Multi-infrastructure restoration modeling to support regional planning for recovery following earthquakes

by

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Bachelor of Science, Engineer, Dordt College, 2014
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Abstract

The complexity and interconnected nature of critical infrastructure systems across metropolitan regions presents a unique challenge for communities to understand how they may respond and recover in the face of a major disruption. Disaster recovery modeling facilitates coordination and planning among stakeholders, but detailed system models are often complex and require significant technical skill to construct and interpret. The first part of this work presents the development and assessment of a simplified seismic recovery model for water, wastewater, and power systems in the Metro Vancouver region of British Columbia, Canada. The model considers important geospatial and interdependent characteristics of multi-infrastructure systems without requiring access to complete operational models. The model is expanded in the second part of this work to consider the effectiveness of disaster risk reduction measures on infrastructure service recovery to the population after the earthquake. Finally, a detailed hydraulic water system analysis is compared to the simplified modeling approach for a seismic hazard scenario to consider how results from each compare given various restoration strategies. Results from the three sections of this work demonstrate the utility of a simplified multi-infrastructure modeling approach for assessing recovery at a regional scale, the potential benefits of investing in disaster risk reduction measures to improve recovery outcomes for residents, and aspects of modeling approaches that provide an understanding of their use and benefits for disaster management purposes.

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Introduction

Disaster management and emergency response planning are complex and ever-evolving fields. As urban populations grow and depend on increasingly interconnected critical infrastructure systems, vulnerabilities of lives and livelihoods become concentrated in densely populated areas and need to be protected. Equipping critical infrastructure system operators, owners, community members, and other stakeholders with the tools that are needed to protect themselves in the face of natural and man-made hazards is an important role.

Modeling hazard behaviour, hazard impact and damages, and the patterns of recovery that systems experience in the aftermath of a disaster can help communities build resilience and the capacity to respond to significant disruptions. In many cases, however, modeling approaches either require significant technical expertise and data to develop, or lack spatial or temporal resolution that make them useful for planning purposes.

The work presented here specifically focuses on the development of novel methods to model the restoration of critical infrastructure systems after earthquakes (though the methodologies presented are not strictly limited to use on earthquakes) and explores the creation and use of novel modeling tools that communities can use (and have used) to plan to respond to significant critical infrastructure disruptions. The following three chapters are written as distinct manuscripts, so there is a degree of repetition in the introduction and motivation for each as they address similar challenges in the space of disaster recovery modeling.

Chapters 1 and 2 were developed out of a broader disaster risk reduction project focused on seismic resilience in the Metro Vancouver region of British Columbia (Sage on Earth Consulting 2022). The basic conceptualization and motivation for those chapters is therefore developed from that project. Contributions from project partners are noted as appropriate. Dr. David Bristow provided project guidance, supervision, technical help, and manuscript editing suggestions, and Andrew Deelstra developed the baseline models and new methodologies presented in chapters 1 and 2.

Project conceptualization, development, and modeling for chapter 3 was done by Andrew Deelstra. Dr. David Bristow provided project guidance, supervision, and manuscript editing suggestions.

The content of Chapter 1 (with minor edits) is published in *Natural Hazards* (Deelstra and Bristow 2023) and is reproduced with permission from Springer Nature in accordance with their policies (Springer Nature 2023). Chapter 2 was submitted to *Resilient Cities and Structures* (ISSN 2772-7416) and is currently under review. *Resilient Cities and Structures* is published by Elsevier, whose terms state that articles may be included in theses or dissertations without the need for written permission (Elsevier 2022). Chapter 3 has not been submitted for publication at this time and there is therefore no concern surrounding copyright and permissions for that chapter.

The following paragraphs provide a summary of each of the chapters contained in this work and the key contributions of each.

Chapter 1

Chapter 1 describes the development of a model of recovery for multiple interconnected infrastructure systems extending throughout a metropolitan region. Current models of infrastructure systems tend to fall into one of two categories:

1) Highly complex and limited to modeling a single type of system in extensive detail. These models are generally geared toward system design and operation planning.
2) Statistical or analytical models that characterize overall recovery of a given system over time but lack a consideration of the spatial processes of restoration or interactions between systems.

The regional infrastructure restoration model developed in this chapter is constructed for use with the Graph Model for Operational resilience (GMOR) and fills the gap between existing modeling methodologies by including spatial components of recovery and interconnections between systems without requiring highly detailed system data or specific technical expertise for use in constructing planning scenarios. Damage and restoration of service are considered for distinct zones that each represent a population of approximately 500 people.

A case study application of the modeling methodology for a single baseline case of the recovery of water, wastewater, and power systems after an earthquake in the Metro Vancouver region of British Columbia is included to demonstrate the use of the model at the scale of a metropolitan region. To develop the model used in the case study, Geographic Information System (GIS) data for the water, wastewater, and power systems in the region was collected from project partners and public data repositories. The data was processed and standardized for use in this model and for other purposes as required by project partners.

Additionally, new methods and processes were developed to simplify the creation of spatial and attribute-specific dependencies between components and systems in the regional restoration model. Further improvements to the modeling process increased the speed at which aggregated zones of infrastructure systems can be created, which is a critical step in developing a regional restoration model.

Methods for assessing restoration using the regional modeling approach are presented as well and include:

- Restoration curves – a plot that includes some metric of restoration (in this chapter, population with restored service is used) on the vertical axis and time on the horizontal axis to show how recovery progresses over time.
- Restoration ranking – demonstrates the likelihood that a zone will recover before or after those around it and can highlight areas that are especially quick to recover or those that may need extra assistance after a disaster.
- Restoration ratio – a ratio between the time at which service is restored to the time it takes to simply repair damage within a zone. The ratio may be used to show the degree to which zones are dependent on resources within their service area and resources outside of their service area.

Chapter 2

The impact of disaster risk reduction measures on spatial and temporal components of critical infrastructure restoration is not well understood. Chapter 2 extends the modeling approach and baseline model of Metro Vancouver infrastructure systems developed in Chapter 1 to assess the effect of disaster risk reduction strategies on system recovery. The following three physical (strategies 1 and 2) and operational (strategy 3) changes are modeled:

1) Upgrading all water and wastewater pipelines made of brittle materials (such as cast iron and asbestos cement) to ductile material (such as ductile iron or HDPE) to reduce their risk of damage due to ground motion from an earthquake.
2) Seismically hardening all water, wastewater, and power facilities (storage tanks, pumps, and substations, for example) by upgrading their components from unanchored to anchored.
3) Doubling crew and equipment availability for completing repairs in the aftermath of the earthquake.

Combinations of the three strategies are also modeled, so a total of eight unique scenarios are developed. Primary work for this chapter involved recalculating damage levels for infrastructure components using updated fragility curves to represent hardened systems and modifying repair resource requirements to represent an increase in repair crew availability. These changes were reflected in the regional restoration model for each of the eight scenarios.

Results from each of the scenarios are compared to those developed for the baseline case presented in Chapter 1 using the assessment methods presented in that chapter as well. These results show variations in the effectiveness of certain changes to highlight how those changes comparatively impact certain areas or systems in the region.

Chapter 3

Subtle operational decisions in restoration processes can have a significant influence on the overall restoration of service across space and time within critical infrastructure service areas. Chapter 3 considers the restoration of service to a water distribution system after an earthquake using two unique methodologies:

1) A detailed hydraulic model, created with the Water Network Tool for Resilience (WNTR) that calculates the flows and pressures of water through storage facilities, valves, pumps, and pipes in the water distribution system. Individual components can be controlled to represent damage to the system, and service restoration is considered for hundreds of individual demand nodes that each represent an average of 30 people.
2) A simplified model developed in the same method as those created in Chapters 1 and 2 and processed using GMOR. This model aggregates damage and restoration of service into only 28 zones (with an average population of 500 people) rather than the individual demand nodes included in the hydraulic model.

The damage and time required to repair damage for each component is kept the same for the development of each model to provide an accurate comparison. Multiple combinations of pipe breaks and leaks with unique repair times are considered to present a range of possible damage and restoration scenarios.

Restoration in the simplified model is processed with GMOR in the same way as in Chapters 1 and 2, while four realistic restoration strategies are considered for the hydraulic model:

1) **Total shutdown:** Water supply tanks and reservoirs are shut immediately when the earthquake occurs and only reopened once all broken pipes are repaired.
2) **Shutoff supply and isolate:** Water supply tanks and reservoirs are shut immediately when the earthquake occurs. Valves are closed within the system to first isolate all broken components and then complete repairs. Tanks and reservoirs are reopened once damaged components are isolated.
3) **Maintain supply and isolate:** Broken components are isolated and repaired in the same way as for the **shutdown and isolate** strategy, but water supply tanks and reservoirs are never shut.

4) **Rolling repairs:** Water supply tanks and reservoirs are never shut. Instead of first isolating all damage, however, damage is isolated and repaired on a component-by-component basis.

Repairs to leaking pipes (rather than broken pipes) are addressed identically for each strategy and repaired in a similar manner to the **rolling repairs** strategy after all broken pipes are repaired.

The results from the scenarios and strategies modeled for this chapter demonstrate how the actions taken by water system operators after a damaging event can have a significant impact on the process of recovery of the distribution system. The hydraulic model results are compared to those produced by GMOR to provide a benchmark for aggregated water restoration models and demonstrate their utility for modeling water distribution system restoration in situations where the information or expertise required to develop a detailed hydraulic model are unavailable.

Chapter 1: Methods for representing regional disaster recovery estimates: modeling approaches and assessment tools for improving emergency planning and preparedness

Abstract

Recovering from earthquakes and other natural hazards can require lengthy restoration periods for damaged critical lifeline systems. To effectively prepare for disasters, planners and emergency managers can use modeling to assess the impacts that a disaster could have over time and how their systems may recover over time. Modeling approaches are often technically complex and require a great deal of data and expertise to develop and assess. While such models are immensely valuable for providing a detailed understanding of a system, their complexity makes them challenging to develop for a large region, especially if interconnections between multiple systems are considered. This work demonstrates the development of a multi-infrastructure restoration model for an entire region that utilizes more commonly accessible infrastructure system data to assess the process of recovery of multiple infrastructure systems. The modeling methodology is applied to perform an earthquake recovery assessment of the water, wastewater and, power systems in the Metro Vancouver Region of British Columbia, Canada. Road and highways are also included in the initial stages of the analysis, but the relatively minimal damage did not necessitate a complete recovery assessment. Assessment methods include measuring outage using service restoration curves, ranking restoration times for different zones to describe areas that are relatively more or less at risk after a disaster, and comparing restoration time and repair time to assess a system's internal and external dependencies. Results from this work indicate that the proposed methodology is a viable approach for modeling the restoration of multiple interconnected infrastructure systems at a regional scale and that the assessment methods considered provide valuable insight that can be used by planners and emergency managers to consider and plan for the restoration of critical services to their communities.

1-1 Introduction

The aftermath of earthquakes can require lengthy timelines for the restoration of infrastructure lifeline systems in communities. Because it is not currently possible to prevent all forms of outages caused by earthquakes, providing communities with opportunities to mitigate their risks, prepare for disaster, and improve their response and recovery processes post-disaster can lead to improved outcomes for residents and businesses in affected communities (Rodríguez, Quarantelli, and Dynes 2007).

One of the ways in which communities can plan to address the risks from natural hazards that they face is by modeling the hazards and their impacts on natural and built environments. Modeling approaches can be broadly grouped into models of hazard behaviour, hazard and disaster impact, and disaster recovery. Here it is important to note the transition in terminology from hazards to disasters. Hazards are naturally occurring phenomena (which may be influenced by human activity), while disasters occur when hazards have some effect on human well-being (Peijun Shi 2019).

Modeling hazard behaviour includes things like predicting the path and intensity of hurricanes (F. Zhang and Weng 2015) or the probability of landslides after rainfall (Salciarini, Fanelli, and Tamagnini 2017). Hazard and disaster impact modeling considers the probable damage to natural and human environments caused by hazards, such as damage to mangroves from tropical cyclones (C. Zhang, Durgan, and Lagomasino 2019) or to water pipelines from earthquake (Bagriacik et al. 2018). Disaster recovery models provide estimates of recovery times or processes required to restore the functionality of services such as power (Duffey 2019), water (Tabucchi, Davidson, and Brink 2010), or sewer systems (M. Liu, Scheepbouwer, and Gerhard 2017) to communities after a disaster.

Hazard behaviour and impact tend to encompass relatively large geographic areas. Earthquakes, wildfires, and floods, for example, are generally not limited in their effects to a single town or city, so it can be beneficial for stakeholders within a broader region to consider how they all may be impacted by a disaster. Modeling recovery at a regional level can therefore promote partnerships between stakeholders and encourage coordination that prevents delays in critical disaster response scenarios (Shinozuka et al. 1995) and enhances regional resilience.

Due to the geographical scale and high population of many regions, modeling response and recovery for an entire region is a complex task. Some researchers, however, have had great success developing recovery models of large, complicated systems. A notable example is Çağnan and Davidson's modeling work on potable water and electric power supply systems using the Los Angeles Department of Water and Power's (LADWP's) systems as case study applications (2003; Davidson and Çağnan 2004). This work was extended and improved over many years to develop comprehensive recovery models of the systems that closely match the restoration patterns observed after the 1994 Northridge, California earthquake (Çağnan, Davidson, and Guikema 2006; Çağnan and Davidson 2007; Tabucchi, Davidson, and Brink 2010). The work was further developed to assess post-earthquake strategies that can improve restoration times for customers in the region (Brink, Davidson, and Tabucchi 2012; Xu et al. 2007).

While the models used to assess the recovery of the LADWP systems are immensely valuable and are designed to be applicable to other regions as well, acquiring the data to do so is often a significant challenge. LADWP had a hydraulic model of the water system available for researchers, and the assessments include only water and power customers served by the LADWP. In many regions, multiple layers of management and control are involved in providing residents with critical infrastructure services. High level services (bulk water transmission, major roadways, etc.) are managed by the regional or higher authority, but local authorities (such as cities or municipalities) are also involved in managing their own infrastructure systems (water distribution to individual homes, neighbourhood roads, etc.) as well.

In systems like these, access to the level of detail required to develop a comprehensive model of critical infrastructure systems is therefore complicated by the multiple organizations involved, to say nothing of the time and labour challenges. Data sharing agreements or privacy and security concerns may further limit access to data, and detailed models of each system may be hosted within different software environments or may not exist at all for some areas. This is not to say that it is impossible to develop comprehensive models of multiple systems in other regions, but doing so is an expensive undertaking that would take years to complete and significant resources to maintain.

As an alternative, simplified models or estimations may be used to represent recovery at a regional level. These are not intended to predict exactly what will happen in a disaster scenario, but instead develop (through participatory planning activities) an awareness of patterns and processes among stakeholders that can enhance community resilience (Miles 2018; Shaw 2014; Mojtahedi and Oo 2017).

Models and methods developed by Han et al. (2009), Nateghi, Guikema, and Quiring (2011) and Liu, Davidson, and Apanasovich (2007), for example, utilize data from numerous historical hurricanes and ice storms to predict outage times and locations for future storms on the Gulf and East Coasts of the United States. These estimations can be employed when a new storm approaches to help residents and operators prepare before the power system is disrupted.

Earthquakes in a given location generally occur with much less frequency than hurricanes and ice storms in the eastern and southeastern United States, but models of recovery after earthquake still use historical data to estimate outage times for different infrastructure sectors. The Applied Technology Council’s ATC-13 report (1985), the US Federal Emergency Management Agency’s (FEMA’s) Hazus

(2022), the National Institute of Building Sciences' (NIBS) Earthquake Loss Estimation Methods (2004), and Zorn and Shamseldin (2015) all use historical data to provide estimations of recovery after earthquake for various infrastructure systems.

These approaches are very valuable for providing estimations of service restoration time that can be used at a regional scale, but lack the spatial resolution and integration of system interdependencies that a detailed model can provide. To bridge the gap between complex, data-intensive system models and models that can be rapidly deployed but are less spatially explicit, this work presents models built for use with the Graph Model for Operational Resilience (GMOR) for regional assessment of earthquake recovery.

Bristow and Hay developed the GMOR to provide a platform for modeling individual entities within infrastructure systems and the dependencies that connect them along with their probability of failure, repair time, and required repair resources (Bristow and Hay 2017; Bristow 2019). The functionality of each entity is tracked over time for a set of trial simulations to demonstrate the restoration of service for each included system.

While GMOR has been used in previous recovery assessments of infrastructure systems (Deelstra and Bristow 2020), their scale was limited to a single municipality. The objective of this work, therefore, is to demonstrate the use of GMOR in the development of a recovery model and subsequent assessment of the restoration of service to interconnected infrastructure systems for an entire region with multiple municipalities using relatively accessible infrastructure system information. In the following sections, the development of the regional infrastructure restoration model that is input into GMOR is shown for a case study region and novel methods for assessment of the model results are presented. Finally, the utility of the model, assessment methods, and opportunities for improvements and future work are discussed.

1-2 Methodology

The methodology concerns the development of a regional infrastructure restoration model for use in GMOR and of a set of recovery assessment techniques (Figure 1-1). The regional infrastructure restoration model takes a damage assessment, repair time estimates and dependencies as inputs. The damage assessment includes strictly physical damage to several infrastructure systems as a function of a given hazard. The infrastructure systems included in the restoration model are water distribution, wastewater collection, electrical power transmission and distribution, and the road and highway network. Each system is described briefly in the following sections with respect to its layout and functionality within a generic study area. A specific case study using the methodology for an earthquake hazard in the Metro Vancouver region of British Columbia, Canada, is provided in Section 1-3 and following. The methodology can be applied to other hazards as well given that appropriate input data and hazard information is available.

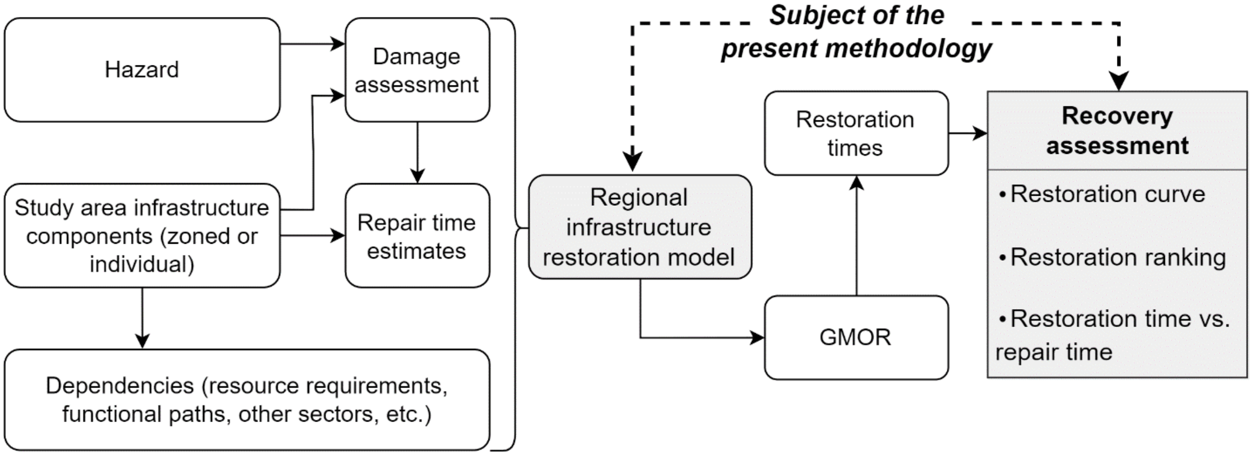

Figure 1-1: Overview of recovery modeling methodology. Shaded shapes are the subject of the present methodology.

1-2.1 Damage and repair time assessment

A brief overview of the damage and repair time needs of the model is given here. Further details of their implementation are presented in the case study found in Section 1-3.

An assessment of damage estimates to infrastructure components and systems is performed using a chosen hazard and location. A limited damage assessment can be performed within GMOR using certain hazard parameters, but a more specialized damage assessment platform that can consider additional hazard information is preferred, provided that each component can be geospatially referenced. Estimated repair times based on the level of damage and component type must be defined as well, and can come from the same source as the damage assessment or from other damage and repair sources.

Infrastructure system data required to produce a model include, at minimum, the location of individual components, such as water pipelines and storage tanks (an example of this is shown in Figure 1-2a). This information is commonly available through Geographic Information System (GIS) data repositories. The location of components alone can be used to produce a damage assessment using generic values from a chosen assessment platform. More detailed infrastructure data, such as pipe material, age, and diameter, however, can be used to produce a more accurate damage assessment. These additional characteristics are often also included in GIS data repositories, may be listed in municipal infrastructure reports, or can be deduced for larger components from an assessment of satellite imagery.

A means of estimating required repair time for individual components based on their level of damage is also necessary for developing a model. This estimation must also include the number of people, crews, or resources required to complete repairs. Availability of resources in the area of interest must therefore also be included as part of the modeling process to provide an estimation of and limit to the rate at which repairs can be completed.

The specific source of this information is not relevant for developing the regional infrastructure restoration model. The information in the following sections related to the damage assessment and its implementation is included solely to provide a more complete understanding of the process used in developing the regional restoration model.

The regional infrastructure restoration model includes resource entities that represent repair crews and the materials and equipment that they use to perform repairs. Repair resource availability is limited such that each repair resource can only be utilized for one repair at a time. Once a repair is completed, the resource entity moves on to the next repair until no more repairs are required. Multiple resource entities can be added so that many repairs can occur concurrently.

Individual component repair times are not affected by altering the number of resources available in the model. Instead, an increase in resources increases the number of possible concurrent repairs, so the overall restoration time of the system is reduced.

The order in which components are repaired is supplied as an input to the model. This order can be based on the physical layout of the underlying infrastructure network, critical facility locations, population, or any number of other factors. Repair order can also be randomized or grouped to provide further control over the progression of repairs.

Here a distinction must be made between repair time and service restoration (or recovery) time. Repair times used as inputs to the model include only the time required to repair single components. Restoration time, on the other hand, includes the time required to repair not only a single component, but to also repair all other components on which that component depends. For example, the water pipelines on a residential street could have their breaks and leaks repaired, but full restoration of water service is only possible when the water storage reservoir and upstream pipes are also repaired. This distinction is critical for the development of one assessment method described in Section 1-6.

1-2.2 Sector Structures

Generic descriptions of the included infrastructure systems are described here. The layout varies based on location but this general approach is the foundation for the methodology used in the regional infrastructure restoration model described in this study.

1-2.2.1 Zones

One key feature of the multi-infrastructure modeling methodology is the separation of a region into distinct zones for both the damage and recovery assessment. These zones provide the ability to structure systems in a way that represents the layout of the various networks while also demonstrating broad trends in damage and recovery in a region. The size of zones used is important, as too large of a zone provides limited local relevance, while too small of a zone overly complicates the model.

In this model, zones are used to aggregate damage and service restoration information for multiple sections of linear infrastructure systems (such as water or wastewater pipelines). Damage and restoration information is separated by sector for each zone, however, so each service provided in a single zone will have a unique entity associated with it in the model. For example, if a zone includes both water and wastewater pipelines, there will be one entity in the model representing damage and restoration to the water pipelines, and a second entity representing damage and restoration to the wastewater pipelines within that zone.

Damage to facilities, such as water treatment plants and electrical power substations, are considered at an individual facility level. The interaction between zones and facilities is detailed in the following sections.

1-2.2.2 Water Supply System

Municipal water supply systems are designed to transport water to residents and other users for a variety of purposes. While each system is unique, this section describes a common structure but should not be read as a comprehensive overview of water supply system design.

Filtration and treatment of raw water is generally provided at one or more large facilities. From these facilities, water enters the transmission part of the system and is distributed via gravity or forced via pumps through large principal feeder mains to local storage reservoirs or tanks throughout the region. From the local reservoirs and tanks, the distribution part of the system branches off through smaller mains and service lines to supply water to end users. The water level in reservoirs is controlled to regulate pressure at a local level, but pressure reduction systems or pressure boosting pumps may be used as well, especially in areas where a single reservoir serves users over a wide range of elevations (Twort, Ratnayaka, and Brandt 2000).

A spatially referenced model of the functionality of the water system in a region requires some method of demonstrating that a water user within the system is connected to the water source via a functional set of pipelines and facilities. A functional path to a user may be possible even if certain portions of the network are damaged or out of service if valves or other tools can be used to isolate the damaged portion (Creaco, Franchini, and Alvisi 2010).

As indicated in Section 1-1, most water operators do not have easily accessible detailed hydraulic models of their water systems that include individual connections, user demands, pump curves, and other information in a fashion that is suitable for disaster risk assessment. By aggregating pipeline data, the number of entities created in a system model is greatly reduced, which is valuable for displaying results at a municipal or regional level. At the same time, the overall network layout of the system is still considered.

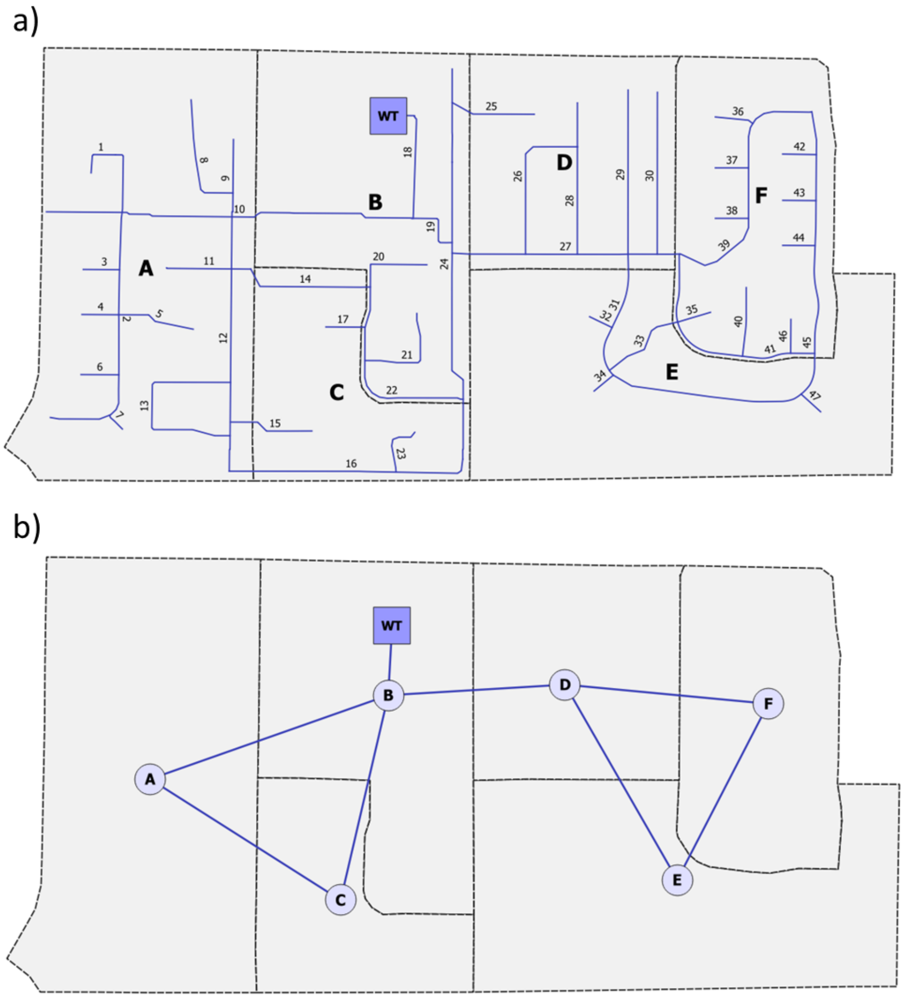

Figure 1-2: The actual layout of the pipelines in the water distribution network (a) and the aggregated version of the network (b). The water storage tank (WT) provides water service to users in each zone.

Within the regional infrastructure restoration model, the water supply system is separated into a transmission system and distribution system. The transmission system carries water from water treatment facilities through large mains, pump stations, and reservoirs and into local tanks, reservoirs, and pump stations. Damage to transmission pipelines is aggregated at a zone level. In many cases, a zone contains only a single length of transmission pipeline, so damage to the modeled transmission system zone effectively represents damage to that section of the pipeline. Water reaches local tank, reservoir, and pump facilities only after transmission pipelines and large reservoirs are repaired and electrical power is available for pump facilities.

The water distribution system is separated into service areas for each point source (local reservoir, tank, or pump station) that is assumed to provide water to residents. Some pumps, for example, are used to fill reservoirs, so the reservoir is considered the point source, not the pump. Within each service area, distribution pipelines are aggregated at a zone level as shown in Figure 1-2 for a simple example network.

Figure 1-2a shows the service area’s distribution system in its original state with 6 separate zones, a single water storage tank (WT) that serves as the service area’s point source, and 47 individual pipeline segments. The zone-aggregated system is shown in Figure 1-2b. Note that the connections between zones follow the overall structure of the original network such that zones are only connected to one another if a water pipeline in the original network crossed the border between them. For example, the node representing zone C is not connected to that of zone E because no pipes cross the border between zone C and zone E in the original network.

The number of breaks and leaks for all pipelines within a zone is summed to derive an overall estimated number of breaks and leaks for that zone. In the present regional infrastructure restoration model, each service area is supplied with water from only a single point source within its municipality. In an actual system, a service area could be supplied with water from one of several point sources due to redundancies and interconnections within the water distribution network. Acquiring sufficient data to model the specific details of these connections, however, is often not possible and the connections may change over time throughout a disaster recovery process. The modeling approach described here is therefore conservative in limiting each service area to a single point source.

For a zone to be supplied with water in a service area, a functional path to the water point source must first be established. A functional path is established when the pipelines within the zone, the pipelines in upstream zones, and the point source are all functional. For users in zone E in Figure 1-2 to be supplied with water, for example, the water storage tank and pipelines within zone B and zone D must first be functional. In other parts of the network, there may be more than one possible path from a zone to a point source, so the restoration time of the earliest recovered path determines the restoration time of the zone.

Note that this modeling approach may be conservative in the restoration time estimates that it provides because any damage in an upstream zone prevents water from flowing through to downstream zones. In an actual system, the damage in a zone may be a small pipe at the end of a dead-end road or easily isolated from the rest of the system, so its effect on the overall network is negligible.

1-2.2.3 Wastewater System

Wastewater from homes and other users flows through pipelines that eventually reach a wastewater treatment plant before being discharged into a river, lake, or ocean. In most municipalities, it is impossible to build the network in such a way that the wastewater treatment plant is at a lower elevation than all users and can operate solely via gravity, so pumps in lift stations are used to force pressurized wastewater to higher elevations or treatment plants (Bizier 2007). In some areas, stormwater and wastewater systems may be combined, though this is not common in modern systems.

The structure of the wastewater collection system in the model is very similar to that of the water distribution system described in Section 1-2.2.2. Pipelines are aggregated into zones within service areas that are dependent on a single wastewater lift station. Paths to the lift station are constructed in the same way as for the water distribution system. Lift stations are connected by large wastewater mains to one another and ultimately to a wastewater treatment plant in a similar manner as the pumps and transmission reservoirs in the water transmission system. Lift stations and treatment plants are both modeled with a dependence on the electric power network described in Section 1-2.2.4.

1-2.2.4 Electrical Power System

Electric power is generally produced in generating stations and transmitted via high voltage wires to substations where the voltage is reduced for further distribution. Additional transformers within the system further reduce the voltage to levels that are appropriate for industrial, commercial, or residential use.

Due to the specialization and complexity of modern electrical systems and the flexibility and redundancy inherent within them, a complete model of a system is challenging to produce and may not be accessible to those outside of power utilities. As a result, a simplified representation of the system is created in the regional infrastructure restoration model. The simplified model is inspired by NIBS and FEMA methodologies for seismic loss estimation for power systems (G & E Engineering Systems Inc. 2004; Federal Emergency Management Agency 2011) and contains only generating facilities and substations.

The electric power distribution system is separated into service areas in the model such that each service area is dependent on a single substation. Each substation is dependent on one or more generating facilities via high voltage transmission lines that pass through other substations. The high voltage transmission lines that connect substations to one another and the generating stations are assumed not to fail in the model. This assumption is based on the NIBS methodology that notes that the rate of damage is generally low for high voltage transmission lines (G & E Engineering Systems Inc. 2004).

Damage to individual substations is provided from the damage assessment. If a substation is damaged, it is assumed that it cannot provide power to users in its service area and cannot provide a functional path for high voltage transmission to other substations until it is repaired. In this way, the power system is modeled very conservatively in that substations are only functional once they are completely repaired, rather than having some partial level of functionality throughout the recovery process.

1-2.2.5 Road and Highway Network

The road and highway network in the model is mostly aggregated at a zone level. Damage to individual road segments is provided by the damage assessment as a probability of occurrence for multiple levels of damage. To calculate the overall damage level for a zone, the probability of damage for each road segment is weighted based on its length and summed with all other road segments within the zone. For scenarios where there is a consistent level of estimated damage throughout a region, aggregating data at a zone level can provide a valuable overview of the effects of the hazard on the region. If minimal overall damage is predicted, however, aggregation may obscure more severe damage. For example, a single road in a zone may be subject to significant damage, but if all other roads in the zone are assumed to be undamaged, the aggregation process would indicate minimal damage in the zone as a whole. To avoid this, road segments in the region are assessed at an individual level as well to pinpoint those that may experience high levels of damage.

1-2.3 Assessment methods

Raw outputs from GMOR for the regional infrastructure restoration model include the service restoration times of individual zones for each considered infrastructure sector as well as for facilities in the region. The methods used to assess these outputs are briefly described here. The utility of the assessment methods is more clearly demonstrated in Section 1-6 using results from the case study presented in the following sections.

One of the simplest methods for assessing GMOR outputs is quantifying the mean or median service restoration time for each zone in the region. A map of average restoration times can quickly show a general overview of what recovery looks like for different municipalities and neighborhoods in the region but does not provide a more detailed understanding of the process of recovery.

Results can also be presented as a restoration curve, which shows some metric of recovery on the vertical axis and time on the horizontal axis. This can be shown at a regional or municipal level to demonstrate the overall patterns of recovery in the region. A restoration curve clearly demonstrates that some zones will recover before the median in individual trials and others will recover after the median. If the population with service is used as a metric for recovery on the vertical axis, the number of person-days of outage can be calculated by quantifying the area above the restoration curve. This measure of outage can be normalized by population to compare different municipalities within the region.

Ranking service restoration times is another way to illustrate patterns of recovery more clearly than median recovery times can on their own. While the mean rank of any zone will closely match the mean service restoration time relative to other zones, looking at the maximum or minimum rank can provide additional insight. For instance, a zone that never ranks beyond the 50th percentile for service restoration time may be beneficial to target for hosting an emergency operations center or resource distribution hub.

Finally, repair times and restoration times can be compared. As described in Section 1-2.1, there is a clear distinction between individual entity repair times and service restoration times, and providing a comparison between these two values can highlight zones and municipalities that are highly dependent on external factors or if internal delays impact their recovery. Equation 1 presents a (hereafter referred to as) restoration ratio that can be used to compare these values. The restoration ratio equation is presented here and described in further detail in Section 1-6.4 in reference to the case study.

$$restoration\,ratio = \frac{restoration\ time\ (zone)}{restoration\ time\ (source) + repair\ time\ (source)} \quad \text{Eq. 1}$$

1-3 Study Area

The study area considered in a use case for this work is the Metro Vancouver region of British Columbia, Canada. The Metro Vancouver region is made up of a partnership of 21 municipalities, one treaty First Nation, and one Electoral Area (Metro Vancouver 2019). The extent of the region is shown in Figure 1-3.

This region is in an area subject to significant seismic hazard which warranted a study of its susceptibility to damage and the process of recovery that it may experience after an earthquake (Bird et al. 2021; Journeay et al. 2015). The service area zones chosen for the region are Census Dissemination Areas (CDAs). These areas have an average population of between 400 and 700 residents, geographically cover the entire region, and are the smallest of the geographic areas for which all census data are disseminated, making them valuable for a variety of assessment purposes (Statistics Canada 2016).

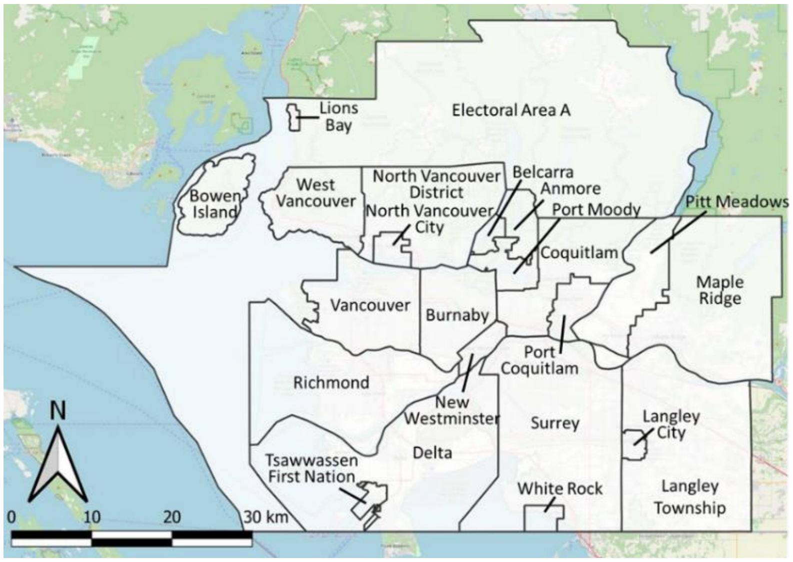

Figure 1-3: Map of the municipalities in the Metro Vancouver region study area. Background map OpenStreetMap (OpenStreetMap contributors 2022).

1-3.1 Hazard and damage assessment

The hazard selected for this case study is a magnitude 6.8 in-slab earthquake with its epicenter west of the City of Richmond. While effects in the region from this earthquake are not expected to be as damaging as other potential earthquakes, it is one of the most likely to occur in the region and was chosen for use in a response planning exercise as part of an ongoing assessment of hazard resilience in the region (Bird et al. 2021). Damage assessment inputs are provided by the Geological Survey of Canada (GSC), part of Natural Resources Canada (NRCan)(Wagner and Chow 2021) and are used for this work and for planning purposes at various levels of government.[1]

For this study, a single median damage scenario is selected for use in the regional infrastructure restoration model. This approach provides a distinct scenario that can be used for planning and

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[1] In the process of assessing the outputs from GSC, it was discovered that the Hazus software referenced the wrong fragility curves for some facility types. The error was reported to the developers to be corrected in future software releases. For this work, the damages were manually calculated using the correct fragility curves, so the error had no effect on the final results.

community preparedness purposes. In previous work done using GMOR, outputs from Hazus led to an extensive range of possible outcomes, which is useful to understand the extremes that can be experienced after a disaster but may be too broad for use in planning exercises (Deelstra and Bristow 2020).

1-3.2 Infrastructure systems

In the following sections, the features of the different studied infrastructure systems are described. The methodology used for their assessment is given in Section 1-2, but its specific application to the systems in the region necessitates further explanation that is provided here and in the Supplemental Information.

1-3.2.1 Water System

The Greater Vancouver Water District (GVWD) is one of the corporate entities of the Metro Vancouver federation and manages bulk water distribution in a majority of the Metro Vancouver region, while municipalities manage water distribution to residents and other users (Metro Vancouver 2011).

The water distribution system starts in the northern part of the region where three watersheds supply water to three main distribution points via two treatment plants. Water from the filtration and treatment plants is then fed by gravity or pumping through GVWD-operated transmission mains to 26 reservoirs (Metro Vancouver 2022b). From the GVWD reservoirs, water is distributed to individual households in the region by means of municipally owned and operated reservoirs and pumps.

The material used in constructing water pipelines has a significant impact on their resilience to earthquake damage. Hazus allows for the categorization of pipe as brittle or ductile, with damage to ductile pipe calculated as 30% of the damage to brittle pipe (Federal Emergency Management Agency 2011). Brittle pipe material types include vitrified clay and cast iron, while ductile pipe material types include most types of plastic pipe, ductile iron, and welded steel (Pitilakis, Crowley, and Kaynia 2014). Where pipeline material is unknown, brittle pipe is assumed in the assessment to provide a more conservative estimate. Overall knowledge of pipe material for the region is well over 90% with close to 70% being ductile pipe, which is included in the damage assessment and the regional infrastructure restoration model.

Information about valves, pressure reduction stations, rechlorination stations, and other water facilities is not included in this assessment due to data availability.

The number of residents supplied water by means of the Metro Vancouver comprises a significant portion of the population in the region, but smaller municipal systems are also present in the region.

Exceptions to the general system layout described here, as well as additional details about the system, are noted in the Supplemental Information.

1-3.2.2 Wastewater System

Like the potable water distribution system, the wastewater collection system in Metro Vancouver is managed jointly by a regional entity, the Greater Vancouver Sewerage and Drainage District (GVS&DD), and local municipalities. Five wastewater treatment plants serve the region and separate it into distinct service areas. Thirty-eight pumps are used to force wastewater toward the wastewater treatment plants within each treatment plant service area (Metro Vancouver 2022a). Brittle and ductile pipeline damage is calculated in the same way as for the water distribution system.

1-3.2.3 Power System

Electrical power supply in the region is provided by BC Hydro. BC Hydro operates 50 generating stations in the province of British Columbia and provides power to over 4 million customers (BC Hydro 2019).

Within the area surrounding the Metro Vancouver region, there are six generating stations (BC Hydro 2015). For the purposes of this study, the system is modeled so that all power to the Metro Vancouver region travels from these six generating stations through three primary substations. The substations are located to the northwest, northeast, and east of the region. The northwest source is the Cheekeye substation, the northeast source is the Lake Buntzen substation, and the eastern source is the Clayburn substation.

Each CDA in the region is assumed to be dependent on the single nearest BC Hydro substation. Exceptions are noted in the Supplemental Information. Individual substations are dependent on a path of functional substations that ultimately leads to one of the three power sources for the region. This approach is conservative in that it assumes that residents can only be provided power by a single substation, while the reality may be that multiple substations can supply power if needed.

1-3.2.4 Road and Highway network

The road and highway network in the region is collected from the province’s Digital Road Atlas (GeoBC 2021). Due to a lack of available data and specialized assessment required, bridges and tunnels are not included in the model. Unpaved roads and privately maintained roads (such as those within a shopping or housing complex) are also not included.

As with the other infrastructure systems in the model, zones for the road and highway network are set at the CDA level. The length of road within each CDA ranges from under 1 kilometer to well over 100 kilometers.

1-4 Damage Assessment

In the following sections, details of how the Geological Survey of Canada's damage assessment is represented in the regional infrastructure restoration model that is input into GMOR are presented.

1-4.1 Water Distribution and Wastewater Collection

For water and wastewater systems, damage to pipelines is collected at the CDA level and is represented as a number of breaks and leaks. For the pipelines in the region, damage is mostly concentrated in areas where there is a known risk of liquefaction. Maps of damaged areas are shown in the Supplemental Information. Damage to facilities, such as pumps and reservoirs, is given by a specific damage state, ranging from no damage to complete failure.

1-4.2 Electrical Power Distribution

Damage to the power system is limited to that of the electrical substations in the region. Given the methodology described in Section 1-2.2.4, generation facilities, local transformers, and powerlines and support structures are assumed to remain undamaged in the assessment. 90 of 91 substations in the region experience slight damage (indicating a failure of 5% of the substations components or minor shifting), while 1 substation experiences moderate damage (characterized by a failure of 40% of the substation components or moderate shifting and misalignment of components) (Federal Emergency Management Agency 2011).

1-4.3 Road and Highway Network

Damage to the road and highway network collected at the CDA level is minimal. As indicated in Section 1-2.2.5, this is a consequence of weighting the damage by the length of each road segment in the CDA. As a result, the damage to individual road segments for this hazard is investigated.

The individual road segment assessment reveals that of the approximately 10,000 kilometers of roadway in the region, less than 5 kilometers are expected to be extensively damaged (full road closure until repaired), and less than 15 kilometers are expected to be moderately damaged (partial road closure until repaired)(Pitilakis, Crowley, and Kaynia 2014). The predicted location of road damage varies and is scattered throughout the region, so it is unlikely to cause complete isolation of any neighbourhoods.

While the impact of road damage is important to acknowledge and may be considered in a planning exercise, the limited extent of the damage and its impact on overall restoration does not warrant further inclusion in this study.

1-5 Repair and Restoration

The restoration of different infrastructure systems in the region is described in the following sections. Repair time parameters are drawn from Hazus (Federal Emergency Management Agency 2011) and based on historical data and expert judgement. The specific parameters used in this study are summarized in the Supplemental Information.

1-5.1 Resources

Available resources in the region represent the number of repair crews capable of making repairs for a specific infrastructure system and location. The values used in the model are developed based on the number of municipalities in the region and historical disaster recovery data. Each entity in the model is dependent on only one type of resource that is assumed to encompass multiple types of repairs and processes. A resource does not represent the same set of individuals but could include multiple types of specialized crews.

Repair resources for most sectors in the region are assumed to be shared throughout the region and not limited to a single municipality. A current mutual aid agreement for the municipalities in the region demonstrates that this is the goal for recovery in the aftermath of a disaster (Gale 2000). The agreement has not yet been tested in the region, however, so the efficiency and execution surrounding sharing resources may lead to unanticipated complications in the recovery process.

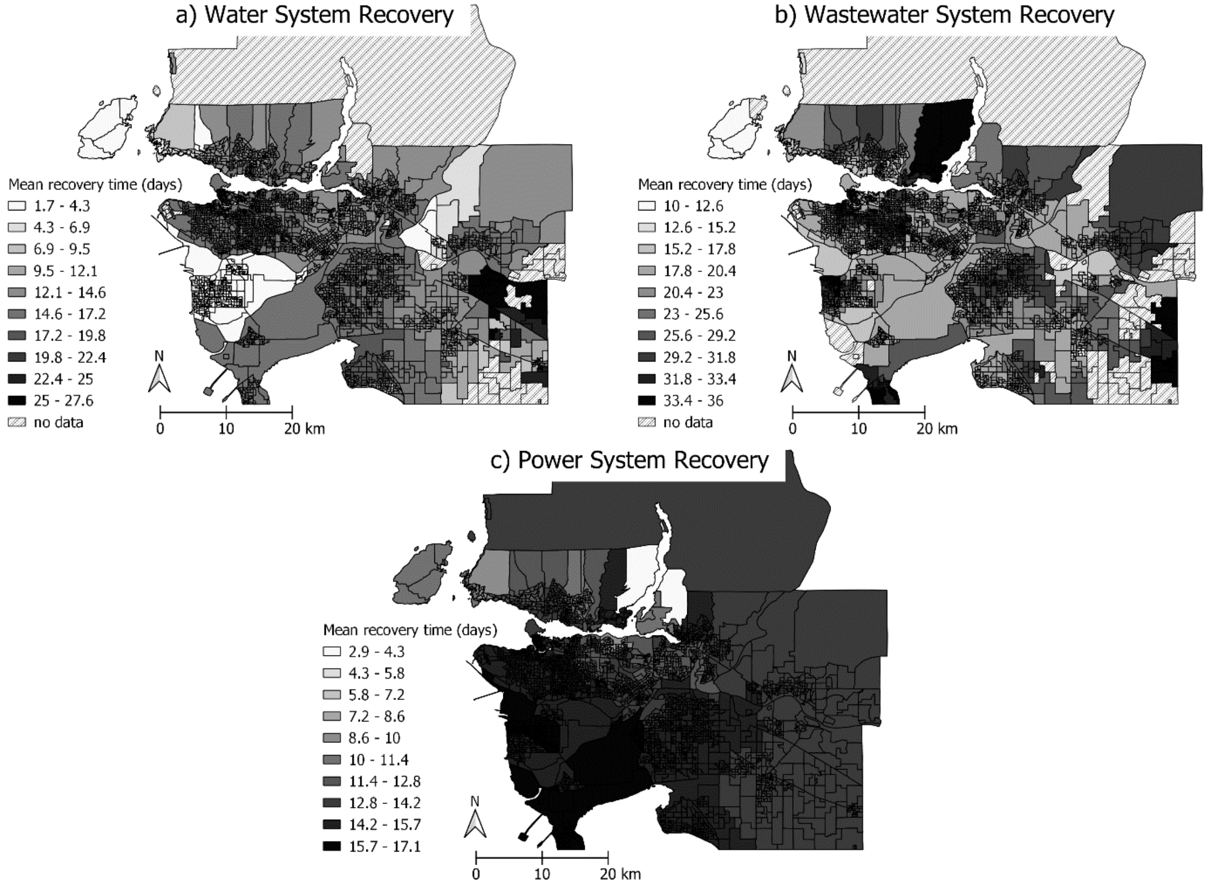
1-5.2 Repair Prioritization

For this case, the order in which repairs are completed is established based on a zone's distance from the source that supplies it. In the case of water, for example, a CDA that is located adjacent to a water reservoir will generally be repaired before a CDA that is located farther away. The order of repair for individual CDAs is not completely predetermined, however. Instead, multiple CDAs are grouped based on their distance from the point source. The order of repair for each CDA within a group is randomized, but every CDA in one group must be repaired before repairs start in the next group. Randomized ordering of repairs within each group reflects the uncertainty of break and leak locations, their detection, and subsequent repair.

It is important to note that the distance from the source entity is not determined based on the physical distance but instead based on the number of nodes (as depicted in Figure 1-2) separating the source and the zone. In this way, repairs and restoration of service propagate outward from each point source over time in an approach similar to that proposed by the Wellington Lifelines Group (which includes the region's utility providers) for service restoration in Wellington, New Zealand, after an earthquake (2012). Other ordering schemes can be considered, such as prioritizing areas with the least amount of damage or highest economic impact (Chang, Svekla, and Shinozuka 2002), but those are not included in this work.

1-6 Results and assessment

The regional infrastructure restoration model for this scenario is run in GMOR using Latin hypercube sampling for repair times, which ensures that a range of repair times are selected from their probability distributions. Results for each sector demonstrate convergence based on a running standard deviation difference between trials of less than 1%. Approximately 500 trials were run for this study.



a) Water System Recovery

b) Wastewater System Recovery

c) Power System Recovery

Figure 1-4: Mean restoration time across all trials for a) water, b) wastewater, and c) power systems. Note the differing scale in each legend.

Section 1-6.1 illustrates mean service restoration time as a metric for recovery, while Sections 1-6.2 to 1-6.4 demonstrate additional methods that can be used to provide additional value in assessing results. Due to the large number of CDAs in the region and multiple sectors being considered, Sections 1-6.2 to 1-6.4 consider a limited geographical scope and sectors for clarity. It should be noted as well that the methods discussed here are presented using CDAs as the entities of interest, but specific components or sectors within the region could be considered instead. Hospitals or banking facility locations, for example, could be isolated in the model results to demonstrate the estimated restoration of those services in the region.

1-6.1 Mean service restoration time

One of the goals of this work is to move beyond using only mean or median service restoration times as metrics for assessment. That said, those metrics are still valuable for demonstrating broad patterns of recovery throughout a region. Figure 1-4 shows a mean service restoration time for each sector for each CDA out of all trial simulations. Mapping the mean service restoration time clearly shows if there are outliers in the results that should be considered in more detail. In some cases, such outliers are expected based on the layout of the network or level of damage experienced. Other situations may require additional investigation.

In many cases, the level of damage does not correlate with the restoration time for individual CDAs within a system. This is caused by the structure of the systems and dependence on supply facilities and other upstream components. Section 1-6.4 specifically demonstrates the often-decoupled nature of damage and restoration time for infrastructure systems and shows how their network structure and dependencies affect the progression of and delays in recovery.

Mean service restoration times show what a region may roughly expect in terms of outage time and recovery after a disaster, but any single outcome will have many zones recover both before and after the mean. As such, the additional assessment methodologies described in the following sections provide additional insights for how the outputs from the modeling process can be used by communities in planning activities to prepare for disasters in their region.

1-6.2 Restoration curves

Restoration curves show a pattern of service restoration after a disaster by demonstrating a specific level of service availability over time. The level of availability can be measured in terms of zones, service areas, or population with restored service on the vertical axis and time on the horizontal axis.

Restoration curves can show if there are delays in restoration (large increase in time with minimal increase in restored service) or if recovery progresses especially rapidly at certain times (large increase in restored service with minimal increase in time). These jumps can be used to identify internal or external dependencies that are critical for the recovery of specific areas in the region. Adjusting the ordering of repairs may help reduce jumps so that recovery progresses more smoothly and predictably. A restoration curve does not show the zones in a consistent order. Instead, it shows the first zone to recover, then the second zone, and so forth, so an individual zone could be first in the restoration curve in one trial and last in another trial.

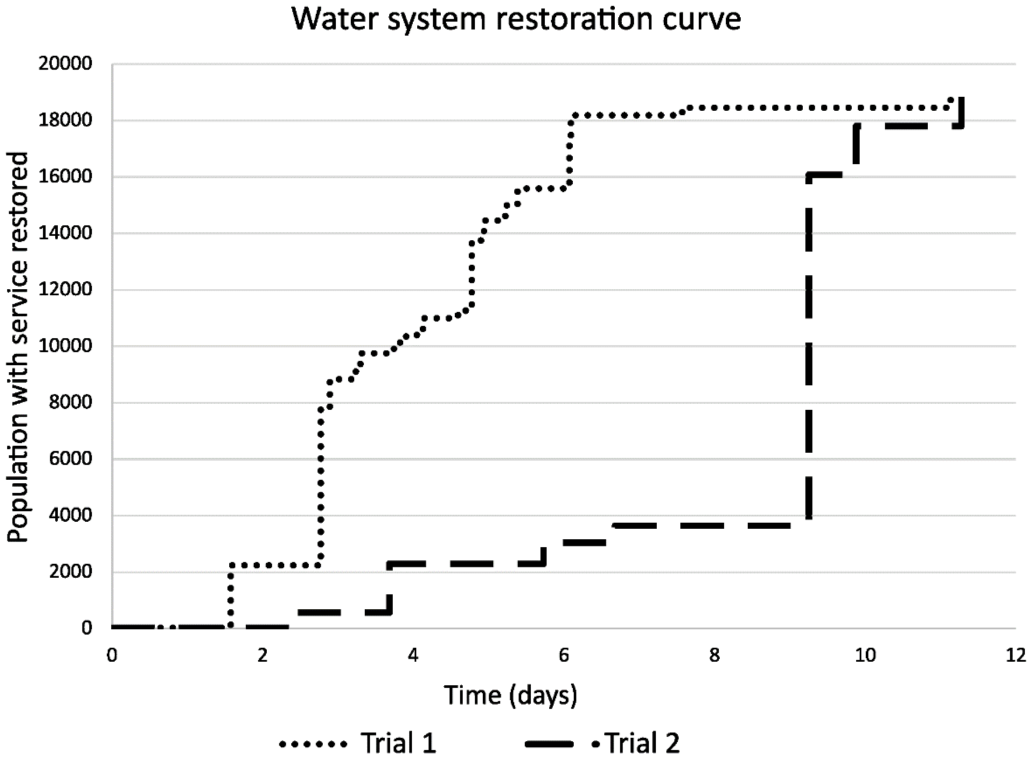


Figure 1-5: Restoration curves for two trials for the water system in one municipality in the study area. While the overall service restoration times for the trials are similar, the number of person-days of outage for Trial 2 is more than double that of Trial 1 due to a delay in the recovery of the power system in Trial 2. This delay prevents a water pump from functioning, leading to the large horizontal jump shown in the figure.

Other valuable metrics can be derived from restoration curves as well. Two trials may result in the same ultimate service restoration time, but the path of recovery to reach that time may vary significantly. Consider a comparison of two of the trials for the water system in one of the region's municipalities shown in Figure 1-5, for example. Both trials result in a very similar overall service restoration time, but Trial 1 results in a much higher population restored to service sooner than Trial 2. By calculating the area above the restoration curve, outages can be calculated using person-days as a metric. In the case of the trials shown in Figure 1-5, the number of person-days of outage in Trial 2 is more than double that of Trial 1 despite a similar overall service restoration time.

A person-day of outage represents one person lacking a service for one day. One day of outage for a zone with 1,000 residents is 1,000 person-days of outage. Two days of outage is 2,000 person-days, and so forth. Comparisons between different parts of a region can be made by dividing the outages by the population to produce an average number of person-days of outage per person that can be quickly compared for any number of zones.

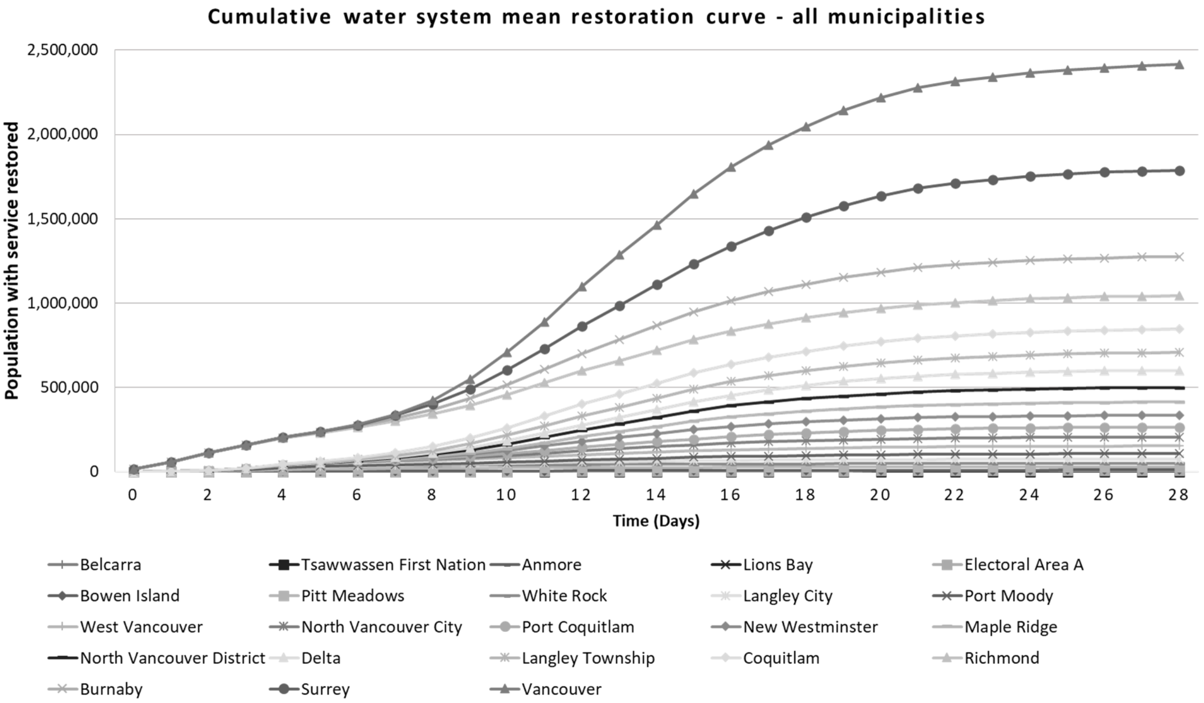


Figure 1-6: Mean restoration curve for the water system for all municipalities in the region. The timeline shown here represents 99% service restoration of the region, while complete restoration takes an additional 20 days.

Areas with similar overall restoration times but vastly different population outage times may have distinct needs in the aftermath of a disaster. Fewer residents initially restored to service indicates that there may be delays in restoration processes from external dependencies (such as the power system dependency causing the delay shown in Trial 2 in Figure 1-5) or other factors, such as resource availability or regional geography. Local community knowledge and input can provide insight into the possible causes for these delays and factors that may help mitigate them.

An overview of the mean restoration curves for the water system for all municipalities is shown in Figure 1-6. Note that only one relatively large municipality, Richmond, shows significant recovery at the beginning of the curve and accounts for over half of the total population recovered in the first week.

Richmond’s water comes directly from the Metro Vancouver transmission pipelines, while other municipalities depend on intermediate pumps and storage reservoirs that slow their recovery. The restoration curve captures the progress of service restoration with much more detail than using solely mean or median restoration times.

1-6.3 Restoration time ranking

Ranking zones by restoration time demonstrates patterns of recovery in the region. Using rank as a measure is valuable even when there is a great deal of uncertainty in resource availability for the region. Specific service restoration times may not be predictable, but the overall pattern of restoration within a region or municipality should not vary significantly because the underlying structure of the network does not change.

Ranking can be used to show if there are significant deviations in recovery for certain zones. For example, if a given zone consistently is ranked near the end for service restoration in a region, it may be valuable to plan for how to address the needs of that population in the aftermath of a disaster. On the other hand, if one area is consistently restored to service before others, it may be valuable for use as a hub of emergency coordination or response activities.

Figure 1-7 shows the minimum, mean, and maximum ranking for two municipalities. In Maple Ridge (left), there is no definite pattern of service restoration for the CDAs in the municipality and it is not clear that some CDAs will always be repaired before others.

In West Vancouver, the situation is significantly different. Some CDAs are consistently restored to service well before others (their maximum ranking is relatively low), while others consistently trail the majority (their minimum ranking is relatively high). This indicates that CDA number zero in West Vancouver would be a good candidate for key water users like hospitals or emergency management centers. In contrast, West Vancouver CDAs that are numbered at or above approximately 70 may need additional resources in the aftermath of a disaster. Even in the best-case scenario for these CDAs, their water service is restored after 60 percent of all other CDAs. Residents in these CDAs may therefore require bottled water distribution sites, hygiene facilities, or other supports.

In Maple Ridge, there is no clear advantage to locating such facilities in one CDA compared to another in terms of water service restoration. The municipality should be prepared to provide supports to residents in all CDAs because any area could experience the slowest restoration of service. Other systems may display different results, however, so considering all users and their requirements is important. Considering overall restoration time is important as well. If, for example, all users are expected to be restored to service in West Vancouver within two days, the level of support needed for the CDAs near the end of the ranking may not be too significant.

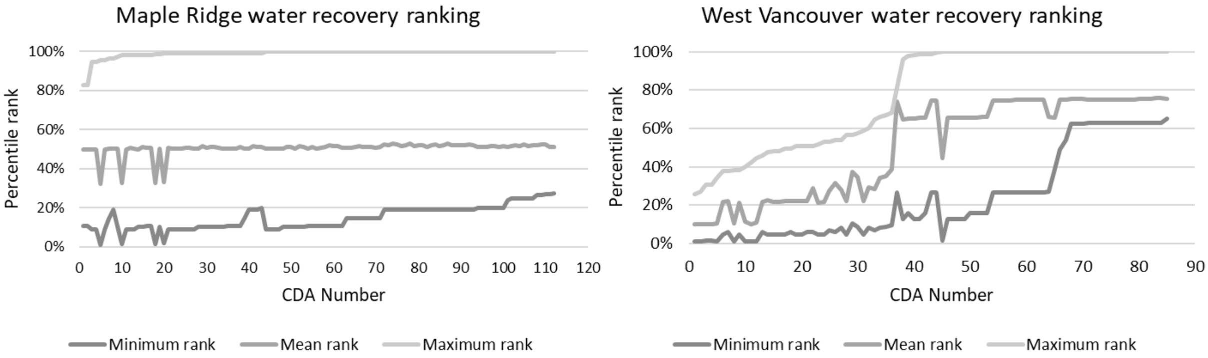


Figure 1-7: Restoration ranking for Maple Ridge and West Vancouver water systems. Note that, for the sake of space and clarity, the CDA number shown here is not the federally assigned CDA. The actual CDA number is included in the full model results, so the ranking can be referenced to the location of the CDA.

Large jumps in minimum or maximum rankings can indicate dependence on separate point sources, such as a different water storage reservoir, for those zones. Alternatively, there may be one damaged zone in a critical location that prevents other zones from being restored. In that case, plans to bypass or isolate the damaged part of the zone while still allowing water to flow to downstream zones can be made.

1-6.4 Restoration ratio

The difference in service restoration and repair times for zones within the region is driven by a combination of the level of damage and the underlying structure of a critical infrastructure network. Assessing the ratio of restoration time to repair time shows areas where repairs may take longer due to the structure of the network rather than the initial level of damage. If there are vulnerable populations or critical facilities in these areas, planners can use this information to prioritize repairs there. In addition, this assessment may help identify areas where additional piping, pumping, or storage infrastructure could be added, especially when the entire region is considered in the assessment. The water transmission system carries water relatively quickly from the main sources to municipal sources, for example, so if there is a particular area that looks more vulnerable or slow to recover, adding water storage and a connection to the transmission system could help significantly improve that area's restoration time.

The restoration ratio equation (Eq. 1 in Section 1-2.3) is structured so that it provides valuable information where a direct division of restoration time by repair time may provide inconsistent results for certain locations. Assume, for example, that service in two neighbouring CDAs is restored after 4 days. In one CDA, the repair time is calculated as 0.1 days while repair time for the other is approximately 1 day. The ratio for the first would be 40, while the second would be only 4 due to the large discrepancy in repair times. The ratio trends toward infinity as repair time approaches 0, so the restoration ratio is used instead. Recall that the restoration ratio compares the restoration time of a zone (in this case, a CDA) to the restoration time of the CDA's point source plus the repair time of the CDA itself. The restoration ratio ignores path dependencies for the sake of simplicity, but effectively normalizes the ratio to provide a valuable comparison between individual CDAs and municipalities.

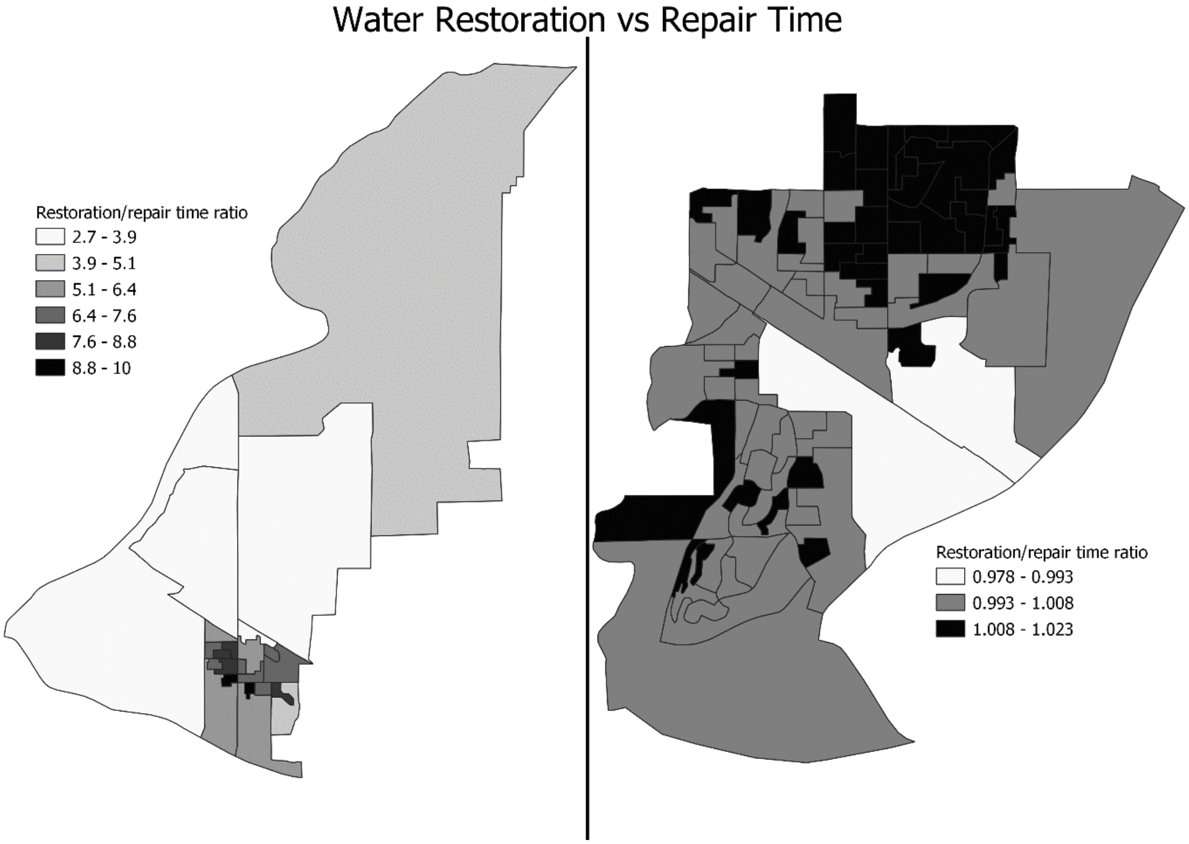


Figure 1-8: Restoration vs repair time ratios for the water system in Pitt Meadows and Port Coquitlam. Note the differing scale in the legends for both municipalities.

A ratio close to 1 indicates that CDAs are restored relatively quickly after their point source is restored, while a value much greater than 1 may indicate that a CDA is far from a source or is in a heavily damaged area. Note that ratios below 1 are possible as well. Assume, for example, that there is minimal damage to the water system in a municipality that can be repaired relatively quickly. The large trunk mains that feed the municipality and the power network are damaged, however, so service cannot be restored until these systems are first restored. At the time that they are restored, however, both the CDA source and CDA itself are restored and the repair time value leads to a larger denominator than numerator in the restoration ratio equation.

This situation indicates a dependence on external factors that operators should be aware of. In this case, a municipality may plan for service restoration to their residents based on the prompt repair to their local system, but dependencies outside of their control could significantly delay service restoration. The model does not account for the storage capacity of local reservoirs or backup power supplies, however, so a delay in restoration times can be mitigated by managing local supply sources while upstream facilities are being repaired.

Figure 1-8 illustrates a comparison of restoration ratios for two municipalities in the study region. Pitt Meadows receives water directly from Metro Vancouver transmission mains, so service reaches the municipality relatively quickly. Therefore, repairs to pipelines within the municipality are the limiting factor when it comes to restoration of water service. In Port Coquitlam, on the other hand, the restoration ratio near 1 indicates that pipelines in the municipality are repaired before water reaches the municipality through a series of transmission mains, pumps, and reservoirs. As soon as the supplying system is available, all pipelines within the municipality are restored to service. Managing local reservoir levels or having backup water sources available could mitigate the effects of delays in restoration due to a dependence on external supply sources.

1-7 Discussion and Conclusions

The restoration of lifeline services in a region after an earthquake is critical for promoting recovery within the region as a whole. This work provides a method by which lifeline service systems and their post-disaster restoration can be modeled at a regional level without requiring access to proprietary information or highly technical system data. While the modeling results are not intended to predict exactly how an earthquake will impact recovery, they provide an opportunity for infrastructure managers, system operators, and system planners to engage with different factors that affect recovery and consider gaps in their knowledge that may impact the preparedness of their communities. Other earthquakes (many of which are noted by Bird et al. (2021)) or entirely different hazards will present varying effects in the region, so it is important for those involved in restoration planning activities to not focus solely on the results from one scenario. Instead, their goal should be to better understand the processes and limitations within their communities that will affect their recovery after any disaster.

Each of the assessment methods described in this work provides additional insight to the recovery process that municipalities may face in the aftermath of a disaster as well. None of the methods should be used independently but are intended to be part of a broader process of assessment, collaboration, and planning. Comparing restoration and repair times using the restoration ratio, for example, does not provide a comprehensive understanding of recovery without also understanding the restoration times themselves. If all zones are restored within a day, for example, the restoration ratio is not as critical as if restoration takes multiple weeks.

There are many opportunities to expand on the work described here. Further investigation could involve the effects of hardening infrastructure systems so that they are less likely to fail or increasing resource availability so that repairs can be completed more quickly. The sensitivity of the overall outcomes in the region to these parameters are not clear and warrant further study as well. Other hazards or regions can also be assessed to determine common effects and provide additional support for implementing interventions that may help minimize them.

Repair priorities can be tailored to suit the needs of specific regions and populations. While a change in the ordering of repairs may not have a significant impact on overall service restoration time for a specific system, it can improve outcomes for specific populations within the region. Schousboe, Lynds, and Ambrose (2013) note that disease outbreaks following the 2011 Christchurch earthquake could be correlated with areas of "higher level[s] of socioeconomic deprivation". This indicates that the effects of a disaster include more than just physical infrastructure impacts and are linked with social vulnerability as well. Weighing social vulnerability with post-disaster needs of different populations is an ongoing area of research that can help guide prioritization of repairs and resource allocation at a local and regional level (Chakraborty et al. 2020; Crowley 2021; Logan and Guikema 2020). Social vulnerability indicators, such as those proposed by Cutter (2003), can help inform this process.

Network-based prioritization optimization can be investigated and utilized as well. The repair prioritization in the current model is based on groups of users at a given distance from a source. Further refinement of this process could lead to improved intermediate recovery and a reduction in person-days of outage without impacting overall service restoration time. Various methods, such as those proposed by Henry and Emmanuel Ramirez-Marquez (2012), may also be used to quantify this improvement in recovery and could be applied to this work.

This work demonstrates the development and utility of a regional multi-infrastructure recovery modeling approach that bridges the gap between inaccessible, highly technical single-infrastructure system models and those that lack spatial resolution and only describe recovery using metrics that apply to a region as a whole. Methods for assessing recovery and service restoration are introduced as well and may be used to provide additional understanding of recovery processes and limitations to those involved in disaster response planning activities. Finally, opportunities are highlighted that can extend the use of this approach to improve disaster planning and recovery outcomes for a variety of regions and populations.

Chapter 2: Assessing the effectiveness of disaster risk reduction strategies on the regional recovery of critical infrastructure systems

Abstract

Communities depend on critical infrastructure systems to support their regular operations and future development. Destructive events, such as natural disasters, disrupt service to these systems and the communities they support. Strategies, such as reducing initial damages, or finding ways to accelerate restoration of service from disruptions caused by disasters and other events are therefore an important consideration for community planning. The relative impacts of such strategies on reducing service outage time at a spatial level are often not well understood. At a regional scale, 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.

2-1 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 (Haimes 2009). 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 tailored to a variety of audiences to enhance the resilience of their communities by engaging them in disaster preparedness and planning processes.

2-2 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 (Ouyang 2014). 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" (2013).

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 2-4.

Models may include only certain systems and thoroughly describe their component specifications, details of crew and material availability 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 (Tabucchi, Davidson, and Brink 2008; 2010) and power (Çağnan and Davidson 2004; Çağnan, Davidson, and Guikema 2006; Çağnan and Davidson 2007) 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 (Brink, Davidson, and Tabucchi 2012; Xu et al. 2007).

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 (Thompson et al. 2019). 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 (2000) and Ogawa et al.'s (2021) 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 (Duffey 2019; Huang, Zhang, and Huang 2022; Porter 2016) and can include methods for improving recovery processes, such as greedy algorithm (2016; Alisjahbana et al. 2022) and multi-objective optimization approaches (2017; Bozorgi-Amiri, Jabalameli, and Mirzapour Al-e-Hashem 2013). Others specifically highlight the uncertainties and difficulties of restoring complex networks and provide strategies for addressing these challenges (González et al. 2016; Fang and Sansavini 2019; Z. Li et al. 2019; Cassottana, Shen, and Tang 2019; Duffey and Ha 2013). Each of these works include specific processes and practices that can be integrated into broader assessment and planning activities.

The final modelling 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. (2009),Guidotti et al. (2016), Karakoc et al. (2019), and the Graph Model for Operational Resilience (GMOR) developed by Bristow and Hay (Bristow and Hay 2017; Bristow 2019).

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 (Deelstra and Bristow 2020; 2023; Deelstra 2019), so its capabilities for supporting the assessment of the considered systems is already established.

2-3 Resilience quantification

The characterization of resilience proposed by Haimes (Haimes 2009) does not include a method for quantifying resilience, but doing so is immensely valuable for comparing different systems. Many of the critical infrastructure 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. (2003) and Cimellaro, Reinhorn, and Bruneau (2005; 2010) 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. (Singh et al. 2022) 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.

2-4 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 (Deelstra 2019; Deelstra and Bristow 2020; 2023).

The network structure of the simplified system is produced by considering borders between zones that linear systems cross as shown in Figure 2-1. 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.

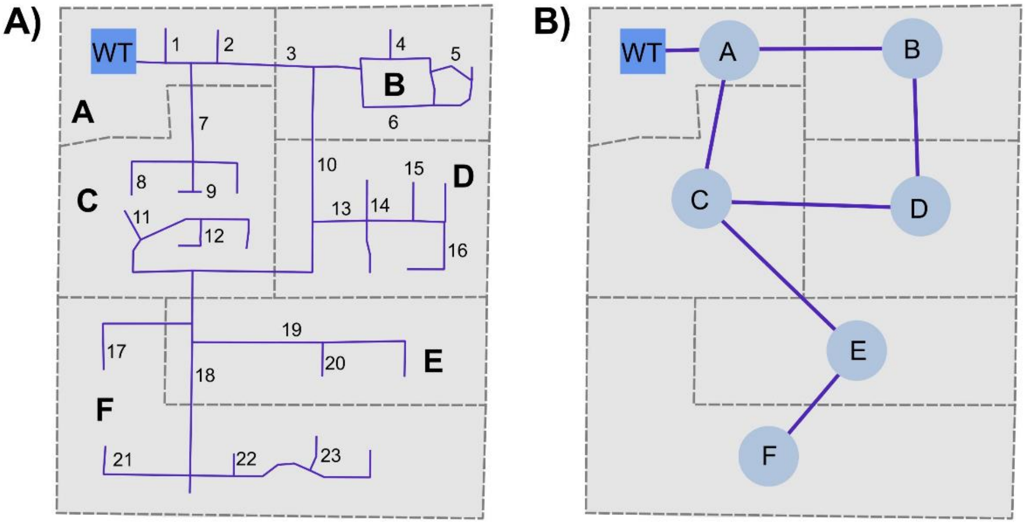


Figure 2-1. Zone layout and aggregation. The six alphabetically labelled zones (A-F) depend on the water storage tank (WT) for water service. (A) Each zone contains multiple pipes that may be damaged in a disaster. (B) Damage estimates for the pipes within each zone are aggregated and represented as 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.

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 Figure 2-1, 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 2-5, 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.

2-4.1 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 done as part of the GMOR modelling process and has no influence on the initial damage assessment process.

2-4.2 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 Figure 2-1, which demonstrates that zones that are closer to the supply node must be repaired to provide functional paths to zones that are farther away.

2-4.3 Repair time, repair cost, and restoration time

It is important to distinguish the repair time identified in Section 2-4.2 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 in 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.

2-4.4 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.

2-4.5 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 2-4.3) 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. (Singh et al. 2022) and discussed in Section 2-3 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 2-7.

2-4.6 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 2-6. Appendix A provides a comprehensive overview of their application as a reference to limit the length of in-text explanation.

2-5 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 (Bird et al. 2021). Ground motions and resulting damages from the earthquake are provided by the GSC (Wagner and Chow 2021), and repair time parameters are established from FEMA's Hazus earthquake manual for each type of infrastructure component considered (Federal Emergency Management Agency 2011).

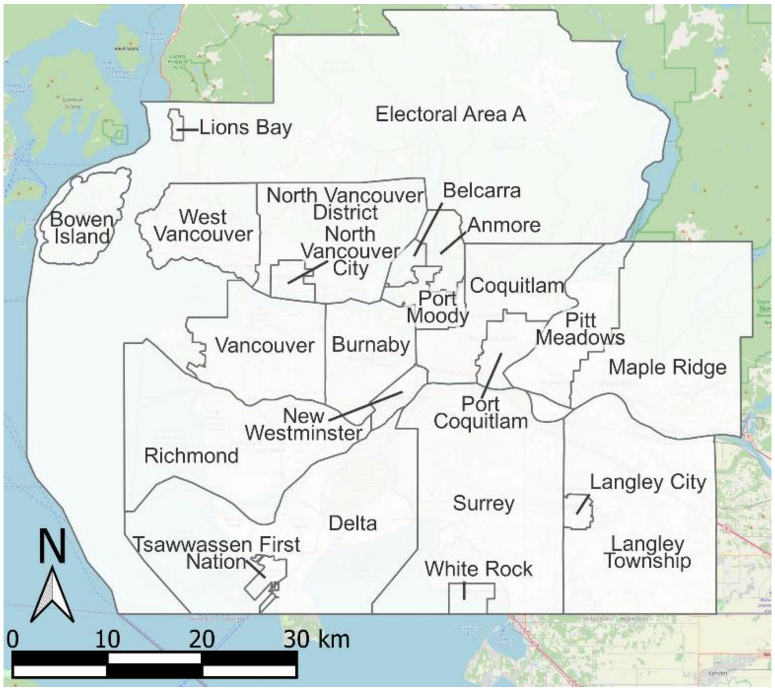


Figure 2-2. Map of the study area with 21 municipalities, Tsawwassen First Nation, and Electoral Area A identified. Background map copyright OpenStreetMap Contributors; licensed under the Open Database License (OpenStreetMap contributors 2022).

Figure 2-2 shows a map of the study region, which consists of 23 local authorities: 21 municipalities, one Electoral Area, and one Treaty First Nation (Metro Vancouver 2021). 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.

2-5.1 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.

2-5.1.1   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 (Metro Vancouver 2022b). 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 (Government of British Columbia 2022), and identifying the use, capacity, and vulnerability of each is not within the scope of this assessment.

2-5.1.2   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 (Metro Vancouver 2022a).

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.

2-5.1.3 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 (BC Hydro 2019). One municipality maintains its own distribution equipment, but is still dependent on BC Hydro for the provision of power to their border (British Columbia Utilities Commission 2012).

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 (G & E Engineering Systems Inc. 2004; Federal Emergency Management Agency 2011). The power system is therefore not modeled using the zone aggregation method shown in Figure 2-1 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.

2-5.2 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 2-4.5, the financial and labour 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 (Federal Emergency Management Agency 2011)). 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 (American Water Works Association 2001) and is therefore modeled as a decrease in the probability of leaks or breaks (Federal Emergency

Management Agency 2011). 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 halve the repair time of a pipe leak, but instead increases the number of repairs that can happen concurrently.

2-5.3 Scenario selection

Eight unique scenarios are developed by using baseline and doubled resource availability for the following 4 scenarios: baseline (no hardening), 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 2-4.4, 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.

2-6 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 2-4.5 and are measured in person-days of outage.

2-6.1 Repair costs

Table 2-1 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.

Table 2-1: 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	1,297	937 (-28%)	1,095 (-16%)	735 (-43%)

An additional distinction is made in Table 2-1 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.

2-6.2 Pipeline repair time reduction and upgrade cost

On its own, the information provided in Table 2-1 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 2-5.2, 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. Figure 2-3 shows this comparison for each local authority for the water and wastewater systems. Note that for the hardening scenarios, all brittle pipelines are replaced and upgraded to ductile pipe, so the percentages shown in Figure 2-3 represent the percentage of brittle pipeline of the total length in each local authority.

The highlighted points in Figure 2-3 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 their seismic vulnerability. In Figure 2-3B, 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 (Federal Emergency Management Agency 2011). This explains the limit of approximately 70 percent reduction in repair time shown in Figure 2-3 for local authorities that currently use primarily brittle pipeline in their water or wastewater systems.

2-6.3 Restoration and outage times

Improvements in restoration time are quantified using the population-outage time metric discussed in Section 2-4.5 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.

Figure 2-4 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 Figure C-1 in Appendix C.

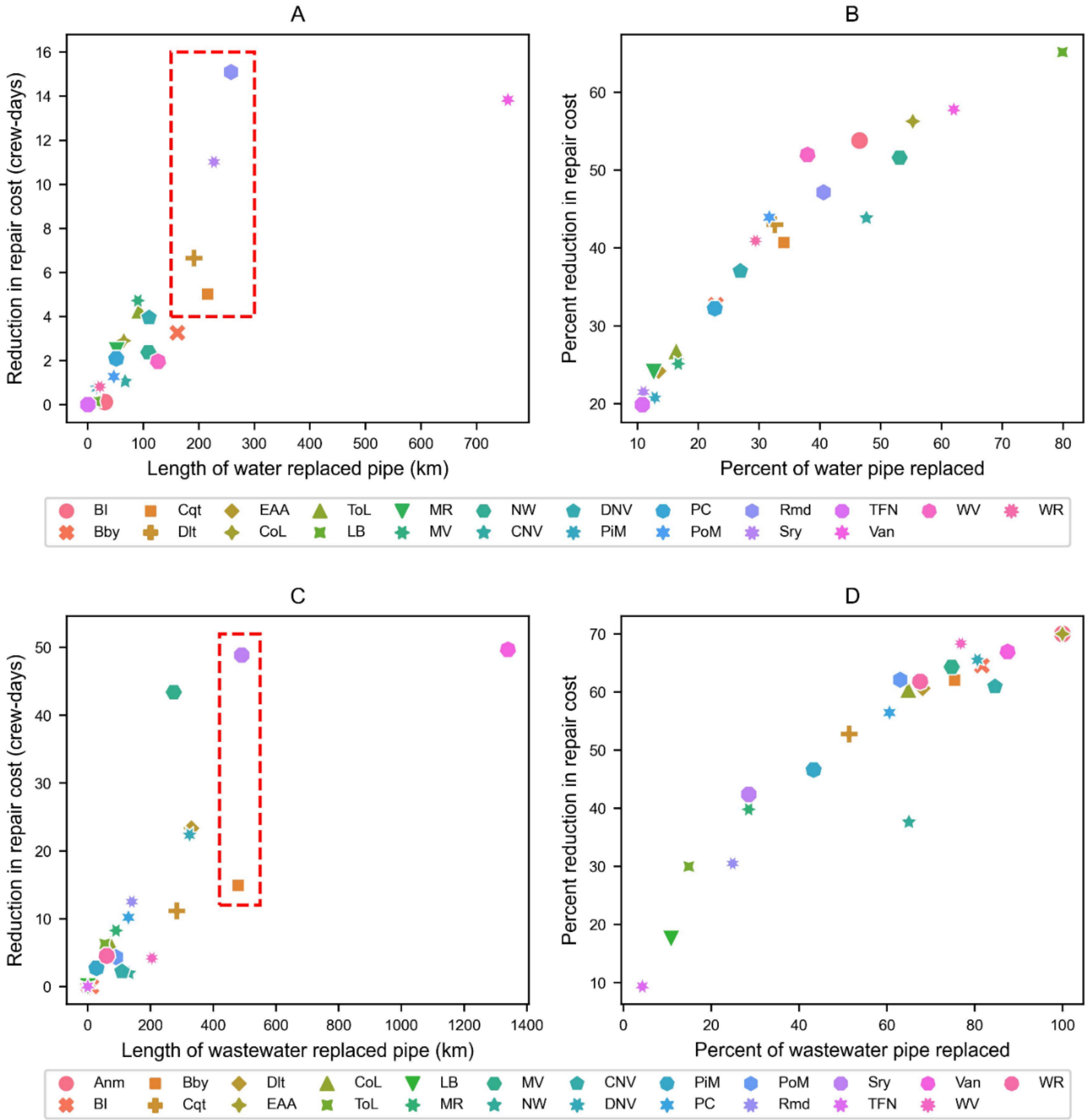


Figure 2-3. Reduction in repair cost due to pipeline hardening compared to the length of pipe replaced for local and Metro Vancouver components of the (A and B) water and (C and D) wastewater systems. (A) and (C) show a reduction in crew-days and length of pipe replaced, while (B) and (D) show the percentage reduction in crew-days and percentage (of the total length of pipeline in the local authority) 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 C-1 in Appendix C.

Hardening infrastructure systems may be assumed to reduce initial system outages, but the restoration curves shown in Figure 2-4 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 service in the zone.

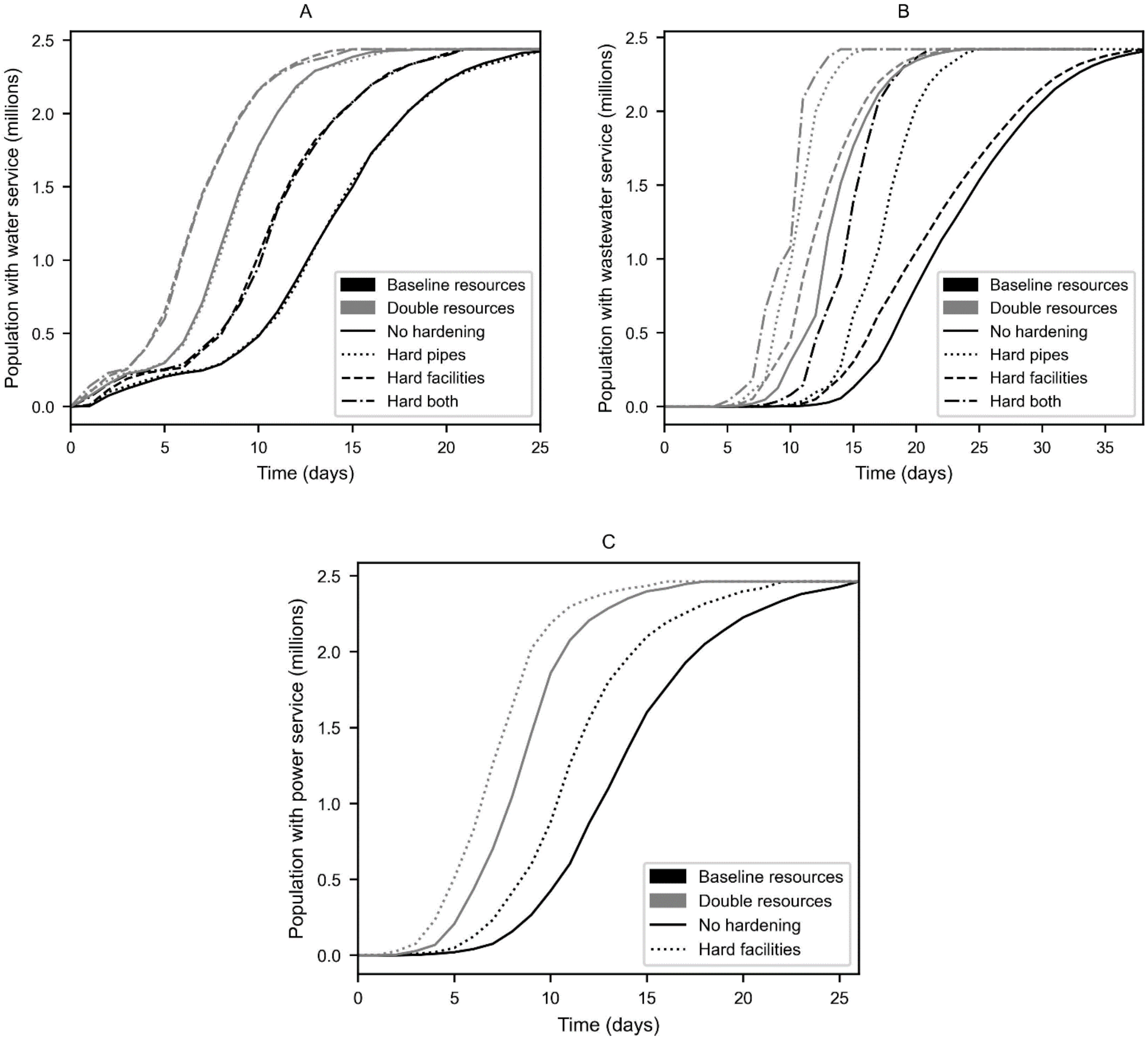


Figure 2-4. Median restoration curves for the (A) water, (B) wastewater, and (C) power sectors in the region showing the restoration of service over time. Black lines represent baseline resource scenarios, while gray lines represent doubled resource scenarios. "Hard both" refers to the hard pipe and facility scenarios and is used to save space in the figures.

Because of this uncertainty and the aggregation process described in Section 2-4, 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 (American Water Works Association 2001; Shinozuka et al. 1995). 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 Figure 2-5 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 2-1), 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 2-6.4.

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

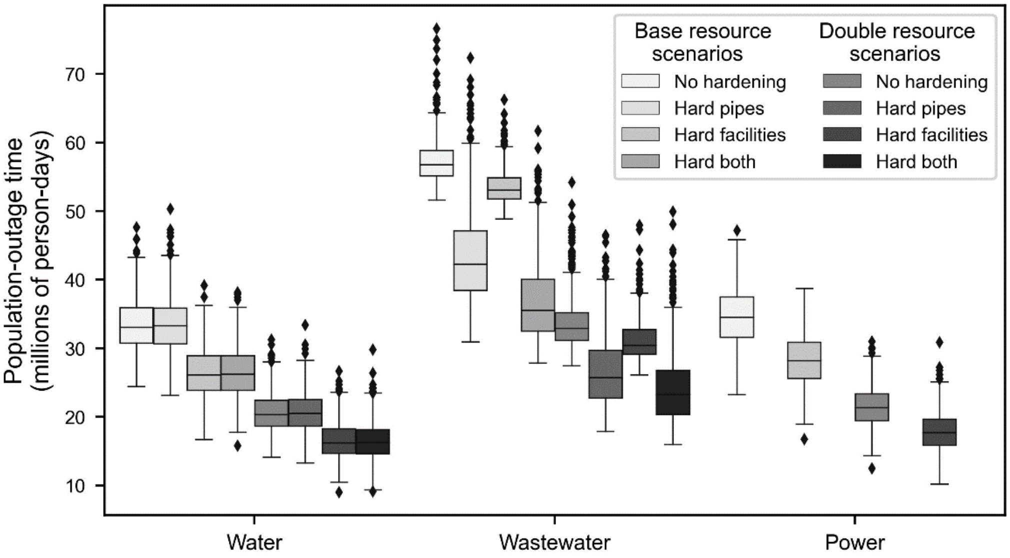


Figure 2-5. Box plots of population-outage time for each sector and scenario in the case study. "Hard both" refers to the hard pipe and facility scenario and is used to save space in the figure. The whiskers of the plot include values within 1.5 times the interquartile range above and below the 75th and 25th percentile values, respectively.

2-6.4 Restoration Ratio

The restoration ratio mentioned in Section 2-4.6 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 Figure 2-5.

Figure 2-6 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. Figure 2-6 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 2-5.1.3. There is therefore no separation between power supply sources and distribution components within each zone that can be used to calculate the restoration ratio.

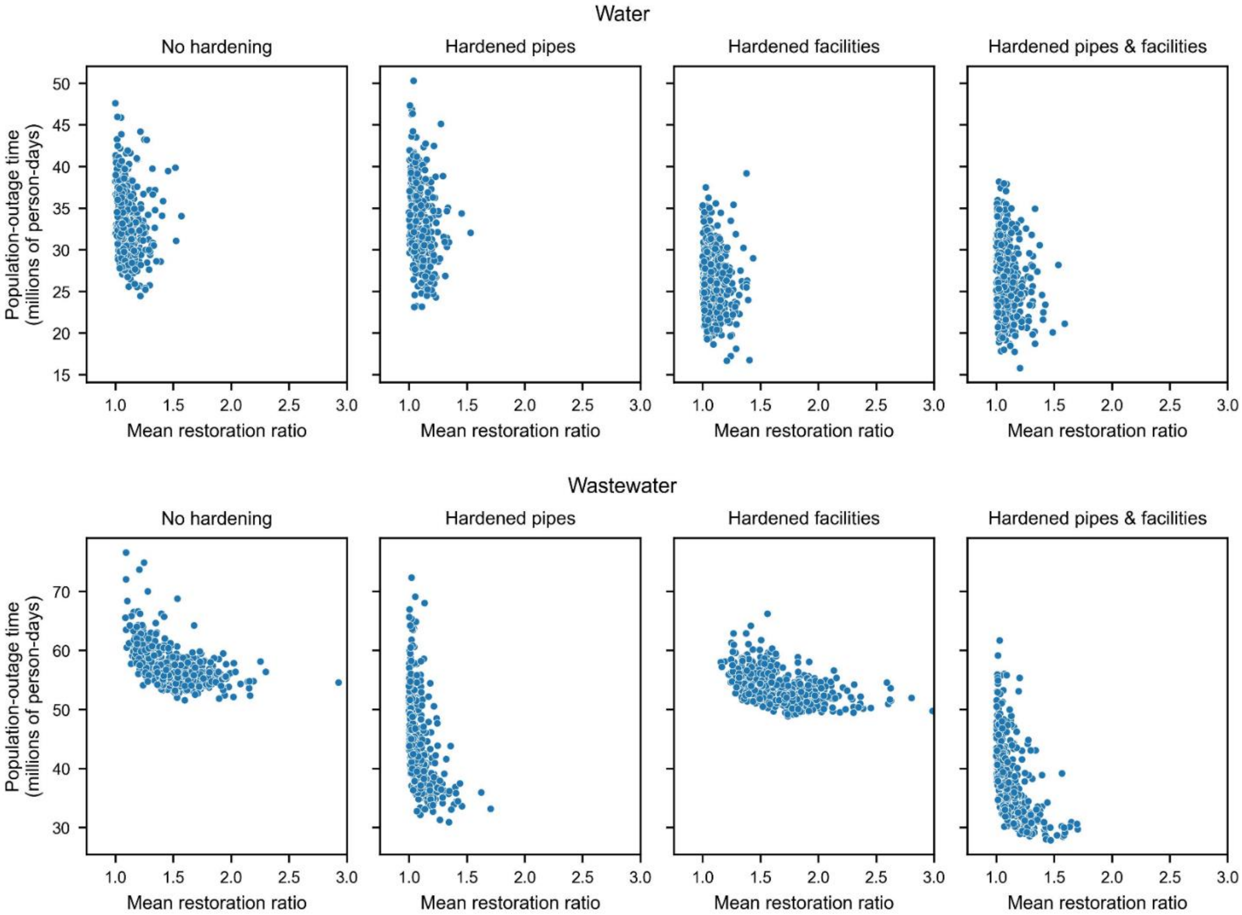


Figure 2-6. Total population-outage time compared to mean restoration ratio for each trial in the four baseline resource scenarios for the water and wastewater sectors. Each point represents one trial in the specified scenario for the identified sector.

Table 2-2 shows the mean restoration ratio and population-outage time for each scenario and trial depicted in Figure 2-6. The values shown in Figure 2-6 and Table 2-2 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 is already sufficient to repair them before the systems on which they depends (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.

Table 2-2: Mean value of the restoration ratio and population-outage time for each scenario for the water and wastewater sectors shown in Figure 2-4. 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	1.1	1.1 (-1%)	1.1 (-1%)	1.1 (-1%)
	Mean population-outage time (millions of person-days and percent change from baseline)	33.5	33.4 (0%)	26.4 (-21%)	26.5 (-21%)
Wastewater system	Mean restoration ratio	1.5	1.1 (-27%)	1.7 (+13%)	1.1 (-24%)
	Mean population-outage time (millions of person-days and percent change from baseline)	57.4	43.8 (-24%)	53.6 (-7%)	37.2 (-35%)

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 resources), 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.

2-7 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) (Emergency Management BC 2022), take years to plan and execute and involve ongoing engagement and collaboration with participants (see (Emergency Management BC 2020) 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.

2-7.1 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 (Gale 2000) 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 (Shinozuka et al. 1995). Other mutual aid agreements exist, including one with Pacific

Northwest states in the United States (*Pacific Northwest Emergency Management Arrangement* 1998), 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. (Emergency Management BC 2021)) indicate that these challenges are already being discussed by some participants.

2-7.2 Investing in upgrades and repairs

The reduction in repair time compared to length of replaced pipe presented in Figure 2-3 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. Figure 2-4 and Figure 2-5, 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 (Hale 2018)) 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, (Wesemann et al. 1996; Casari and Wilkie 2005) 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 (Emergency Management BC 2008). 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.

2-7.3 Community considerations

Adding a normalization parameter, as presented by Singh et al. (Singh et al. 2022), 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 (T. H. Y. Li, Thomas Ng, and Skitmore 2016) 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 (Shaw 2014). 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 (Applied Technology Council 2016; Chakraborty et al. 2020; Logan and Guikema 2020; Chang et al. 2021).

2-7.4 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.

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 (Nocera et al. 2018; Pitilakis, Crowley, and Kaynia 2014). 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 2-2, can further improve recovery processes to reduce outage times.

2-8 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 very 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. The approach utilized demonstrates the recovery and resilience of physical infrastructure systems and should be used in conjunction with other tools that consider not just physical structures that contribute to resilience, but social, economic, and other aspects as well.

Chapter 3: Applicability of an aggregated water system model for disaster recovery modeling

Abstract:

Modeling the restoration of critical infrastructure systems that are vulnerable to damage and disruption from natural disasters allows planners and policy makers to make informed decisions about how to best invest in disaster risk reduction strategies and prepare for disasters to protect the communities that they serve. Models are imperfect representations of physical systems, so it is essential to understand the benefits and drawbacks of a modeling approach to properly interpret its results. The Graph Model for Operational Resilience (GMOR) is a computational modeling platform that tracks the recovery of infrastructure systems over time based on the dependencies within and between systems, their estimated level of damage after a disaster, and resource requirements and availability. Linear infrastructure systems in models developed for GMOR are aggregated into service zones rather than modeling each individual component. This reduces the size and complexity of the model and allows it to be constructed even where uncertainties about the system exist. Further, this process provides an opportunity to model multiple infrastructure systems rather than developing a single system in detail. In this work, an aggregated model and detailed hydraulic model of a water supply system are subject to a simulated earthquake to consider how their recovery progresses after a major disruption. The two modeling approaches are compared for multiple damage scenarios to assess the applicability of the aggregated model and provide a benchmark for future modeling work. Results from this work indicate that, given an understanding of their constraints and limitations, aggregated models can effectively provide a range of recovery scenarios to be used for emergency management and disaster recovery planning purposes.

3-1 Introduction

Water distribution systems are critical for sustaining the health and wellbeing of communities throughout the world. If a disaster occurs, components within water systems may be damaged and cause residents to lose access to this critical service.

Modeling damage, loss of service, and restoration of water distribution systems can provide planners and other stakeholders with information about the disruptions that their communities might face and estimates of how long it may take for service to be restored. With this information, they are better equipped to implement changes to their operational or response activities to reduce the negative impacts of disasters and improve the disaster resilience of the communities they serve. In addition, models may be used as a part of the development of exercises that promote greater understanding of operations and better coordination between those involved in emergency response activities (Perry 2004).

All models are subject to some degree of uncertainty that is primarily determined by the purposes that they are designed to fulfill. A detailed network model of a water or wastewater system, for example, is important for accurately assessing the needs of a community and having the right equipment and procedures in place to meet those needs. Certain specific characteristics of these networks may not be fully captured in a model, but attempting to match physical and modeled operations as closely as possible is the goal of such models (Ostfeld et al. 2012).

For disaster planning or assessment scenarios, however, systems may be presented in a less detailed manner using simplified models or broad characterizations of damage and recovery. This process allows multiple stakeholders to be involved regardless of their level of expertise with each system under consideration.

In addition, planners or exercise participants are often tasked with working across disciplines and large geographical areas (see (Emergency Management BC 2020; Bird et al. 2021) for example). Coordinating with multiple management entities to acquire detailed information about their system operations is a daunting task, and the complexity of integrating multiple possible sets of standards, software, privacy considerations, and interconnected systems may quickly become unmanageable before planning activities can even begin. Reducing the complexity of modeled systems for use in planning scenarios can avoid the downfalls of working with highly detailed models while still providing the opportunity for stakeholders and community members to engage in emergency management activities.

While simplified models have distinct benefits, they often lack spatial and temporal resolution that are valuable for visualizing patterns and processes of recovery throughout a region. The goal of the work presented here is to therefore demonstrate the development and use of a simplified model that incorporates spatial and temporal characteristics of service restoration and compare its results to those produced by a highly detailed water distribution system model. This work can then be used to provide a point of reference for similarly simplified models to illustrate the conditions and operating procedures under which such models may best be utilized.

This is accomplished by comparing the results from a simplified model and a detailed hydraulic model for a damage and recovery assessment for an identical study area and simulated earthquake. Results from a detailed hydraulic model are highly dependent on assumptions that are made in how damage and restoration are approached, so multiple scenarios with varying assumptions are considered. The simplified model can then be compared to a range of scenarios to determine how it may best be used. This work considers only the physical components and connections within the water distribution system and makes no attempt to assess characteristics related to water quality.

3-2 Background

Detailed hydraulic and water quality models of water distribution systems are essential for estimating the demands that systems face and ensuring that these demands will be met with a proper combination of equipment and management. The continued development of Geographic Information Systems (GIS) and other computational tools has automated much of the process of calculating system parameters (Twort, Ratnayaka, and Brandt 2000). Since then, researchers have attempted to create increasingly comprehensive models of water distribution systems to better plan pipe sizing (Walski et al. 1987), system expansion, control mechanisms (Marchi et al. 2014), and sensor location (Hart et al. 2007), provide more accurate representation of physical systems (Ostfeld et al. 2012), and more.

One commonly used tool for modeling and assessing water distribution systems is the United States Environmental Protection Agency's (EPA) EPANET software (United States Environmental Protection Agency 2020). EPANET allows users to develop comprehensive system models that includes physical asset attributes and quality monitoring, system operation and management activities (Rossman, Tryby, and Janke 2020).

Beyond using EPANET to assess systems under normal (or expected) conditions, additional tools are available to simulate systems exposed to various hazards. One such tool is the Water Network Tool for Resilience (WNTR), also developed by the EPA to work directly with EPANET models for resilience assessment (Klise et al. 2017). WNTR allows users to simulate disasters and assess the damage and loss of service they cause. Repair activities can be modeled to demonstrate how service is restored throughout the system over time.

Detailed hydraulic models require a significant amount of data to create and assess, so simplified models may be developed as an alternative. Some methods of simplifying systems involve reducing the network to its most essential components in order to maintain hydraulic characteristics, demands, and quality indicators without the complexity of a full model (Di Nardo et al. 2018; Paluszczyszyn, Skworcow, and Ulanicki 2013). These methods generally are used to facilitate decision-making for maintenance or management activities, however, and their practice of removing pipelines from the modeled network does not allow for a spatial assessment of damage to the whole system.

Other models are based on general recovery patterns observed in historical disasters such as those developed for electrical power systems subject to hurricanes and ice storms by Liu, Davidson, and Apanasovich (2007) and for multiple infrastructure systems subject to earthquakes by Zorn and Shamseldin (2015). Restoration curves included in Hazus (Federal Emergency Management Agency 2011) and other hazard modeling software fit this description as well. These generalized models are incredibly valuable for providing an overview of disaster impacts and present a fascinating understanding of the correlations between disaster impacts over many decades in locations throughout the world. Because of their general nature, however, they also tend to lack a spatial component that would add value to the results that they produce.

The Graph Model for Operational Resilience (GMOR) is a computational modeling platform designed to model the spatial and temporal restoration of service of critical infrastructure systems based on the connections within and between different systems (Bristow and Hay 2017; Bristow 2019). GMOR can be used to bridge the gap between complex, system-specific models of critical infrastructures and more general models that lack spatial or temporal resolution.

Models developed for use in GMOR can consider damage to every component in multiple linear infrastructure systems without the need for detailed system operations information. Instead, linear components are aggregated into zones to create simplified versions of interconnected networks. In this way, only the location and layout of components (which is generally relatively accessible via GIS repositories from municipalities or other sources) and certain attributes (such as material and diameter of pipelines, if available) of the system are needed to develop a model for use in GMOR. Dependencies within and between parts of one or more systems can be included to provide estimates of recovery time based on initial damage levels and repair crew and resource availability. While GMOR is capable of assessing models of multiple infrastructure systems, this work and the methodology described in the following sections specifically focus on water distribution networks.

3-3 Methodology

As indicated in Section 3-1, the goal of this work is to provide a comparison of a hydraulic model and simplified aggregated model of a water distribution system subject to an earthquake. WNTR is chosen as the tool for assessing an EPANET hydraulic model of a water network, and GMOR is used to assess an aggregated model of the same network where zones are delineated based on population. An overview of the methodology is shown in Figure 3-1. A single earthquake scenario and distribution system are modeled to compare restoration timelines using the two modeling approaches.

Sections 3-3.1 to 3-3.9 detail the creation of each model based on the properties of the distribution system and describe the methodology developed to produce damage scenarios for each model based on the properties of the considered earthquake scenario. Two damage methodologies are modeled for use with GMOR and are described in Section 3-3.11. Four repair strategies are created for the WNTR model and are described in Section 3-3.10.

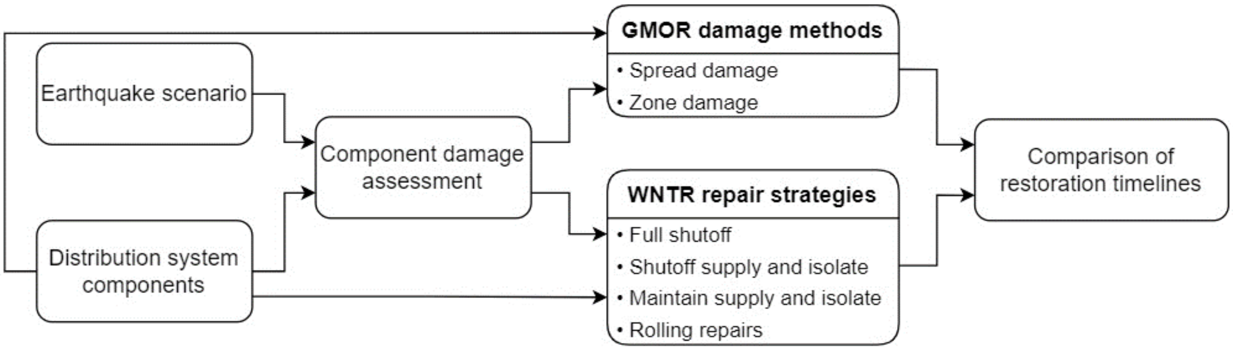


Figure 3-1: Methodology overview. The same earthquake and system components are used in each model of the water distribution system. The noted GMOR damage methods and WNTR repair strategies are detailed in later sections.

3-3.1 Water distribution system structure – aggregated model

An example of the method used to create an aggregated water distribution system model for use in GMOR is shown in Figure 3-2. Individual pipes are collected and represented as a single node for each zone and water service is assumed to be either available or unavailable to the entire population of the zone at the same time.

The network structure of the water distribution system in the aggregated model connects nodes based on pipes that originally crossed the borders between the zones that the nodes represent. For example, node B is not connected to node C in Figure 3-2B because no pipe crossed the border between zone B and zone C in Figure 3-2A. In this way, the original layout of the system is generally respected. For larger networks, water transmission systems that convey water from treatment facilities to storage tanks or reservoirs in each service area can be modeled separately from the distribution system to more accurately represent the structure of each system (Deelstra and Bristow 2023).

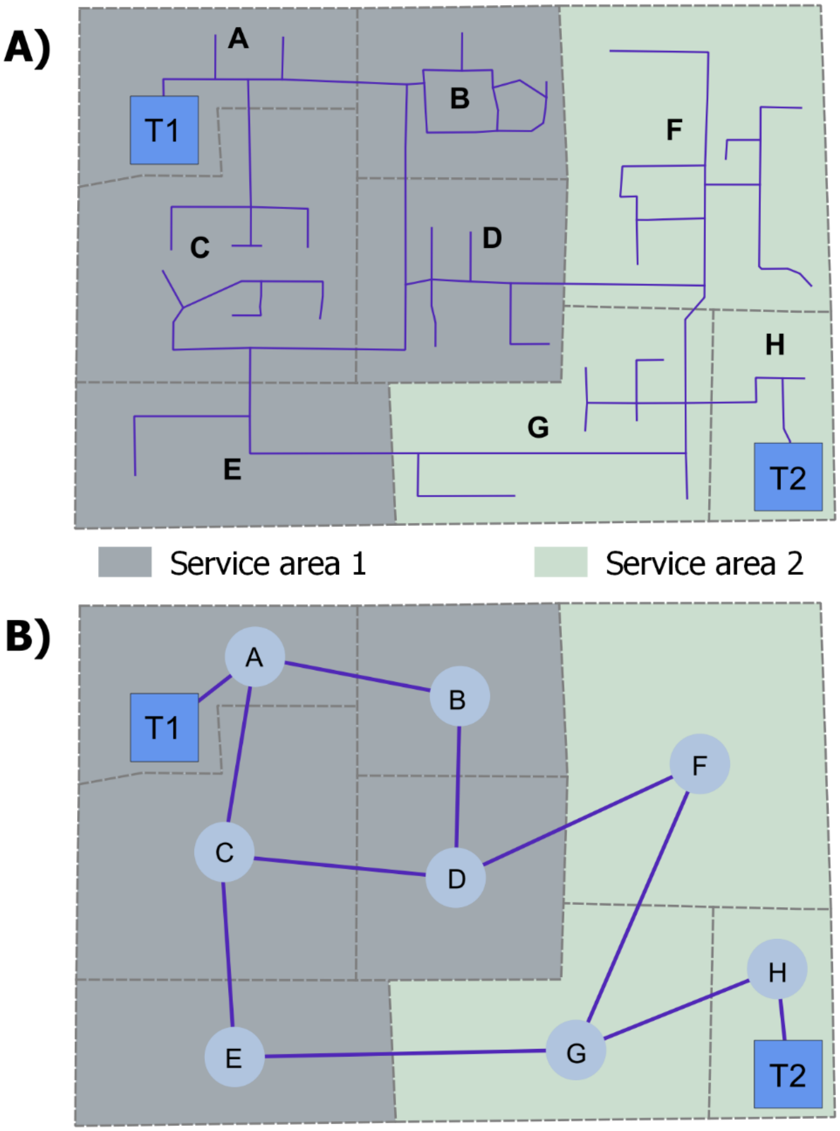


Figure 3-2: Method of aggregating a water distribution system for two service areas. The squares marked T1 and T2 represents water storage tanks that provide service to Service area 1 and Service area 2, respectively. Individual pipes from part A are aggregated by alphabetically delineated zones into the nodes shown part B. Nodes are only connected to neighboring nodes if a pipeline crossed the border between the zones in the original system.

The simplified zonal model collects the total amount of damage that must be repaired in each zone, but the completion of repairs to a zone does not indicate an immediate restoration of service there. A path of functional zones from a working water source to the zone is needed in order to restore service to a repaired zone. In Figure 3-2, for example, zone D can only have its service restored after its damage, any damage to the water storage tank T1, damage in zone A, and damage in zone B or zone C are repaired.

In an area with more than one supply source, each zone is modeled so that it depends on the single nearest supply source for its service. Functional path connections can be made through zones that do not share a service area, however. For example, even if zone C is non-functional in the distribution system shown in Figure 3-2, zone E may still be restored to service if tank T1 and zones A, B, D, F, and G are functional, despite the fact that zones F and G are not in the same service area as zone F.

3-3.2 Water distribution system structure – WNTR hydraulic model

The WNTR hydraulic model includes the connections between pipes, valves, and other water distribution system features and their hydraulic characteristics. Like most hydraulic models of water systems, however, service connections to individual users are not explicitly modeled. Instead, demand nodes are placed throughout the modeled network to represent groups of users for a general area. Demand nodes are different than the nodes for the aggregated model shown in Figure 3-2 and each represent significantly fewer users than the aggregated model nodes.

3-3.3 Hazard parameters

The WNTR module provides an option to generate earthquake parameters, but it is limited in its extent and models only ground motion in terms of peak ground acceleration (PGA) and peak ground velocity (PGV), and not ground failure as a result of permanent ground deformation (PGD) (Klise et al. 2020). For the purposes of the case study presented in this work, therefore, existing hazard maps from another location are used as the basis for the earthquake to include the effects of ground failure.

3-3.4 Damage scenarios – pipelines

This work examines the repair of breaks and leaks in water supply pipelines to assess the effects of damage and repair on service loss and restoration. To provide a range of possible pipe damages to use in the assessment of the two chosen modeling methodologies, five distinct earthquake damage scenarios are developed and described in Section 3-3.5.

To match the damage conditions that are used in previous models developed for use in GMOR, Hazus fragility functions are used to calculate the estimated repair rate for each pipe segment in the region based on the pipe diameter, material, ground motion, and probability of ground failure to which it is subjected (Federal Emergency Management Agency 2011). Multiplying the Hazus repair rate by the length of each pipe and summing the results provides an estimated total number of breaks and leaks for the pipes in a given area.

Pipe breaks and leaks affect water distribution systems differently. A pipe break prevents water from passing through the pipe and instead spills its contents into the surrounding ground. Breaks have a significant impact on the water distribution system and often result in a loss of service to users in the areas around them due to the inability of water to pass through broken pipes and the high demand caused by water spilling out. A pipe leak is much less severe. Water can still pass through leaking pipes, so they have a limited effect on the pressures and capacity of the surrounding network. Some water is lost, however, so depending on the type and size of the leak, nearby residents may be affected. (Peixin Shi and O'Rourke 2008). In addition, repairing a leak generally requires the leaking pipe to be isolated from the remainder of the network, which can temporarily disrupt service to nearby areas.

3-3.5 Damage clustering

To assess the effect of pipe breaks and leaks on the water distribution system using the detailed hydraulic model and WNTR, individual broken or leaking pipes must be identified and modeled. Multiplying the repair rate of a pipe (calculated using fragility curves as noted in Section 3-3.4) by its length, however, generally produces a fractional number of breaks and leaks for that pipe. Because it is impossible to to have a partial break or leak in a pipe (this is referring to whether a break or leak exists, not the size of the break or leak), some method must be used to translate the fractional value to whole numbers of breaks and leaks in individual pipes.

The standard methodology for estimating the location of breaks and leaks uses a Poisson process with a mean arrival rate equal to the pipe repair rate (Peixin Shi and O'Rourke 2008). While testing this methodology for the case study area presented in Section 3-4, however, it provided an estimate of only two broken pipes for the entire study area, whereas summing the number of breaks using the Hazus methodology resulted in a total of nineteen broken pipes. Bagriacik et al. (2018) note that Hazus estimates of total breaks and leaks for a set of pipes are reasonably accurate, so a methodology that produces a quantity of breaks and leaks equal to those estimated by Hazus is desired. It is assumed that the Poisson process described by Shi and O'Rourke (2008) underestimates the number of breaks and leaks for short pipe segments because the length of the pipe is almost always less than the estimated distance along the pipe to the first location of damage.

A new method is therefore developed to produce a total number of breaks and leaks equal to that estimated from the Hazus fragility curves and uses a constrained k-means clustering process (Levy-Kramer 2022) to select pipes that are then modeled as broken or leaking. An example of this process is illustrated in Figure 3-3 with parameters from Table 3-1 and is used to identify specific locations of pipe breaks and leaks for use in the detailed hydraulic model that is assessed using WNTR.

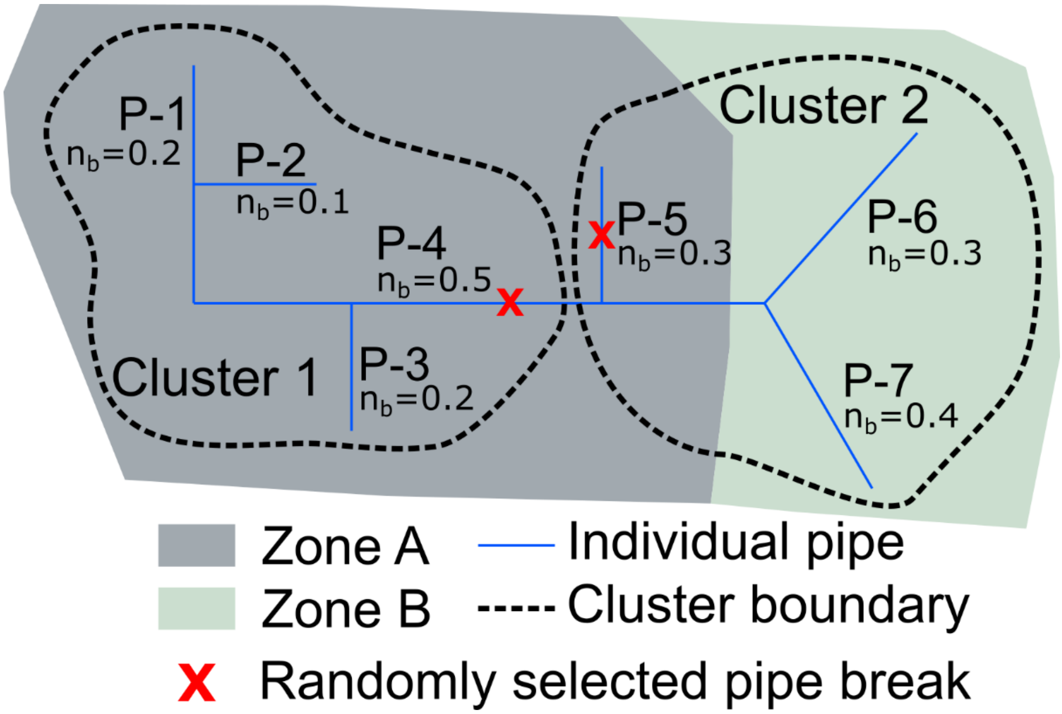


Figure 3-3: Damage clustering and selection process. n_b represents the number of breaks calculated for each individual pipe. A constrained k-means clustering process is run to create clusters of pipes with a total number of breaks that sum up to approximately 1, such that each cluster is assumed to contain one broken pipe. A single pipe is selected to be broken in the model using a weighted random selection process.

Table 3-1: Parameters and calculations used for the damage clustering process illustrated in Figure 3-3. The pipe breaks indicated in the “Break” column are selected using a weighted random choice process.

Pipe	Zone	Length (m)	Repair rate (breaks/km)	Number of breaks (n_b)	Break cluster	Break
P-1	A	200	1	0.2	1	No
P-2	A	100	1	0.1	1	No
P-3	A	100	2	0.2	1	No
P-4	A	500	1	0.5	1	Yes
P-5	A	100	3	0.3	2	Yes
P-6	B	200	1.5	0.3	2	No
P-7	B	200	2	0.4	2	No

Number of breaks per zone in aggregated model using damage aggregation methods:

Zone	Spread damage	Zone damage
A	1.3	2
B	0.7	0

Using fragility curves from the Hazus technical manual for ground motion and ground failure (Federal Emergency Management Agency 2011), an estimated repair rate per unit length of pipe is produced. A fraction of repairs are estimated to be pipe leaks, and the remainder are estimated to be pipe breaks. Multiplying the break and leak repair rates by the length of an individual pipe results in an estimation of the number of breaks and leaks in that pipe. This value is generally not a whole number, however, as described previously and shown in Table 3-1.

To select individual damaged pipes for the detailed hydraulic model, therefore, fractional break and leak values are clustered to produce groups in which the sum of the fractional breaks or leaks for all the pipes in each group is approximately equal to one. Figure 3-3 and Table 3-1 demonstrate this process using only estimated breaks for clarity, but the process is the same for estimating leaks.

Creating clusters with a specified parameter value (in this case, for example, the sum of the fractional breaks and leaks should be equal to one) requires a constrained clustering process. Standard k-means clustering produces a defined number of clusters for a set of items such that each item is assigned to the cluster with the nearest mean location to the item. With the standard process, however, there is no guarantee that the number of items within each cluster is consistent. A constrained k-means clustering process is therefore used in which a minimum cluster size can be defined. In this way, each cluster is guaranteed to have a certain minimum size, which limits the maximum possible size of a single cluster as well. Due to the layout of the system and fractional damage estimates, it is not possible to create clusters of exactly the same size. As such, the minimum cluster size parameter used in the constrained clustering process is set slightly below one.

Some clusters therefore sum to slightly less than one and others to slightly more than one break or leak, but for the purposes of modeling damaged pipes in the network, each cluster is assumed to contain a single broken or leaking pipe. From within each cluster, one pipe is selected using a weighted random choice method, where the probability of an individual pipe being selected is based on its individual estimated number of breaks or leaks divided by the sum of all breaks or leaks for the cluster.

The constrained k-means clustering process does not produce the same clusters every time it runs, and selecting pipes to be modeled as damaged using a weighted random choice does not produce the same set of pipes every time a new selection is made. As indicated in Section 3-3.4, five scenarios are generated with different sets of broken and leaking pipes for each, so the clustering and selection process is repeated five times. More than five damage scenarios are of course possible, but this serves as a starting point for the purposes of this work. Within each scenario, the broken and leaking pipes are the same, but their repair times vary based on a normal distribution for multiple simulation trials.

3-3.6 Aggregated model damage methodologies

The individual broken and leaking pipes selected using the approach described in Section 3-3.5 are used to create the detailed hydraulic model that is assessed using WNTR. The aggregated model assessed using GMOR, however, does not represent the hydraulic effects of individual pipe breaks and leaks, so two damage methodologies are considered for this model.

The first, referred to as the **spread damage** methodology, does not use the clustering approach described in Section 3-3.5. Instead, the fractional number of breaks or leaks for each pipe (produced by multiplying its repair rate by its length) is simply multiplied by the estimated time required to repair a single break or leak and summed with repair times for all other pipes within each zone. In this way, all zones are marked as damaged (all pipes generally have at least some probability of damage and a subsequent required repair time) at the start of a simulation and therefore may be useful in representing the uncertainty associated with predicting the location of earthquake damages.

The second method implemented for the GMOR assessment of the aggregated model, referred to as the **zone damage** methodology, uses the damages developed using the clustering approach described in Section 3-3.5 but aggregates them at a zone level. In this way, only zones that contain pipes that are selected as broken or leaking in the hydraulic model are marked as damaged in the aggregated model. Zones identified as damaged using the **zone damage** methodology are therefore more scattered throughout the study area.

In summary, the detailed hydraulic model assessed using WNTR incorporates individual pipe breaks and leaks to assess their effects on the functionality of the water distribution system. Two damage methodologies are considered for the aggregated model assessed using GMOR. The first aggregates fractional damages at a zone level to represent damage to pipes in each zone. The second aggregates individual breaks and leaks at a zone level, such that each zone always contains a whole number of breaks or leaks.

3-3.7 Damage scenarios – other infrastructure

To compare the detailed and aggregated modeling approaches while maintaining a degree of simplicity that allows for the consideration of multiple scenarios, the network models are designed to be as similar as possible and not affected by external factors. The power network, for example, is assumed to be undamaged by the earthquake, so any dependencies on power within the system are assumed not to fail. In addition, components such as facilities and valves are assumed not to fail. The scope of this work is therefore limited to water pipelines only. Additional assumptions are indicated in the context of the scenarios described in the following sections.

3-3.8 Break and leak modeling

Pipe breaks and leaks are modeled as demand nodes within the WNTR model. The demand that a damaged pipe places on the water system depends on the estimated area from which water can escape. This area is referred to as the leak area regardless of whether it is caused by a break or a leak in the pipe.

Pipe beaks cause a significant loss of water in the system and are modeled with a leak area equivalent to the cross-sectional area of the pipe (Hwang, Lin, and Shinozuka 1998). Leaks are generally much less severe. Hwang, Lin, and Shinozuka use a consistent estimate of 3% of the pipe cross-sectional area for the leak area for pipe leaks (1998), but this work uses an updated method presented by Shi and O'Rourke in which the area depends on probable types of damage based on the pipe material (2008).

3-3.9 Damage repair times

The estimates for the time needed to repair individual breaks in leaks used in the aggregated model are those used in previous models developed for use in GMOR and come from Hazus (Federal Emergency Management Agency 2011). These times represent the overall break or leak repair process and implicitly include all individual repair activities.

For the models created for the work presented here, an explicit separation of tasks is used to produce a more detailed breakdown of the repair time. To create a set of times for repair activities that sum to the value of those produced using the Hazus methodology, individual times presented by Tabucchi, Davidson, and Brink based on their assessment of repair times from the 1994 Northridge earthquake (2010) are scaled to match those included in the Hazus methodology. Tabucchi, Davidson, and Brink's work separates repairs into multiple tasks, of which travel, inspection, isolation, and repair are relevant to the work presented here. They provide an estimate of repair time for each task that falls within a triangular distribution with a given minimum, mode, and maximum value. A full summary of the relevant values from their work is included in Table D-1 in Appendix D.

For this work, the repair tasks are broken down into three parts: pre-repair travel and isolation, direct repair, and reconnection and post-repair travel and use a combination of the times presented by Tabucchi, Davidson, and Brink. Pre-repair travel and isolation include the time required to travel to a damaged area and close valves to isolate the damage from the rest of the system. Direct repair is the time required to complete repairs to the pipes themselves. Reconnection and post-repair travel include the time required to reopen valves that were previously shut and travel to the next location.

Table 3-2: Original mean total repair times for breaks and leaks from the Hazus technical manual compared to the separated task times used in this work.

Hazus (mean time)		This work (mean time)	
Task	Time	Task	Time
Leak repair (total time)	4 hr	Pre-repair travel and isolation	1.35 hr
		Leak repair	2 hr
Break repair (total time)	8 hr	Break repair	6 hr
		Reconnect and post-repair travel	0.65 hr

Table 3-2 presents a summary of the repair times calculated for each activity to match those used by Hazus and assume a repair crew size of four workers. Because overall leak and break repair times are calculated from a normal distribution, the times required for each task are scaled proportionally to sum to the overall time for each repair.

To provide an estimate of travel time to and from repairs, a required travel distance of 10 kilometers is estimated for each repair – 5 kilometers before the repair, and 5 kilometers after the repair. The study area is relatively small and travel time contributes minimally to overall repair time, so this is assumed to be a reasonable simplification for the purposes of this work. The mean repair times for each task shown in Table 3-2 do not exactly match the mode of the triangular distributions presented by Tabucchi, Davison, and Brink, but fall well within the range of the distributions.

3-3.10 WNTR repair strategies

Four distinct repair strategies are modeled using WNTR and are named and described in the following sections. The repair strategies are developed based on similar methods used in historical earthquake response and identified in other case studies or exercises (see, for example, Shinozuka et al. 1995; Tabucchi, Davidson, and Brink 2010; Kang and Lansey 2013; Bird et al. 2021). In particular, strategies in which water supply tanks and reservoirs are immediately shut off from the rest of the system assume the use of seismically activated shutoff valves that close automatically if they detect an earthquake.

In each of the four strategies, a segment refers to a group of pipes that share a set of isolation valves. To repair a pipe within a given segment, therefore, valves for the entire segment must be shut, so all pipes within the segment are isolated from the rest of the water distribution system during that time. In some cases, isolating one segment from the rest of the system blocks service to one or more downstream segments. Segments that block access to others when they are isolated from the network are referred to as primary segments (Hernandez Hernandez and Ormsbee 2021).

3-3.10.1 Full shutoff

The **full shutoff** recovery strategy involves immediately shutting valves from all water tanks and reservoirs that provide water to the study area at the time of the earthquake and only reopening them once all pipe breaks are repaired. While this strategy may seem to represent an unnecessarily conservative response, it has the advantage of reducing the overall time required to repair damaged pipes in the network because segments do not need to first be isolated from the rest of the system in order to complete repairs. In addition, stored water is conserved and can be distributed to residents from individual storage locations while repairs are completed.

3-3.10.2 Shutoff supply and isolate

In this strategy, valves from tanks and reservoirs are immediately shut down at the time of the earthquake. Instead of being reopened when all pipe breaks are repaired, however, they are reopened once all damaged segments within the system are isolated by means of isolation valves. Repairs to individual pipes begin only after all damaged segments are separated from the rest of the network. Once all pipes within a damaged segment are repaired, the isolation valves for that segment are reopened to reconnect it to the rest of the network.

3-3.10.3 Maintain supply and isolate

This strategy is the same as the shutoff and isolate strategy with the exception that valves from water supply reservoirs and tanks are never shut. Instead, the supply sources remain connected to the network in an attempt to maintain some level of service to the distribution system.

3-3.10.4 Rolling repairs

In the previous two strategies, all broken pipes are isolated from the rest of the water distribution system before any repairs are completed. In this strategy, an individual segment is isolated from the system and repairs commence immediately on broken pipes in that segment. As soon as repairs are completed, the segment's isolation valves are reopened to reconnect it to the rest of the distribution system. In this strategy, there is no time at which more than one segment is isolated from the network (unless a segment happens to be isolated by the closure of a primary component).

3-3.10.5 Commonalities for all WNTR repair strategies

For each of the modeled strategies, the leak repair process is the same. Because leaks are generally not severe enough to disrupt service to the network, they often are much harder to detect than pipe breaks (Tabucchi, Davidson, and Brink 2010) and therefore take more time to discover. As such, all pipe leaks are repaired only after all pipe breaks are first repaired. Leak repairs occur on a rolling basis, such that only one component is isolated from the network at a time, regardless of the overall repair strategy used to repair broken pipes.

The ordering of repairs is also completed in the same way for each of the WNTR scenarios. First, damage in the network is assessed to determine if any breaks occur in primary segments. If a primary segment does contain damage and if a segment blocked by the primary segment also contains damage, the damage to the primary segment is prioritized for repair before other segments.

Primary segments are prioritized for repairs for two reasons. First, their repair facilitates water service to downstream segments that they would otherwise block. Second, it is assumed that primary segments are nearer than other components to water supply sources. Because of this, their pipes are likely more prone to significant water loss if they experience a break or leak than pipes located farther from the supply source.

After determining if there are any primary segments and prioritizing them for repairs, isolation and repair is prioritized by damaged pipe diameter. Because the leak area of a broken pipe is equal to its cross-sectional area, the larger a pipe is, the more water it can lose if it is broken. Demand from broken pipes can be tens of times greater than the regular demand in the same area of the network, so it is critical to isolate large breaks from the system as quickly as possible to reduce their strain on the system.

All broken pipes within a segment are repaired during the same segment isolation period so that valves are not closed and reopened multiple times to repair multiple pipes within a given segment. The pre-repair travel and isolation and reconnection and post-repair travel times for all pipes within a segment are therefore aggregated. All valves for a segment are not shut and reopened at the exact same time to isolate it from the system. Instead, the time at which valves are shut is a fraction of the total pre-repair travel and isolation time. Consider, for example, a segment with a total pre-repair travel and isolation time of 6 hours that requires four valves to be shut to isolate it from the network. The first valve is shut at 1.5 hours, the second valve at 3 hours, the third valve at 4.5 hours, and the final valve at 6 hours. Reopening the valves during the reconnection and post-repair travel time segment follows the same pattern.

In some cases, segments that border one another may both contain damaged pipes. If this occurs, the valves that separate them are not closed and reopened twice. Instead, any shared valves are shut when the first segment to be repaired is isolated from the network. When repairs to that segment are complete, all valves except the shared valves are reopened. The shared valves are reopened after repairs to the second segment are completed, which may or may not occur immediately after the repairs to the first segment.

3-3.11 Aggregated model repair strategies

Damages in the aggregated model are repaired at a zone level based on the damage generated for each zone using the methodologies identified in Section 3-3.6. Repairs are prioritized in groups based on the distance (measured in terms of the number of intermediate zones, not physical distance) from a zone to its supply source. For Service area 1 in Figure 3-2, for example, zone A is in a group on its own and is prioritized first, followed by a group of zones B and C, then a group of zones D and E. All zones within a group are repaired before repairs start on zones in the next group, so zone B is always repaired before zones D and E. Within a group, however, the repair order is randomized for each trial, so zone B could be repaired before zone C in one trial, while zone C may be repaired before zone B in the following trial.

3-4 Case study

To develop the case study for this work, the University of Kentucky's Water Resources Research Institute (KWRRI) Water Distribution System Research Database (Ormsbee et al. 2022) was consulted to select an existing EPANET model to serve as the foundation for the creation of multiple model types.

3-4.1 Model and study area selection

The goals for selecting a model include a population served by the water system that is large enough to be reasonably split into zones with multiple hundreds of people in each. In addition, a system that includes solely (or at least primarily) distribution components is desired. While bulk transmission systems can be included in aggregated models, the additional complexity of doing so is beyond the scope of the work presented here. Finally, it is beneficial to use a model based on an actual water system rather than a system designed for model testing or other purposes. Using a model of an existing system provides the opportunity to include the actual population and their distribution throughout the study area.

Based on this research, the system model in the KWRRI database designated KY V18 (Hernandez Hernandez and Ormsbee 2021; Hernandez Hernandez 2021) is selected. This system is an updated version that includes isolation valve locations for an earlier system model designated KY 18 (Hoagland et al. 2015; Hoagland 2015) and is based on a system in the state of Kentucky. The system includes 112 miles of pipe, one reservoir, three pumps, and three water storage tanks. According to United States Census Bureau data (United States Census Bureau 2021), approximately 14,000 people live in the area served by the water distribution system.

A map of the pipes, reservoir, and storage tanks in the water distribution system produced using the QGIS ImportEpanetInpFiles plugin (Kyriakou 2021) and overlaid on the census blocks in the study area (United States Census Bureau 2022) is shown in Figure 3-4. The EPANET model includes valves and junctions as well, but those are not included in Figure 3-4 for clarity. The reservoir in the EPANET model is part of the water treatment facility that is connected to the water supply source for the entire study area. As such, the level of the reservoir stays the same throughout each simulation, while tanks require a connection to the reservoir to be refilled if they are drained.

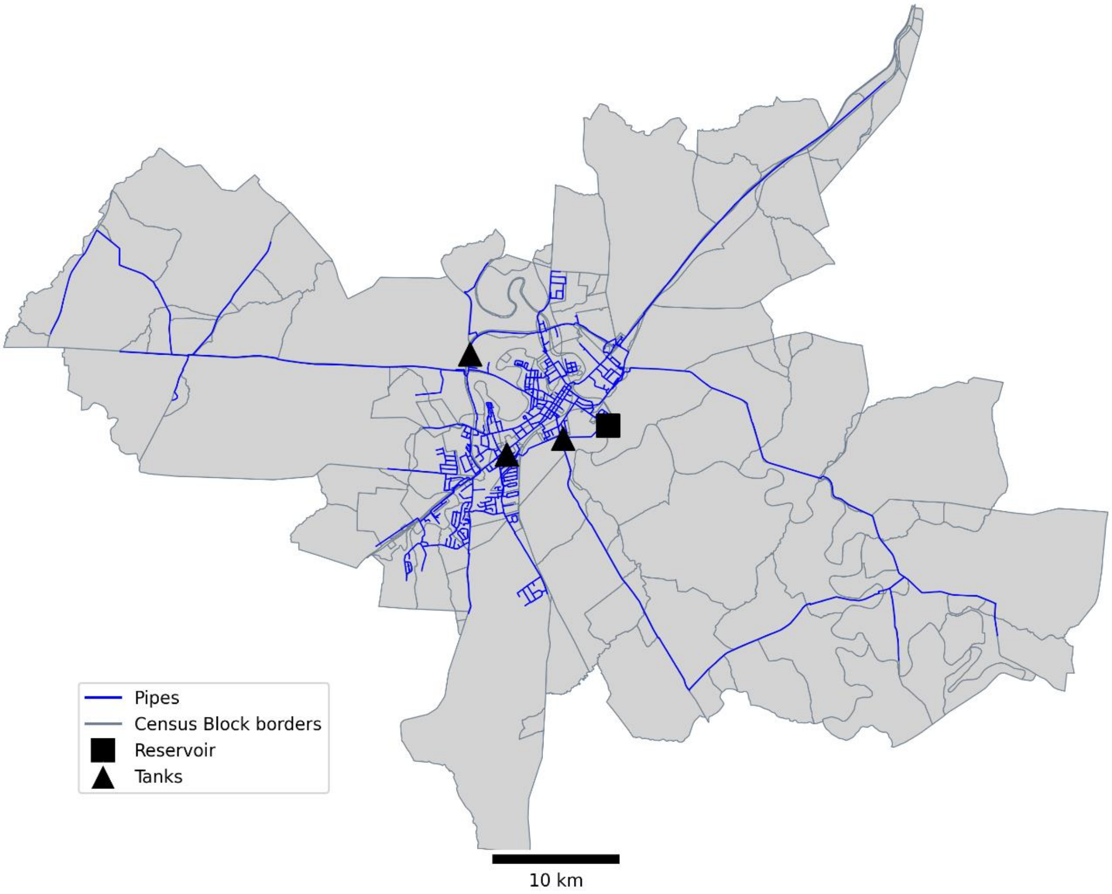


Figure 3-4: Overview of the water distribution system.

3-4.2 EPANET model modifications

Multiple discrepancies exist in the descriptions and geometries of the valved and non-valved versions of the EPANET model. Based on additional research, it was determined that the non-valved model more accurately represents the actual distribution system, so multiple modifications were made to the valved model to better align it with the information contained in the non-valved model. Further, the EPANET model did not include pipe material information, so additional sources were consulted to determine material type as it is an important consideration for determining pipe repair rates. The modifications and additions made to the model are not described here in detail but are included in Appendix D for reference.

3-4.3 Segment identification

A key consideration in the WNTR repair strategies noted in Section 3-3.10 is the identification of pipe segments that can be separated from the rest of the system using isolation valves. To identify the segments for the system in the study area, the pipe network and the 468 valves that it contains are processed using the Python NetworkX library (Hagberg, Schult, and Swart 2008). From this assessment, 345 segments are identified.

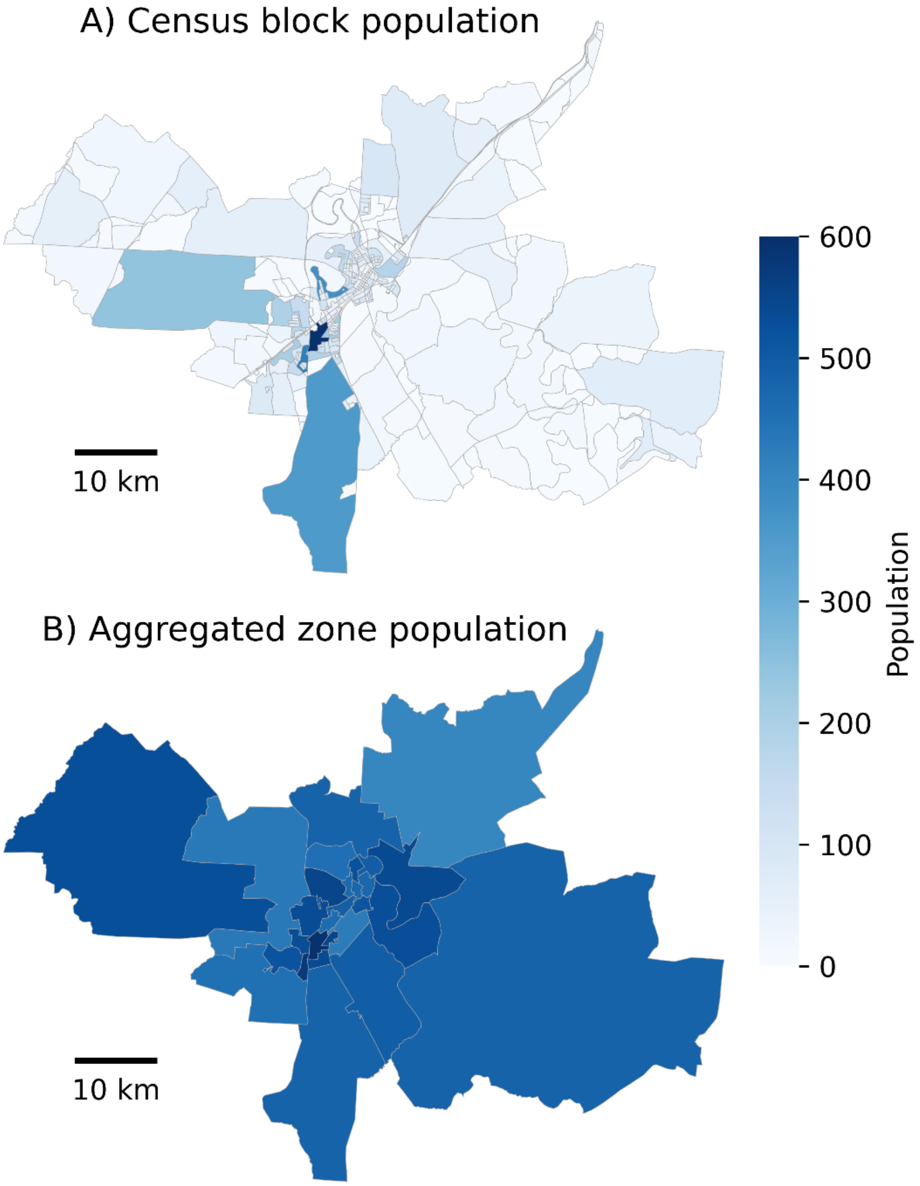


Figure 3-5: Map of A) Census block and B) Aggregated zone populations for the case study area. Census blocks are merged based on their population and location to produce zones with roughly 500 residents in each.

3-4.4 Aggregated model creation

Population information for the study area is collected from United States Census Bureau census blocks (United States Census Bureau 2021) and represents a total population of approximately 14,000 residents. Census blocks are used because they provide full spatial coverage of the study area and are frequently used for other population or disaster assessment reporting. The boundaries for the study area are selected based on the locations of the water pipelines and census block shapes. Populations within each of the 409 Census blocks in the study area range from 0 to 577, with an average population of 33 residents. A map of Census blocks and their population is shown in Figure 3-5A.

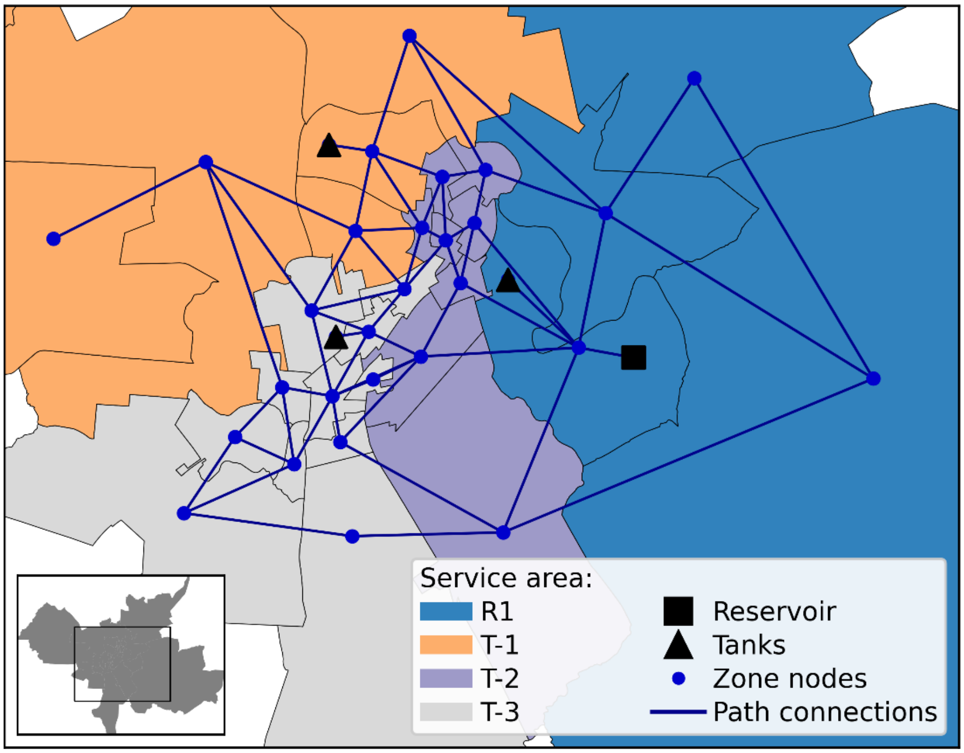


Figure 3-6: Service areas separated by supply source and connections between zones for the aggregated water system model. The inset map shows the entire study area and marks the portion that is enlarged for clarity. Path connections between zones are established using the method demonstrated in Figure 3-2. The nodes shown in this map of the system are provided for reference and their specific location within a zone is irrelevant.

To produce zones for the aggregated model that are similar in population to those used in previous models, Census blocks must be combined. Existing models run using GMOR use Statistics Canada Census Dissemination Areas (CDA) (Statistics Canada 2016) as the smallest geographical unit, which have an average population of 400-700 residents. A population of approximately 500 residents per zone is selected for this study, so 28 zones are created. Creating zones with similar populations to previous models is not required for the case study, but provide a means by which the current model and former models can be more accurately compared.

Zone boundaries are created using a constrained k-means clustering algorithm (Levy-Kramer 2022) that groups points (in this case, zone centroids) into a certain number of clusters with a minimum number of points in each. Duplicate points are generated based on the population of each Census block to provide a weighting parameter for the clustering process. In this way, the population in each cluster is relatively consistent. Due to the effects on the clustering process of weighting and differing populations within each Census Block, the algorithm does not produce clusters with exactly 500 residents in each. They instead range in population from 402 to 594. Each Census block is joined with the others in its cluster to produce the zones shown in Figure 3-5B.

The method demonstrated in Figure 3-2 is then used to separate zones into service areas that each depend on a single water supply source and to establish connections between zones that provide paths from each zone to its supply source. A map of the study area with zone connections and service areas is shown in Figure 3-6.

3-4.5 Earthquake hazard and damages

As indicated in Section 3-3.3, the WNTR software library includes an earthquake module to generate ground motions (PGA and PGV) (Klise et al. 2020), but it does not include probabilities of damage from ground failure (PGD), which can have a significant impact on pipe damage rates (American Lifelines Alliance 2001). As a result, existing ground motion and ground failure maps are developed from an earlier study in a different location (Wagner and Chow 2021) and used to perform the damage assessment rather than doing so using WNTR. It is therefore important to note that the damage calculated for this scenario is not specific to the study area location and is instead used solely for this case study to demonstrate the use of various modeling methodologies.

Based on the ground motion and ground failure parameters for each pipe, it is estimated that there are nineteen broken pipes and five leaking pipes in the study area. Using the clustering methodology described in Section 3-3.5, five unique damage scenarios are developed, each with nineteen pipe breaks and five pipe leaks.

Within each of the five damage scenarios, the locations of the broken and leaking pipes are the same, but the time required to repair each pipe is randomized based on a normal distribution using the repair times described in Section 3-3.9 for 100 individual simulation trials. A map of the breaks and leaks identified for each of the five damage scenarios is included in Appendix D.

For each of the four WNTR and two GMOR repair strategies defined in Sections 3-3.10 and 3-3.11, the total required repair time is the same for each trial. In this way, a single trial can be properly compared across the repair strategies. An exception to this is the repair time for the **full shutoff** strategy. As noted in Section 3-3.10.1, tanks and reservoirs are disconnected from the network until all pipe repairs are completed, so there is no sense in closing isolation valves if no water is flowing from the start.

In the following sections, it is important to note the language used to describe different parts of the modeling and simulation process. A damage scenario refers to one of five possible sets of pipe leaks and breaks for the study area as described in Section 3-3.4. Trials refer to individual simulations of damage and restoration for the water distribution system. Between trials, the repair time for each pipe varies based on the normal distribution for the type of repair required. In the aggregated model, the order of zone repair varies between trials as well as described in Section 3-3.11. Damage methodologies refer to the **spread damage** and **zone damage** methodologies described in Section 3-3.6. Repair strategies refer to the **full shutoff**, **shutoff supply and isolate**, **maintain supply and isolate**, and **rolling repairs** strategies described in Section 3-3.10. For each trial, the two damage methodologies and four repair strategies are compared.

3-4.6 Functionality and restoration

Functionality of the water system is indicated by the number of residents in the region with water service available over time after the simulated earthquake. Functionality is presented primarily using restoration curves, which plot population with service restored on the vertical axis and population on the horizontal axis. From the restoration curve, loss of functionality can be quantified in terms of population-outage time by calculating the area above the restoration curve.

For the model simulated in WNTR, water service availability is calculated based on the pressure available at each of the 495 demand nodes in the system. Each demand node is assumed to provide service to a specific number of people based on its estimated outflow rate and the population of the zone in which the demand node is located. It is important to note that the type of demand for each node is unknown, so it is not possible to represent a decrease in demand at any node due to a potential loss of commercial or industrial users that may result from an earthquake, which may skew the results. Once the demand node reaches a minimum required pressure of 30 pounds per square inch (psi), residents that depend on that node are counted as having service. The pressure may later drop below 30 psi, at which point residents are again without service.

For the aggregated system model processed using GMOR, water service availability is represented for populations at a zone level, with zones being restored to service following the process depicted in Figure 3-2. Once a zone is restored to service in the aggregated model, it cannot lose service, so the population with service always increases during a simulation.

This work assumes that a single repair crew is available to begin repairs immediately after the earthquake and continuously throughout the recovery period. In both modeling approaches, the repair crew can only work on one task at a time. For the WNTR simulation, this means that valves are actuated sequentially and only one can be worked on at a time. For the GMOR simulations, repairs progress one zone at a time, so the repair crew cannot work on one zone until the previous zone repairs have been completed. While it is more likely that multiple repair crews would work during the day and not work at night rather than having a single repair crew available throughout the recovery period, this assumption provides a means to more accurately compare the two modeling approaches and results in negligible changes to overall recovery times.

3-5 Case study scenarios and results

The overall population-outage for each damage scenario and repair strategy is shown in Table 3-3. Based on the values shown here, it is clear that the WNTR **shutoff supply and isolate** and **maintain supply and isolate** repair strategies are best for the damage scenarios considered in this work. Discussion surrounding the potential benefits of the **full shutoff** and **rolling repairs** strategies for other damage scenarios is included in Sections 3-5.2 and 3-7. For the purposes of this work, however, the focus of the following sections will be the two best performing WNTR repair strategies and the two GMOR repair strategies. Additional figures that demonstrate findings for the other repair strategies are included in Appendix D.

Table 3-3: Overall population-outage times for each of the pipe damage scenarios and repair strategies measured in thousands of person-days of outage. The four highlighted repair strategies are the focus of assessment for the remainder of this work.

	Damage scenario					
Repair strategy	1	2	3	4	5	Average
WNTR full shutoff	75.5	78.0	76.5	77.3	77.7	77.0
WNTR shutoff supply and isolate	40.8	34.1	26.4	37.5	36.0	34.9
WNTR maintain supply and isolate	49.1	41.3	46.8	66.3	62.4	53.2
WNTR rolling repairs	92.8	89.6	89.3	97.0	100.0	93.7
GMOR zone damage	44.8	37.3	43.8	61.5	36.5	41.4
GMOR spread damage	59.9	61.6	61.2	44.6	62.3	61.3

All values are thousands of person-days of outage.

3-5.1 Restoration curves

Population-outage times are useful for quantifying the effect that an earthquake might have on service in a region but lack the insight that restoration curves can provide in demonstrating the process of recovery after a disruption of service. Figure 3-7 shows mean restoration curves for the two considered WNTR repair strategies and both GMOR repair strategies for each of the five damage scenarios.

The restoration curves demonstrate both the wide variability in recovery processes between damage scenarios as well as the effect that each repair strategy has on the rate of restoration in the study area. In particular, the location of pipe breaks and the segments that must be isolated to repair them have a significant impact on recovery that is apparent in the WNTR modeling results. Further discussion surrounding these impacts is presented in Section 3-6.

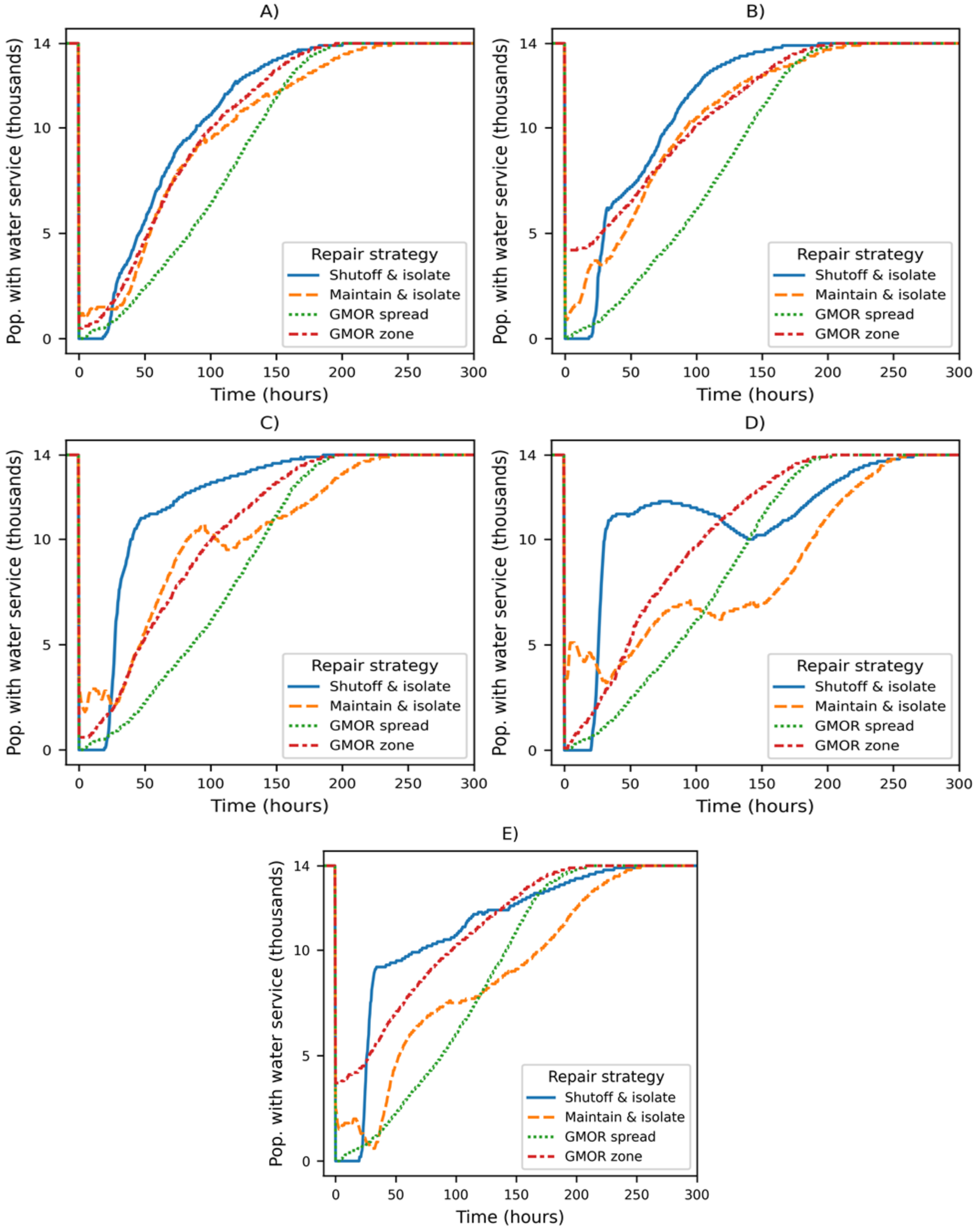


Figure 3-7: Mean restoration curves for the two considered WNTR repair strategies and the two GMOR repair strategies for each of the five damage scenarios (Figure parts A-E, in order). Full restoration curves that include all repair strategies are included in Appendix D.

3-5.2 Spatial restoration

Along with the pace of service restoration demonstrated by restoration curves, spatial patterns of recovery are important to consider as well. For this work, the spatial resolution is limited to that of individual zones. As indicated in Section 3-3.2, the hydraulic model does not represent thousands of individual users in the study area, but instead groups their demand for water into hundreds of demand nodes. As a result, not all census blocks contain demand nodes, so attempting to associate a specific population with each demand node using census block resolution is challenging.

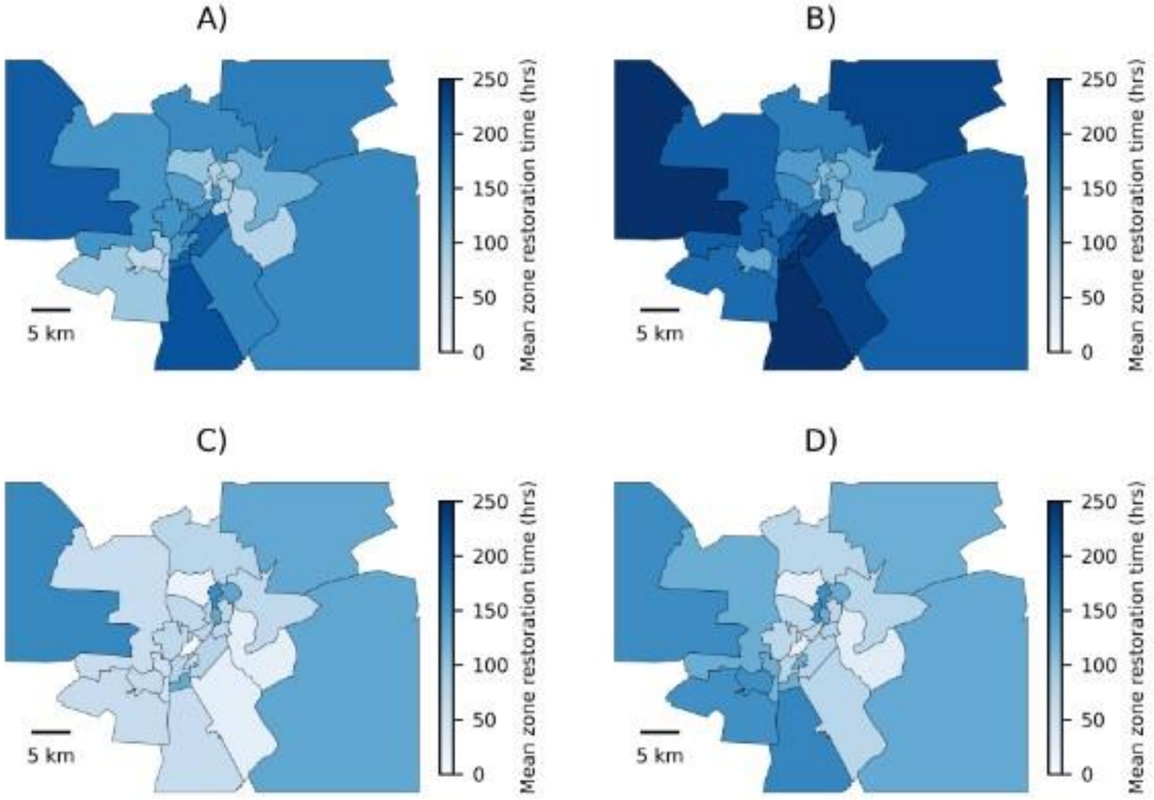


Figure 3-8: Mean final service restoration time for each zone for damage scenario 1 for the WNTR A) Shut down and isolate, B) Maintain and isolate repair strategies and GMOR C) Zone and D) Spread damage methodologies.

Instead, the process mentioned in Section 3-4.6 is used where the demand for a single demand node is divided by the total demand for the zone in which it is located and multiplied by the total population of the zone. In this way, each demand node provides service to a number of people in proportion to its demand within a given zone. The restoration curves shown in Figure 3-7 use the individual demand node populations for calculating the restoration of service to users, but all spatial comparisons of restoration are done at a zone level.

Figure 3-8 shows the mean final service restoration time for each zone for the first damage scenario to demonstrate how the results vary across the different considered damage methodologies and repair strategies. Note that the value shown for the restoration time for each zone in Figure 3-8 is the time required to restore service to the entire population of the zone. Most residents in the zone may have service restored much earlier, but the restoration time indicated represents all residents having service.

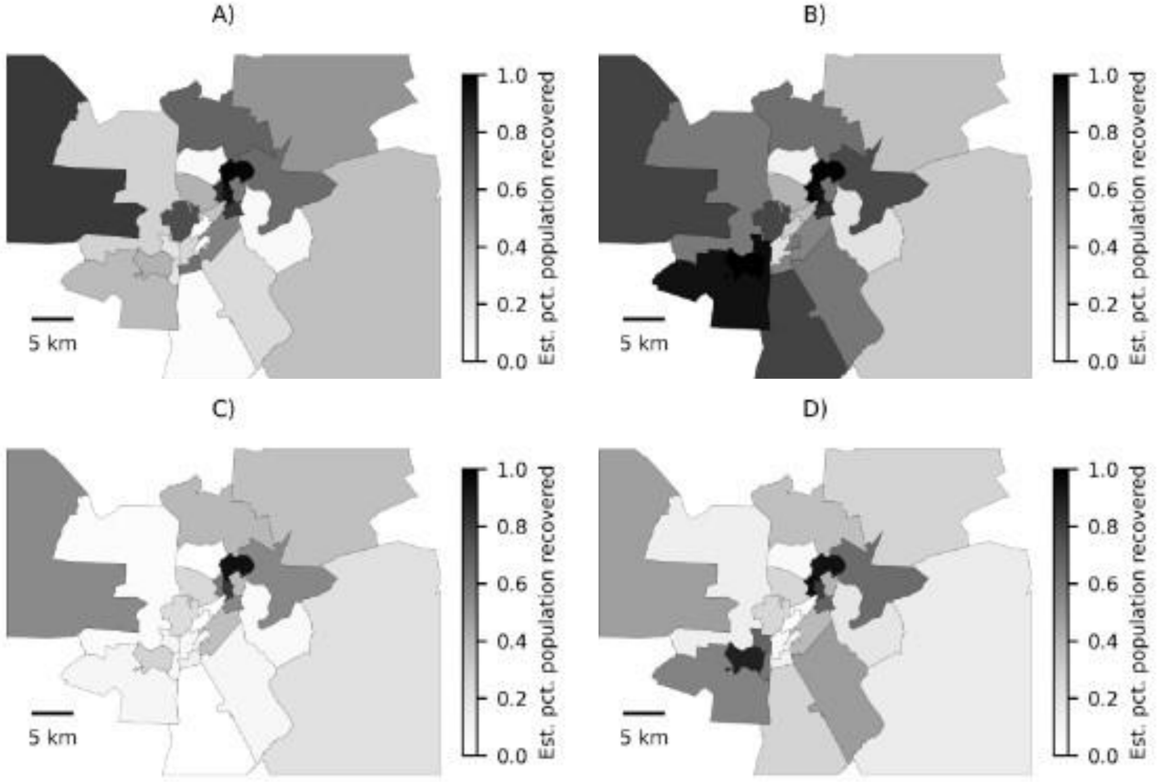


Figure 3-9: Comparison of zone repair times for the aggregated model simulated in GMOR and the hydraulic model simulated with WNTR. The value shown represents the mean estimated percentage of the population recovered (as calculated in the WNTR model) for each zone at the time estimated for the zone’s recovery in the aggregated model processed in GMOR. The comparisons are for A) GMOR zone vs WNTR shutoff and isolate, B) GMOR zone vs WNTR maintain and isolate, C) GMOR spread vs WNTR shutoff and isolate, and D) GMOR spread vs WNTR maintain and isolate. The darker the shading, the higher the population within the zone that is restored to service in the WNTR model before the GMOR model.

An additional set of maps is therefore provided in Appendix D to highlight population comparisons between the WNTR and GMOR modeling approaches. Figure 3-9 considers the restoration time of individual demand nodes within each zone and the estimated population that each demand node serves. The restoration time from the GMOR model for each zone is subsequently compared to the restoration times and populations of individual demand nodes within each zone to estimate the percentage of the population with service at the time the GMOR model shows that service is restored.

For example, if the restoration time indicated in the GMOR model for a zone occurs before the restoration time of any of the individual demand nodes within that zone in the WNTR model, then 0 percent of residents have service when the GMOR model indicates they will. If the GMOR model restoration time falls between two demand node restoration times, the estimated percentage of the population restored is interpolated between the demand node populations. Figure 3-9 only shows results of this assessment for damage scenario 1. A full set of maps for all damage scenarios is provided in Appendix D.

3-6 Discussion

As shown in Table 3-3, the mean total population-outage time for the GMOR **zone damage** methodology falls between that of the two considered WNTR strategies for all damage scenarios. In addition, with the exception of damage scenarios 4 and 5, the GMOR **spread damage** methodology results in a higher mean total population-outage time than the WNTR strategies. For developing estimates of total disruption in terms of population without service throughout the recovery process, therefore, aggregated modeling approaches can demonstrate results that are within a reasonable range. The **zone damage** method may be considered more realistic, while the **spread damage** method provides a conservative estimate of recovery.

It is clear from the restoration curves shown in Figure 3-7, however, that different damage scenarios and repair strategies have a significant effect on the process of restoration in the study area that the aggregated modeling approaches are unable to capture. The restoration curves also highlight the need for operators and community members to be involved in disaster management and planning activities.

Consider damage scenario 4, for example, and the significant decrease in service indicated after approximately 80 to 100 hours. In this damage scenario, water levels in the supply tanks in the study area approach their minimum levels, cannot be promptly refilled due to damaged and isolated pipe segments that they would otherwise depend on, and are unable to provide adequate pressure to users even though all damage has been isolated. While a brief loss of service is likely inconsequential for most users who previously regained service, it may be preferable to only reconnect segments to the network after sufficient tank capacity is regained to ensure service demands are met. This may reduce the number of users with service at the start of the restoration curve, but it would avoid multiple changes in service availability. These types of decisions should be made with consideration for all members (and critical services) in a community as they can have a significant impact on the pattern of restoration after a disaster.

Spatially, the restoration of the aggregated model shown in Figure 3-9 does not closely mirror that of the detailed hydraulic model. This is especially apparent in the central portion of the study area, where zone restoration in the aggregated model tends to lag behind the detailed model. The cause of this discrepancy is directly related to the approach that models each zone in the system as dependent on a single supply source. The dark shaded zones in the center of the study area are located near two water supply tanks and the water supply reservoir, but are each only dependent on a single source. As such, the redundancies inherent in the system in that area are not captured by the aggregated model.

3-7 Opportunities for future work

This work represents a small sample of the possibilities for this area of research. The system modeled is limited in its size and the damage considered includes the same number of breaks and leaks for each trial. While the **full shutoff** and **rolling repairs** repair strategies are not the most effective for the damage scenarios considered here, they may be effective in other situations. With fewer pipe breaks and subsequent water loss, for example, completing repairs on a rolling basis could be an effective strategy to maintain service without a significant drop in service to residents in the area. Damage to isolation valves or other facilities could also complicate repair activities but are not included in this work.

On the other hand, a much more severe, widespread damage scenario may necessitate shutting tanks and reservoirs until all repairs are completed to avoid the need to isolate dozens of segments individually throughout a region. Testing the sensitivity of the system to the number of breaks and leaks could provide valuable insight into response strategies and how detailed and aggregated modeling approaches reflect the change in damage.

Additional network layouts can be considered as well. The KY 18 system is classified as a looped system (Hoagland 2015; Hoagland et al. 2015), indicating that there are numerous paths for water to take within service areas. In contrast, branched systems are more common in some locations and include far fewer redundant paths, so damage to distribution pipelines may cause outages at a much wider scale. Assessing the use of aggregated models for these and other network layouts could increase the utility of this work as well.

The GMOR modeling approach remains useful for the rapid development and computation of planning scenarios, which can be utilized in exercises to identify vulnerabilities in complex systems (Abbass 2015). In the future, modifications to the aggregated model could increase its alignment with the results shown in the detailed WNTR model as well. Modeling each zone as dependent on multiple supply sources, for example, could better capture the redundancies that are more clearly visible in the detailed model. Adding a delay for supply tank availability or pressure stabilization in the system for some zones could increase the accuracy of the aggregated model as well. For most of the zones shown in Figure 3-9 where the aggregated model recovers much more quickly than the hydraulic model, for example, the zones all have some water service availability after all breaks and leaks in the system are repaired, but it takes time for the pressure to build up in the system to an extent that it provides useful service to residents. This could likely be directly implemented into the aggregated model or simply considered within the context of emergency management planning activities.

3-8 Conclusions

This work demonstrates the use and benefits of aggregated models for assessing the restoration of a water distribution system. The results produced indicate that the patterns of restoration derived from an aggregated model can provide a valuable baseline for planning scenarios, especially in situations where the availability of detailed system data is limited or emergency response actions are uncertain. The total population-outage time calculated with an aggregated model reflect a reasonable scenario based on an estimated level of initial damage.

Aggregated models require few computing resources to process and run, so multiple simulations with varying parameters can be quickly developed and tested. For the work presented here, for example, each WNTR simulation requires between 5 and 10 minutes to run on a high-performance computing cluster. In contrast, 500 GMOR simulations can be run on a consumer-grade laptop computer in less than one minute, representing an improvement of over three orders of magnitude. This does not include the time required to develop and model system controls (valve opening and closing, pipe breaks and leaks, etc.) for the hydraulic model, which requires a significant investment of time as well.

While aggregated models are not appropriate for developing detailed designs or operational specifications for water systems, their potential for use in disaster management and emergency response planning is substantial and should continue to be developed. They provide reasonably realistic and actionable situations that community members and planners can explore and test and require significantly less investment of time and resources to create than detailed hydraulic models. Each modeling approach has its own benefits and should be used to continue to enhance the disaster resilience of communities throughout the world.

Conclusions

The work presented in the preceding chapters includes advancements in the understanding of critical infrastructure restoration from disasters by using multi-infrastructure recovery modeling that are valuable for emergency management and response planning at a regional level. While it is impossible to model the full range of possible impacts from disasters or to precisely predict the process of recovery that a system will follow, models can help planners, operators, and other stakeholders think critically about the systems that provide resilience to their communities.

Chapters 1 and 2 of this work specifically highlight the benefits of simplified regional multi-infrastructure models and tools that can be used to assess community resilience using the results from such models. Models that are simplified using a system aggregation process provide regional stakeholders with the opportunity to consider the interactions within and between systems at a wide geographical scale without the technical system information or expertise required to create highly detailed models of individual systems.

Chapter 3 confirms the applicability of using aggregated models to develop scenarios for planning purposes for water distribution systems by showing that the simplified modeling approach can capture important restoration dynamics. It also provides a benchmark for future work in the space of aggregated modeling and discusses ways in which more complex dynamics can be captured within the aggregated model. Results from Chapter 3 highlight the significant benefits in speed that aggregated modeling approaches provide that allow users to develop and test a multitude of scenarios in a shorter amount of time, with less required data and labour.

There is no way to prevent all disasters from occurring and impacting the physical infrastructure systems that support lives and livelihoods in communities throughout the world. Equipping communities with tools (such as those presented in this work) to plan and protect themselves from the harmful effects of disasters, however, can ensure that they are as prepared as possible to face disruptions when they occur.

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Appendix A: Additional Details for Infrastructure Sectors

An overview of the implementation of the study methodology is presented in the text and the general approach is applicable for a majority of the systems in the study area. There are a number of municipalities in the study area, however, that do not fit the general approach. The details of these differences are separated by sector and addressed in the following sections.

A-1 Water system exceptions

A-1.1 Metro Vancouver reservoir systems

Some municipalities do not operate their own reservoirs or do not have water service coverage throughout the municipality using only their own reservoirs. In these cases, it is assumed that water is distributed straight from Metro Vancouver reservoirs to some or all the Census Dissemination Areas (CDAs) in the municipality (instead of the Metro Vancouver reservoirs providing water to local reservoirs that then serve the CDAs). The separation of service from different reservoirs is determined based on the locations of the CDAs and reservoirs and the layout of the pipe network in the municipality. The City of Delta, City of New Westminster, City of Burnaby, City of Vancouver, and City of North Vancouver all are directly served either only by Metro Vancouver reservoirs or by a combination of Metro Vancouver and municipally operated reservoirs.

A-1.2 Municipally managed systems

Some municipalities are not served by the Metro Vancouver water system and instead manage and maintain their own water treatment and distribution systems or use a combination of self-managed and Metro Vancouver resources. In some cases, these municipalities are tied into the Metro Vancouver system as well but are isolated by valves from the Metro Vancouver system during normal operations.

Given the assumption in the model that each CDA is served by only a single water point source, municipalities that run their own systems and are connected to the Metro Vancouver system are split based on available knowledge and an assessment of the layout of the piping network. Municipal annual water quality reports, for example, may indicate the population served by their system compared to the Metro Vancouver system, so CDAs are grouped by location and population in an attempt to match the service estimates indicated in the utility report.

Lions Bay is a small municipality northwest of the rest of the region and operates its own small water distribution system. As of 2019, two treatment plants and five reservoirs supply water to approximately 1300 residents in the community (Village of Lions Bay 2020).

West Vancouver is located west of the treatment and filtration facilities in the northern part of the region and also operates its own treatment and distribution system to supply approximately half of its needs. The water comes from two surface sources and is treated at two small treatment plants before being distributed throughout the district (District of West Vancouver 2020b). In addition, West Vancouver is tied into the Metro Vancouver system at five points to provide for the rest of its needs (District of West Vancouver 2020a). Because the methodology used to produce the GMOR model limits the water supply to a single point source for each CDA, the municipality is split roughly in half at a CDA level based on population, with the half closer to the West Vancouver treatment facilities being supplied solely by those sources and the other half being supplied solely by the Metro Vancouver system.

The Township of Langley is served by five groundwater-supplied municipal and private systems as well as by tie-ins to the Metro Vancouver system. As of 2019, roughly 85 percent of the residents (accounting for 38 percent of total usage) in the township are served by the local system, while the remainder are served by connections to the Metro Vancouver system or private or community wells. Interconnections with other municipalities are available to provide additional water supply in case of emergency (Township of Langley 2020).

The City of White Rock operates its own water supply system that is fed by seven wells, two pumping stations, and three reservoirs located throughout the City (City of White Rock 2020).

Bowen Island is a small island off the coast of the mainland of the region that is not supplied with water from the Metro Vancouver system. The island contains seven separate systems that utilize 17 wells, ten reservoirs, and three pumps to provide water to a majority of its approximately 3700 residents. Others are served by private or communal systems (Bowen Island Municipality 2018; 2020b).

A-1.3 Metro Vancouver Transmission System Tie-in

The City of Richmond and City of Pitt Meadows both receive water directly from the Metro Vancouver Transmission system via pressure reduction stations that tap into the high pressure Metro Vancouver mains (City of Richmond 2020; City of Pitt Meadows 2022). The pressure reduction stations allow the cities to provide water to residents without the need for pressure regulation functionality that is commonly produced by reservoirs or other pumping infrastructure.

A-1.4 Unknown Services

Some CDAs within the region are not represented in the study due to a lack of available data. In some instances, it is assumed that individual well systems serve the residents there but, with close to ten thousand total wells registered in the region (Government of British Columbia 2021), it is not possible to differentiate each of their individual uses. In other cases, it is assumed that the pipe systems have not yet been mapped or released in an accessible format. Satellite imagery of some areas, for example, indicates new housing developments, but municipal Geographic Information System (GIS) repositories do not yet contain the infrastructure data for them.

A-2 Wastewater system exceptions

In some cases, it is clear from GIS data that wastewater from different parts of a single CDA flows to separate lift stations, but a single lift station for the CDA is chosen for the assessment based on visual inspection of the lift station with the higher percentage of pipeline represented in the CDA.

A-2.1 Municipally managed systems

Two small municipally managed wastewater treatment plants process liquid waste for communities outside of the Metro Vancouver service area. One serves 94 connections in the Village of Lions Bay (Jaffer 2020) and the other serves 92 connections on Bowen Island (Bowen Island Municipality 2020a).

A-2.2 Unknown services

It is assumed that any CDAs that are not connected to the Metro Vancouver or municipally managed wastewater treatment systems depend on septic tanks and fields for wastewater service.

A-3 Power system exceptions

The City of New Westminster buys power in bulk from BC Hydro, but maintains its own electrical distribution system within the city rather than depending entirely on BC Hydro infrastructure (British Columbia Utilities Commission 2012). In the model, this means that all CDAs in the city are dependent on a specific substation rather than being dependent on the nearest substation, as is the case for all other CDAs in the model.

A-4 General exceptions

Travel times for repair are not explicitly included in the model. The repair time parameters used, however, indicate the overall time required to perform a repair based on historical data and expert judgement and therefore implicitly include travel time. In addition, the repair times include a measure of uncertainty (captured by the standard deviation time for repairs) that is assumed to accommodate variability in travel and repair times.

Damage to components in the GMOR model does not include damage on the user side of a connection to a municipal service. For water and wastewater service, pipes within individual buildings are not considered in the assessment. Power lines are not included in the model, so service connections to individual homes are therefore not included either.

A-5 Water and wastewater system damage

Figure 1 and Figure 2 show the damage level calculated in the case study for the water and wastewater systems, respectively. In these figures, damage includes breaks and leaks to both municipal water distribution and Metro Vancouver water transmission systems contained in each CDA.

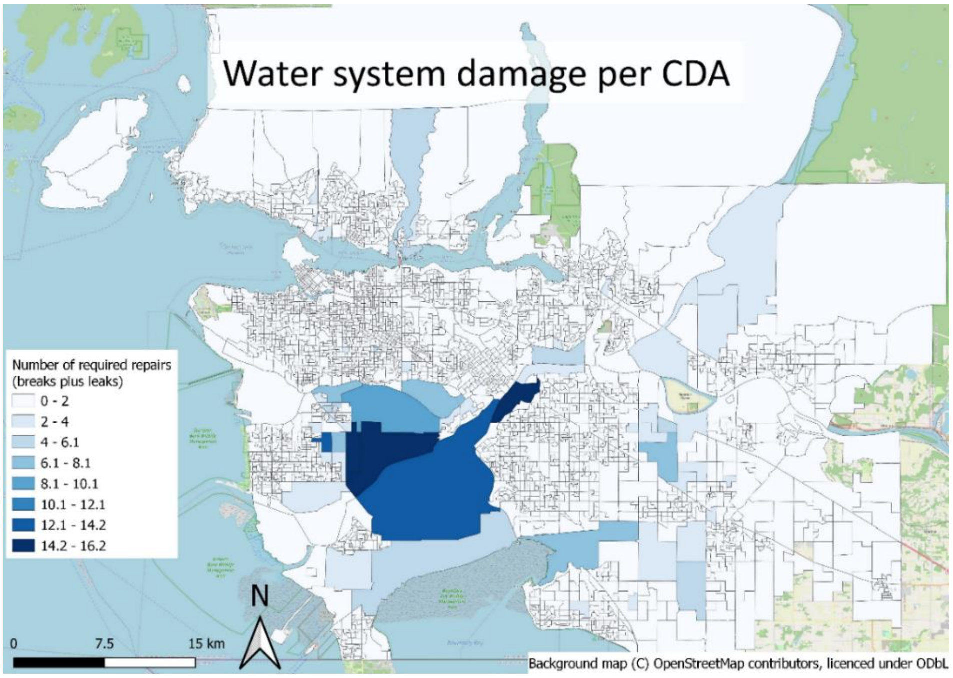


Figure A-1: Water system number of breaks plus number of leaks for each CDA. Background map OpenStreetMap (OpenStreetMap contributors 2022)

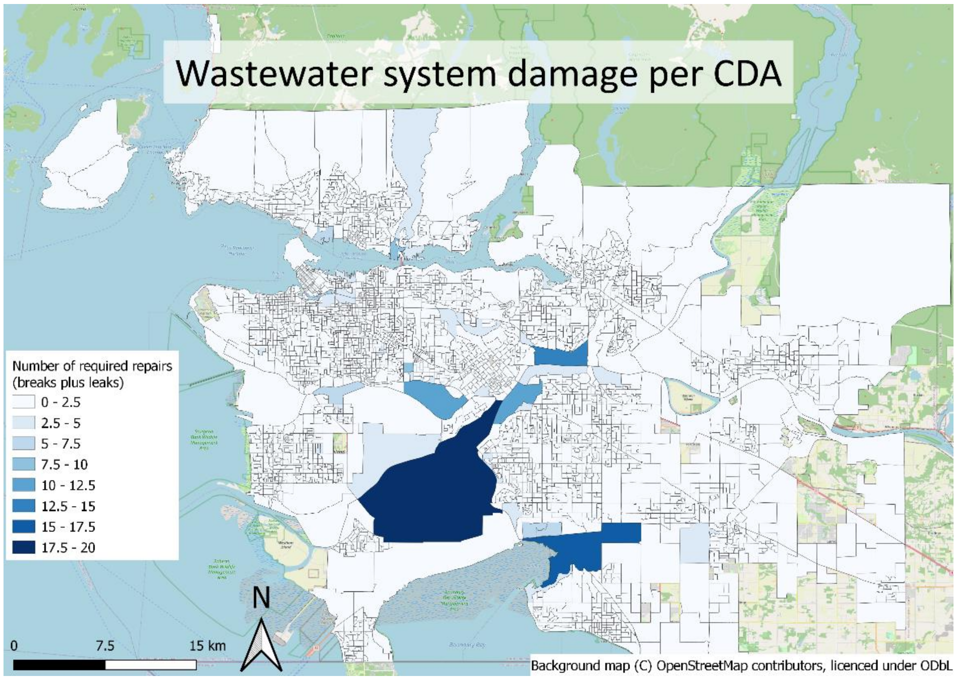


Figure A-2: Wastewater system number of breaks plus number of leaks for each CDA. Background map OpenStreetMap (OpenStreetMap contributors 2022)

A-6 Repair times and resources

Table 1 shows the parameters used in the model to calculate the repair time for all types of facilities and pipelines included in the model. Repair times are normally distributed based on the mean and standard deviation shown in Table A-1.

Table A-1: Repair time parameters (in days) for facilities and pipelines in the model (from Federal Emergency Management Agency 2011).

	Damage state 1		Damage state 2		Damage state 3		Damage state 4		Damage state 5	
Facility type	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Water pumping plant	0	0	0.9	0.3	3.1	2.7	13.5	10	35	18
Water storage tank	0	0	1.2	0.4	3.1	2.7	93	85	155	120
Water well	0	0	0.8	0.2	1.5	1.2	10.5	7.5	26	14
Water treatment plant	0	0	0.9	0.3	1.9	1.2	32	31	95	65
Wastewater treatment plant	0	0	1.5	1	3.6	2.5	55	25	160	60
Wastewater lift station	0	0	1.3	0.7	3	1.5	21	12	65	25
Electric power substation	0	0	1	0.5	3	1.5	7	3.5	30	15

Repair task	Mean	SD
Repair pipeline leak	0.313	0.156
Repair pipeline break	0.625	0.313

Repair times for breaks and leaks water and wastewater pipelines provided by Hazus documentation are given based on the number of hours required to perform repairs. This value was scaled to fractions of a day for the GMOR model, assuming that a 16-hour workday is adopted for a post-disaster scenario.

Appendix B: Simplified example scenario and assessment

A minimal example network and assessment are provided here to illustrate the interaction between model parameters and demonstrate the assessment tools used for the case study in the main text.

B-1 Example network and scenarios

Figure B-1 shows the layout of the example network, in which one supply source (represented by a square node) provides a single type of service to four zones (represented by circular nodes), each of which have a population of 1,000 people.

A hazardous event damages components in all nodes, and three response scenarios are considered. The first scenario is presented here and the other two are discussed in later sections. In the first scenario, one repair crew is available to complete repairs to all nodes and can work on only one node at a time. The time required to repair each node is indicated in parentheses below the node name in Figure B-1. Repairs are prioritized starting with the source then moving alphabetically through the zones and the crew does not move on from a node until repairs there are completed.

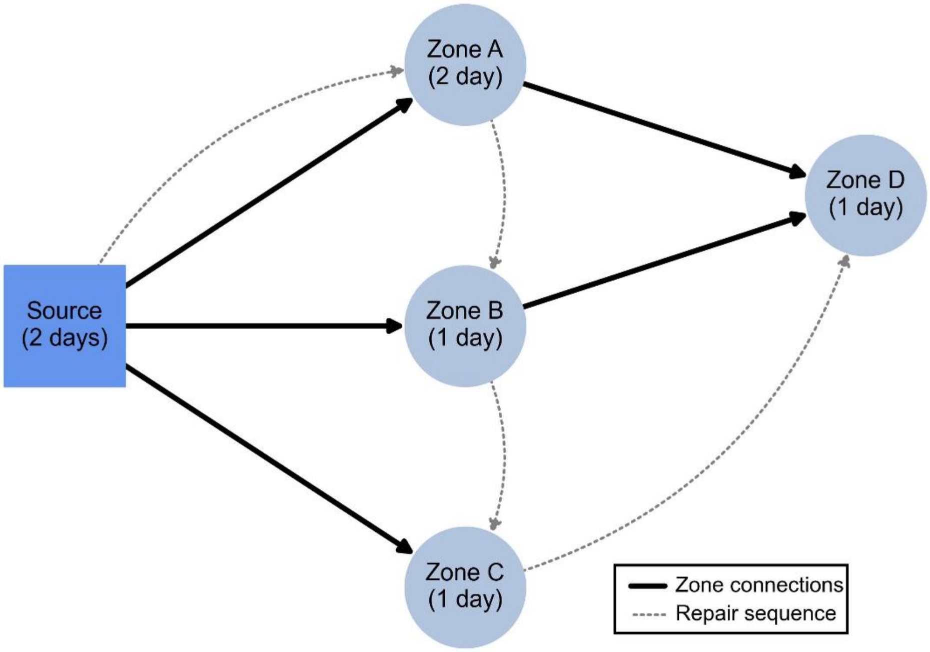


Figure B-1: Example network layout. Black solid lines indicate the paths between the nodes by which service is supplied through the system. Thinner gray dotted lines show the order in which repairs are completed. The time required to repair damage to a node is shown in parentheses below the node name.

Because of the network structure of the system, a zone can only be restored to service once the source node and any intermediate zones are repaired. Zone D, for example, can have service only after the source and Zone A or Zone B are repaired first. Based on the structure of the network, the required repair time for each node, and the sequence of repairs, Figure B-2 shows the timeline of repairs for the system.

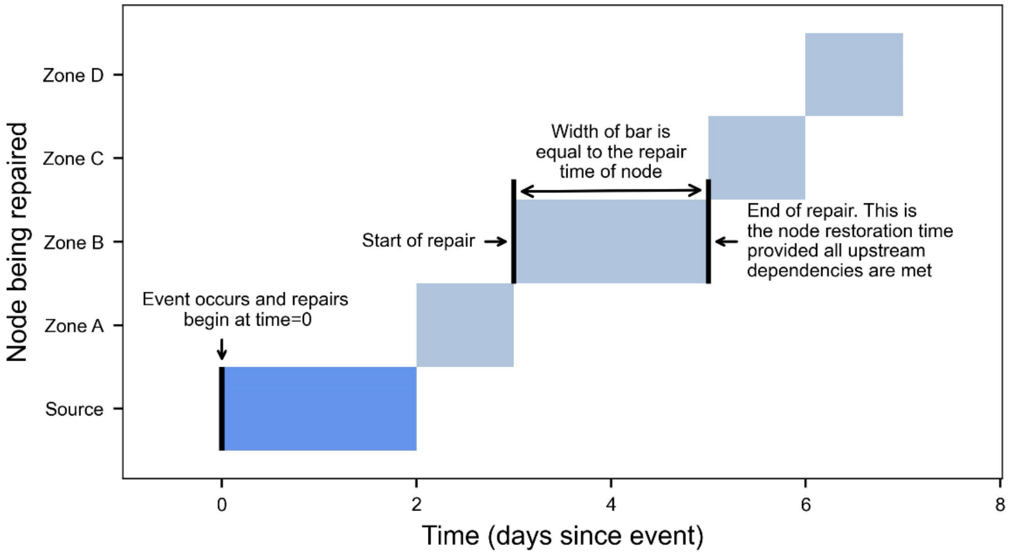


Figure B-2: Timeline of recovery for the source and zones in the system. Because this scenario assumes the availability of only a single repair crew, repairs must happen sequentially. Each coloured bar represents the time during which repairs occur for the node indicated on the vertical axis. The annotations included for Zone B are typical for all nodes

B-2 Scenario results

Table B-1 shows the repair and restoration parameters for the first example scenario. Recall from the main text that the numerical value of repair time and repair cost are the same, but repair costs are measured in crew-days rather than days. Restoration time of a zone includes the time required to complete repairs to that zone and a connected set of zones between it and the supply source.

The restoration time of each zone represents its service outage time and is multiplied by its population to produce a population-outage time. The population-outage time is used to quantify the loss of resilience of each zone and the system as a whole.

Table B-1: Repair and restoration values for the example scenario.

Node	Repair time (days) and Repair cost (crew-days)	Restoration time (days)	Population	Population-outage time/ loss of resilience (person-days)
Source	2	2	0	0
Zone A	1	3	1,000	3,000
Zone B	2	5	1,000	5,000
Zone C	1	6	1,000	6,000
Zone D	1	7	1,000	7,000
Totals	7	-	4,000	21,000

B-3 Scenario assessment

Population-outage time alone may be used to assess the loss of resilience of a system, but other tools provide additional insight to the processes that surround recovery, dependencies within and between systems, and benefits that may be realized through the implementation of disaster risk reduction (DRR) strategies.

The assessment tools described here include restoration curves, restoration ratios, and restoration ranking. They are applied to the example scenario here and to the case study scenario in the main text.

B-3.1 Restoration curve

A restoration curve (also known as a resilience or recovery curve) provides a visualization of the progression of recovery of an infrastructure system. The curve includes time on the horizontal axis and functionality on the vertical axis. Steep (positively sloped) lines on the restoration curve indicate a rapid progression of recovery while flatter portions indicate slow progress. For the purposes of this work, functionality is measured by the number of people with service supplied by the source.

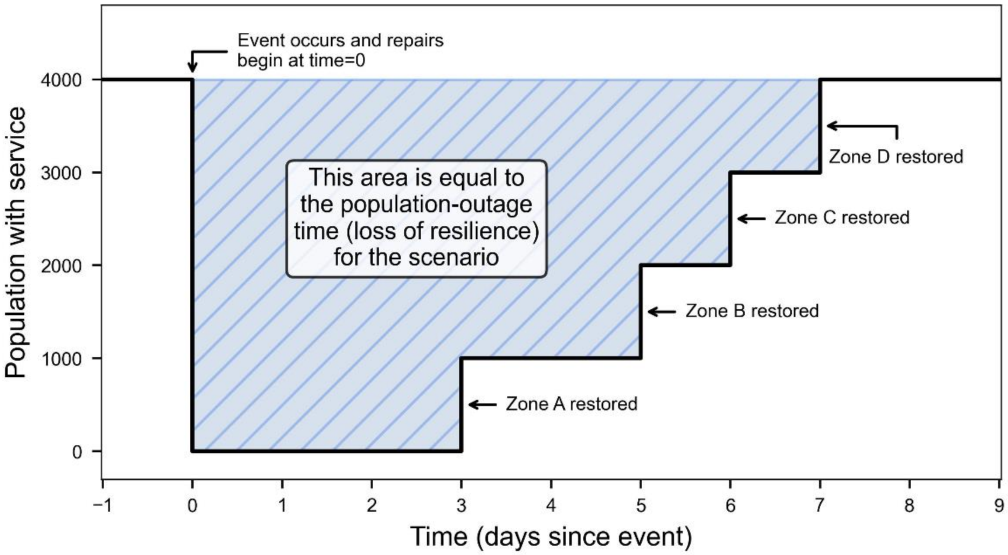


Figure B-3: Restoration curve (solid black line) for the example scenario. Time since service was disrupted is shown on the horizontal axis and population with service restored is shown on the vertical axis. The area above the curve is equal to the total population-outage time for the scenario. Each increase in service restoration is annotated with the associated zone.

The area above the restoration curve represents the loss of system resilience (in this case measured in population-outage time) and can be used to demonstrate the effect of DRR strategies on both system resilience and the pace of recovery. Specific portions of the recovery process where strategies are most beneficial may be identified from the restoration curve as well. For instance, some strategies are most effective in the immediate aftermath of a disaster whereas others may influence longer term recovery patterns.

Figure B-3 shows a restoration curve for the first example scenario that is drawn from the values noted in Table B-1 and the recovery timeline shown in Figure B-3. Note that the restoration curve does not include the recovery of the source node. The source enables the recovery of populations within the zones but does not have its own population and is therefore not shown on the restoration curve.

B-3.1.1 Restoration ratio

The restoration ratio (Equation B.1) for a given infrastructure distribution system in a zone, proposed by Deelstra and Bristow (2023), compares the time taken to restore service to a zone with the time required to repair the components associated with that service in the zone. It uses values that are readily accessible from a recovery modeling process and is useful for describing the level of dependence that a system has on different resources. The restoration ratio consists of the restoration time of the system in a zone (rest_{zone}) divided by the sum of the restoration time of the source that supplies the zone (rest_{source}) and the repair time of the distribution system components within the zone (RT_{zone}).

$$\frac{\text{rest}_{zone}}{\text{rest}_{source} + \text{RT}_{zone}} \tag{B.1}$$

For example, the terms in the restoration ratio for a water system in a specific zone would describe the following:

- rest_{zone} – The time at which water service is restored to the users in the zone
- rest_{source} – The time at which the water reservoir that provides service to the zone is functional
- RT_{zone} – The time required to repair the water pipes within the zone.

Note that RT_{zone} only includes repairs to components outside the source. If a water reservoir is located within a zone, for example, the repair time for the reservoir is not included in RT_{zone} because its repair time is already captured in the source restoration time (rest_{source}).

The denominator of the restoration ratio includes the restoration time of the source for the considered zone to provide a consistent baseline for zones that depend on different sources. If the zone restoration time was simply divided by its repair time, the result would vary widely across zones and provide little value for comparing systems in different areas.

Alternatively, eliminating the zone repair time from the equation and dividing the zone restoration time by the source restoration time is problematic due to the frequency with which sources are undamaged and have restoration times of 0. In structuring the restoration ratio as shown in Equation B.1, its value is positive unless the repair times of both the source and the zone are 0.

B-3.1.2 Shared and external resources

The restoration ratio provides an indication of the level to which infrastructure systems depend on either their own resources or on other systems within each zone. Infrastructure dependence is separated into shared and external resources. Shared resources refer to those that a system in a given zone is dependent on for repairs. In a municipality, for example, it is likely that all water pipeline repairs are completed using the same resources and crews. Therefore, for any zone within the municipality, the shared resource for the water pipelines within that zone is the municipal pipeline repair crew. Increasing the number of those crews increases the number of pipeline repairs that can be completed concurrently in the municipality.

External resources refer to those that are not shared by the zone for the given system. Powerline repair crews are an external resource to a zone's water distribution pipelines, for example, because the pipelines are only indirectly dependent on the power system via their connection to facilities or components that require power. Increasing the number of repair crews in the power sector has no effect on the speed at which repairs can be made to water pipelines (assuming pipeline crews do not require external power to complete repairs).

B-3.1.3 First scenario restoration ratio

For the first example scenario (all nodes dependent on the same resource), the restoration ratio for each zone is calculated as shown in Table B-2. Zone A experiences the best-possible case repair scenario because the repair crew begins its repairs on the zone immediately after the source is repaired. As a result, Zone A's restoration ratio is 1 while for all other zones it is greater than 1, indicating that they are repaired after the source and after at least one other zone.

Table B-2: Restoration ratio for the baseline example scenario. In this scenario, the source and zones are all dependent on the same repair resource.

Zone	rest_{source} Source restoration time (days)	RT_{zone} Zone repair time (days)	rest_{zone} Zone restoration time (days)	$\frac{\text{rest}_{zone}}{\text{rest}_{source} + \text{RT}_{zone}}$ Zone restoration ratio
A	2	2	3	1
B	2	1	5	1.25
C	2	1	6	2
D	2	1	7	2.33

B-3.1.4 Second scenario and restoration ratio

Consider now a scenario in which repairs to the source are done by one type of crew and repairs to the zones require a different type of crew. Repairs to the zones are completed in the same order as in the first scenario. Table B-3 shows the updated repair time, restoration time, and restoration ratio values for the zones in the modified scenario. Because repairs to Zone A can begin immediately instead of starting after the source is repaired, the average restoration ratio for the zones decreases.

Table B-3: Restoration ratio for the second scenario. In this scenario, the source and zones depend on separate repair resources instead of sharing a resource.

	rest_{source}	RT_{zone}	rest_{zone}	$\frac{\text{rest}_{zone}}{\text{rest}_{source} + \text{RT}_{zone}}$
Zone	Source restoration time (days)	Zone repair time (days)	Zone restoration time (days)	Zone restoration ratio
A	2	2	2	0.67
B	2	1	3	0.75
C	2	1	4	1.33
D	2	1	5	1.67

B-3.1.5 Restoration ratio interpretation

A restoration ratio of less than 1 indicates a greater dependence on external resources or systems. For example, the system in Zone A in the second scenario is repaired and therefore capable of being restored to service one day before the source. Its service cannot be restored, however, until the source is repaired. No matter how many additional zone repair crews are available, Zone A will not have its service restored any earlier. Only a reduction in restoration time of the source would contribute to an earlier return to service for Zone A.

Zone B exhibits an edge case in which its restoration ratio is less than 1, but its service restoration is not actually hindered by the repair of the source. This situation arises when a zone's repairs begin before but end after the source becomes functional and is limited in its occurrence to one instance per repair crew. Given there are generally fewer repair crews than zones in most regions (this is a reasonable assumption for zones with a population of 1,000, but should be reconsidered for larger zones), the scope of this situation is limited but important to note.

Zone C and Zone D have restoration ratios greater than 1, which indicates that they are repaired after both the source and at least one other zone. Their ratio decreased in the second scenario, however, indicating an increased dependence on the shared resource (zone repair) compared to the first scenario.

B-3.1.6 Discussion and third scenario

Given the potential for edge cases identified in the second scenario and the variations in repair and restoration times that may be experienced throughout a region, the restoration ratio is not intended to provide a standardized metric for all systems and locations. Instead, it illustrates trends that may be useful for assessing the value of DRR strategy implementation. Consider, for example, a proposal to hire a repair crew for the source and each zone (5 crews total) in the example location for the purposes of improving disaster resilience.

Table B-4: Restoration ratio for the third scenario. In this scenario, the source and zones each have dedicated resources allocated for their repairs.

	rest_{source}	RT_{zone}	rest_{zone}	$\frac{\text{rest}_{zone}}{\text{rest}_{source} + \text{RT}_{zone}}$
Zone	Source restoration time (days)	Zone repair time (days)	Zone restoration time (days)	Zone restoration ratio
A	2	2	2	0.67
B	2	1	2	0.5
C	2	1	2	0.67
D	2	1	2	0.67

In this third scenario, each zone is repaired before the source and is therefore highly dependent on the source and its repair crew for restoration. A calculated restoration ratio of less than 1 for each zone (shown in Table B-4) confirms this and indicates that zone repair resources may not have been effectively utilized in this case. Each zone could have its service restored just as quickly if only 4 total repair crews were used, leading to identical outcomes for the zones while leaving one repair crew available for other purposes.

In this simplified example case, there is no way to reallocate the remaining zone repair crew to improve the resilience of the system. At a regional scale, however, the large number of zones, available resources, and system types provides ample opportunities to consider different ways that resources could be used. Some of these opportunities and their associated challenges are discussed in Section 2-7 of the main text.

Appendix C: Additional results data

To conserve space in the main text, additional details pertaining to the results of the case study are included here.

C-1 Local authority abbreviations

Figure 2-3 in the main text includes abbreviations for local authorities to reduce the size of the figure legend. The abbreviations and full names are presented in Table C-1.

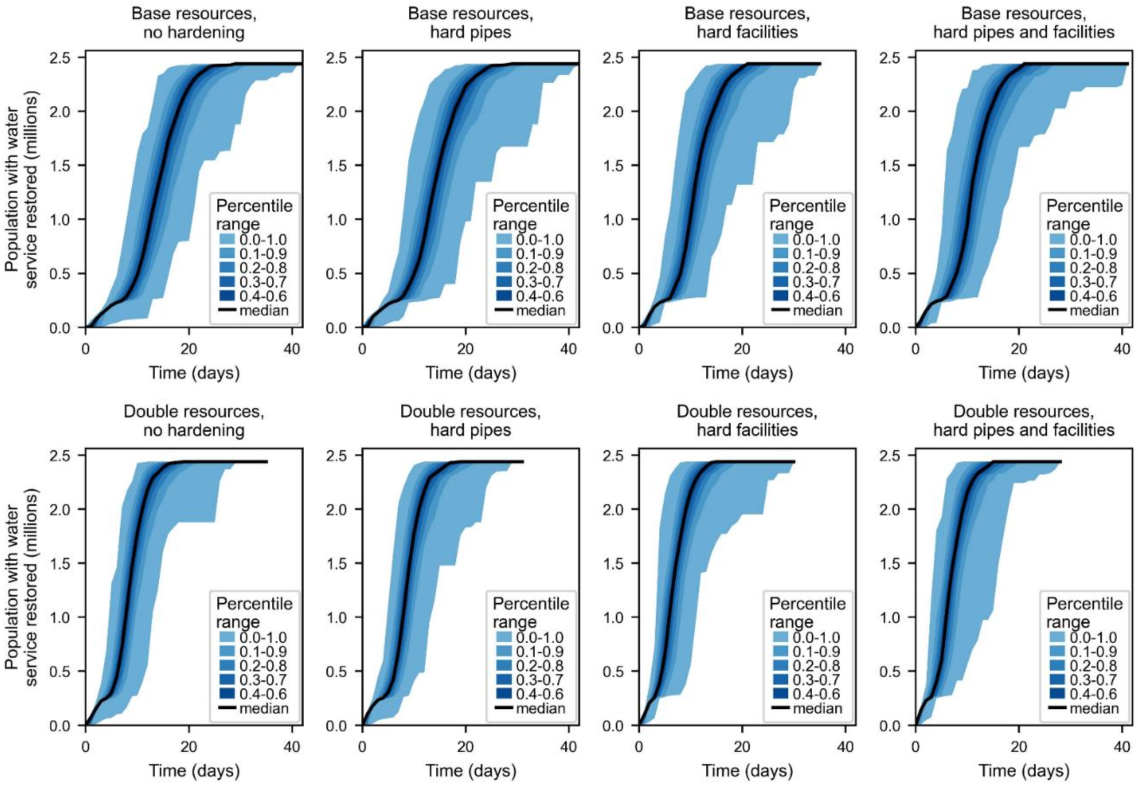
Table C-1: Local authority abbreviations and names.

Abbrv.	Name	Abbrv.	Name	Abbrv.	Name
Anm	Anmore	LB	Lions Bay	PoM	Port Moody
BI	Bowen Island	MR	Maple Ridge	Rmd	Richmond
Bby	Burnaby	MV	Metro Vancouver	Sry	Surrey
Cqt	Coquitlam	NW	New Westminster	TFN	Tsawwassen First Nation
Dlt	Delta	CNV	North Vancouver City	Van	Vancouver
EAA	Electoral Area A	DNV	North Vancouver District	WV	West Vancouver
CoL	Langley City	PiM	Pitt Meadows	WR	White Rock
ToL	Langley Township	PC	Port Coquitlam		

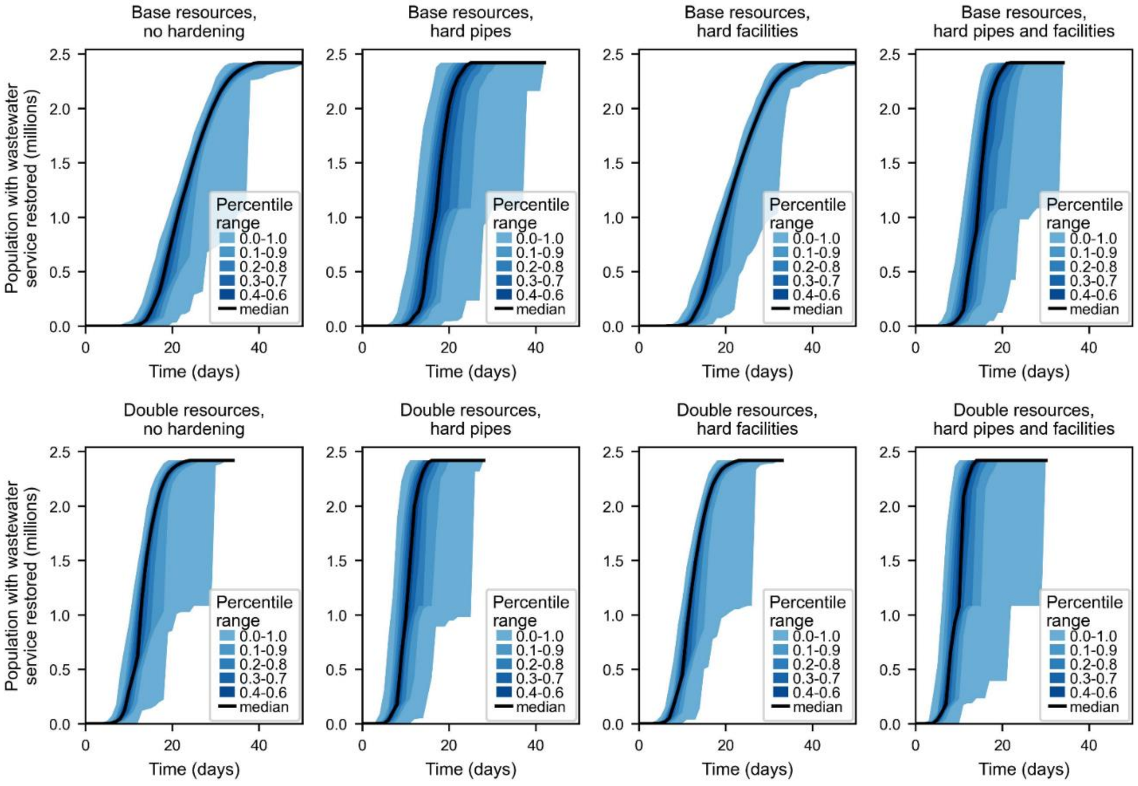
C-2 Full restoration curves

Restoration curves that include all modeled results for each sector are shown in Figure C-1. These are an extension of the median curves shown in Figure 2-4 in the main text.

A


Base resources, no hardening
Base resources, hard pipes
Base resources, hard facilities
Base resources, hard pipes and facilities
Double resources, no hardening
Double resources, hard pipes
Double resources, hard facilities
Double resources, hard pipes and facilities
Population with water service restored (millions)
0.0
0.5
1.0
1.5
2.0
2.5
Time (days)
0
20
40
Percentile range
0.0-1.0
0.1-0.9
0.2-0.8
0.3-0.7
0.4-0.6
median

B


Base resources, no hardening
Base resources, hard pipes
Base resources, hard facilities
Base resources, hard pipes and facilities
Double resources, no hardening
Double resources, hard pipes
Double resources, hard facilities
Double resources, hard pipes and facilities
Population with wastewater service restored (millions)
0.0
0.5
1.0
1.5
2.0
2.5
Time (days)
0
20
40
Percentile range
0.0-1.0
0.1-0.9
0.2-0.8
0.3-0.7
0.4-0.6
median

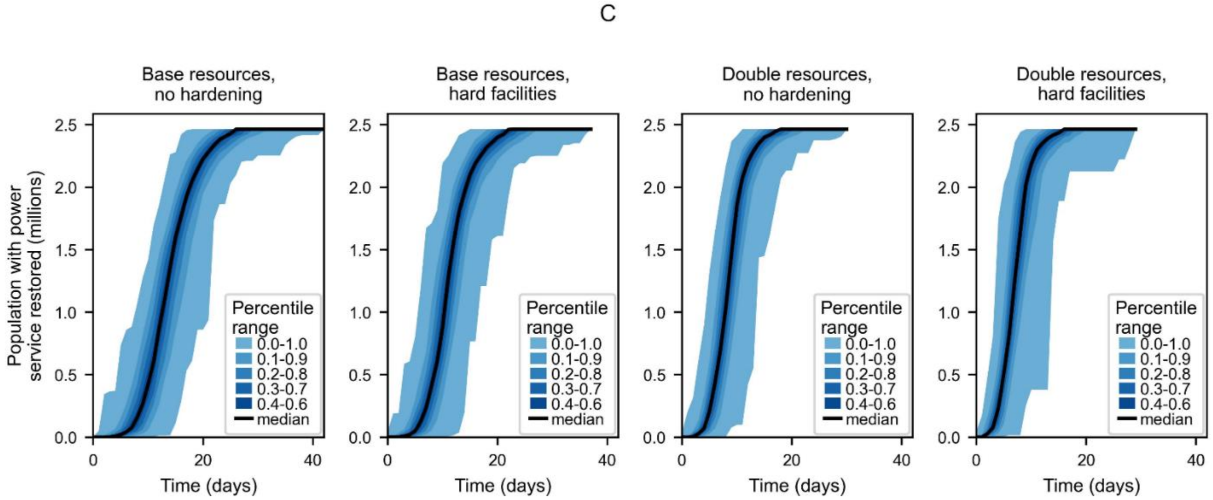


Figure C-1: Restoration curves for (A) water, (B) wastewater, and (C) power sectors. The shaded areas indicate the estimated population with service over time for the noted percentile range. For the (A) water system in the "Base resources, hard pipes" scenario, for example, the worst-case (0^{th} percentile) trial indicates that approximately 1 million residents have service restored and the best-case indicates close to full restoration at a time of 20 days post-earthquake.

Figure C-1 shows that, while the worst-and best-case trials for each scenario encompass a wide range of possible restoration outcomes, most trials are relatively consistent, with results near the median in most cases.

C-3 Population-outage time for each scenario

The total mean population-outage time for each sector for each scenario is provided in Table C-2.

Table C-2: Total population-outage time for each sector and scenario in the case study. The first number in each cell is the mean population-outage time from all trials for the given scenario and the number in parentheses is the change from the baseline value.

	Population-outage time (millions of person days and percent change from the baseline resource, no hardening scenario)							
	Baseline resource scenarios				Double resource scenarios			
Sector	No hardening	Hard pipes	Hard facilities	Hard pipes and facilities	No hardening	Hard pipes	Hard facilities	Hard pipes and facilities
Water	33.5	33.4 (0%)	26.4 (-21%)	26.5 (-21%)	20.7 (-38%)	20.7 (-38%)	16.5 (-51%)	16.5 (-51%)
Wastewater	57.4	43.8 (-24%)	53.6 (-7%)	37.2 (-35%)	33.9 (-41%)	26.7 (-53%)	31.3 (-46%)	24.2 (-58%)
Power	34.7	34.7 (0%)	28.3 (-18%)	28.3 (-18%)	21.5 (-38%)	21.5 (-38%)	17.9 (-48%)	17.9 (-48%)

Appendix D: Repair time parameters and EPANET model modifications

D-1 LADWP Repair time parameters for individual water supply system repair tasks

Table D-1 indicates the repair time parameters originally developed by Tabucchi, Davidson, and Brink based on their assessment of repair activities performed in response to the 1994 Northridge earthquake (Tabucchi, Davidson, and Brink 2010). They include times for other tasks in their work, but the values in Table D-1 are the only ones used for the purposes of Chapter 3.

Note that the values included in Table D-1 assume a crew size of only two, whereas the work presented in Chapter 3 assumed (based on Hazus repair times) a crew size of four.

Table D-1: Triangular distribution repair time parameters for select water system repair tasks *(from Tabucchi, Davidson, and Brink 2010)*

Event	Minimum	Mode	Maximum
Inspect a distribution damage location	0.5 h	0.5 h	1 h
Isolate distribution damage at one demand node	1 h	2 h	4 h
Repair a distribution leak	3 h	4 h	6 h
Repair a distribution break	4 h	6 h	12 h
Travel a distance D (km)	D/80 h	D/40 h	D/25 h

D-2 EPANET model modifications

As indicated in Section 3-4.1, the original EPANET model of the KY V18 had a number of problems that needed to be addressed before using it for the case study in Chapter 3.

D-2.1 System relocation

The original geographic location of the model did not match any known location, even after testing multiple coordinate reference systems. This may have been done for privacy or security reasons, so the location will not be listed here, but it was eventually determined. Having the actual location available provided the opportunity to use actual US Census Bureau population information for the study area rather than assuming the population based on recorded system demands.

D-2.2 Material addition

In addition to gaining population information, the material for each pipe was able to be determined using the actual location information as well. The EPANET file did not contain any pipe material information, but the state of Kentucky maintains a GIS database of public water systems in the state (Kentucky Infrastructure Authority 2022). This information was correlated with the pipeline data in the EPANET file to add materials to each of the pipes in the study area. Adding material provided an additional possibility to separate pipes into ductile or brittle materials, which provides a more accurate damage assessment.

D-2.3 Valve relocation and modification

A majority of the valves in the study area were shifted from where they should have been located by a consistent distance. The locations of the valves were therefore modified to move them to the correct location. Initially, the incorrect locations contributed an extra 20 miles of pipe to the system compared to the non-valved system. By moving the valves to their correct locations, this discrepancy was reduced to less than 40 feet between the valved and non-valved datasets.

In addition, the diameter listed for each of the valves was far beyond a realistic diameter for a valve in a piping system. Because the valves are only opened and closed in the model (rather than being partially open or partially closed), it is unlikely that this would make a difference, but the diameters were modified to match the largest diameter of pipe that entered the valve.

Appendix E: Additional figures

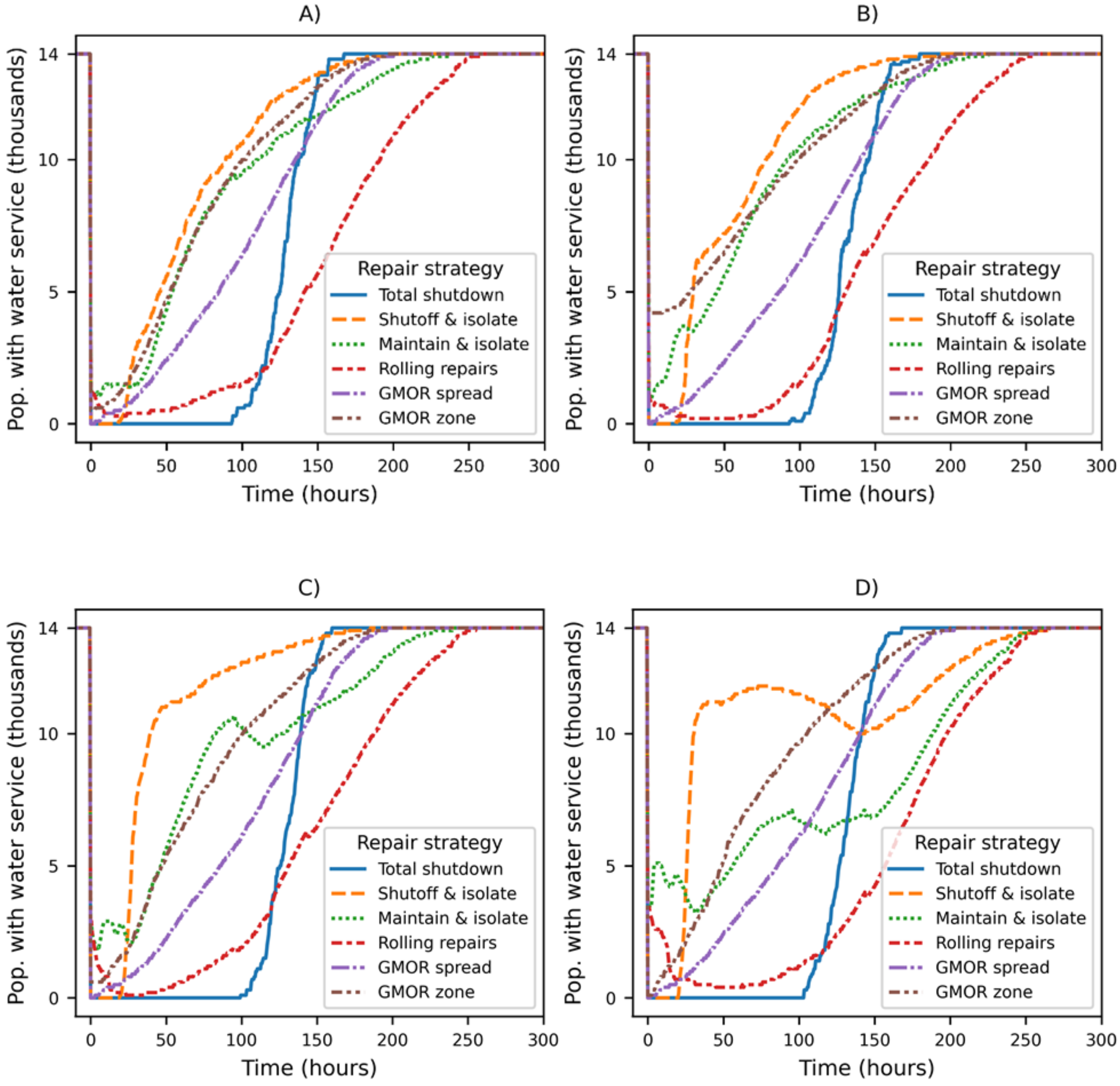
E-1 All damage scenarios

Figure E-1: All damage scenarios included in the case study.

Figure E-1 shows the location of pipe breaks and leaks for all five damage scenarios.

E-2 Restoration curves

Figure E-2 shows restoration curves for all of the WNTR repair strategies and GMOR damage methodologies. It is interesting to note that the **total shutdown** repair strategy shows the fastest overall restoration tie out of all of the response strategies due to the lack of isolation of individual components that it requires. Even though the population-outage time from this strategy is not the smallest, it may be a beneficial strategy to consider, especially in situations where there is extensive or widespread damage expected.



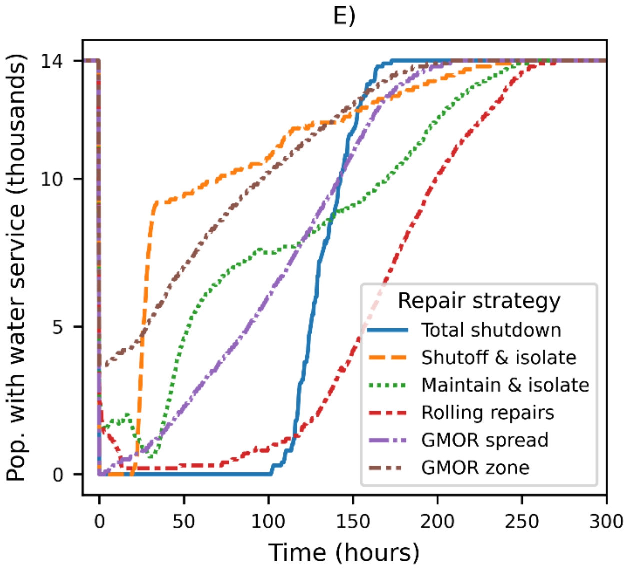


Figure E-2: Restoration curves including all WNTR repair strategies and GMOR damage methodologies.

E-3 Mean zone repair time estimates

Figure E-3 through Figure E-7 show mean restoration time estimates for individual zones in the study region for each of the repair strategies and damage methodologies and each damage scenario. It's important to note that the repair time is the time at which it is assumed that all residents within a zone are restored to service. As such, for the WNTR scenarios especially, the restoration time may be skewed by a small segment of the population within a zone that takes significantly longer to be restored to service than the rest of the users in the zone.

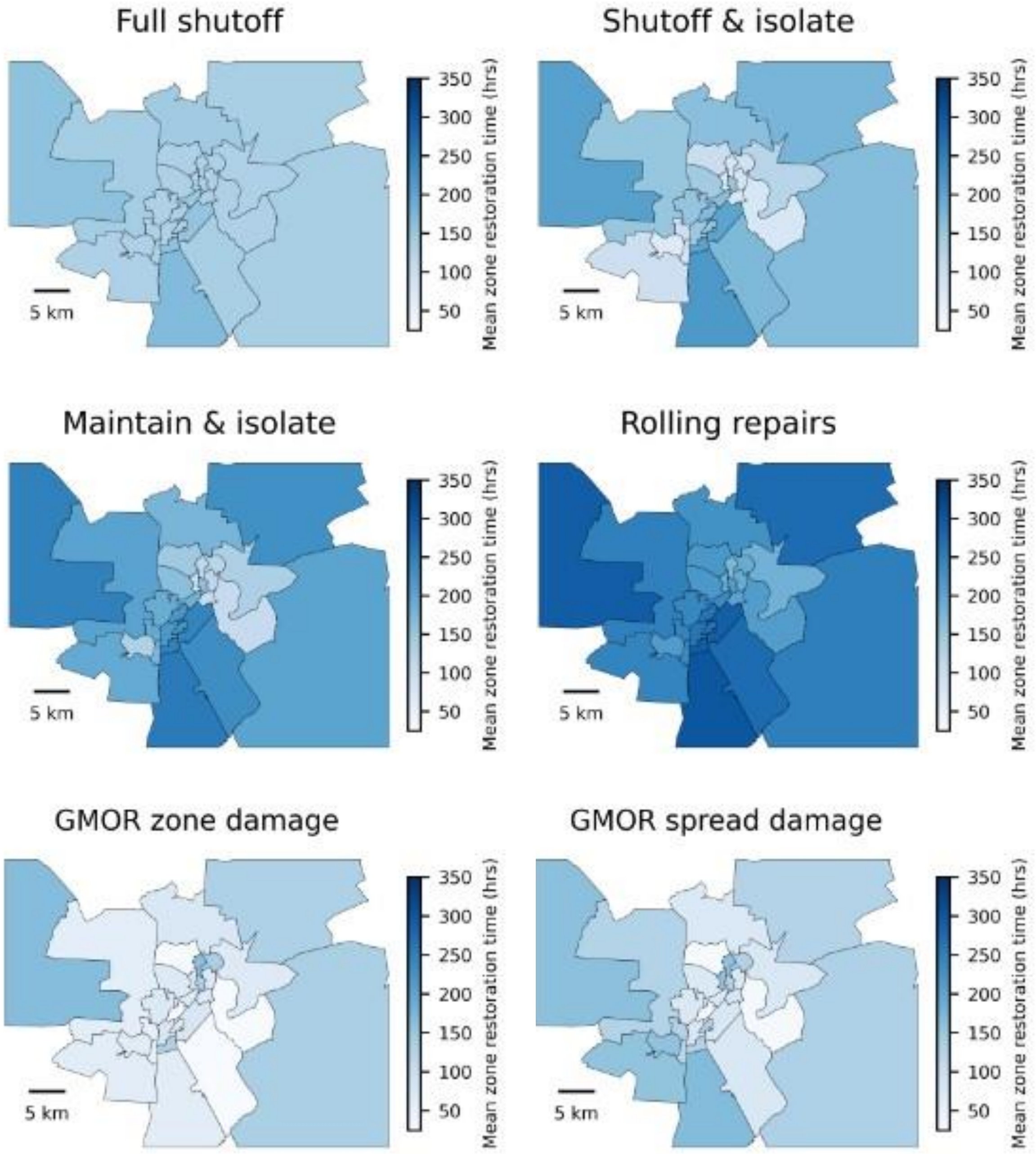


Figure E-3: Restoration times for each repair strategy and damage methodology for damage scenario 1.

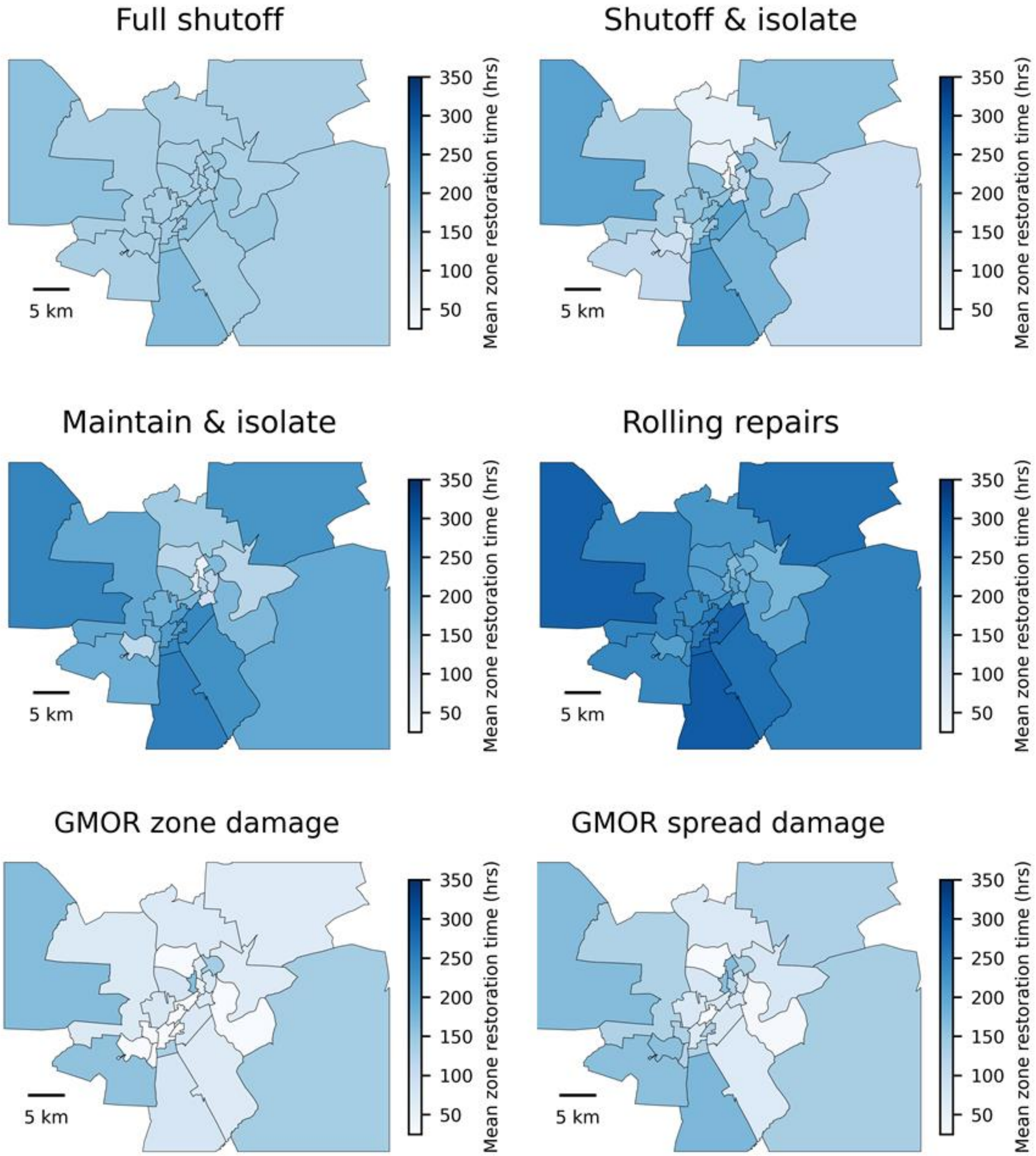


Figure E-4: Restoration times for each repair strategy and damage methodology for damage scenario 2.

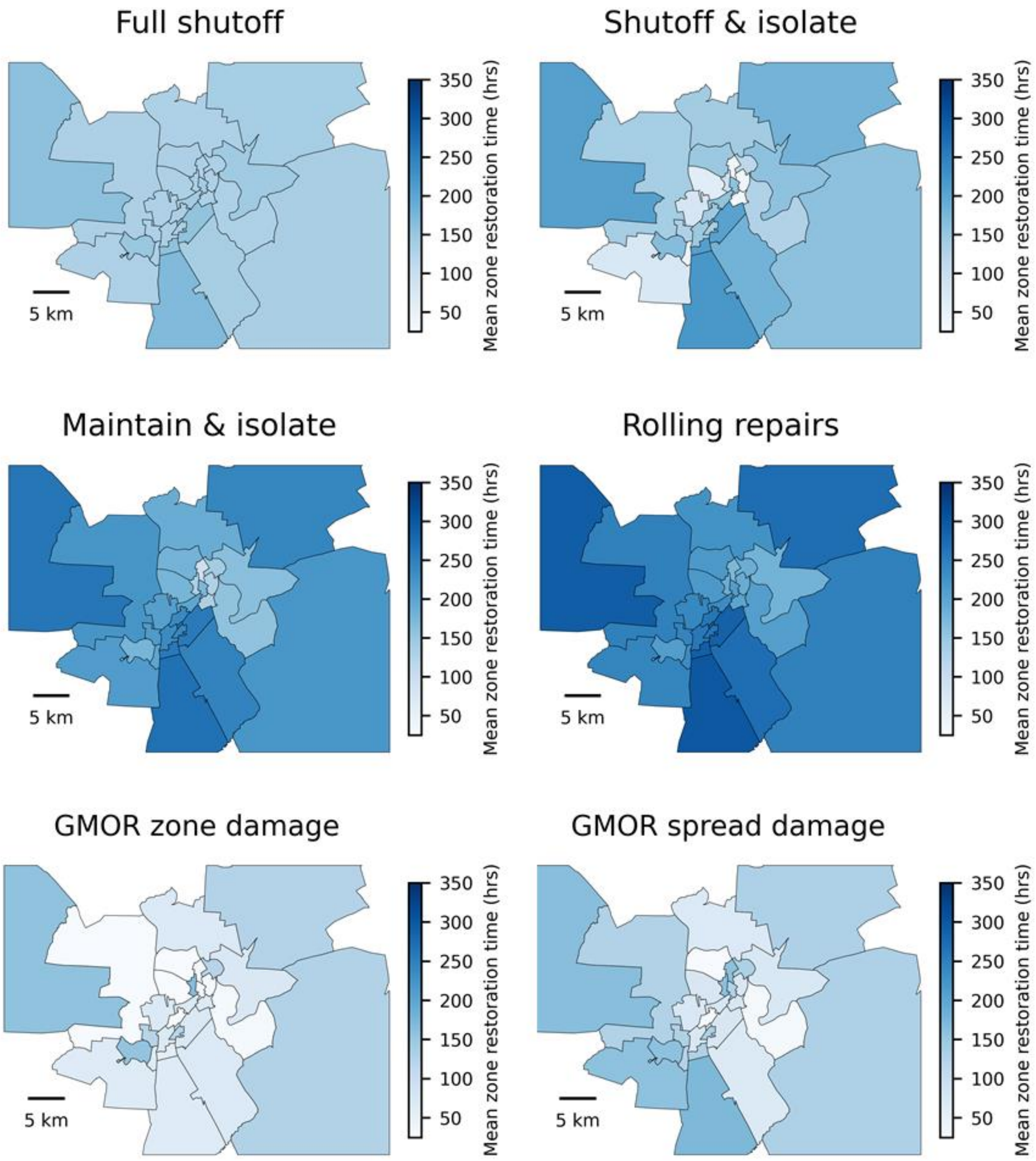
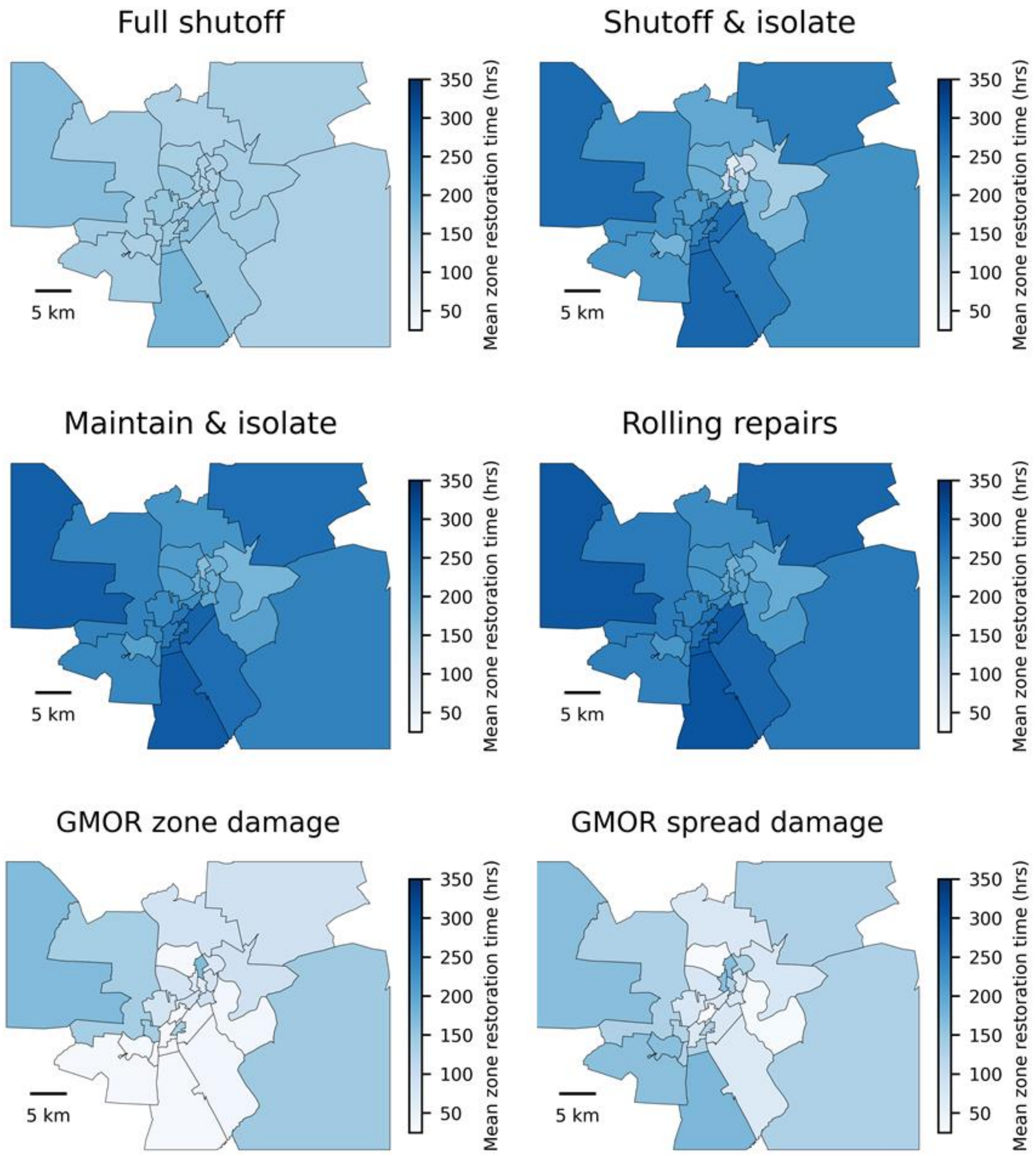


Figure E-5: Restoration times for each repair strategy and damage methodology for damage scenario 3.



Full shutoff

Shutoff & isolate

Maintain & isolate

Rolling repairs

GMOR zone damage

GMOR spread damage

Figure E-6: Restoration times for each repair strategy and damage methodology for damage scenario 4.

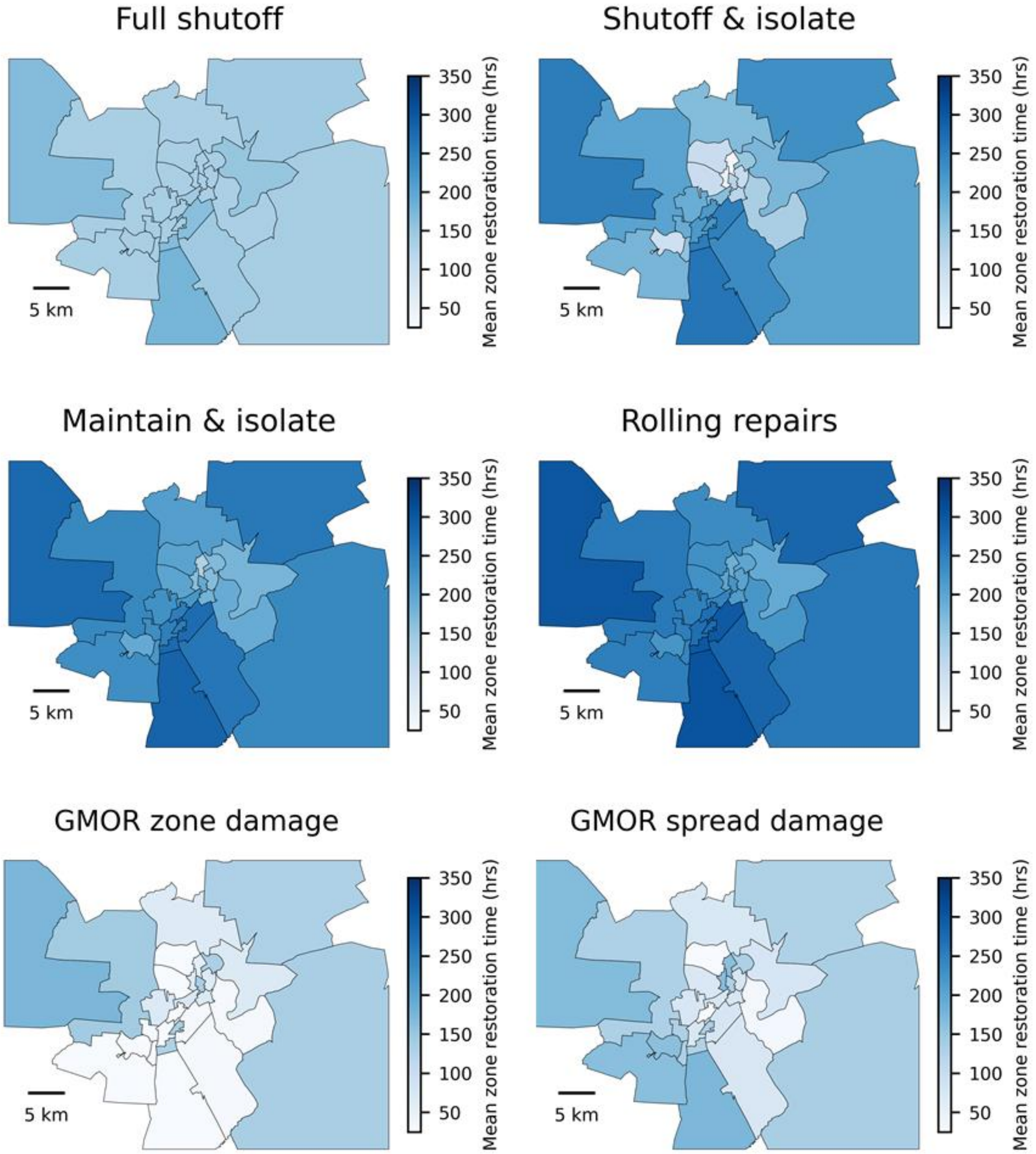


Figure E-7: Restoration times for each repair strategy and damage methodology for damage scenario 5.

E-4 Comparative restoration times

Figure E-8 through Figure E-17 show restoration time comparisons for all WNTR repair strategies compared to both GMOR damage methodologies. The darker the shading of a zone, the higher the population restored in the hydraulic model in that zone compared to the overall zone restoration time indicated in the aggregated model.

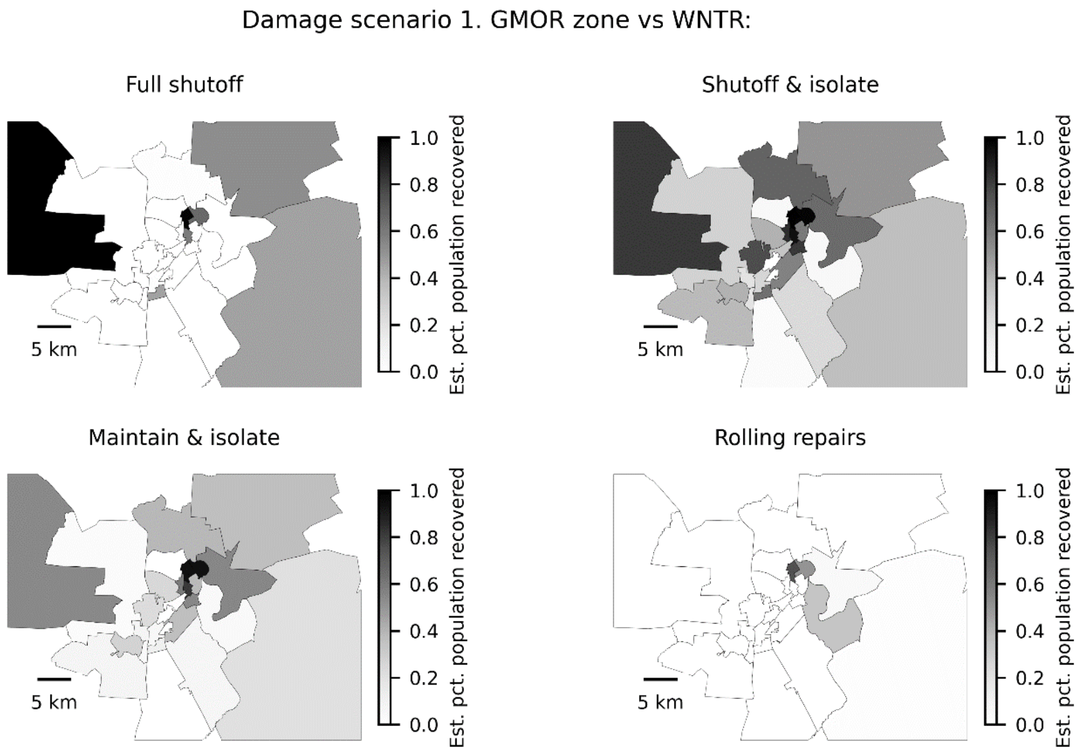


Figure E-8: Percentile recovery estimate for damage scenario 1, GMOR zone damage vs each WNTR repair strategy.

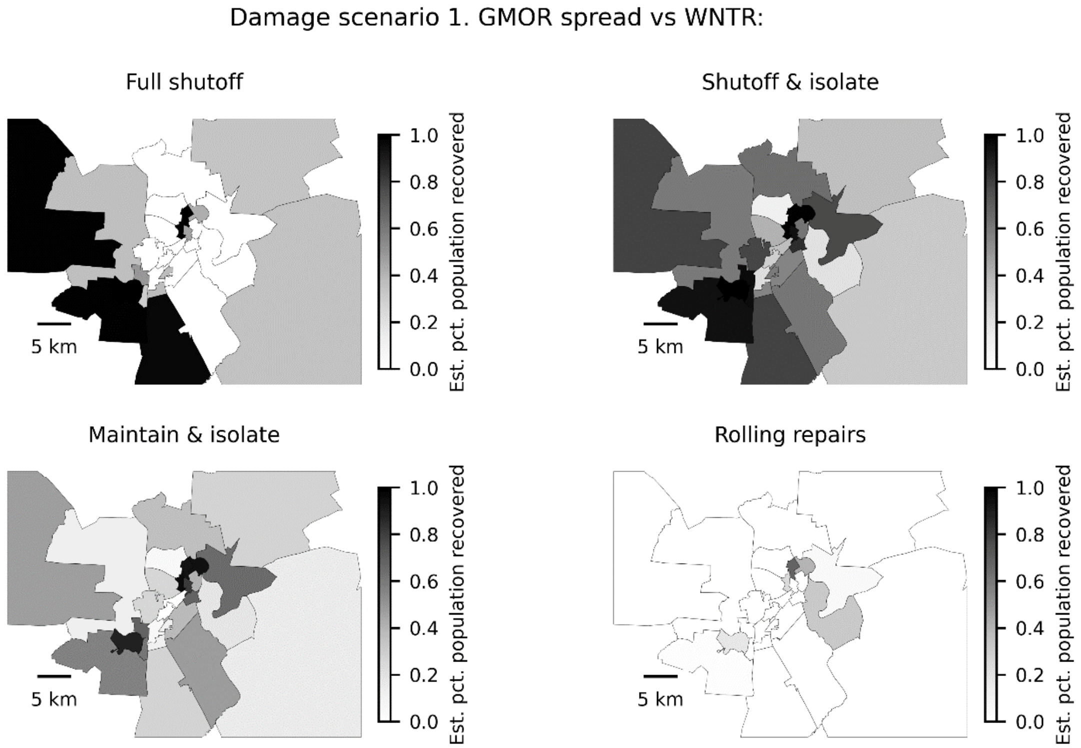


Figure E-9: Percentile recovery estimate for damage scenario 1, GMOR spread damage vs each WNTR repair strategy.

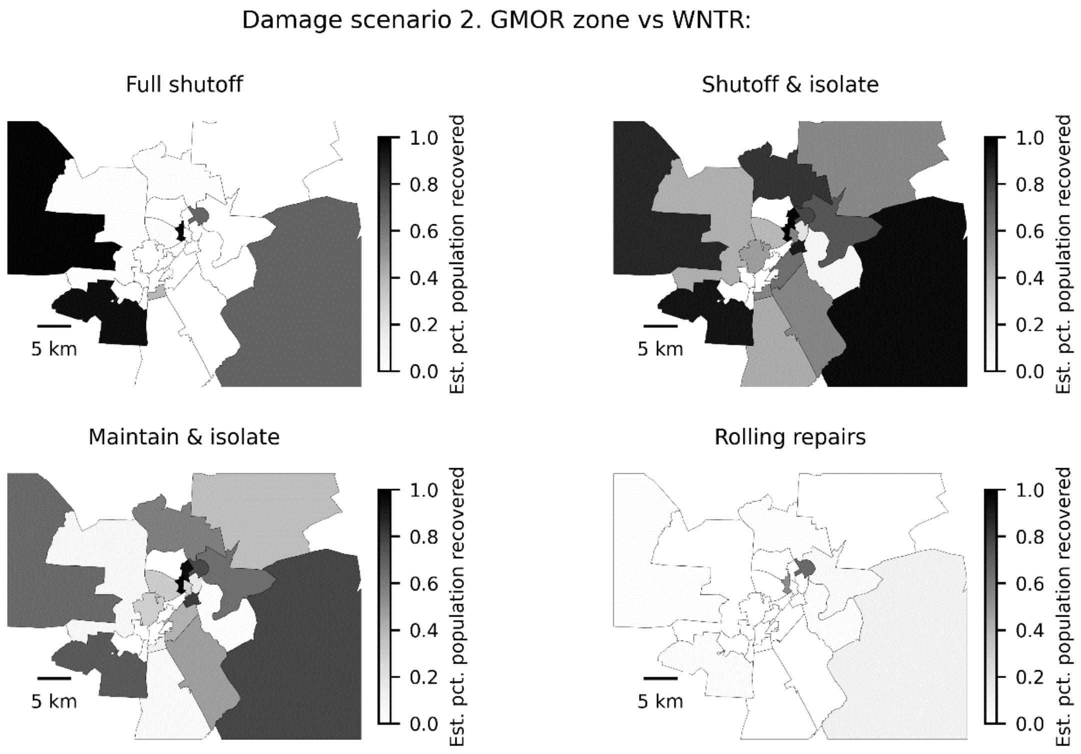


Figure E-10: Percentile recovery estimate for damage scenario 2, GMOR zone damage vs each WNTR repair strategy.

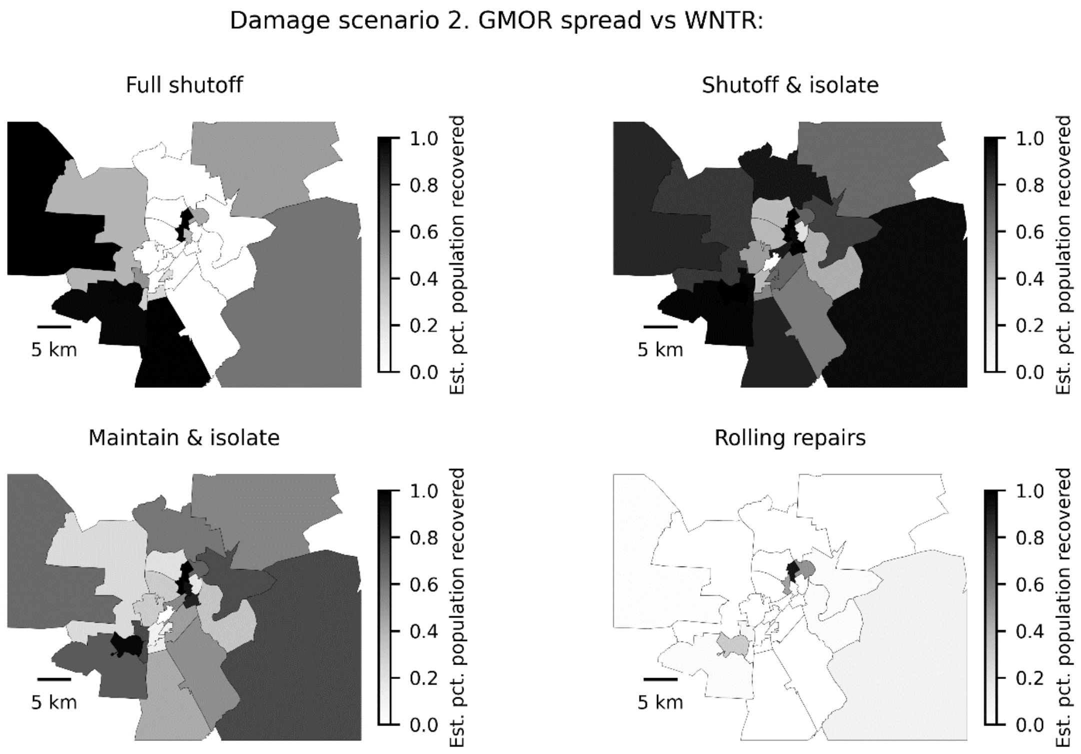


Figure E-11: Percentile recovery estimate for damage scenario 2, GMOR spread damage vs each WNTR repair strategy.

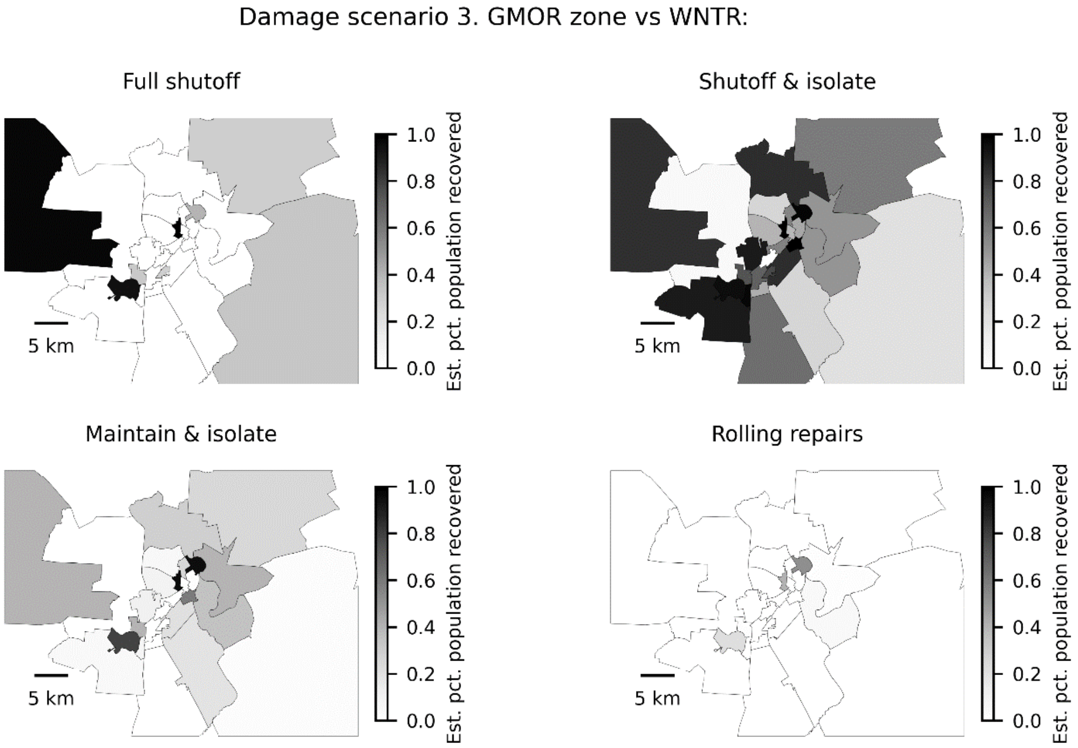


Figure E-12: Percentile recovery estimate for damage scenario 3, GMOR zone damage vs each WNTR repair strategy.

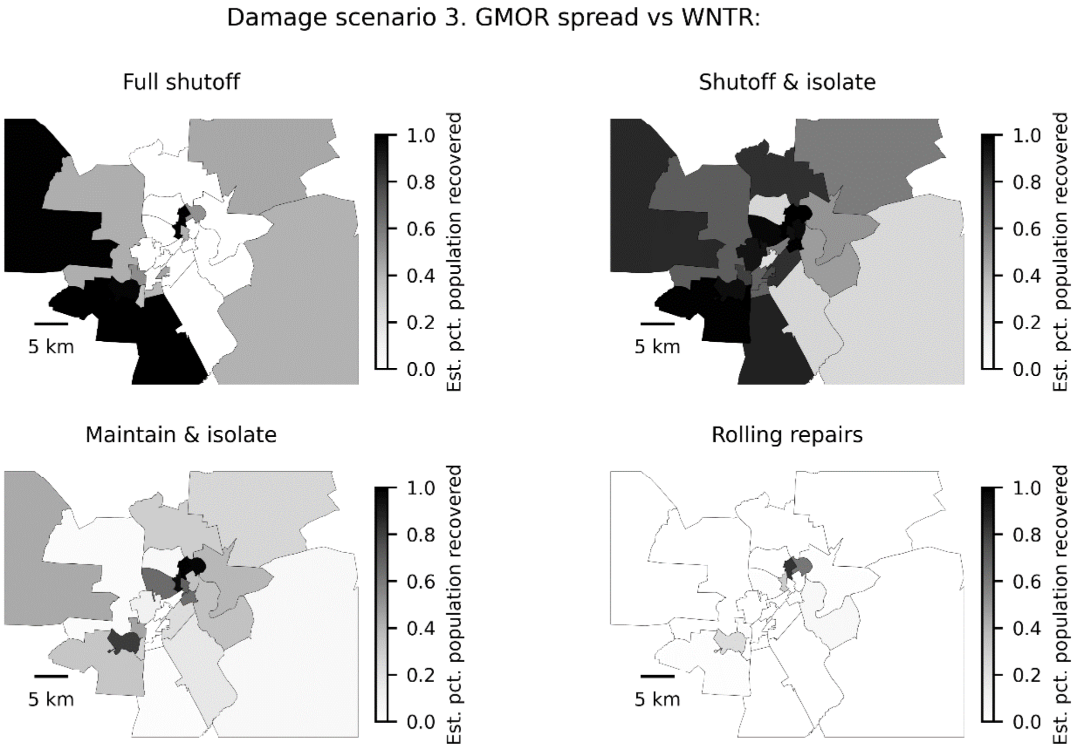


Figure E-13: Percentile recovery estimate for damage scenario 3, GMOR spread damage vs each WNTR repair strategy.

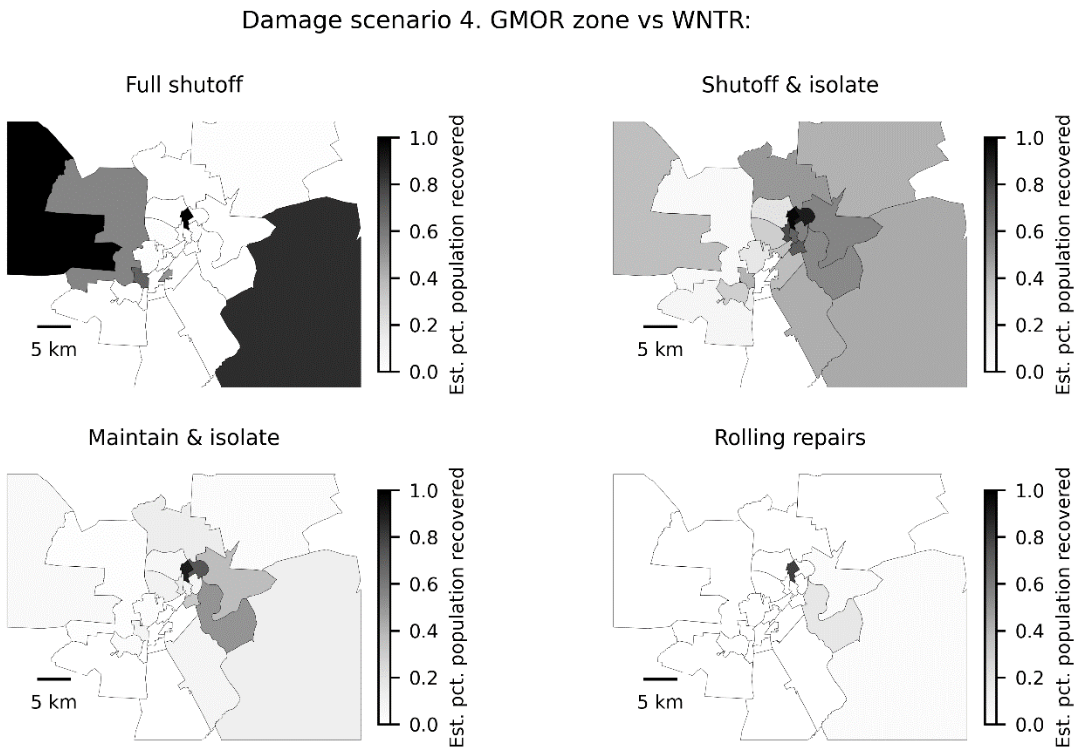


Figure E-14: Percentile recovery estimate for damage scenario 4, GMOR zone damage vs each WNTR repair strategy.

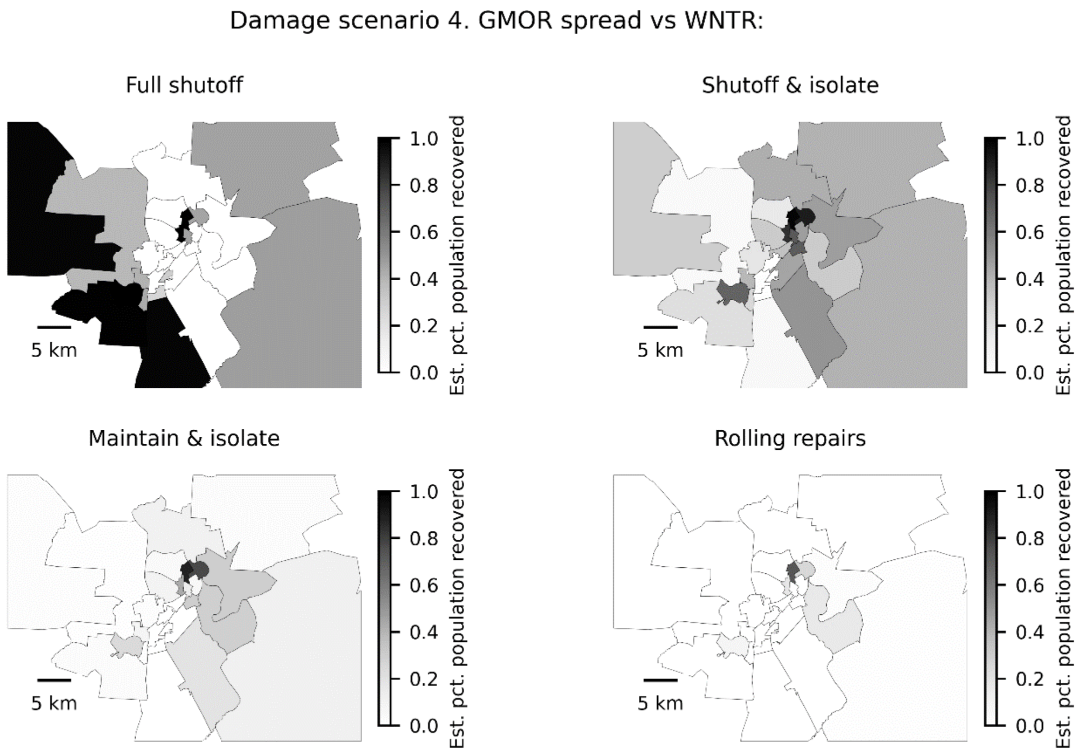
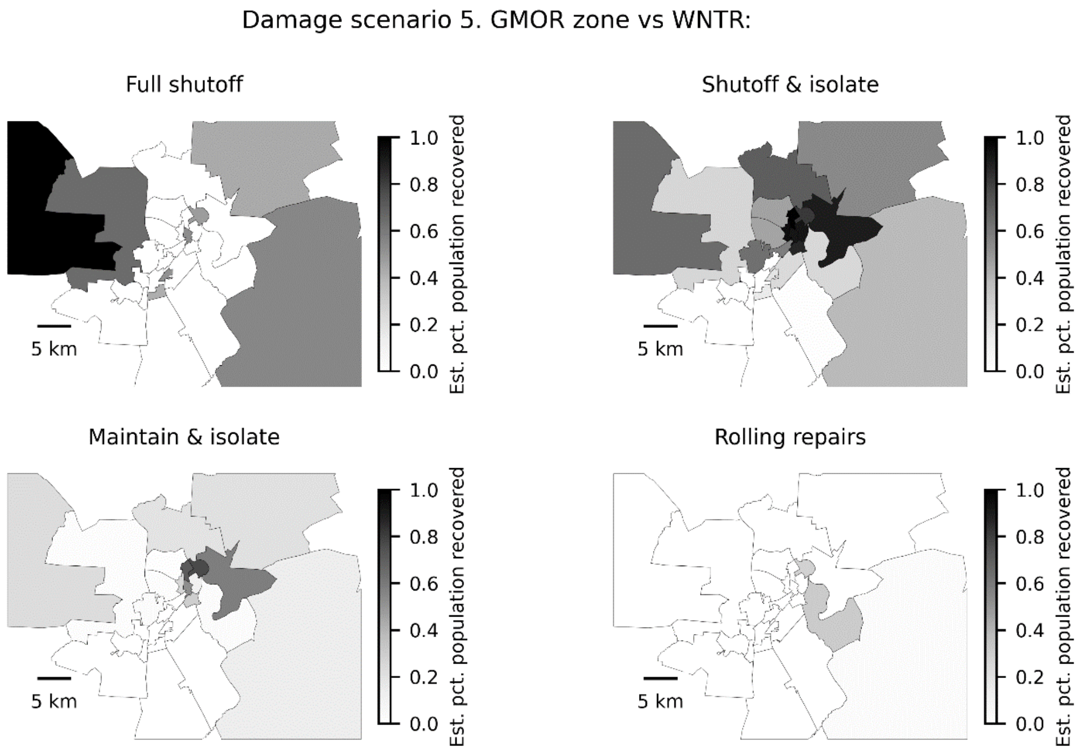


Figure E-15: Percentile recovery estimate for damage scenario 4, GMOR spread damage vs each WNTR repair strategy.


Damage scenario 5. GMOR zone vs WNTR:

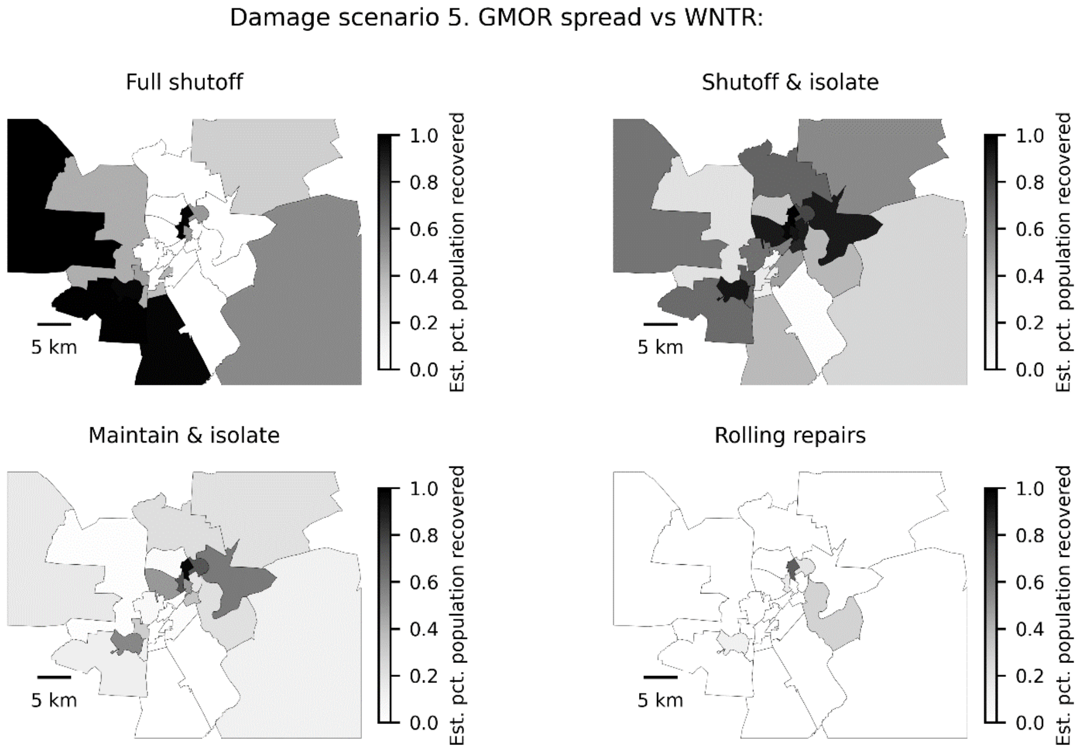
Full shutoff

Shutoff & isolate

Maintain & isolate

Rolling repairs

Figure E-16: Percentile recovery estimate for damage scenario 5, GMOR zone damage vs each WNTR repair strategy.


Damage scenario 5. GMOR spread vs WNTR:

Full shutoff

Shutoff & isolate

Maintain & isolate

Rolling repairs

Figure E-17: Percentile recovery estimate for damage scenario 5, GMOR spread damage vs each WNTR repair strategy.