Measuring Resilience of Metro Vancouver's Water and Liquid Waste Systems

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Disclaimer

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EXECUTIVE SUMMARY

This research project aims to support future implementation of the Resilient Region Strategic Framework, which is currently being developed by Metro Vancouver to guide staff in integrating resilience into all areas of their work. This project provides potential tools, such as Key Performance Indicators (KPIs), to monitor and plan for regional resilience. The key objectives of this project were to:

1. **Conduct a literature review on the best practices by local government and utility providers in measuring and benchmarking resilience;**
2. **Interview staff to to discuss desired outcomes, areas of opportunity, limitation on data collection; and,**
3. **Identify Key Performance Indicators (KPIs) to assist future monitoring and planning of resilience.**

While the Resilient Region Strategic Framework discusses resilience across all services and communities Metro Vancouver serves, the scope of this project is limited to the resilience of Metro Vancouver's Water and Liquid Waste Services. Often considered as "utility lifeline systems," these services are vital to the region of 2.7 million residents to survive any adverse events and further thrive in recovery. Therefore, this project starts with providing measurement tools for resilience in water and liquid waste infrastructure and service operations, with a potential for transferability to other areas of services in the future.

Based on a systematic literature review, this project has adopted a conceptual framework to define and measure resilience in water and liquid waste systems. Additionally, the project identified resilience KPIs based on a set of selection criteria. Integrating feedback from the Resilience Steering Committee and expert staff in both departments, the project further reassessed KPIs to be relevant to the Metro Vancouver context and be actionable.

The author hopes these findings to be useful tools for staff to evaluate resilient capacity to specific challenges without adding another layer of burden. In fact, interviews with staff confirmed that Metro Vancouver already monitors most of the theKPIs listed in Table X and X. This project applies a resilience lens on these existing indicators to facilitate communication within the organization and aid in planning, without sacrificing staff's autonomy in advancing resilience. The project recommends further internal engagement to improve performance thresholds beyond the regulatory requirements and matrix evaluation to minimize trade offs. Additionally, affordability indicators are examined in the Appendix.

As this project focuses on outward-facing, physical aspects of resilience, further research should be performed to analyze the resilience of Metro Vancouver's governance as well as the capacity of the communities to manage and adapt to shocks and stresses.

PROJECT OVERVIEW

BACKGROUND

Serving 2.7 million residents in the Lower Mainland, Metro Vancouver delivers various services essential for the region to function and thrive. These include providing clean, safe drinking water and liquid waste services. Under Metro Vancouver's governance model, the Greater Vancouver Water District (GVWD) owns and operates the water supply, treatment and transmission to its member municipalities. Similarly, the Greater Vancouver Sewerage and Drainage District (GVS&DD) owns and operates a network of sewers, pumps and five wastewater treatment plants connected to municipal sewer systems. Both water and liquid waste systems are often considered as "lifeline utility services" fundamental for communities and businesses. Maintaining and operating these systems are critical to public health, the environment and the economy. Therefore, it is imperative that these systems must be prepared and be resilient to fully function in any adverse event, ranging from acute shocks such as natural disasters and chronic stresses such as climate change.

Table 1.

Overview of Metro Vancouver's Water & Liquid Waste Services

	Water Services	**Liquid Waste Services**
Governing body within MV	Greater Vancouver Water District (GVWD)	Greater Vancouver Sewerage and Drainage District (GVS&DD)
Goals	• Provide clean, safe drinking water • Ensure the sustainable use of water resources • Ensure the efficient supply of water	• Protect public health and environment • Use liquid waste as a resource • Effective, affordable and collaborative management
Physical components	• Three source storage reservoirs and three supplemental alpine reservoirs • Two water treatment plants (Seymour Capilano; Coquitlam)	• A system of sewers and pump stations • Five wastewater treatment plants (Annacis Island, Iona Island, Lions

	and eight disinfection facilities ● Storage reservoirs and tanks ● A system of transmission water mains and pump stations	Gate, Lulu Island, Northwest Langley)
Relevant shocks & stresses	● *Shocks:* Flooding, windstorms, wildfire & smoke, landslides, earthquakes ● *Stresses:* Climate change, aging infrastructure, population growth	

Note. The goals for water and liquid waste services are from the Drinking *Water Management Plan*, by Metro Vancouver, 2011, (http://www.metrovancouver.org/services/water/about/plans/Pages/default.aspx#:~:text=This%20plan%20has%20three%20goals,the%20efficient%20supply%20of%20water.), the Integrated *Liquid Waste and Resource Management Plan*, by Metro Vancouver, 2010, (http://www.metrovancouver.org/services/liquid-waste/Pages/default.aspx), respectively.

In light of the Covid-19 pandemic, Metro Vancouver has been investigating ways to integrate resilience into areas of their work. Previous studies and staff workshops have defined resilience as "*the ability to proactively manage shocks and stresses, and thrive in the face of change.*" Studies further identified relevant shocks and stresses the region is anticipating and their potential consequences. For example, Metro Vancouver expects climate change to bring drier, warmer summers and wetter winters with more extreme events in the future (Metro Vancouver, 2016). High temperature and dry spells together increase the probability of water shortages as watersheds would recharge more slowly and the demand for water use would rise. Increased wildfire risks would negatively impact water qualities due to ash and contaminants as well as water supplies to fight fire. Wetter winters will present more challenges to liquid waste management due to increased flooding and sewer overflow risks. Furthermore, both water and liquid waste services would need to accommodate the population growth of another million by the year 2050 and subsequent development pressure, accordingly (Metro Vancouver, 2018). In addition to identifying shocks and stresses, Metro Vancouver has performed gap analysis and made recommendations for planning resilience in the long term. These recommendations include developing safe-to-fail protocols for regional infrastructure including water and liquid waste systems (Seinen, M., 2021).

In July 2020, Metro Vancouver's Board of Directors endorsed the development of a Resilient Region Strategic Framework. Guided by the principles of equity, reconciliation, and prosperity, the framework aims to advance resilience within Metro Vancouver's governance, infrastructure, as well as communities and member municipalities that they serve (Metro Vancouver, 2021, p.12).

PURPOSE & SCOPE

This project aims to assist the future implementation of the Resilient Region Strategic Framework by providing tools to measure Metro Vancouver' progress on achieving their objectives. Specifically, this project has examined approaches to measure resilience and proposed potential key performance indicators (KPIs) for future monitoring and planning resilience. While the Resilient Region Strategic Framework is a high level policy across all services, this project focuses on Metro Vancouver's water and liquid waste services. While KPIs identified by this project are specific to the water and liquid waste infrastructure and operations, this project also contains some findings that may be transferable to other areas of services. These findings include a conceptualization of resilience and criteria for selecting KPIs**.** The author hopes that these findings may aid Metro Vancouver's staff in facilitating future resilience dialogue and present an opportunity for shared learning among departments.

Table 2.

Scope of the Project

Question	**Response**
Resilience **for** whom?	The regional population
Resilience **of** what?	MV's integrated water infrastructure and operations
Resilience **to** what?	Relevant shocks and stresses identified by MV

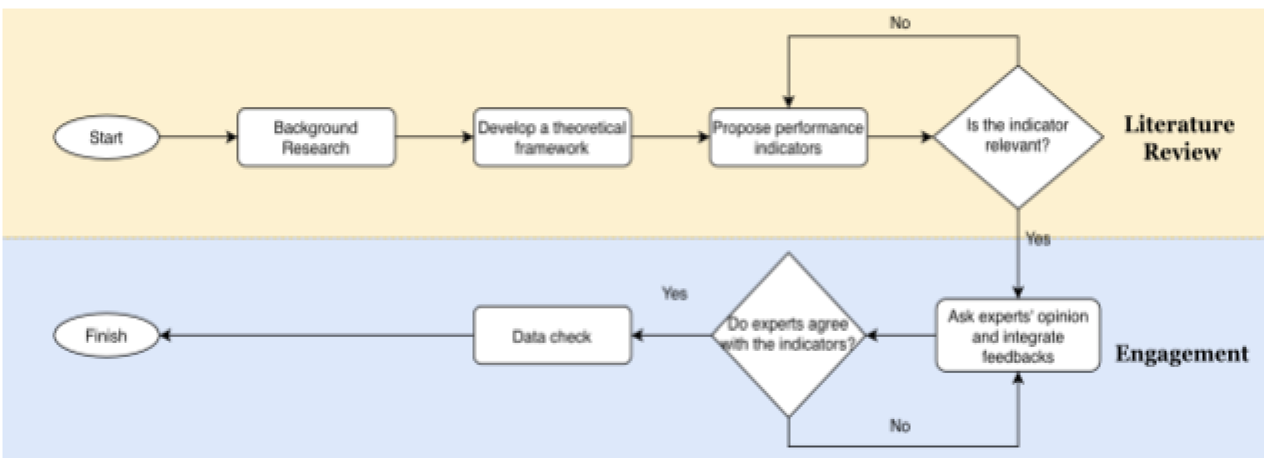
As this project primarily focuses on the technical and physical side of resilience, social and environmental aspects of resilience are missing in its scope. Nonetheless, the resilience of water and liquid waste systems has a strong connection to social equity. In the event of system degradation, it is likely that the socially vulnerable population bears disportionately severe impacts (Bergstrand, K. et al., 2015). In hopes of partially addressing socio-economic aspects of resilience, this project briefly discusses affordability indicators in the appendix.

METHODOLOGY

This project has mainly performed two research methodologies: literature review and internal engagement. First, a comprehensive literature review was followed to develop a theoretical framework for the project and further identify potential KPIs for water and liquid waste systems. Second, feedback from the Resilience Steering Committee and interviews with staff provided opportunities for reassessing KPIs and determining data availability and affordability.

Figure 1.

Research Process



Note. Adapted from "Developing a Framework for Measuring Water Resilience," by B. Balaei, et al., 2018, *Natural Hazards Review, 19*(4), p.3

LITERATURE REVIEW

A process of systematic literature review was followed (Xiao, Y., & Watson, M., 2017). First, literature was searched based on keywords, including resilience, water or wastewater utility, water system, and performance indicators. Second, the resulting body of literature was further narrowed down by reviewing abstracts. Third, the quality of each literature was assessed by examining the full texts. Fourth, relevant data from the selected literature were extracted and categorized by themes. Finally, these findings were further analyzed and synthesized to develop a conceptual framework, choose a selection criteria, and investigate resilience KPIs.

ENGAGEMENT

Four expert staff in the departments of Water services and Liquid Waste Services were interviewed on zoom. Ten semi-structured, open-ended questions were asked during these interview sessions in order to discuss desired outcomes, share findings and gain feedback, as well as to identify areas of opportunities and constraints.

FINDINGS

CONCEPTUAL FRAMEWORK

Definition of resilience

Resilience is an elusive concept that can be approached in various ways. A literature review was performed to clarify what this project attempts to measure in terms of resilience and how resilient systems look like over time. Resilience can be seen as the aggregate of various dimensions, such as resilience domains, attributes and adverse event cycle as shown below (Bruneau, M., et al., 2003; Davis, C. A., et al., 2018). Resilience domains include social, economic, technical and organizational. Social and economic domains together indicate the ability of communities to withstand and recover from shocks and stresses. Technical and organizational domains refer to resilience of infrastructure and services. This project primarily focuses on technical domains of water and liquid waste systems. Resilience attributes include robustness, redundancy, resourcefulness and rapidity. Together, these attributes determine how resilient the systems are at each step of an adverse event.

Table 3.

Resilience Attributes

Attributes	Definition
Robustness	The ability of a system to withstand an adverse event without degradation or loss of function
Redundancy	The extent to which a system can substitute functional requirements
Resourcefulness	The ability to identify problems, set priorities and mobilize physical and human resources
Rapidity	The ability to recover system performance in a timely manner
Adaptive Capacity	The capacity to adapt to future shocks and stresses in the long-term

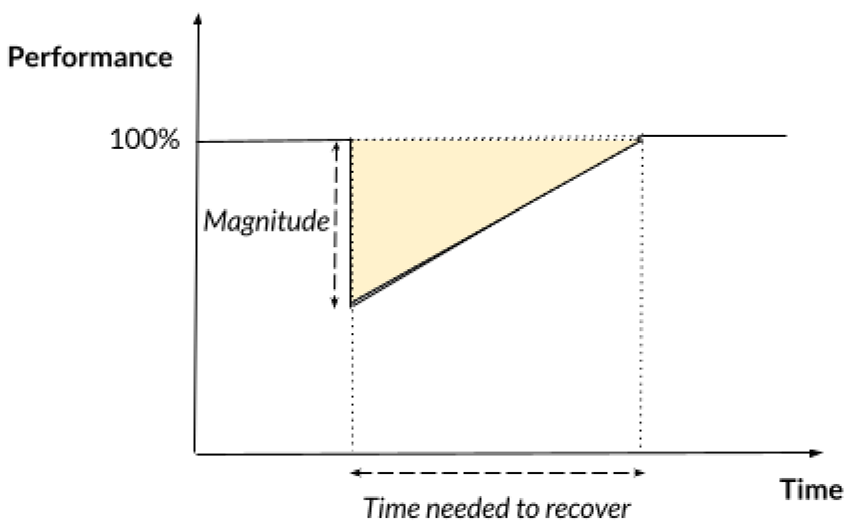
Note. The definitions are from "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities," by M. Bruneau, et al., 2003, *Earthquake Spectra*, *19*(4).

Approaches to measure resilience

This project further identified benchmark cases of measuring resilience. Using the idea of "Resilience Triangle" is a widely accepted approach in both research and practice such as civil engineering. It models the resilience of a specific system by performing failure scenarios and measuring performance over time. With the triangle shown in Figure 2 representing the total resilience loss, the indicators of resilience include the magnitude of performance loss and time needed to recover. This approach, however, requires performing numerous failure analyses that are beyond the scope of this project. Additionally, this approach has more room for uncertainties as failure scenarios contain variables, such as types of shocks and stresses and steps within adverse event cycles.

Figure 2.

Resilience Triangle



Note: Adapted from "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities," by M. Bruneau, S. Chang, et al., 2003, *Earthquake Spectra*, *19*(4), p.737

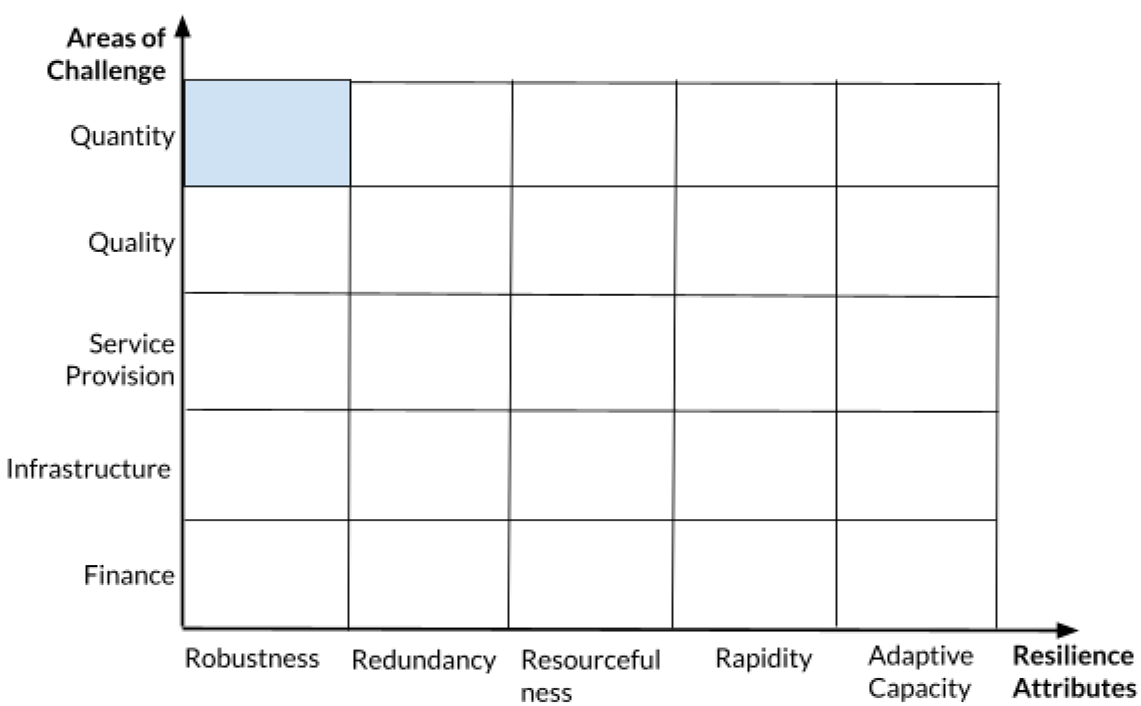
Instead, this project adopts an indirect approach to evaluate system resilience. It examines impacts of the relevant shocks and stresses to Metro Vancouver, and innate system properties including their behaviors during those events. This project finds such impact- or consequence-based approach strategic and beneficial as the resulting measurement of resilience would be less susceptible to unknown variables (Sweetapple, C. et al. 2018). Additionally, this approach is appropriate to the scope of the Resilient Region Strategic Framework as it evaluates comprehensive system resilience against various stresses and shocks rather than resilience to specific scenarios.

Proposed Framework

This project proposes a conceptual framework for measuring resilience, consisting of the two dimensions: areas of challenges and resilience attributes. Given similar system properties, water and liquid waste systems share areas of challenge, such as quantity, quality, service provision, infrastructure as well as finance. Resilience attributes are listed on the horizontal axis of the framework.

Figure 3.

Proposed Framework for Water and Liquid Waste Systems



Note. Adapted from "Establishing Characteristics to Operationalize Resilience for Lifeline Systems," by Davis, C.A., et al., 2018, *Natural Hazards Review, 19*(4).

Each rectangle within the framework indicates the extent to which a system is resilient against the shocks and stresses relevant to Metro Vancouver. For example, the colored rectangle in Figure 3 can be interpreted as: how robust the water or liquid waste system is against quantity-related challenges, such as reduced water supply and increased demand. For the reference, Table 4 below specifies the challenges specific and relevant to Metro Vancouver's water and liquid waste systems. Based on this framework, this project subsequently identifies KPIs for each resilience attribute against these challenges.

Table 4.

Anticipated Challenges on Metro Vancouver's Systems

	Water system	**Liquid waste system**
Quantity	Reduced water supply; increased water demand	High flow events and flooding; sanitary and combined outflows
Quality	Altered surface water quality	Degradation of effluent quality
Service Provision	Service interruptions	
Infrastructure	Infrastructure breakdown; power outage	
Finance	Threatened financial sustainability; resilience investment gap	

Note. Challenges are identified from "Climate ready water utilities adaptation strategies guide for water utilities," by US EPA, 2015, p14.

SELECTION CRITERIA

Based on literature review and feedback from the Resilience Steering Committee, this project has established and followed the primary criteria for selecting resilience KPIs over others. These include practicality, validity, objectivity and simplicity. Secondary criteria are further identified, and further statistics validation through sensitivity and correlation analyses will be required to meet them.

Table 5.

Criteria for Selecting Resilience KPIs

Primary Criteria	**Example**
Practicality	• Is the indicator quantitative rather than qualitative? • Is the indicator actionable?
Validity	• Is the indicator a proxy for the targeted resilience dimension?
Objectivity	• Can the indicator be used over time based on recalibrated data?
Simplicity	• Is the indicator easy to comprehend and use?
Secondary Criteria (Requires further research)	**Example**
Sensitivity	• Is the indicator sensitive to changes to reflect system deterioration or improvement?
Non-redundancy	• Is the indicator independent and specific?

Note. Criteria are from "Developing a Framework for Measuring Water Supply Resilience," by B. Balaei, et al., 2018, *Natural Hazards Review, 19*(4); "Resilience-based Performance Metrics for Water Resources Management under Uncertainty," by T. Roach, et al., 2018, and *Advances in Water Resources, 116;* "The City Water Resilience Approach," by ARUP, 2019, https://www.arup.com/perspectives/publications/research/section/the-city-water-resilience-approach

KEY PERFORMANCE INDICATORS

Initially identified from a literature review, resilience KPIs were subsequently reassessed via staff interviews. Final KPIs and their metrics are listed in Table 6 and 7 for Metro Vancouver's water and liquid waste systems, respectively.

Table 6.

Resilience KPIs for Metro Vancouver's Water Services

	Robustness	Redundancy	Resourcefulness	Rapidity	Adaptive Capacity
Quantity	Supply & demand stress (ex) Available supplied being used (%)	Emergency volume (gallons/customer) Pipe capacity (gallons/m)	Supply diversity (Gini-Simpson Index)	Reservoir yield over annual source inflow (%)	Conservation capacity (L/person/day)
Quality	Source water qualities (% of samples exceeding the standards) Water age (time) Water qualities before and after filtration / treatment (pollutant units; %)	Diversity of monitoring methods (ex) active monitoring (Gini-Simpson Index)	Frequency of sample checks (per month; year) Frequency of watershed monitoring (per month; year)	Elapsed time to failure detection (hours) Elapsed time that the contaminant is present in the system (time; %)	Water treatment plants update (Projected time; %)
Service Provision	Total number of customer interruptions (per year)	Supply points to meet critical or all demands (%)	Inspection frequency (per month; year)	Total duration of customer interruptions (hours per customer)	Non-revenue water (% of operating cost; MG)
Infrastructure	Average age of assets by class (years)	Power redundancy (ex) backup power or fuel tanks (%; gallons)	Planned maintenance (%; hours)	Response time to repair and install (hours)	Energy intensity (kWh/MG)

		Network redundancy (%; m)	Availability of critical parts and equipment (%)		GHG emissions (million metric tons of CO2 equivalents)
Finance	Resource productivity ($/MG)	Bond rating	Allocated fund for resilience investment ($; %)	Rate recovery (%)	Resilience investment gap (%, $/time)
		Debt to equity ratio			

Note. Indicators are identified from "A systematic review of quantitative resilience measures for water infrastructure systems," by S. Shin, Lee, S., et al., 2018, *Water, 10*(2); "Benchmark performance indicators for utility water and wastewater pipelines infrastructure," by A. Ganjidoost, et al., 2018, *Journal of Water Resources Planning and Management, 144*(3); "Disaster resilience of critical water infrastructure systems," by J. C. Matthews, 2016, *Journal of Structural Engineering, 142*(8); "Systems measures of water distribution system resilience," by US EPA, 2015, https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=521634&Lab=NHSRC; "Resilience in regulated utilities," by M. Keogh, & C. Cody, 2013, https://pubs.naruc.org/pub/536F07E4-2354-D714-5153-7A80198A436D; and further reassessed through staff interviews.

Table 7.

Resilience KPIs for Metro Vancouver's Liquid Waste Services

	Robustness	Redundancy	Resourcefulness	Rapidity	Adaptive Capacity
Quantity	Sewer capacity (gallons/m)	Sanitary sewer storage tanks capacity (gallons)	Frequency of inflow & infiltration monitoring (per month; year)	Inflow & Infiltration efficiency	Sewer pipe separation rate (%)
	Sanitary & combined sewer overflow rate (%; volume per year)	Stormwater storage capacity (gallons)	Rehabilitation (hours)		
Quality	Wastewater influent & discharge quality (pollutant units; %)	Diversity of monitoring methods (ex) DNA sequencer (Gini-Simpson Index)	Frequency of sample checks (per month; year)	Elapsed time to failure detection (hours)	Wastewater treatment plants update (Projected time; %)
			Odor complaints (per month; year)	Elapsed time that pollutant is present in the system (time; %)	
				Ambient water qualities (pollutant units)	
Service Provision	Total number of customer interruptions (per year)	Waterproof sewage pumps (%)	Inspection frequency (per month; year)	Total duration of customer interruptions (hours per customer)	Adoption of intelligent water systems (ex) automated service provision (Projected time; %)
Infrastructure	Operation certificate compliance (%)	Power redundancy (ex)	Planned maintenance (%; hours)	Response time to repair and install (hours)	Energy intensity (kWh/MG)

	Average age of assets by class (years)	backup power or fuel tanks (%; gallons)	Availability of critical parts and equipment (%)		GHG emissions (million metric tons of CO_2 equivalents) Resource recovery (ex) nutrient, biosolid reuse, biogas production
Finance	Resource productivity ($/MG)	Bond rating Debt to equity ratio	Allocated fund for resilience investment ($; %)	Rate recovery (%)	Resilience investment gap (%, $/time)

Note. Indicators are identified from "Benchmark performance indicators for utility water and wastewater pipelines infrastructure," by A. Ganjidoost, et al., 2018, *Journal of Water Resources Planning and Management*, *144*(3); "Reliable, robust, and resilient system design framework with application to wastewater-treatment plant control," by C. Sweetapple, et al., 2017, *Journal of Environmental Engineering*, *143*(3); "Resilience theory incorporated into urban wastewater systems management. State of the art," by P. Juan-Garcia, D. Buter, et al., 2017, *Water Research*, *115*; "Disaster resilience of critical water infrastructure systems," by J. C. Matthews, 2016, *Journal of Structural Engineering*, *142*(8); and further reassessed through staff interviews.

INSIGHTS & RECOMMENDATION

This project aims to provide tools to measure the resilience of water and liquid waste services without adding another layer of burden on staff. The conceptual framework and indicator selection criteria may facilitate resilience dialogue within the organization. Interviews with staff confirmed that most of the resilience KPIs identified in this project are already monitored and collected. This project, as a result, provides a structured resilience-based lens to look at the existing KPIs, aiding staff to assess specific resilience domains and identifying a room for improvement. Using these existing KPIs also ensures staff flexibility and autonomy in advancing resilience. Instead of establishing new resilience KPIs, the project recommends further engagement to expand performance thresholds beyond the regulatory requirements. These newly agreed performance thresholds will help Metro Vancouver to proactively prepare and adapt to changes, while reflecting the region's specific needs and conditions.

Both literature review and interviews revealed potential trade offs among resilience attributes as an action to improve specific resilience attributes may negatively impact the other. For example, upsizing water pipes will improve the robustness to meet water supply, at the price of rapid recovery from system failure and water quality in terms of water age. In order to fully capture and minimize these trade offs, employing matrix evaluations is recommended (Keogh, M., & Cody, C., 2013).

As the scope of this project was limited to the resilience of infrastructure and service operation, further research is required to examine social and organizational aspects of research. The author recommends adopting a bottom-up approach to assess community resilience and integrate a social equity lens (Cutter, S. L., et al., 2008). Furthermore, expert staff has emphasized the importance of organizational elements, such as training, corporate culture and leadership, to advance resilience. Hence, the internal capacity of Metro Vancouver to manage and adapt to shocks and stresses should be further examined.

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APPENDIX

AFFORDABILITY INDICATORS

Urban systems, such as water and liquid waste systems, require continuous investment to improve resilience. Without senior government cost sharing, however, these infrastructure updates and adoption of new innovations can be very expensive and may burden ratepayers. For example, in order for Metro Vancouver alone to recover the cost of the upgrades for the Iona Island and North Shore wastewater treatment plants, it would need to increase the sewerage utility rate by 600% over the next two decades for some households (Metro Vancouver, 2010).

The challenge of making water and liquid waste services resilient and affordable at the same time, especially without cost-sharing of senior governments, seem nearly insurmountable. Metro Vancouver has a mission to be resilient enough to deliver these services against any potential shocks and stresses. However, the increased cost for resilience often tends to create disproportionate impacts on socio economically vulnerable groups. Against the backdrop, Metro Vancouver must ensure financial sustainability to continue operating (Metro Vancouver, 2021). Acknowledging potential trade offs between resilience and affordability, this project examines recent research on affordability indicators of water and liquid waste services.

The conventional approach to determine household affordability is to measure the average cost of utility services out of median household income. Both the US EPA and recent research consider a combined annual water and liquid waste bill of less than 4.5% of median household income to be "affordable" (Mack & Wrase, 2017; USCM, AWWA, & WEF, 2013). While it is a widely accepted affordability standard, this approach fails to reflect important socioeconomic elements. For example, looking at median income of a household alone does not address income disparity within the region. The indicator further discounts the essential cost of living other than water and liquid waste services. Such cost includes mortgage payments or rents which tend to be higher in Metro Vancouver. Thus, the conventional affordability indicator leaves out the economic tradeoffs that households must face to survive and thrive.

There has been research effort to improve affordability indicators. To specifically measure the affordability of utility bills to low-income households, new indicators below are proposed. The affordability of the utility bill to the 20th percentile income group includes other essential cost of living into the equation. Alternatively, the second indicator expresses utility costs in terms of hours of labor at minimum wage.

Figure 4.

Proposed affordability indicators

1. $$\textbf{Affordability rate of 20th percentile income group} = \frac{\text{Average number of persons in a household} * \text{Combined water \& liquid waste bills}}{\text{Household income} - \text{Essential household expenses other than water \& liquid waste bills}}$$

2. $$\textbf{Hours of labor at minimum wage} = \frac{\text{Average number of persons in a household} * \text{Combined water \& liquid waste bills}}{\text{Minimum wage}}$$

Note. Reprinted from "Measuring household affordability for water and sewer utilities," by M. P. Teodoro, 2018, *Journal AWWA, 110*(1), p.15.

The author recommends Metro Vancouver to adopt either of these alternative indicators in measuring affordability. The rule of thumb of looking at these indicators are the following: water and liquid waste services are deemed affordable when the first indicator (affordability of utility to the 20th percentile income group) is lower than 10% and the other (utility cost in terms of minimum wage labor) is lower than 8%. However, further discussion within Metro Vancouver and external socioeconomic analysis should be done to reassess these thresholds to better reflect the specific need of the region as well as the financial sustainability of Metro Vancouver as a corporation. While these indicators may seem more complex than the conventional one, Metro Vancouver may expedite economic analyses by taking advantage of available data. Adopting these affordability indicators will inform Metro Vancouver of specific regional needs and conditions and further aid in long-range planning to make its core services affordable and resilient.