the mean break rate, the authors summarized pipeline damage statistics for traveling wave effects from five past earthquakes. All pipes, independent of size, age, kind or location, were modeled with the same mean break rate value. No "leakage" failure modes were adopted. The authors suggest that a break rate of 0.02/km/yr. corresponds to about Intensity VII, and a break rate of 0.10/km/yr. corresponds to about Intensity VIII.

Two types of common seismic hazard phenomenon contribute to the mean breaking rate in the WDN distribution lines as transient ground deformation (TGD) and permanent ground deformation (PGD). The TGD for the underground pipelines is the event resulted from ground shaking. The PGD are mainly the effect of fault displacement, landslide, and liquefaction ground failures. TGD usually happens with low or intensity, whereas PGD occurs with a higher intensity, can appear in the form of vertical settlement (S), lateral spread (LS), or combination of both (O'Rourke 2003).

Regression models proposed in ALA (2001) for assessing mean break rate due to TGD and PGD are expressed as following:

[4] n_{TGD} =$K_1. K_t$ × 0.00241 × PGV

[5] n_{PGD} =$K_2. K_t$ × 2.58 × $PGD^{0.319}$

Where, n_{TGD} is mean break rate for transient ground deformation, n_{PGD} is mean break rate for permanent ground deformation, PGV = peak ground velocity (cm), PGD = permanent ground deformation (cm). K1 and K2 = correction factors for pipeline properties respectively for TGD and PGD which is shown in Table

1; and K_t = correction factor for the structural health of the pipe that is given in Table 2. Kt depends on the pipeline failure history. The combined break rate is estimated using probability of significant liquefaction as follows (ALA 2001):

[6] n = (1 - P_{liq}) × n_{TGD} + P_{liq} × n_{PGD}

Where P_{liq} = probability of liquefaction in percent obtained from a liquefaction potential map.

Table 1. Adjusting coefficient for break rate for TGD and PGD (Adapted from ALA 2001)

Pipe material	**K1**	**K2**
Cast iron	1.00	1.00
Welded steel	0.15	0.70
Welded steel	0.70	0.70
Asbestos cement	1.00	1.00
PVC	0.50	0.80
Ductile iron	0.50	0.50

Table 2. Coefficient for structural health condition

Number of previous breaks	**K2**
0	1.00
1 - 4	2.00
5 - 8	8.00
≥ 8	37.00

4.2 Evaluation of the vulnerability of the WDN

Vulnerability is evaluated from the following equation by considering the parameters regarding behavior of the pipe with weighting factor derived from Adhikary et al. (2018) and Zohra et al. (2012). Where coefficient for pipe diameter and type are Cd and Cp respectively, co-efficient for hazard intensity, severity of ground motion x and ground condition is Cg, Cf is the weight factor for fault crossings, Cs is the weight factor for settlement and landslide, Cg is the weight factor for ground type, Ci is the weight factor for the seismic intensity and Cl is the correction factor for liquefaction shown in table 1.

[7] Vulnerability Index, W = Cd.Cp.Cf.Cs.Cg.Ci.Cl

Table 3. Weighting factors for diameters, material, landslide and settlement, seismic intensity and liquefaction potential (adopted from Adhikary et. al. 2018).

Cd		**Cp**		**Cs**		**Ci**		**Cl**	
Diameters (mm)	Factor	Material	Factor	Landslide	Factor	Intensity (MMI)	Factor	Liquefaction	Factor
ø <75	1.6	Ductile Iron	0.3	No Risk	1	MMI<8	1	0 ≤PL<5	1
75 < ø <150	1	Cast Iron	1	Average Risk	2	8<MMI<9	2.1	5 ≤PL<15	2
150 < ø <250	0.9	Steel	0.3	Important Risk	2.4	9<MMI<10	2.4	15 ≤PL	2.4
250 < ø <450	0.7	Poly Vinyl Chloride	1			10<MMI<11	3		
450 < ø <1000	0.5	Asbestos Cement	2.5			11<MMI	3.5		
ø > 100	0.4								

5. Seismic Resilience Evaluation of VWDN

To attain a realistic assessment of Seismic Resilience Index (SRI) for pipelines, three probabilistic seismic hazard scenarios were anticipated for Vancouver, BC, Canada established from past seismic events. These three earthquake scenarios consider seismic attacks are ranging between MMI 7 to MMI 10 (very strong to severe) and are formed using empirical data of past earthquakes, which includes ground motion and break rates of lifelines and the estimated peak ground acceleration (PGA). The adopted three exposure scenarios for an earthquake are designated as; SC1: MMI<8, SC2: 8<MMI<9 and SC3: 9<MMI<10.

Upon estimating PGV and PGD, break rate is calculated using Eqn. (4) – (6). Failure probabilities are then estimated using Eqn. (3). Expected risk E(R) has been determined from Eqn. 1. We have considered the parameters mentioned above that govern the behavior of the pipelines in terms of magnitude and likelihood of the hazard to find SRI. The Seismic Resilience Index (SRI) is derived using Eqn. (2) and are illustrated as resiliency maps for VWDN developed applying the ArcGIS software which is shown in Fig. 3(a), 3(b), and, 3(c). These maps are produced by arranging the computed Vulnerability Index (W) determined from Eqn. (7) classifying into five categories ranging from very low (less than 7) to very high (more than 30) clusters of vulnerability groups. The expected risk for VWDN is calculated to be lowest as 0.02 and observed at SC1 (MMI < 8) in the Downtown neighborhood. The highest value of the risk is detected at SC3 (9< MMI< 10) in the Victoria-Fraserview neighborhood and it is estimated to be 0.44.

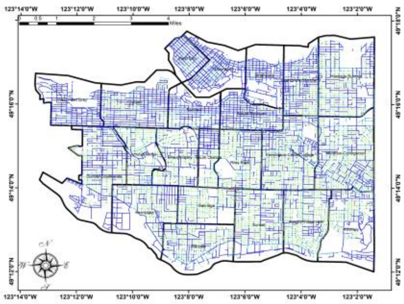

Figure 3(a) Seismic Resiliency Index_SC2

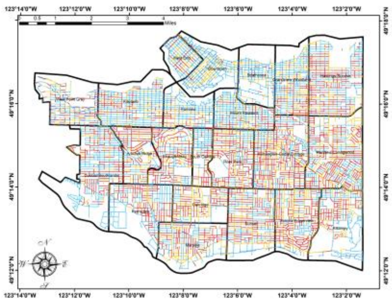

Figure 3(b) Seismic Resiliency Index_SC2

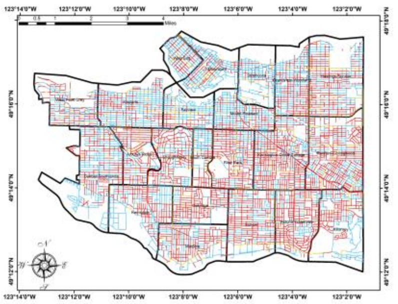

Figure 3(c) Seismic Resiliency Index_SC3

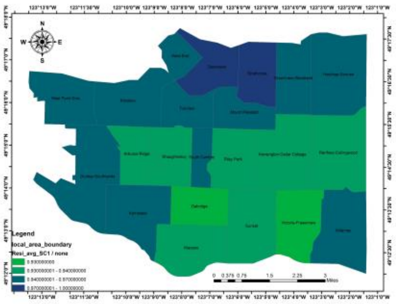

Figure 4(a) Resilience Map SC1

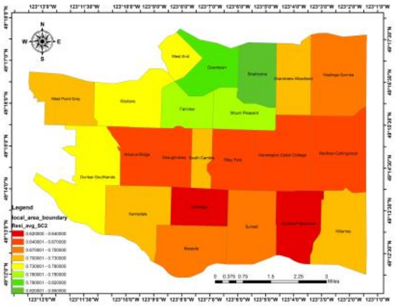

Figure 4(b) Resilience Map SC2

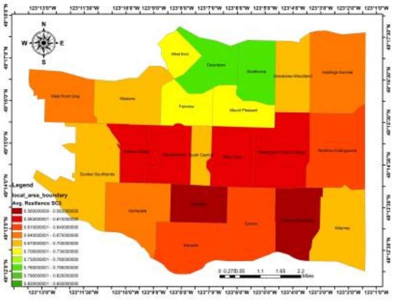

Figure 4(c) Resilience Map SC3

Based on SRI number found by using Eqn. 1, least, medium and extreme scenarios are set with an upper and lower limit of pipeline fragility and seismic resiliency and are shown in Table 4. All the neighborhoods in the study area are ranked from most resilient to least resilient based on index metrics and are shown in Table 4. The highest value of resiliency during the extreme scenario is observed in the Strathcona neighborhood and estimated as 0.79 followed by Downtown in the second position with the resiliency of 0.78. Victoria-Fraserview is found as the least resilient neighborhood in the entire 22 domains with the resilience of 0.56 right before Oakridge that shows a resiliency of 0.58. The overall change of resiliency in Victoria-Fraserview for SC1, SC2, and SC3 are 0.93, 0.62 and 0.56 respectively showing an ultimate reduction of 39.78% reduction in resilience. For Strathcona, the respective resiliences are found as 0.98, 0.83 and 0.79 for SC1, SC2 and SC3 with a reduction rate of 19.39%. Based on the resiliency obtained in the study, illustrated Water Distribution Network Maps (Figure 5. are produced for the least resilient area assigning the pipelines from Class I to Class V, where Class I represents the most critical water mains and Class V represents least critical pipelines for maintenance criteria.

Table 4. Rank of neighborhood with Resilience

Rank	Name	RES_SC1	RES_SC2	RES_SC3	Reduction in Resiliency (%)
1	Strathcona	0.98	0.83	0.79	19.39
2	Downtown	0.98	0.82	0.78	20.41
3	Fairview	0.97	0.78	0.73	24.74

4	Mount Pleasant	0.96	0.77	0.72	25.00
5	West End	0.96	0.76	0.72	25.00
6	Kitsilano	0.96	0.75	0.7	27.08
7	Dunbar-Southlands	0.95	0.74	0.69	27.37
8	South Cambie	0.95	0.73	0.69	27.37
9	Grandview-Woodland	0.96	0.73	0.68	29.17
10	Killarney	0.95	0.73	0.68	28.42
11	Kerrisdale	0.95	0.71	0.66	30.53
12	West Point Grey	0.96	0.72	0.66	31.25
13	Hastings-Sunrise	0.95	0.7	0.65	31.58
14	Marpole	0.94	0.69	0.64	31.91
15	Renfrew-Collingwood	0.94	0.67	0.62	34.04
16	Sunset	0.94	0.68	0.62	34.04
17	Riley Park	0.94	0.67	0.61	35.11
18	Shaughnessy	0.94	0.67	0.61	35.11
19	Kensington-Cedar Cottage	0.94	0.66	0.60	36.17
20	Arbutus-Ridge	0.94	0.66	0.59	37.23
21	Oakridge	0.93	0.64	0.58	37.63
22	Victoria-Fraserview	0.93	0.62	0.56	39.78

Maintenance scenarios for the least resilient neighborhood Victoria-Fraserview (VF) are illustrated as maintenance map in Figure 7. VF is considered as a first priority because of the extreme exposure of the seismic vulnerability in the water mains. The resiliency of the system reveals improvement when 10 maintenance planning with network map is generated integrated with the geographical location using software ArcGIS.

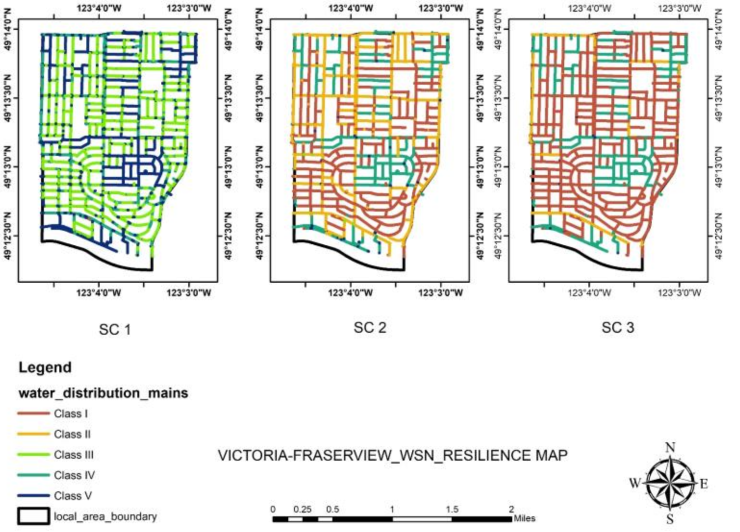

Figure 5 Maintenance Map for VF

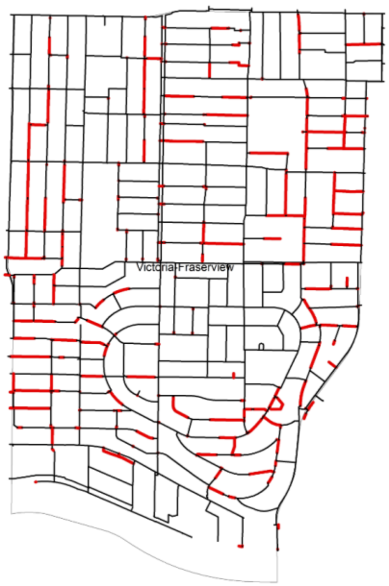

Figure 6 Maintenance Map

The alternative replacement pathways exhibit an increase in resilience ranging from 0.8% to 41.52% and an estimated 15.17% to 89.96% increase of the invulnerability in the network mains. Taking cost as a vital limiting agent in the replacement of WDNs, afterward, evaluation of robust replacement alternatives are performed in Table 5 to find out maintenance planning strategy that gives the lowest budget considering replacement cost of water mains.Table

Table 5 Replacement alternatives for maintenance with cost

Replacement Alternatives	No. of pipeline to change	VI decrease %	Total length (m)	Pf avg decrease	Avg RI Initial	Avg RI Final	Increase in RI %	Unit Cost ($/m)	Total Cost $M
Diameter_150	45	0.65	615	0	0.560	0.567	1.30	500	0.30
Diameter_200	1188	6.02	34572	0	0.560	0.591	5.20	500	17.28
Diameter_450	1188	27.33	34572	0	0.560	0.684	18.07	700	24.20
Diameter_700	500	15.17	14254	0	0.560	0.631	11.19	850	12.11
All CI to DI	1965	61.77	57814	3.19	0.560	0.839	33.24	500	28.90
All CI to Steel D<305	1965	61.77	57814	1.06	0.560	0.835	32.96	670	38.73
All CI to PEHD	1965	89.96	57814	3.19	0.560	0.958	41.52	500	28.90
All CI to Steel D>450	1965	61.77	57814	4.26	0.560	0.841	33.38	700	40.46
TOP 500_Steel_D_300_DI	500	19.764	14254	0	0.560	0.651	13.93	670	9.55
TOP 500_Steel_D_450_DI	500	21.147	14254	1.06	0.560	0.660	15.19	700	9.97

6. Conclusion

This method was simplified for the ease of calculation hence creating some provision for limitations. One of them would be not considering the hydraulic design criteria and joint condition, where it was expected that joints would be operational during a hazard. Also, the number of previous breaks were assumed from past earthquake history from observation due to the lack of information on real data.

Regardless of these limitations, this technique could be beneficial as, instead of the whole system in general, it carries out the resilience of each element separately. Another advantage is it can lead to illustrates not only to identify the component undergoing failure but also the location of that component in a supply system. Also, readiness can be improved for earthquakes attacks by performing maintenance and preparedness planning. This practice can be further used to achieve a feasible retrofitting for the lifeline and developing plans and actions for replacement and repairing.

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Reference

Adams, J. and Halchuk, S. 2005. A review of NBCC 2005 seismic hazard Results for Canada – the interface to the ground and prognosis for urban risk mitigation. 57th Canadian Geotechnical Conference

Adhikary, S., 4, Nasiri, F. and Bagchi, A. 2018. Vulnerability Assessment of Water Supply Network Against Seismic Hazards: A Case Study in Vancouver. CSCE Annual Conference, 2018, Fredericton, Canada, June 13 – June 16.

Albert, R., Jeong, H., and Barabasi, A. -L., 2000. Error and Attack Tolerance of Complex Networks. Nature London, UK, 406: 378-382.

American Lifelines Alliance. 2001. Seismic Fragility Formulations for Water System, P-1 Guideline, ASCE ASCE. (2013). “Report card for America’s infrastructure.” ⟨http://www.infrastructurereportcard.org/⟩ (Jan. 15, 2015).

Bent, A. L. (2002), "The 1933 Ms= 7.3 Baffin Bay earthquake: strike-slip faulting along the northeastern Canadian passive margin", Geophysical Journal International, Wiley, 150 (3): 724–736, Bibcode:2002GeoJI.150..724B, doi:10.1046/j.1365-246X.2002.01722.x

Bruneau, M., et al. (2003). “A framework to quantitatively assess and enhance the seismic resilience of communities.” Earthquake Spectra, 19(4), 733–752. 10.1061/(ASCE)ST.1943-541X.0001341, C6015001.

Cassidy, John F.; Ellis, Robert M.; Rogers, Garry C. (April 1988), "The 1918 and 1957 Vancouver Island earthquakes", Bulletin of the Seismological Society of America, Seismological Society of America, 78 (2): 617&ndash, 635

Chang, S. E., and Shinozuka, M. (2004). “Measuring improvements in the disaster resilience of communities.” Earthquake Spectra, 20(3), 739–755.

Fragiadakis, M., Christodoulou, S. E., and Vamvatsikos, D. (2013) “Reliability assessment of urban water distribution networks under seismic loads.” Water Resour. Manage. 27(10), 3739–3764.

Fragiadakis, M., and Christodoulou, S. E. (2014) “Seismic reliability assessment of urban water networks.” Earthquake Eng. Struct. Dyn. 43(3), 357–374.

Jayaram, N., and Srinivasan, K. (2008). “Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing.” Water Resour. Res., 44(1), W01417.

Kessler, A., Ormsbee, L., and Shamir, U. (1990). “A methodology for least-cost design of invulnerable water distribution networks.” Civ. Eng. Syst., 7(1), 20–28.

Natural Resources Canada, http://www.earthquakescanada.ca/pprs-pprp/pubs/GF-GI/GEOFACT_largest-earthquakes_e.pdf, Natural Resources Canada, earthquakeinfo@nrcan.gc.ca

O'Rourke, M. J., and Nordberg, C. 1992. Longitudinal permanent ground deformation effects on buried continuous pipelines. *National Center for Earthquake engineering Research*, NCEER-92-0014, NY, US

Piratla, K. R. (2015). “Investigation of sustainable and resilient design alternatives for water distribution networks.” Urban Water J., 13(4), 412–425.

Prasad, T. D., and Park, N. S. (2004). “Multi objective genetic algorithms for design of water distribution networks.” J. Water Resource Plan. Manage. 10.1061/(ASCE)0733-9496(2004)130:1(73), 73–82.

Romero, N., O’Rourke, T. D., Nozick, L. K., and Davis, C. A. (2010). “Seismic hazards and water supply performance.” J. Earthquake Eng., 14(7), 1022–1043.

Todini, E. (2000). “Looped water distribution networks design using a resilience index based heuristic approach.” Urban Water, 2(2), 115–122.

Yazdani, A., and Jeffrey, P. (2010). “A complex network approach to robustness and vulnerability of spatially organized water distribution networks.” Physics, in press.

Yazdani, A., and Jeffrey, P. (2011). “Complex network analysis of water distribution systems.” Chaos: An Interdiscip. J. Nonlinear Sci., 21(1), 016111

Zohra, H. F., Mahmoud, B. and Luc, D. 2012. Vulnerability assessment of water supply network. Energy Procedia, Elsevier, 18: 772-783.