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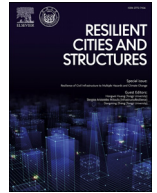
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## Full Length Article

# Assessing the effectiveness of disaster risk reduction strategies on the regional recovery of critical infrastructure systems

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## ABSTRACT

Communities depend on critical infrastructure systems to support their regular operations and future development. Destructive events, such as natural disasters, threaten to disrupt service to these systems and the communities they support. Strategies designed to reduce the impacts from disasters and other events are therefore an important consideration for community planning. At a regional level, coordination between communities supports the efficient use of resources for implementing disaster risk reduction (DRR) measures and completing post-disaster repairs to meet the needs of all residents. Coordination is challenging, however, due to the complexity of regional systems and competing stakeholder interests. This work presents a case study model of regional water, wastewater, and power systems, and demonstrates the effect of seismic hardening and increased resource availability on post-earthquake repair requirements and critical infrastructure recovery. Model results indicate that implementing DRR strategies can reduce required repair costs by over 40 percent and outage severity by approximately 50 percent for the studied sectors. Not all strategies are effective for all sectors and locations, however, so this work discusses the importance of comprehensive, coordinated, and accessible emergency planning activities to ensure that the needs of all residents are considered.

## 1. Introduction

As cities grow and become increasingly interconnected, natural and human-caused disasters present a clear threat to the functionality of infrastructure systems that support the physical and economic well-being of communities throughout the world. Protecting these systems is vital for ensuring that the populations that depend on them can survive even in the face of significant disruptions.

The concept of resilience characterizes a system or population's ability to withstand a disaster or disruption and recover within an acceptable amount of time and at an acceptable cost [1]. Assessing resilience can include examining the response of physical components to certain types of disruptions, the capabilities of repair teams and materials, mutual aid agreements, and other activities that are essential to system recovery. Throughout the assessment process, gaps in understanding and capabilities are revealed that can be used to inform and encourage investment in strategies that reduce the risk of future failure.

The goal of the work presented here is to demonstrate the use of a flexible modeling approach to evaluate the efficacy of Disaster Risk Reduction (DRR) strategies on critical infrastructure system resilience. Existing and novel assessment metrics are described and demonstrated through a case study of regional water, wastewater, and power systems subject to a simulated earthquake. Results are provided that can be tai-

lored to a variety of audiences to enhance the resilience of their communities by engaging them in disaster preparedness and planning processes.

## 2. Critical infrastructure modeling

To assess and predict the response of critical infrastructure systems to changes and stresses, computer models are often developed using data gathered from physical models, historical damage and disaster information, expert judgement, and other sources [2]. The creation and use of such models is an area of extensive research, and all models have benefits and drawbacks based on the needs of their users. No model can predict precisely how a system will respond to a hazard, but as posited by the Flood Committee member contributors to the United States Federal Emergency Management Agency's (FEMA) Hazus flood technical manual, "Planning decisions made with the benefit of model results will be better than decisions made without any consideration of science" [3].

For the purposes of assessing resilience, a model should generally indicate the extent to which system functionality fails, how likely it is to fail, or how its recovery progresses after a disruption. Specific quantifications of resilience that are used in this work are presented in Section 4.

Models may include only certain systems and thoroughly describe their component specifications, details of crew and material availability

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and movement, and operational strategies to address both system failure and system recovery due to disruptions. Studies of the effect of the 1994 Northridge Earthquake on the Los Angeles water [4,5] and power [6–8] systems, for example, include highly detailed models that are immensely valuable for scheduling restoration activities for those systems. Brink et al. and Xu et al. extend this restoration modeling to devise strategies that will reduce outage times in future earthquake scenarios [9,10].

Thompson et al. consider both the current demands that power and water systems in another region face and how they may change in the future due to population growth or environmental stresses [11]. This work highlights the extensive impact that changes may have on system performance and emphasizes the need to prepare for such changes. It also demonstrates the benefits of using models to assess multiple configurations of existing systems.

Other models also consider specific systems but only focus on estimating either damage or restoration. Examples of damage estimation include Isoyama et al.'s assessment of pipelines [12] and Ogawa et al.'s [13] study of building damage (and its impact on residents) subject to earthquakes and subsequent tsunami and fires.

Models of restoration may consider the effects of multiple hazards or system modifications [14–16] and can include methods for improving recovery processes, such as greedy algorithm [17,18] and multi-objective optimization approaches [19,20]. Others specifically highlight the uncertainties and difficulties of restoring complex networks and provide strategies for addressing these challenges [21–25]. Each of these works include specific processes and practices that can be integrated into broader assessment and planning activities.

The final modeling approaches included here provide more general approaches for including different systems and the dependencies within and between them. Such models can incorporate features from the specialized models described previously or other studies to cover a wide range of systems and scenarios. Examples include network dependency approaches developed by Ünen et al. [26], Guidotti et al. [27], Karakoc et al. [28], and the Graph Model for Operational Resilience (GMOR) developed by Bristow and Hay [29,30].

It can be challenging to develop detailed system models because the technical knowledge and system specifications required to do so is often inaccessible or would require significant resources to acquire. This may be especially true at a regional level, where systems are managed using proprietary tools or where the sharing of specific system information is restricted for security reasons. Constructing a simplified model can therefore serve a dual purpose of requiring less specialized input data and presenting results in a way that is accessible to a broader audience. Such a model does not intend to show precisely what damage and restoration will look like to the extent that some of those previously listed attempt to do, but instead proves valuable in identifying trends and patterns for the purposes of informing and enhancing planning and recovery activities.

To develop the model for the assessment presented in this work, the Graph Model for Operational Resilience (GMOR) platform is selected. GMOR provides methods for aggregating infrastructure systems into service areas, tracking the dependencies within and between them, and estimating their restoration over time after a disaster based on individual repair times and resource availability. Results from a GMOR model can be processed at varying scales and levels of detail. In addition, GMOR was utilized for earlier studies in the region [31–33], so its capabilities for supporting the assessment of the considered systems is already established.

### 3. Resilience quantification

The characterization of resilience proposed by Haines [1] does not include a method for quantifying resilience, but doing so is immensely valuable for comparing different systems. Many of the critical infras-

tructure modeling works mentioned in the previous section include a discussion of system resilience, though not all specifically quantify it.

For the quantification of resilience, methods proposed by Bruneau et al. [34] and Cimellaro, Reinhorn, and Bruneau [35,36] are commonly used. In these works, the resilience of a system is measured by its functionality or capabilities in the aftermath of a disaster and throughout the recovery process. Examples of criteria that the authors use include the availability of beneficial services (such as hospitals or businesses) and the avoidance of negative consequences (such as casualties or economic losses).

Singh et al. [37] builds on this work by integrating loss of functionality, repair time, and a normalization parameter (in their case, floor area) to develop a resilience deficit index for buildings. Normalizing on a per unit basis in this way provides an especially useful method for comparing loss of resilience across multiple scenarios and locations.

In the following sections, a brief overview of the creation of the GMOR model is presented, metrics for quantifying damage, recovery, and resilience are discussed, and the use of the GMOR model for assessing recovery and resilience is developed. Using the results from the assessment, DRR strategies and scenarios are compared to evaluate their effectiveness, and opportunities for future work and enhancements are discussed.

## 4. Methodology

The GMOR model uses an approach that simplifies infrastructure systems within a region by separating them into distinct service zones based on criteria such as population or size. Damage to linear infrastructure systems within each zone is aggregated to produce a total damage level for each system for the zone [31–33].

The network structure of the simplified system is produced by considering borders between zones that linear systems cross as shown in Fig. 1. The full structure of most infrastructure systems is complex, so separating the system into zones in this way simplifies the network (and therefore reduces the data input complexity and computational resources required to assess it) while still maintaining its overall structure.

While service areas and paths of linear features are collected at a zone level, facilities are still represented as individual entities in the model. Each water storage tank, for example, is considered independently in the damage assessment. In this way, damage to facilities can be individually identified and assessed.

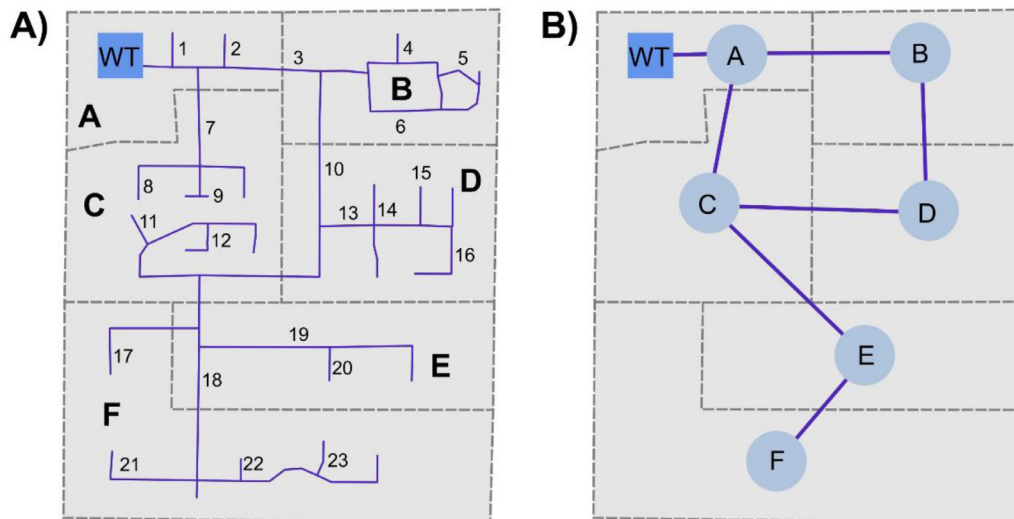
To restore service to zone D in Fig. 1, for example, the water storage tank (WT) and all pipes in zone A must first be repaired. In addition, all pipes in zone B or zone C must be repaired, as well as the pipes in zone D itself. This process provides conservative estimates of restoration times in that it assumes all service is lost in a zone if there is damage to any of the pipes in the zone.

Systems can be further separated to increase the level of detail of the model if desired. In the case study described in Section 5, for example, the bulk water transmission system is modeled separately from the water distribution system to include the distinct paths and facilities that are utilized by each. Interdependencies between systems, such as the dependence of a pump or treatment plant on electrical power, can be modeled as well. In this way, the interactions between different systems can be studied to assess how each one impacts the region as a whole.

### 4.1. Damage assessment

An assessment of estimated damages is performed for the infrastructure system(s) and hazard in a study area. Results from the damage assessment are used as inputs to the GMOR model and indicate the degree to which components in each system are damaged based on the hazard.

Damage should be estimated for individual components or segments of linear infrastructure, if possible, to consider the different damage characteristics that each possesses. The zone aggregation of damage is



**Fig. 1.** Zone layout and aggregation. The six alphabetically labelled zones (A-F) depend on the water storage tank (WT) for water service. (A) Each zone contains multiple pipes that may be damaged in a disaster. (B) Damage estimates for the pipes within each zone are aggregated and represented as a single node. Nodes are connected only where a pipe crosses the border between the zones. For instance, zone D borders zone E, but the nodes are not connected because a pipe does not cross the border between them.

done as part of the GMOR modeling process and has no influence on the initial damage assessment process.

#### 4.2. Repair time and resource requirements

Repair time and resource requirements are based on the estimated level of damage and component type. That is, a specific type of repair for a specific type of component will always have the same mean repair time and resource requirements. Repair time values may be defined using probability distributions or single values.

Resources included in the model represent repair crews and the materials and equipment that they require to perform repairs. Individual component repair times do not change with increased or decreased crew availability. Instead, increasing resource availability increases the number of repairs that happen concurrently.

The order in which repairs are completed can be specified, randomized, or grouped based on certain characteristics. The order of repairs for the water distribution system, for example, may have zones grouped by distance from a supply node (such as a reservoir or pump). Zones that are closer to the supply node are prioritized for repairs before those that are farther away. The rationale for this process is based on the network structure illustrated in Fig. 1, which demonstrates that zones that are closer to the supply node must be repaired to provide functional paths to zones that are farther away.

#### 4.3. Repair time, repair cost, and restoration time

It is important to distinguish the repair time identified in Section 4.2 from the repair cost and restoration time discussed in future sections. For the purposes of this work, repair time refers only to the time required to repair broken components within a system, such as the water pipelines in a single zone, and is measured in days. Repair cost is measured in crew-days and has the same numerical value as repair time for a given repair because a crew is assumed to be working for the duration of the repair.

Restoration time refers to the total time required to restore service to a zone based on its repair time and dependencies. For a zone within a water system, for example, the restoration time includes the repair time of that zone and the repair time of any water supply facilities and intermediate zones as well. Due to repair crew limitations, only a certain

number of repairs can be completed concurrently. Service restoration time is the same as the service outage time for a given zone.

#### 4.4. Scenarios and trials

Disaster risk reduction strategies may be implemented in multiple ways to reflect changes to physical assets in the region or in response activities. Changes to facilities or linear infrastructure systems can be included to reflect investments in structural upgrades, and resource availability can be adjusted to increase the rate at which repairs are made.

Here it is important to distinguish between definitions of scenarios and trials as used in this work. A scenario refers to the characteristics of a system and includes the implementation (or lack thereof) of DRR strategies. For a given scenario, therefore, the level of initial damage to each system and availability of resources in the region does not change. A trial refers to an individual model simulation within a given scenario and includes certain variations that produce a range of results for assessment.

In each trial, the required repair time and repair order vary based on applicable scenario parameters (probability distributions of repair times and randomization of repair order, for example). Results from each trial produce an estimate of restoration time for each entity included in the model.

On their own, estimated restoration times are valuable for planning purposes, but additional processing and assessment methods increase the utility of the model results. These methods offer improved insights into regional patterns of recovery and provide useful metrics for comparing the effectiveness of DRR strategies. The following sections describe the methods used for assessing and comparing restoration processes across a variety of scenarios.

#### 4.5. Costs, benefits, and resilience quantification

Appropriate metrics to assess the costs and benefits of risk reduction strategies and resilience measures should be based on the needs of local stakeholders and community members and can vary widely within a region. As such, the selection of location-specific metrics is beyond the scope of this work and more generally applicable measures of costs and benefits are used instead.

Costs are quantified by the number of crew-days (as described in Section 4.3) required to complete repairs. For the work presented here,

there is no distinction made between crew types in terms of their operational costs (such as worker salaries or fuel for equipment). The cost required to implement DRR strategies (such as replacing pipes or adding seismic bracing) is also not included.

Benefits derived from DRR strategies are measured by a reduction in the severity of service outages. Service outage time on its own is challenging to compare across different scenarios due to possible outliers in the restoration process. For example, if one zone with a small population takes many times longer to recover than all other zones in a region, presenting the time required to restore service to the entire region would indicate severe outages despite a vast majority of residents recovering relatively quickly.

Instead, the time required to restore a given service in each zone is multiplied by the zone's population to better represent the magnitude of an outage and quantify the loss of system resilience. This quantity is referred to as the population-outage time and is measured in person-days. The effect of DRR strategies on recovery can therefore be compared between scenarios or groups of zones at any scale with a consistent unit of measurement.

This method of quantification is similar to that presented by Singh et al. [37] and discussed in Section 3 but does not include a normalization parameter and therefore does not present loss of resilience on a per unit basis. The inclusion of such a parameter may be useful, however, and is discussed in Section 7.

#### 4.6. Simplified example scenario and assessment

Appendix A presents a simplified example scenario to demonstrate interactions between repair time, repair cost, repair order, restoration time, and population-outage time, and describes tools and metrics that enhance the resilience assessment of a system. These tools include restoration curves and restoration ratios and are also used for the assessment provided in Section 6. Appendix A provides a comprehensive overview of their application as a reference to limit the length of in-text explanation.

### 5. Case study

The case study presented here considers the effectiveness of DRR strategies for a simulated earthquake in the Metro Vancouver region of British Columbia, Canada. The Metro Vancouver region is an area subject to significant seismic threat that warrants an assessment of the systems in the region and how they may respond to a seismic event. A simulated magnitude 6.8 earthquake with its epicenter near the western part of the region developed by the Geological Survey of Canada (GSC) for emergency response exercises is chosen for this assessment [38]. Ground motions and resulting damages from the earthquake are provided by the GSC [39], and repair time parameters are established from FEMA's Hazus earthquake manual for each type of infrastructure component considered [40].

Fig. 2 shows a map of the study region, which consists of 23 local authorities: 21 municipalities, one Electoral Area, and one Treaty First Nation [41]. In the following sections, the mention of local systems, resources, or components refers specifically to those managed by local authorities as opposed to those managed by the regional (Metro Vancouver) authority.

#### 5.1. Systems of interest

The case study explores recovery of the water distribution, wastewater collection, and electric power distribution systems in the region after the considered earthquake. A baseline scenario is considered in which systems are modelled using GMOR with no specific DRR measures in place. Additional scenarios are developed that include DRR strategies to provide a comparison to the baseline case. A brief overview of the infrastructure systems and strategies is offered in the following sections.

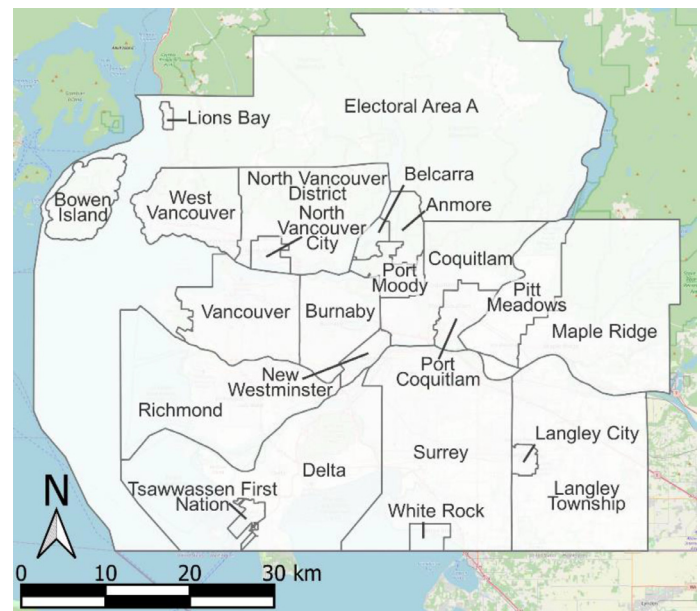


Fig. 2. Map of the study area with 21 municipalities, Tsawwassen First Nation, and Electoral Area A identified. Background map copyright OpenStreetMap Contributors; licensed under the Open Database License [42].

##### 5.1.1. Water system

A majority of residents in the region are provided with potable water that is initially conveyed through large transmission mains and facilities managed by the Greater Vancouver Water District (referred to hereafter as the Metro Vancouver system). The Metro Vancouver transmission mains branch across the region to fill reservoirs and storage tanks. From there, distribution systems are managed by local authorities to reach individual customers [43]. Exceptions to this general layout include well-water users, a few municipalities that operate independent systems, and some local areas that receive water directly from the Metro Vancouver system rather than from local reservoirs.

The water system model separates the Metro Vancouver transmission system from the local distribution systems in such a way that the network structure of each system is considered separately. The transmission portion of the model generally extends across the region and ends at various reservoirs. Local systems are then created with a dependency on these reservoirs. Independent systems are modeled separately, and well-water users are not specifically included in the model. Approximately 10,000 wells are registered in the region [44], and identifying the use, capacity, and vulnerability of each is not within the scope of this assessment.

##### 5.1.2. Wastewater system

Most of the region's wastewater collection service is provided by the Greater Vancouver Sewerage and Drainage District (referred to hereafter as the Metro Vancouver system) and local authorities as well. Local systems collect wastewater at a local level and pass it on via pumps or gravity flow to larger Metro Vancouver pipelines and pump stations. Five wastewater treatment plants serve the region, separating wastewater collection into five large service areas [45].

The wastewater system is modeled in a similar way to the water system in that the local and Metro Vancouver systems are separated. Local systems extend to the nearest Metro Vancouver pump station, and the Metro Vancouver portions of the model connect each pump station to the appropriate wastewater treatment plant based on their location. A few independent municipal systems are modeled separately as well.

### 5.1.3. Power system

Power is provided to users in the region by BC Hydro, which operates and maintains most of the electrical power generation and distribution system in the province [46]. One municipality maintains its own distribution equipment, but is still dependent on BC Hydro for the provision of power to their border [47].

The power system is modeled using a method similar to that developed by the US National Institute of Building Sciences (NIBS) and FEMA that includes only generating facilities and substations and assumes that damage to transmission lines is generally minimal [40,48]. The power system is therefore not modeled using the zone aggregation method shown in Fig. 1 but instead assumes that power service is restored to users when their nearest substation is functional. Substations are in turn modeled as nodes in a network that require a functional connection to a generating facility to be restored to service.

### 5.1.4. System interdependencies

As noted in Section 4, interdependencies between infrastructure systems can be included in the regional restoration model. For the purposes of this case study, water and wastewater pumps are modeled with a dependency on the electrical power system. This dependency is created based on the zone that the pump is in. That is, electrical power for the pump is assumed to be available if the power system is functional in the zone in which the pump is located.

## 5.2. Disaster risk reduction strategies

Three types of DRR strategies are considered for this case study: seismically hardening water and wastewater pipelines, seismically hardening water, wastewater, and power facilities, and increasing post-disaster resource availability. As indicated in Section 4.5, the financial and labor costs required to implement these strategies are not included in this work.

In the GMOR model, seismically hardening facilities involves updating the fragility functions for facilities from those with non-anchored components to those with anchored components (based on FEMA's Hazus earthquake manual parameters [40]). The baseline case assumes that no facilities are hardened, so hardening applies to all facilities in the region. Many facilities in the region are in fact seismically hardened, but the status of all of them is not known, so this assumption provides a conservative scenario to demonstrate the effect of DRR strategies on the system. Further, it is assumed that even if a facility has anchored components or is designed to a certain seismic standard, upgrades can still be made that decrease its probability of failure.

Hardening pipelines involves upgrading pipelines made of brittle materials (such as vitrified clay or cast iron) to ductile materials (such as high density polyethylene (HDPE) or ductile iron), which allows them to move and flex in an earthquake rather than breaking [49] and is therefore modeled as a decrease in the probability of leaks or breaks [40]. Data gathered for this study includes the construction material for over 90% of existing pipelines in the region. Facility hardening provides a reduction in the estimated level of damage and leads to a decrease in required repair time.

The increased resource scenarios involve doubling the number of crews available for making repairs in the model. This increase has no effect on the initial level of damage, but may drastically reduce post-disaster repair and outage times. It is important to again note that increasing resources does not reduce the time required to complete individual repairs in the model. Doubling the size of a repair crew does not halve the repair time of a pipe leak, but instead increases the number of repairs that can happen concurrently.

## 5.3. Scenario selection

Eight unique scenarios are developed by using baseline and doubled resource availability for the following 4 scenarios: baseline (no harden-

ing), hardened pipes only, hardened facilities only, and hardened pipes and facilities. A total of 500 trials are run for each of the 8 scenarios.

As indicated in Section 4.4, the level of damage to individual components remains the same for all trials in a scenario, but the repair time and the order in which repairs are completed varies in each trial. Repairs are ordered by grouping components (facilities or zones) in each sector based on certain attributes. In the water distribution system, for example, zones are grouped based on their distance from their supply source (water reservoir or pump). Nearby groups are prioritized for repairs before distant groups, but prioritization within each group is randomized. The components within each group are the same for each scenario.

## 6. Case study results and assessment

Results from the case study are presented here in terms of both changes to damages and changes to restoration times. Damage is measured by considering the repair cost needed to restore each system. The repair cost is simply the sum of the total required repair time for each system and is measured in crew-days. Restoration times for each zone are multiplied by the zone population as described in Section 4.5 and are measured in person-days of outage.

### 6.1. Repair costs

Table 1 shows the required repair cost separated by sector for each scenario. The value in parentheses indicates the percent change in repair time for each scenario compared to the baseline scenario. Repair costs are measured in crew-days and are the same for the baseline resource scenarios as they are for the doubled resource scenarios, so the table only shows four scenarios. Recall that doubling resources only increases the number of crews available to work, not the time it takes to repair individual components. If this was not the case, continually adding crews would eventually result in infinitesimally small repair times, which is impossible to achieve.

An additional distinction is made in Table 1 between pipeline repairs and facility repairs in the water and wastewater sectors to further differentiate repair costs. Hardening wastewater pipelines results in the largest individual reduction in required repair cost, providing almost 50 percent of the total possible reduction in crew-days. This improvement is due to the significant length of relatively fragile brittle pipe in the wastewater system. The water and wastewater systems in the region contain a similar total length of pipe, but the length of brittle pipe in the wastewater system is almost twice that of the water system.

### 6.2. Pipeline repair time reduction and upgrade cost

On its own, the information provided in Table 1 is valuable for providing a high-level overview of the benefits of upgrading infrastructure systems, but it is unlikely that all changes in the region can be undertaken at the same time. In addition, the cost of pre-emptively upgrading pipelines in some areas may not be worthwhile if the resulting savings from reduced damage is minimal. Therefore, separating repair time improvements and upgrade costs by location can highlight areas that benefit most from upgrades.

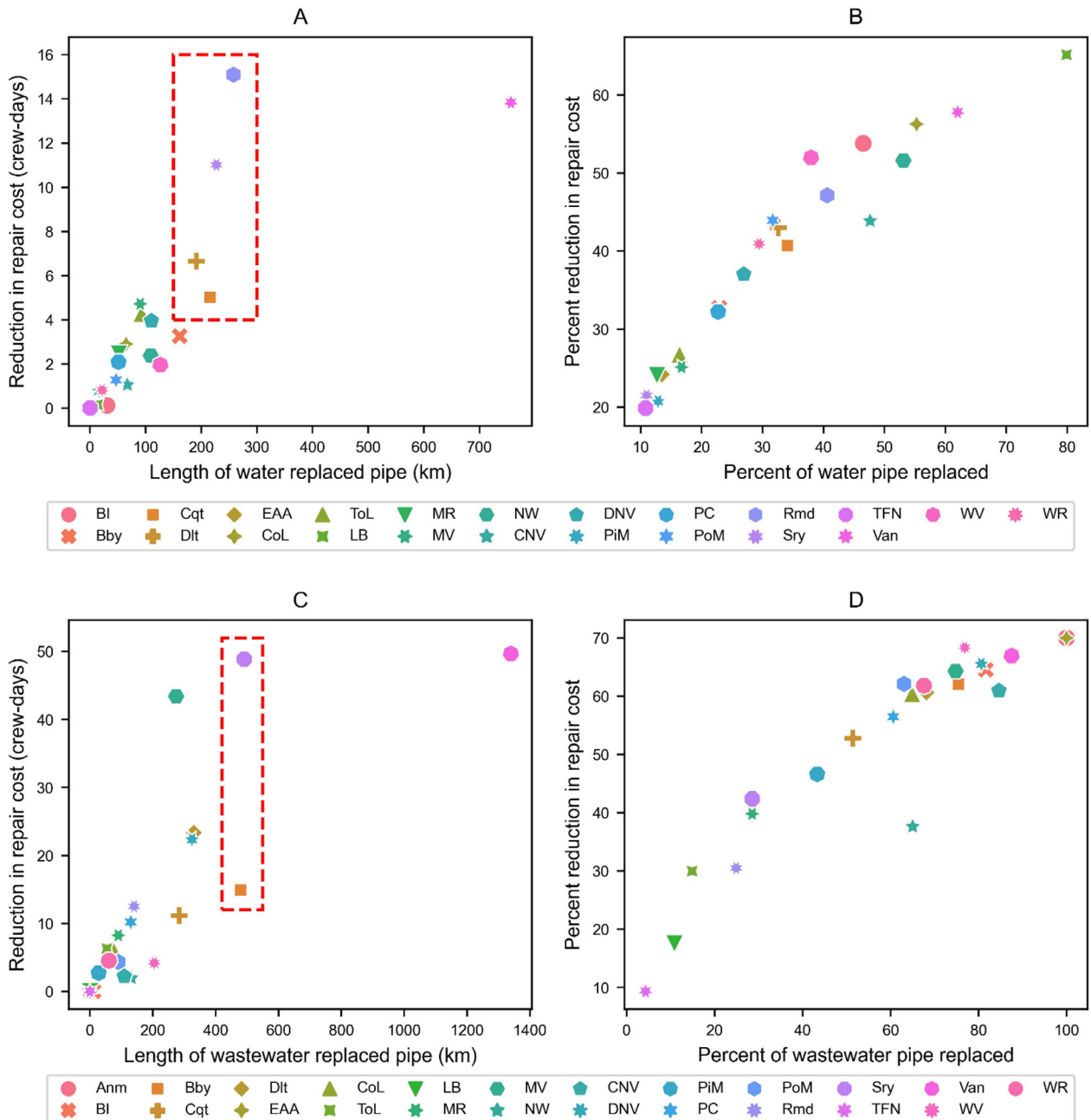
As indicated in Section 5.2, the cost to upgrade infrastructure is not explicitly included in this assessment. For pipeline replacement, however, the length of pipeline replaced can be used as a proxy for the cost to upgrade and compared for different local authorities to demonstrate where investment in upgrades might be most beneficial. This comparison assumes that the cost per unit length to upgrade is similar throughout the region. Fig. 3 shows this comparison for each local authority for the water and wastewater systems.

The highlighted points in Fig. 3 illustrate how this process can be used to target priority areas for pipeline replacement. Multiple local authorities may have similar lengths of brittle pipeline, but some may benefit significantly more from pipeline replacement than others due to

**Table 1**

Mean repair cost for each of the considered scenarios. The first number represents the cost in crew-days and the number in parentheses represents the percent change in repair cost for each DRR scenario compared to the baseline scenario.

Sector	Baseline scenario repair cost in crew-days	Hard pipes scenario repair cost in crew-days	Hard facilities scenario repair cost in crew-days	Hard pipes and facilities scenario repair cost in crew-days
Water pipes	232	149 (-36%)	232 (0%)	149 (-36%)
Wastewater pipes	521	244 (-53%)	521 (0%)	244 (-53%)
All pipes	753	393 (-48%)	753 (0%)	393 (-48%)
Water facilities	255	255 (0%)	134 (-47%)	134 (-47%)
Wastewater facilities	70	70 (0%)	49 (-30%)	49 (-30%)
Power facilities	219	219 (0%)	159 (-27%)	159 (-27%)
All facilities	544	544 (0%)	342 (-37%)	342 (-37%)
Totals	1297	937 (-28%)	1095 (-16%)	735 (-43%)



**Fig. 3.** Reduction in repair cost due to pipeline hardening compared to the length of pipe replaced for local and Metro Vancouver components of the (A and B) water and (C and D) wastewater systems. (A) and (C) show a reduction in crew-days and length of pipe replaced, while (B) and (D) show the percentage reduction in crew-days and percentage of pipe replaced. Note that some local authorities are not included in the figure because of a lack of infrastructure, lack of information, or lack of brittle pipelines needing replacing. As such, local authorities may be represented by different symbols in parts (A) and (B) compared to parts (C) and (D) of the figure. Full names for the for the local authority abbreviations used in the legends are identified in Table B.1 in Appendix B.

their seismic vulnerability. In Fig. 3B, for example, Surrey and Burnaby are shown to have 491 km and 479 km of brittle pipe, respectively, but Surrey's repair cost decreases by more than three times as much as Burnaby's as a result of replacing the brittle pipes (49 crew-days vs 15 crew-days). If upgrades are made, Surrey should likely be prioritized over Burnaby due to the increased return on investment of doing so. This depends, of course, on the population served in each municipality, the importance of the considered pipes in the overall structure of the network, and the cost and complexity of performing upgrades in each municipality.

The quantity of breaks and leaks in ductile pipe is estimated as 30 percent that of brittle pipes using the Hazus earthquake damage probabilities [40]. This explains the limit of approximately 70 percent reduction in repair time shown in Fig. 3 for local authorities that currently use primarily brittle pipeline in their water or wastewater systems.

### 6.3. Restoration and outage times

Improvements in restoration time are quantified using the population-outage time metric discussed in Section 4.5 and visualized using restoration curves. For restoration curves included here, only the recovery of the first 99% of the population is included. The remaining portion of the population that takes longer to recover is certainly important to consider, but the first 99% of the curve most clearly demonstrates the restoration process and improves the scaling of the included figures.

Fig. 4 shows a comparison of median restoration curves for each scenario and sector in the region. Separating restoration curves by local authority is also possible and can be useful to demonstrate the effectiveness of different treatment options on each. Note that the restoration curves for the power system include only baseline and hardened facility scenarios because the power system has no pipelines and is not modeled with any functional dependencies on the water or wastewater systems. As a result, hardening pipelines in the model has no effect on the power system. A set of restoration curves that show the full range of recovery over time for each sector and scenario is included in Fig. B.1 in Appendix B.

Hardening infrastructure systems may be assumed to reduce initial system outages, but the restoration curves shown in Fig. 4 still indicate an almost complete failure of service in most scenarios. This is not an error but is instead related to assumptions made in developing the GMOR model. Due to the uncertainty inherent in an earthquake damage assessment, it is impossible to predict exactly where pipeline leaks or breaks may occur and the impact that they may have on the overall level of service in the zone. Because of this uncertainty and the aggregation process described in Section 4, damage to any pipe in a zone is assumed to disrupt service to the entire zone. The use of seismically-triggered shutoff valves or emergency response procedures could produce a similar effect by stopping the flow of water after an earthquake to reduce water loss [49,50]. Service to the zone is only restored after all pipe segments and necessary facilities are repaired.

Box plots of population-outage times for each sector and scenario are shown in Fig. 5 and a table with numerical results is provided in Appendix B. Note that despite the water and wastewater systems both experiencing significant reductions in required repair time for hardened pipe scenarios (36% and 53%, respectively, as indicated in Table 1), only the wastewater system shows demonstrable improvement in its population-outage time for those scenarios. This difference is further explored using the restoration ratio in Section 6.4.

Hardening both pipes and facilities results in significant improvements in all sectors, indicating that investment in DRR strategies may result in critical services being restored to residents substantially sooner in a disaster scenario. This degree of improvement could mean the difference between maintaining a safe home and significant challenges for many residents in the region.

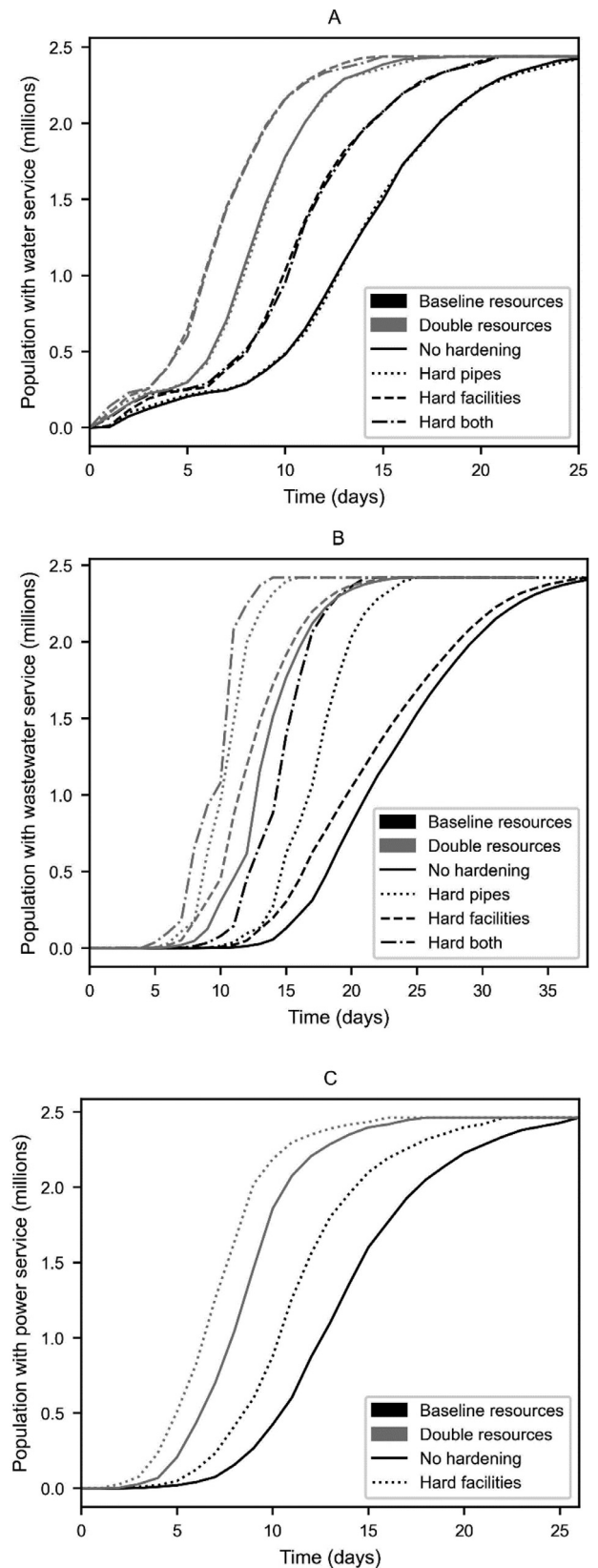


Fig. 4. Median restoration curves for the (A) water, (B) wastewater, and (C) power sectors in the region showing the restoration of service over time. Black lines represent baseline resource scenarios, while gray lines represent doubled resource scenarios. “Hard both” refers to the hard pipe and facility scenarios and is used to save space in the figures.

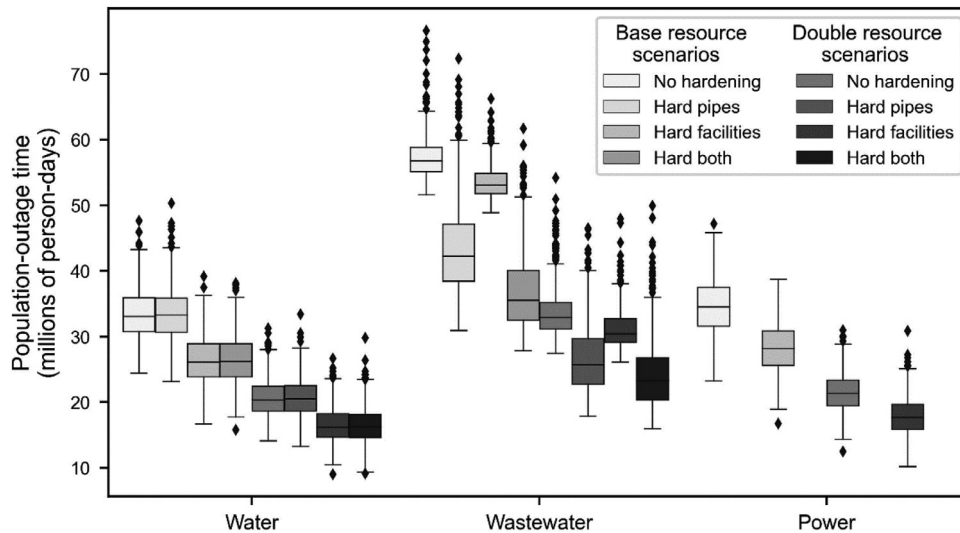


Fig. 5. Box plots of population-outage time for each sector and scenario in the case study. “Hard both” refers to the hard pipe and facility scenario and is used to save space in the figure. The whiskers of the plot include values within 1.5 times the interquartile range above and below the 75th and 25th percentile values, respectively.

Table 2

Mean value of the restoration ratio and population-outage time for each scenario for the water and wastewater sectors shown in Fig. 6. The value in parenthesis indicates the percent change from the baseline scenario.

		Baseline	Hard pipes	Hard facilities	Hard pipes and facilities
Water system	Mean restoration ratio	1.10	1.09 (-1%)	1.09 (-1%)	1.09 (-1%)
	Mean population-outage time (millions of person-days and percent change from baseline)	33.47	33.40 (0%)	26.43 (-21%)	26.48 (-21%)
Wastewater system	Mean restoration ratio	1.49	1.08 (-27%)	1.68 (+13%)	1.13 (-24%)
	Mean population-outage time (millions of person-days and percent change from baseline)	57.41	43.75 (-24%)	53.60 (-7%)	37.16 (-35%)

6.4. Restoration ratio

The restoration ratio mentioned in Section 4.6 and described in detail in Appendix A can further demonstrate the effects of DRR strategies and provide additional explanation of the limited effectiveness of pipeline hardening on the water system illustrated in Fig. 5.

Fig. 6 illustrates the relationship of population-outage times and restoration ratios for the water and wastewater systems for the baseline resource scenarios. Each point in the figure represents the total population-outage time and mean restoration ratio for all zones for a single trial in the noted scenario. Fig. 6 only includes baseline resource scenario results, but patterns are similar for the doubled resource scenarios. The power system is not included because distribution lines are not considered in the model as noted in Section 5.1.3. There is therefore no separation between power supply sources and distribution components within each zone that can be used to calculate the restoration ratio.

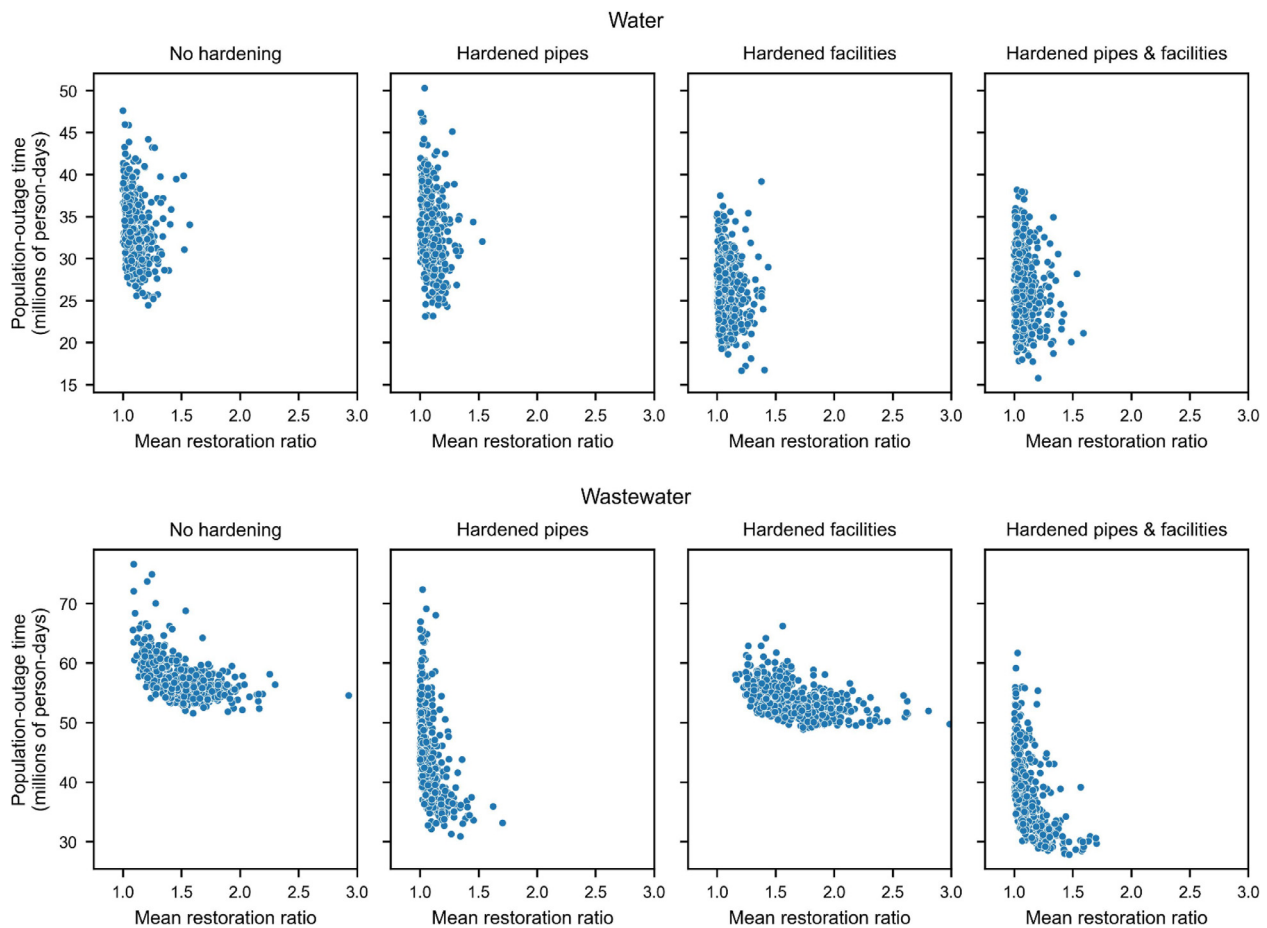
Table 2 shows the mean restoration ratio and population-outage time for each scenario and trial depicted in Fig. 6. The values shown in Fig. 6 and Table 2 confirm the dependence that each system has on shared or external resources. A low baseline restoration ratio for the water system indicates that it is highly dependent on external resources (non-local pipeline repairs) for its recovery. That is, the resources available to complete local water pipeline repairs in the baseline scenario are already sufficient to repair them before the systems on which they depend (transmission system, facilities, power system, etc.) are functional.

Reducing the required repair time for local pipelines by hardening them therefore does not meaningfully reduce the system outage time because the dependence on external systems remains unchanged. Taken to the extreme, this indicates that local water pipelines may be completely undamaged after an earthquake, but users will still experience a loss of service due to external factors.

In contrast, hardening facilities reduces the required repair time of external systems such that more of them are repaired before local water systems. This has a significant effect on the population-outage time of the water system, reducing it by 21 percent. The restoration ratio again changes little in this scenario, indicating that the system is still highly dependent on external resources and could therefore experience additional improvements from further investment in external hardening or resource increases.

The wastewater system is significantly more dependent on shared resources (local wastewater pipeline repair crews), and its population-outage time and restoration ratio decrease by 24 percent and 27 percent, respectively, in the hardened pipe scenario. In the hardened facilities scenario, the restoration ratio for the wastewater system increases by 13 percent, indicating an increasing trend toward dependence on shared resources. That is, the sooner external components are repaired, the more dependent a system is on its own resources for recovery.

As such, the wastewater system exhibits a balance of dependence on both internal and external resources that is characterized by: 1) an average baseline restoration ratio of greater than 1 (most zones are repaired after the source and other zones), 2) a decreasing restoration ratio as internal repair times decrease (increasing dependence on external re-



**Fig. 6.** Total population-outage time compared to mean restoration ratio for each trial in the four baseline resource scenarios for the water and wastewater sectors. Each point represents one trial in the specified scenario for the identified sector.

sources), and 3) an increasing restoration ratio as external repair times decrease (increasing dependence on shared resources). The water sector, on the other hand, is already highly dependent on external resources, so only a considerable decrease in shared resources or increase in external resources would significantly change its restoration ratio.

The restoration ratio can be used to evaluate resource allocations for regional and local authorities. As noted, for example, damage to local water pipelines in the model is repaired quickly enough to avoid causing delays to the restoration of the system in the base resource case. Adding crews to repair water pipelines may therefore incur significant costs while not providing additional benefits to residents. If additional crews are able to complete other repairs instead, residents may benefit from a faster restoration of other services without negatively impacting the resilience of the water sector.

There is no ideal restoration ratio, so communities should seek to balance the needs of their residents with an efficient use of their resources. Zones far away from a source will likely have a restoration ratio that is much greater than 1, but that is neither inherently good nor bad. If all zones have a very high restoration ratio, it may indicate a need for additional resources, while a very low ratio for all zones may indicate an inefficient use of existing resources.

## 7. Discussion and future work

Each of the DRR strategies applied to this case study provides benefits to the restoration of water, wastewater, and power systems in the study region. These benefits are realized as reductions in post-disaster repair requirements or reductions in system outage times and vary in

their efficacy based on the type and structure of each system. Choosing strategies to implement is beyond the scope of this work and should instead be done at a local and regional level by weighing costs and benefits with the needs and priorities of affected communities.

In the remainder of this section, key insights from the case study and their potential integration into decision-making or planning processes are highlighted. Comprehensive emergency response exercises, such as those developed by Emergency Management British Columbia (EMBC) [51], take years to plan and execute and involve ongoing engagement and collaboration with participants (see [52] for example) that cannot be captured in a single manuscript. This work is therefore intended to supplement and inform such processes rather than replace them.

### 7.1. Mutual aid agreements and resource allocation

Key to the results presented in this work is the assumption that an existing mutual aid agreement between local authorities [53] allows crews and resources to be allocated anywhere in the region to repair water and wastewater systems rather than finishing repairs within their local authority before moving to others. Ensuring that there are no barriers to this process should be a priority if regional disaster management is desired, as coordination between groups can be a significant challenge in disaster response scenarios [50]. Other mutual aid agreements exist, including one with Pacific Northwest states in the United States [54], but it is likely that local response will be the most immediate and streamlined.

The language used in mutual aid agreements should be discussed if integrated regional recovery is to be prioritized over local recovery. For

example, agreements may limit the definition of emergencies to immediate threats to health and safety and encourage sharing of local resources only in such situations. These threats are clearly important to address, but additional coordination could be immensely valuable even after immediate danger is mitigated.

Consider, for example, two zones in different local authorities that both require repairs to water pipes after an earthquake. Residents are not in immediate danger and are being provided with alternative water supplies (so the situation may no longer constitute an emergency). The first zone's pipe damage is to a major distribution line that serves tens of thousands of residents, while the second zone's damage is limited to local service lines that serve a few homes. At a regional level, sending repair crews from the second zone to the first provides the greatest reduction in population-outage time, and it is significantly easier to continue to provide alternative water supplies to a few residents in the second zone than to thousands in the first. For the second local authority, however, extending their own outage by sending repair crews elsewhere provides no local benefit and adds the additional cost of providing their residents with alternative water supplies.

As is, the model used in the case study assumes that regional recovery is the priority, so such situations should be considered to determine how they would be addressed in an actual emergency. Reviews of EMBC's emergency response exercises (e.g. [55]) indicate that these challenges are already being discussed by some participants.

### 7.2. Investing in upgrades and repairs

The reduction in repair time compared to length of replaced pipe presented in Fig. 3 offers a starting point for identifying locations that may benefit most from upgrades. Pipes could further be separated and targeted for replacement based on their diameter or criticality in the system. Uncertainty in the damage assessment and potential for different hazards to cause different levels of damage, however, could diminish the benefits of such an approach.

A comparison of the length of replaced pipe and the decrease in outage time for each scenario can be done as well to provide additional insight into the potential benefits of completing upgrades. Fig. 4 and Fig. 5, for example, clearly demonstrate that pipe replacement has a negligible impact on the loss of resilience and restoration time of the case study region's water system, so upgrades may not seem beneficial. If the costs to do such an upgrade are negated by a reduction in post-disaster repair costs, however, it may still be worthwhile to do so. Estimated costs (from previous projects or databases like those given in [56]) should certainly be included in this type of assessment.

Financial incentives can be employed in conjunction with rapid work approval processes to encourage contractors to complete work ahead of schedule. Such incentives increase the direct costs to complete repairs, but the regional economic benefits realized by an earlier return to service can far outweigh these costs (see, for example, [57,58] for evidence of this from the 1994 Northridge earthquake).

Repairs to system components after a disaster can be used as an opportunity to upgrade and improve system resilience, but funding mechanisms may not be structured to support this practice. Existing guidelines for financial assistance provided by the government of British Columbia, for example, indicate that costs to enhance public works are not eligible for emergency response and recovery funding if they exceed the cost to restore the system to its pre-disaster state [59]. If enhancements are made, local authorities are responsible for the difference in cost to do so, but they may not be prepared to incur such costs in the aftermath of a disaster. As a result, the system is returned to its pre-disaster state and cannot benefit from opportunistic or synergistic upgrades (replacing undamaged brittle wastewater pipe with ductile pipe while the road is disturbed for repairs to the water system, for example) that would otherwise enhance its long-term resilience.

### 7.3. Community considerations

Adding a normalization parameter, as presented by Singh et al. [37], can enhance comparisons of population-outage times throughout the region. Using population for normalization, for example, provides the average estimated outage time per person in one or more zones. Population-outage times can also be normalized to the cost of performing upgrades or repairs to demonstrate the economic impacts that outages have on the region. For large groups of zones, however, normalizations may obscure outliers in the recovery process that are important to consider when working at a regional scale.

To ensure that the needs of all community members are adequately addressed in the aftermath of a disaster, decision making and planning processes should include technical experts, system operators and maintainers, local and regional planners, policy makers, residents, and others. Facilitating decision making with such unique groups is challenging but improves outcomes for large projects [60] and recognizes that they will all be involved in the disaster recovery process regardless of their individual expertise.

Developing community awareness of disaster risk and post-disaster recovery needs is therefore an essential part of disaster preparation as well [61]. As part of this preparation, communities should be aware of the potential for cascading effects from damaged infrastructure systems based on their locations [62]. A road could be closed, for example, due to water or wastewater leaks or downed power lines. There are complications in accounting for the high number of co-located systems in a metropolitan region and uncertainty surrounding the full range of spatial failure effects. Future work can examine methodologies for including such impacts in a regional-scale disaster restoration model like that presented here.

With access to the appropriate data, simply identifying locations in which multiple infrastructure systems intersect is relatively straightforward, however, so correlating this information with probabilities of damage and local knowledge can highlight areas that are especially vulnerable to cascading failures as part of a more detailed assessment in individual communities [62,63]. Societal needs and the costs and benefits of DRR implementation must also be considered as part of a comprehensive assessment to ensure that all community members are represented even if they cannot take part in the assessment process [64–67].

### 7.4. Modeling

Additional engagement with local authorities can improve model development and clarify assumptions. Model results depend on model inputs, and the inputs to the case study in this work are developed using data and assumptions based on earlier studies and historical disasters. Modifying the inputs with feedback from local authorities (details about resource availability, seismically hardened components, etc.) can strengthen the results of the model and improve local awareness of disaster risks. An example of the implementation of this type of process and recommendations for its success are included in [68].

Location-specific interdependencies can also be considered in the modeling process based on community input. As noted in Section 5.1.4, the case study included in this work considered a limited number of dependencies between infrastructure systems. Other interdependencies may exist or may not be of significant concern in some cases. For example, if backup generators are available for powering water and wastewater pumps, their dependence on the overall electrical power grid is less critical.

Further simulations and assessments with additional scenarios can help capture the effect of interdependencies on each of the modeled infrastructure systems. For the purposes of this work, a limited number of scenarios was selected, but others can certainly be considered. Hardening facilities or increasing resource availability only in the power sector, for example, would provide additional insight into the dependence that other systems have on the power network.

Social or functional infrastructures that depend on multiple physical systems could be included in the model as well. Examples include the healthcare or food distribution systems that require water, wastewater, power, road, telecommunication, and other infrastructures to function properly [69,70]. For the purposes of this work, only the functionality of physical systems is included, but social systems can be modeled by connecting their functionality to the availability of physical systems.

Technical opportunities exist to enhance the modeling processes used in this work as well. Physics-based or other fragility functions could be included to more accurately represent components and conditions in the region [71,72]. Effects from other hazards can also be considered to identify similarities in damage that would further support investment in risk reduction measures.

This work may be used as an initial step in identifying beneficial investments for reducing community disaster risk, but the strategies presented here do not necessarily present optimal repair sequences. As such, optimization methods, such as those developed by the researchers mentioned in Section 2, can further improve recovery processes to reduce outage times.

## 8. Conclusion

Disaster risk reduction (DRR) strategies are intended to reduce the negative impacts that communities experience after a disaster. This work describes methods for assessing the resilience of regional critical infrastructure systems and changes to the resilience based on the implementation of DRR strategies.

Results from the assessment indicate that the effectiveness of such strategies is highly dependent on the resilience of individual system components and the availability of resources to complete repairs. For some components, pre-disaster upgrades are highly effective in reducing system outage times, while others may not benefit from replacement unless they are damaged in a disaster.

This work provides tools that can support planning decisions by highlighting areas where information is lacking or additional assessment is needed. It is one part of a comprehensive process that includes more than just the recovery of physical systems, but should consider social vulnerability, equity, and community recovery as well.

## Relevance to resilience

This work addresses the effectiveness of disaster risk reduction strategies on improving recovery outcomes in critical infrastructure networks. The reduced recovery times of these systems directly contributes to an increase in system resilience that is further discussed in the work.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.rncs.2023.05.001](https://doi.org/10.1016/j.rncs.2023.05.001).

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