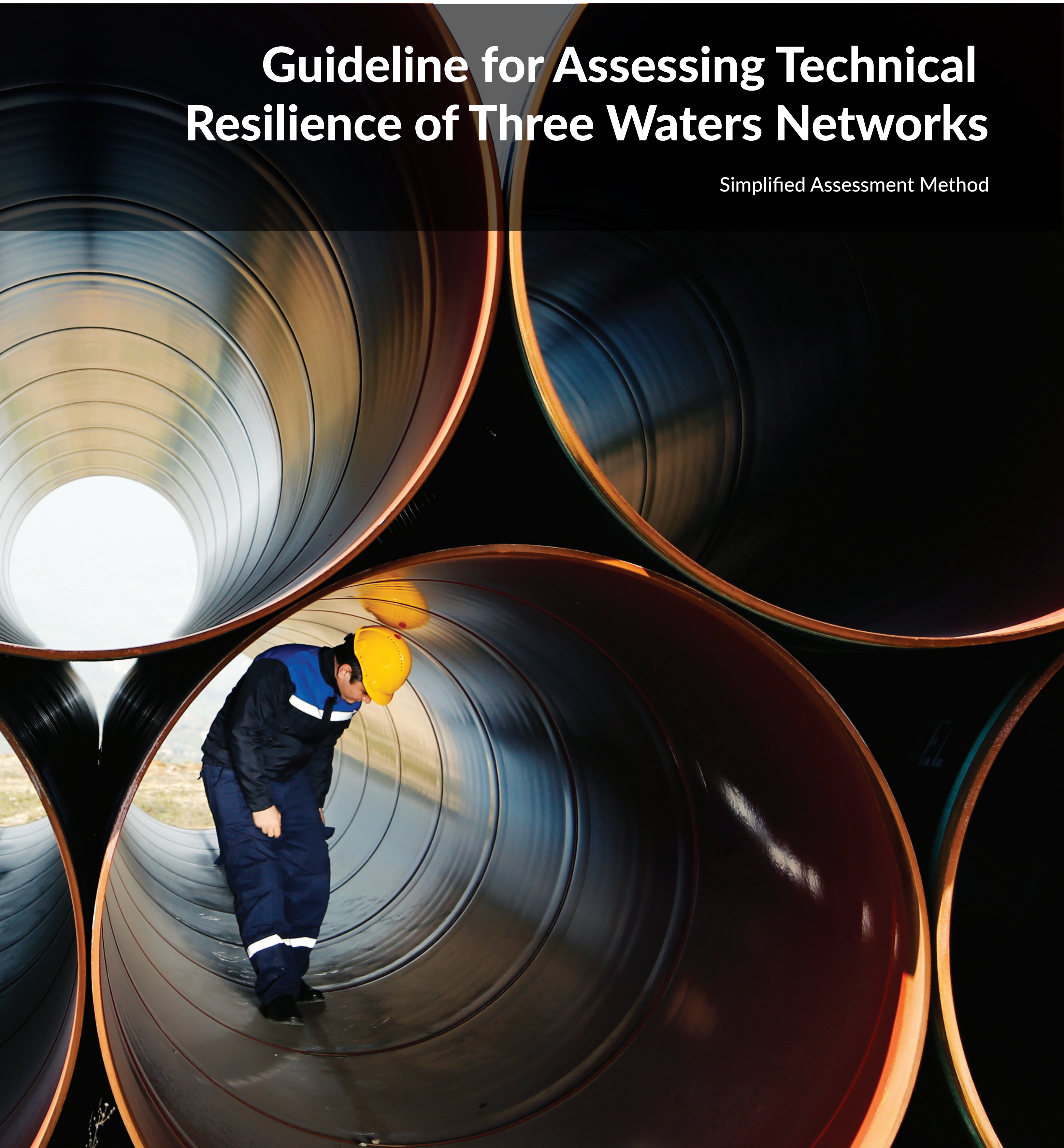
Guideline for Assessing Technical Resilience of Three Waters Networks

Simplified Assessment Method



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Acronyms

CDEM	Civil Defence Emergency Management
CES	Canterbury earthquake sequence
IIMM	International Infrastructure Management Manual
IPWEA	Institute of Public Works Engineering Australasia
LOS	Level of service
LPI	Liquefaction Potential Index
LSI	Liquefaction Severity Index
LSN	Liquefaction Severity Number
Mw	Earthquake moment magnitude
PGA	Peak ground acceleration
PGD	Peak ground displacement
PGV	Peak ground velocity
SCIRT	Stronger Christchurch Infrastructure Rebuild Team
UCQC	University of Canterbury Quake Centre
Water NZ	Water New Zealand

Pipe materials

AC	Asbestos cement
BB	Brick barrel
CI	Cast iron
CLS, GALV, STEEL	Steel (with or without lining and coating)
DI	Ductile iron
EW	Earthenware
GRP	Glass reinforced polymer
PE, HDPE, MDPE, LDPE PE80, PE100	Polyethylene (of different densities)
RCRR	Reinforced concrete rubber ring jointed
UPVC	Polyvinyl chloride

Table of Contents

Table of Figures

List of Tables

1 Introduction

1.1 Guideline objective

This guideline provides a framework for assessing technical resilience of three waters piped assets.

The guideline has been prepared to support local authorities and the private sector (including asset managers, operators and engineers) at local and regional levels with assessing technical resilience and in developing strategies to improve network resilience, and inform pre-event planning and post-event emergency support and recovery.

The guideline aims to standardise the assessment of technical resilience across New Zealand and to encourage collaboration, while maintaining the ability for users to tailor the assessment approach to fit the specific requirements and needs of their community.

1.2 Guideline scope

Resilience contains technical, organisational, social and economic aspects. This guideline focuses on the assessment of technical resilience of three waters piped networks only.

The guideline has been developed by drawing on existing literature and guidance on asset management and resilience assessment frameworks, and by incorporating lessons learnt from the Canterbury earthquake sequence of 2010-2011.

The guideline is a component of an industry funded 'Evidence-based Investment Decision Making for three Waters Networks' project that is being managed by the Quake Centre at Canterbury University.

1.3 Defining resilience

Resilience of a system can be defined as the:

> ... ability of systems (including infrastructure, government, business and communities) to proactively resist, absorb, recover from, or adapt to, disruption within a timeframe which is tolerable from a social, economic, cultural and environmental perspective.
>
> Money et al, 2017, p.7.

Note: Understanding of three waters resilience is only achieved if the technical, organisational, social and economic components of resilience are appropriately assessed and considered together (Figure 1).

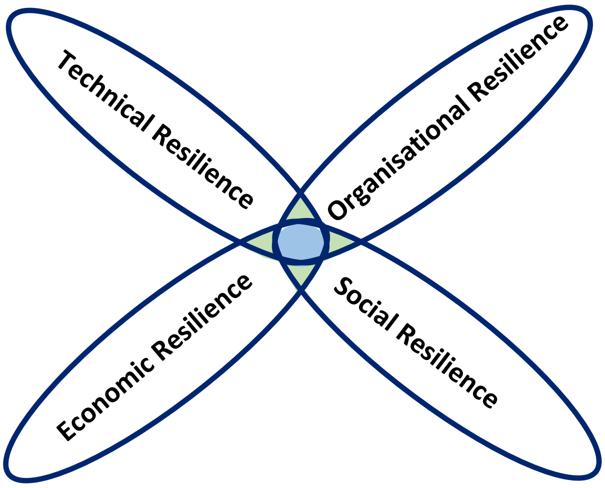

Figure 1: Balanced understanding of resilience.

1.3.1 Technical resilience

Technical resilience is a key component of system resilience and can been defined as the ability of the three waters network to accommodate and mitigate the effects of an extreme event on the level of service provided. This considers physical effects and consequences of an extreme event on the network such as an extreme weather or geological event. Technical resilience may be achieved through the physical robustness and flexibility of the network, its isolation from the hazard, or ease of repair.

Other elements of system resilience not covered by this guideline are:

Organisational resilience This is the responsiveness and effectiveness of organisations managing and operating a three waters network to: understand the problem, implement emergency response, and develop and implement recovery plans to provide temporary service where needed; and to reinstate network service to customers (typically staged with time).

Social resilience	Social resilience is the ability of the community to accommodate and adapt to disruption and work together to provide support. This will depend on the severity and extent of an event affecting day to day life, vulnerability of customers, ability of the community to develop alternative means to become temporarily self-sustainable, importance of the customer to community support (e.g. hospitals, community centres, schools), and spatial location.
Economic resilience	This refers to the ability of the community on a local, regional or national scale to accommodate and mitigate the effects on the economy (short- and long-term) of the extreme event disrupting three waters infrastructure. It also considers the community's ability to sustain economic activity by reducing reliance on three waters infrastructure through relocating or distributing operations, and its repair and recovery planning to reduce long-term adverse effects.

1.4 Benefits of a resilience assessment

The community and asset owners can derive benefits from the knowledge developed when completing a resilience assessment of three waters networks, including:

- An improved understanding of networks, potential natural hazards, vulnerable areas and consequence spatially.
- Reduced cost of improving resilience through early and detailed assessment targeting areas where the greatest value can be achieved. Significant improvement can be achieved at low or no cost if approached in this way.
- Improved and informed disaster response.
- Improved community confidence resulting from an understanding of the risks and what has been done to reduce them, and facilitation of managed recovery.
- Maximised value of existing assets through targeting renewals that extend the life of assets (where effects on network resilience are very small), and focusing on assets that provide greatest benefit to network-wide operation.
- Informed high-level strategic management actions following events to facilitate timely recovery, prioritisation of assets for repair, and improved robustness in recovery planning.
- Assessment outputs that can feed into:
    - Asset management (NZ Metadata Standard, International Infrastructure Management Manual [IIMM])
    - Disaster planning for both emergency and recovery phases
    - Financial planning
    - City planning

- Identified strengths and weaknesses of the networks in terms of resilience.
- Ability to determine strategies to systematically improve network resilience and performance.
- Ability to make rational and informed decisions on operational investment relating to asset upgrade and/or renewal, capital work projects, and future land development.

1.5 Applicability

This guideline has been developed specifically for assessing the technical resilience of three waters assets within distributed networks. Three waters networks are:

Water supply	Piped water and irrigation networks between the exit of the water supply plant/well (but not the plant/well itself) and any intermediate pump stations, through to the customer.
Wastewater	Piped networks and any intermediate pump stations to the entry to any wastewater treatment facility (but not the wastewater facility itself).
Stormwater	Stormwater conveyance networks from the point of stormwater entry into an engineered piped/open channel network to the point of discharge, including any intermediate pump stations.

The guideline is applicable to both pressurised and gravity pipelines. Reservoirs, water intakes, supply wells and treatment facilities are critical elements of the overall resilience of three waters networks and should not be ignored. Specific detailed engineering review of these assets is required. Each assessment needs to be tailored closely to the specific hazard profile, asset vulnerability and engineering design. Concepts presented within this guideline for distributed assets can be incorporated into detailed assessments for discrete assets.

1.6 Technical resilience assessment framework

Figure 2 provides a high-level schematic of the resilience assessment framework.

Compile data and characterise hazard

- Compile data on asset attributes, condition and location. Assess land condition. Define Equivalent Standard Customer.
- Inspect site to review existing and past hazards. Review regional geology, geomorphology and geotechnical investigation data.
- Compile available hazard assessments. Establish hazard characterisation and anticipated consequences to land performance and post-event asset functionality. Conduct high-level assessment to quantify hazard spatially.

Damage assessment

- Identify hot spots within the network that are most susceptible to natural hazards.
- Assess asset vulnerability to damage by estimating risk and considering empirical relationships developed from real wold experience.

Consequence assessment

- Review asset criticality considering network flow pathways, redundancy, asset independency and robustness.
- Identify critical customers across the network.
- Identify the proportion of customers across the network reliant on asset operation.

Resilience review

- Review, at a high level, the spatial variability of hazards across the network, and broad effects on network operation.
- Assess spatial variation of risk of customer service disruption, both short-term during the emergency phase and longer-term during the period of rebuild.
- Prioritise assets across the network based on benefit to network-wide resilience if risk of asset damage was reduced, considering vulnerability and criticality of assets assessed network-wide relative to each other.

Figure 2: Technical resilience assessment framework.

1.7 Assessment method options

The three waters resilience project has developed two methods for assessing the technical resilience of three waters piped networks. They are:

1. **Simplified** A qualitative assessment based on engineering judgement.
2. **Advanced** A quantitative assessment based on analytical modelling with spatial assessment capability to estimate damage and network consequence.

Both methods follow the framework presented in Figure 2 but require different levels of data and analysis. The selection of which method to follow is primarily based on community size, as this indirectly infers the size and complexity of the network. The Simplified method is the minimum assessment level recommended for all communities and this guideline details that approach.

1.8 Factors influencing resilience

Three waters networks are generally extensive and distributed. The key factors that influence the resilience of the network are:

1. Network layout and the interdependence between assets.
2. Asset robustness and the ability of the asset to remain functional when damaged.
3. Environmental factors that influence the degree of damage assets sustain during an extreme event, such as ground deformation or flood elevation.

A resilience assessment cannot predict damage and consequences with precision. Assessment, therefore, should not focus on discrete elements but on the outcomes of the assessment spatially across the entire network. Sensitivity checks need to be undertaken to establish where effort is best applied in assessing network resilience. Figure 3 presents an example of the typical influence of different elements on resilience assessment outcomes.

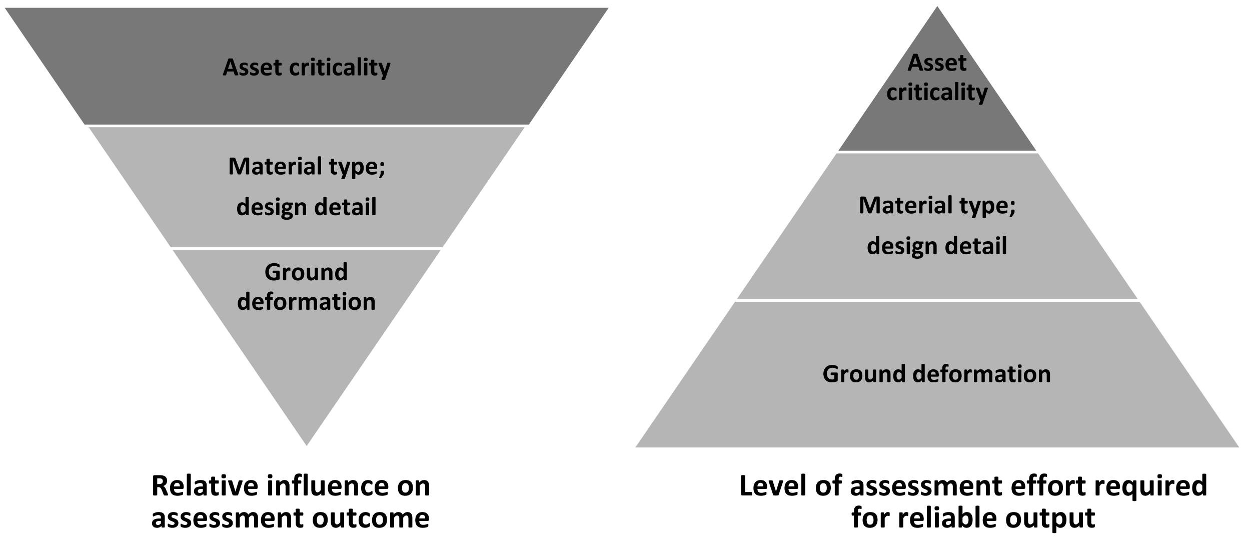

Figure 3: Schematic presenting typical influence of resilience assessment inputs on output of assessment, and uncertainty associated with various elements.

Undertaking a criticality assessment provides significant value to a technical resilience assessment as it is a dominant influencer on the resilience assessment output and is typically not resource intensive.

Conversely, accurately estimating damage has high uncertainty and is typically resource intensive (varying with the level of detail considered). Therefore, for damage assessment where only prioritisation ranking is required (i.e. not predicting recovery timeframes or specific repair costs), a Simplified assessment is recommended. This should incorporate a sensitivity check for a range of inputs into the damage assessment to determine the specific influence of the assessment on prioritisation ranking outcomes. Where improved definition is demonstrated to benefit the resilience prioritisation assessment, this can be refined in a targeted manner.

For simplicity, the resilience assessment presented within this guideline considers that each of the three waters networks operate independently. Following completion of a resilience assessment of individual three waters networks, outcomes should be compared to rationalise the overall resilience strategy.

2 Simplified assessment method

2.1 Method overview

The Simplified assessment method is based on engineering judgment, and the use of simplified indexes (Resilience Index) that can be tracked with time. The method requires the following key inputs:

- Data on network assets, condition and performance.
- Hazard scenarios and anticipated consequences.
- Network characteristics and vulnerabilities developed from local experience.
- Knowledge of performance of assets during extreme events both nationally and internationally.

The quality of assessment outcomes from this approach is dependent on the knowledge and experience of the assessment team. The assessment team should include technical specialists, asset managers, network operators and asset owners – individuals with a range of skills and experience with the network to provide a balanced assessment and promote a constructive and positive challenging of assessment outcomes.

The effectiveness of the Simplified assessment method also relies upon the establishment of a diverse review team. Third party review of data sources, methodology, base assumptions and outputs of the assessments is recommended, providing fresh review and a challenge of assumptions.

Outputs of the assessment will vary between localities and with time, with differences in perceptions and team dynamics. Repeatability of outcomes requires consistency in both the team performing the assessment and the approach followed.

The Simplified assessment method, when performed by an effective team of skilled individuals with good knowledge of the specific network and hazards, will provide a high-value outcome. This approach generally provides a good, simplified, high-level understanding of the key issues influencing network resilience, and will identify high-level opportunities for improvement. However, Simplified assessment can struggle to provide adequate definition across network elements, or to consider the complexities of distributed networks and interactions. Where this complexity exists within the network, the Advanced assessment method should be followed. The Advanced assessment method is not covered further in this guideline but is described in detail in the draft document *Guideline for Assessing the Resilience of Three Waters Networks* (yet to be published).

2.2 Compiling asset data

Assessment quality is dependent on the quality of the data and the influence that each component has on the outputs. Undertaking a review of data quality, preforming gap analysis, and updating where necessary, will support a three waters resilience assessment.

2.2.1 Network data

The attributes and spatial arrangement data of the three waters network is of critical importance to the resilience assessment. The critical network data elements for resilience assessment are:

- Database of asset information comprising spatial location and asset attributes. Recommended minimum data is (in order of importance for assessment):
  - Asset spatial location, along with links to adjacent assets where these exist, and knowledge of flow pathways
  - Pipe/structure material type
  - Pipe/structure diameter/size
  - Date of installation
  - Asset condition.
- Location and construction details for critical components of the network, focusing on key structures.
- Understanding of historic design and construction details for pipes and manholes.
- Knowledge of critical supporting services for operation of the network, and critical assets (such as pump stations, wells and treatment facilities).

Asset taxonomy, data format and failure mechanism should be standardised in advance of the data documentation process. A standardised and unified data documentation and management system is necessary to provide confidence in resilience assessment across the network. The New Zealand Asset Metadata Standards (NZAMS) have been developed for three waters assets in New Zealand to assist with standardisation and depth of data collection nationally. They aim to establish a standardised specification for asset data collection, entry and storage, and consequently to enforce analytical capabilities to support evidenced-based investment decisions. NZAMS recognises various levels of sophistication in the data and provides relevant data attribute guidance.

Continual improvement of network data captured and stored within a GIS system (data captured, consistency and quality) is important to support long-term resilience assessment and strategic management of the network.

2.2.2 Land condition

The majority of three waters facilities and assets are buried in the ground. As asset performance is strongly linked to the adjacent ground, sufficient understanding of ground conditions for critical assets (detailed) and across the network (broad) is important. This understanding will enable the establishment and ranking of the influences of geotechnical hazards on the wider network and individual components. Aspects of land condition to be compiled include:

- Information on geology and ground conditions, including; geological maps, hazard mapping, and ground investigation data. Using a geotechnical database as a central repository of geotechnical information provides benefits beyond resilience assessment. For example, the New Zealand Geotechnical Database (www.nzgd.org.nz; Ministry of Business, Innovation and Employment, 2019) provides a mechanism for storing and sharing geotechnical information nationally.
- Topographical information such as LiDAR surveys.
- Historic land use registers to provide knowledge of change to the physical characteristics of land, such as historic filling (where available).

2.3 Characterise hazard

The Simplified method relies on generalised and high-level hazard responses, rather than a detailed analytical assessment. Data for the hazard assessment is collated from available local or regional hazard assessments or national assessment (data repositories include: Ministry for the Environment (MfE), Ministry of Business, Innovation and Employment (MBIE), local and regional councils, NZS1170, RiskScape).

Below are recommendations for informing hazard scenario selection for resilience assessment:

- Develop a register of past extreme events with a summary of consequences.
- Compile hazard data: location-specific hazard studies, academic research, standards/guidelines, and compiled national risk data such as included in RiskScape (www.riskscape.org.nz; NIWA, GNS Science , 2019).
- Undertake a high-level multi-hazard assessment to identify the natural hazards that dominate the vulnerability of the network and pose the greatest risk to the community.
- Identify representative hazard scenario(s) appropriate for the resilience assessment. This may be for a specific event expected in the future with defined characteristics, or a theoretical scenario considering occurrence probability and likely severity of consequence.

The likelihood and consequence of the following natural hazards should be considered in the hazard assessment:

Earthquake	Strong ground motion induced by an earthquake can induce shearing of the ground, triggering landslides and rockfall, liquefaction and associated ground deformation and differential settlement. Ground shaking and soil-structure interaction can also result in structural defects developing in pipes and structures which can reduce their functionality and useful life. The severity of the hazard depends on the magnitude of the earthquake, distance to epicentre, and characteristics of the earthquake and local and regional geology.
Landslide	Instability of slope resulting in downward movement of rock or soil, either large-scale, large-strain movement or creep. The extent and severity of landslides depends on the landslide triggering mechanism, local geology and topography.
Flooding	Flooding from coastal, fluvial or pluvial inundation and groundwater rise. This can result in networks being overwhelmed, blockages, triggered wastewater overflows, and damage to water sensitive electrical and communication utilities.
Erosion	Loss of land adjoining waterways and coastal margins associated with flowing water and/or wave action and rise in water levels compromising asset foundation support leading to failure.
Tsunami	Ocean waves with extremely long wavelengths can induce surges of water that flow inland for extensive distances with very high wave heights. They may cause damage to infrastructure by impact, flood damage, erosion and loss of supporting infrastructure, and are frequently triggered by large earthquakes and or large-scale landslides beneath the ocean.
Volcanic eruption	Violent discharge of lava, lahar or ash from the ground. They can cause damage to infrastructure from flow impact (lava and lahar), and blockage and failure from ash surcharge, as well as loss of supporting infrastructure and displacement of communities.
Extreme weather events	Heavy snow, hail, high winds and extreme temperatures have the potential to damage networks and reduce levels of service.

To characterise natural hazards, it is important to:

1. Consider notable features within the region, including but not limited to: major faults, liquefiable soils, proximity to waterways, geology exhibiting high instability.
2. Perform field review of existing and past hazards influencing network assets (e.g. walkover, review aerial images).
3. Review regional geology and geomorphology, and compile available geotechnical investigation data and assessments.

The hazard consequence can be broken into broad descriptive categorisations with corresponding descriptions of typical observations. Refer to Figure 4 for an example categorisation for earthquake induced land damage. Using this example, earthquake ground performance characterisation may include assessment of; liquefaction trigging potential (qualitative or quantitative), setback to free faces, geotechnical indices informing performance (LPI, LSI, LSN), understanding of geology and geomorphology.

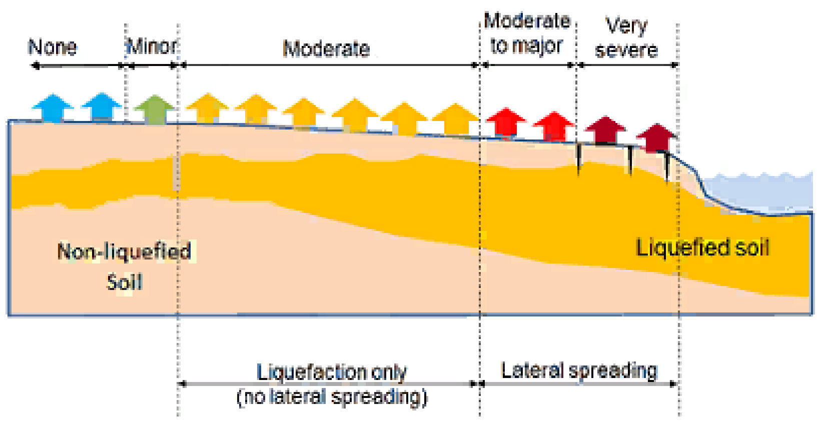

Figure 4: Example of possible categorisations of hazard consequence for earthquake land damage.

Modified from Canterbury Geotechnical Database (2013) and Cubrinovski et al. (2014).

No liquefaction: No liquefaction, ground deformation <50mm

Low: Ground cracking or ejected liquefied material. Settlement <50mm, Lateral displacement <25mm

Minor: Minor ground cracking but no observed ejected liquefied material. Settlement <100mm, Lateral displacement <50mm

Moderate: No Lateral spreading but minor to moderate quantities of ejected material. Settlement 100-250mm, Lateral displacement 50-200mm

Major: Moderate to major lateral spreading or large quantities of ejected material. Settlement >250mm, Lateral displacement >200mm

2.4 Simplified damage assessment

Damage assessment for the Simplified method focuses on broad expectations of relative asset performance based on an empirical assessment of performance on a large-scale basis, rather than a location-specific detailed assessment. Rather than quantifying the expected damage rates, the Simplified method focuses on estimating the relative risk of loss of service between different assets.

Below is a list of useful references for estimating high-level asset damage during earthquake scenarios. This list is not exhaustive and literature review should be regularly undertaken to ensure that the resilience assessment utilises the current state of knowledge.

- Cubrinovski M, Hughes M, Bradley B, Noonan J, Hopkins R, McNeil S, English G (March 2014). *Performance of Horizontal Infrastructure in Christchurch City though the 2010-2011 Canterbury earthquake sequence*. University of Canterbury.
- O'Rourke T, Jeon S, Toprak S, Cubrinovski M, Hughes M, van Ballegooy S, Bouziou D (February 2014). *Earthquake Response of Underground Pipeline Networks in Christchurch, NZ*. Earthquake Spectra, Vol 30, No. 1 pp183-204
- Cubrinovski M, Hughes M, Bradley B, McCahon I, McDonald Y, Simpson H, Cameron R, Christison M, Henderson B, Orense R, O'Rourke T (December 2011). *Liquefaction Impacts on Pipe Networks*. University of Canterbury.
- American Lifelines Alliance (2001), *Seismic Fragility Formulations.*
- Pineda-Porras, O., Najafi M., (2010). *Seismic Damage Estimation for Buried Pipelines: Challenges after three decades of progress*. Journal of pipeline systems engineering and practice, ASCE.
- Opus International Consultants Ltd, GNS Science, Water NZ (March 2017). *Underground Utilities – Seismic Assessment and Design Guidelines*. Ministry of Business, Innovation and Employment, NZ Government.

For the purposes of supporting an assessment, the relative risk of loss of service for a range of pipes used within New Zealand three waters networks is provided in Table 1. This has been developed for earthquake assessment. Damage to pipelines is dominated by ground deformation; frequently there are 10 to 20 times more pipe faults associated with ground deformation than wave propagation. The relative performance of different pipe materials is dependent on the strength and brittleness of the pipe and typical joint connections for pipe type. These relative performance factors can be used as a first pass triage assessment for relative pipe performance across the network for the Simplified method of assessing earthquake induced damage.

Knowledge of damage rates for landslides, erosion, tsunami, volcanic erosion and sea-level rise natural hazards is limited. Quantification of damage estimates are typically based on first principles build-up of outcomes considering: areas affected, likely severity of devastation, and anticipated mechanisms leading to the loss of service. By example, assessment could include a review of damage scenarios to above ground structures and supporting infrastructure, sedimentation/blockage damage, asset burial, infiltration and submersion.

Damage to node structures such as pump stations, treatment plants and manholes requires review of static and seismic buoyant uplift (for earthquake scenarios). Review of design detailing is also required to assess the vulnerability of the asset connections within the network that could result in damage or loss of critical services.

Table 1: Relative damage factors for earthquake scenarios for pipe normalised to PVC.

Pressure Pipe Type	Simplified relative damage factors for earthquake scenarios for pressure pipe normalised to PVC					
	Wave Propagation	Ground Deformation				
	No Liquefaction	Low	Minor	Moderate	Major	Severe
Ground Settlement	-	<0.02m	0.02m – 0.10m	0.10m – 0.25m	0.25m – 0.50m	>0.5m
Lateral Displacement	-	<0.02m	0.02m – 0.05m	0.05m – 0.20m	0.20m – 0.40m	>0.4m
Thickness of Liquefied Layer	-	-	2m - 4m	4m - 8m	5m - 10m	5m - 10m
Pressure Network						
Polyethylene (LDPE, MDPE & HDPE, <50mm dia)	0.10	1	1.5	3	4	5
Polyethylene (MDPE & HDPE, >50mm dia)	0.01	0.5	1	1	1.5	2
Polyvinyl Chloride (PVC)	0.05	1	1	1.5	2	3
Ductile Iron	0.05	1	2	4	5	7
Steel	0.10	1	1	2	3	5
Wrought Iron	0.15	2	3	5	7	9
Cast Iron	0.20	1	2	4	5	7
Asbestos Cement	0.30	3	4	6	7	10
Galvanised Steel (<50mm dia)	0.35	5	7	11	15	20
Gravity Network (Suggested initial values - in need of further research)						
Polyethylene	0.01	1	2	3	4	6
Polyvinyl Chloride (PVC)	0.05	4	7	10	15	20
Asbestos Cement	1	25	35	60	80	110
Reinforced Concrete Rubber Ring Jointed	3	50	60	90	110	150
Earthenware	10	250	300	450	550	800

Note:

- For gravity networks not all defects affect post disaster functionality and/or require remedial. Damage factors to be reduced based on proportion of damage expected to require repair/ replacement.
- Provided as an example, to be refined considering the characteristics of the network materials, construction quality and age.

2.5 Consequence assessment

The consequence of asset damage and its effect on the network's level of service is dependent on the location of the damaged asset, the proportion of the network affected, the criticality of customers served by the asset, and the duration and cost of remediation.

The detail and sophistication of a consequence assessment can vary substantially from:

- A judgment-based assessment using high-level knowledge of the network composition and spatial variance in hazard (Simplified Consequence Assessment), through to
- A detailed modelling and network analysis (Detailed Consequence Assessment).

A Simplified Consequence Assessment or a Detailed Consequence Assessment can be applied to the simplified resilience assessment presented in this guideline.

Assessment method selection is primarily based on community size, as this indirectly infers the size and complexity of the network. In most cases adoption of a Detailed Consequence Assessment is recommended, as significant insight into network characteristics and the impact on level of service can be readily assessed though GIS network interrogation. The Detailed Consequence Assessment Method is recommended for communities where the Equivalent Standard Customers exceeds 10,000 (refer to Section 2.5.2 for description). The Simplified Consequence Assessment is the minimum assessment level recommended for all communities.

2.5.1 Simplified Consequence Assessment

The criticality of the asset can be simply estimated by considering the pipe diameter, as typically the larger the pipe diameter, the greater number of customers affected. When considering typical pipe diameters for gravity and pressurised three waters networks, the criticality factors shown in Table 2 may be applied to pipe assets.

Table 2: Example of simplified pipe criticality rating for different pipe network type and diameter.

Network Type	Pipe Diameter	Simplified Asset Criticality Rating
Pressurised	<50mm	1
	50-100mm	2
	100-150mm	3
	150-200mm	7
	200-300mm	20
	>300mm	50
Gravity	≤100mm	1
	100-150mm	2
	150-300mm	3
	300-600mm	7
	600-900mm	15
	900-1200mm	25
	>1200mm	50

Note:

- Provided as an example, to be refined considering the characteristics of the network materials, construction quality and age.
- For non-pipe assets (e.g. pump stations, chambers) the Simplified Asset Criticality Rating can be estimated based on the largest diameter pipe entering/exiting the asset.

The consequence of damage to a treatment facility, pump station node structure or dedicated main to an isolated community requires a subjective assessment on an individual asset basis. Treatment facilities are always critical structures of high importance, while pump station importance is generally proportional to size/capacity. Where a single pipe supplies or services an isolated community, a higher criticality rating than that suggested by its diameter may be justified.

Manholes are distributed below ground structures and the vulnerability of these assets will vary depending on their construction detailing. Repeated use of design details that are vulnerable to damage can lead to widespread loss of service, potentially with a significant disturbance to levels of service.

2.5.2 Detailed Consequence Assessment

Detailed Consequence Assessment considers the specific spatial arrangement of the three waters network, likely effects of hazard induced damage to assets on levels of service across the network, and the distribution, specific vulnerabilities and demands for service from different customers across the community.

Defining the Equivalent Standard Customer

Three waters assets are not equal in terms of their importance and the influence they have on the level of service that customers experience. Neither are all customers within a community of equal importance. Examples of critical customers include public services that significantly influence the quality of life of the wider community (e.g. hospitals, schools and emergency services) and private organisations that support the community (e.g. supermarkets and industry). Vulnerable individuals (e.g. elderly or chronically sick) also warrant an improved level of service relative to the wider community.

Considering the importance of customers to supporting community welfare, not just spatially across the network, can provide additional definition to the technical resilience assessment.

To account for the varying levels of importance of different customers, an Equivalent Standard Customer is defined for resilience assessment purposes. The Equivalent Standard Customer is normalised to be equivalent to a standard residential property, being the most common customer of three waters assets across communities.

Table 3 provides an example of a characterisation of relative Equivalent Standard Customers for different high demand customer types. Determining the number of Equivalent Standard Customers allocated to different stakeholders should be community-specific, considering the particular dynamics and characteristics of the community. This is best performed by Territorial Authorities in consultation with the community and stakeholders.

The total number of Equivalent Standard Customers each asset services can be determined to inform asset criticality ranking. The approach presented differs from the 1-5 critically ranking presented in the Three Waters NZ Metadata standards as it provides a greater spread of values. This greater spread is to allow a clear ranking of asset importance.

Table 3: Example of definition of Equivalent Standard Customer for different stakeholders within a community.

High Demand Customer	Number of Equivalent Standard Customers
Hospital	1000 - +5000
Medical Centre	150
Rest Home/Aged Care Facility	100 - 500
School/Preschool	20 - 200
Emergency Services/Civil Defence	500
Marae	10 - 50
Local/ Regional Government	20 - 100
Airport	100 - 1000
Port	100 - 1000
Industry * >1000 employees	300
Industry * >300 employees	30
Industry * >100 employees	10
Industry * >10 employees	5
Commercial Business >300 employees	30
Commercial Business >100 employees	10
Commercial Business >10 employees	3
Food Distribution Organisation (e.g. supermarket)	50
Townhouse/Apartment Complex	No. units within complex
Vulnerable Community Members (aged, chronically sick, disabled, etc.)	5
Standard Residential Property	1

* Industry that is reliant on three waters operation to manufacture/process.

Notes:

- This table is provided as an example to commence discussion. Specific allocation of equivalent customers should be determined by a resilience assessment team that considers the specific characteristics and resilience of the community.
- Where a range is provided, variability is expected with different tiers of importance or size.

Completing the Detailed Consequence Assessment

A Detailed Consequence Assessment aims to compare the relative risk of the reduction of level of service in a spatial environment by developing a range of measurement indices. Consequence assessment should consider both pipelines and node assets, such as pump stations and manholes. Examples of the application of indices for consequence assessment and asset prioritisation are presented below:

Asset criticality Number of Equivalent Standard Customers within the network that are reliant on asset operation, demonstrating the importance of the asset within the network, considering spatial arrangement and linking of assets.

Loss of service risk Development of a pipe fault index through the network, allocated to each individual property, by tracing and summing faults along the trace that are anticipated to influence service to each property. The index acts as a proxy to indicate the relative risk of an individual property losing service relative to another property and can be spatially displayed as a heat map. This assessment assumes that all faults are equal on average, and the change in risk of service loss is assumed to be proportional to the potential number of pipe faults. A range of factors can influence the pipe fault index:

- Properties that are located further away from the treatment plant or supply source will naturally experience higher fault counts and greater risk of adverse effects on level of service.
- Pipe faults are significantly influenced by adverse performance of the land. Pipeline routes passing through zones with high potential for liquefaction, lateral spread or landslides exhibit substantially higher risk of developing faults and loss of service.
- Network flow pathways that incorporate a high proportion of modern ductile/flexible pipe materials and connection details, such as PE and uPVC, will exhibit lower risk of loss of service than old and/or pipes that exhibit brittle mechanisms of failure.

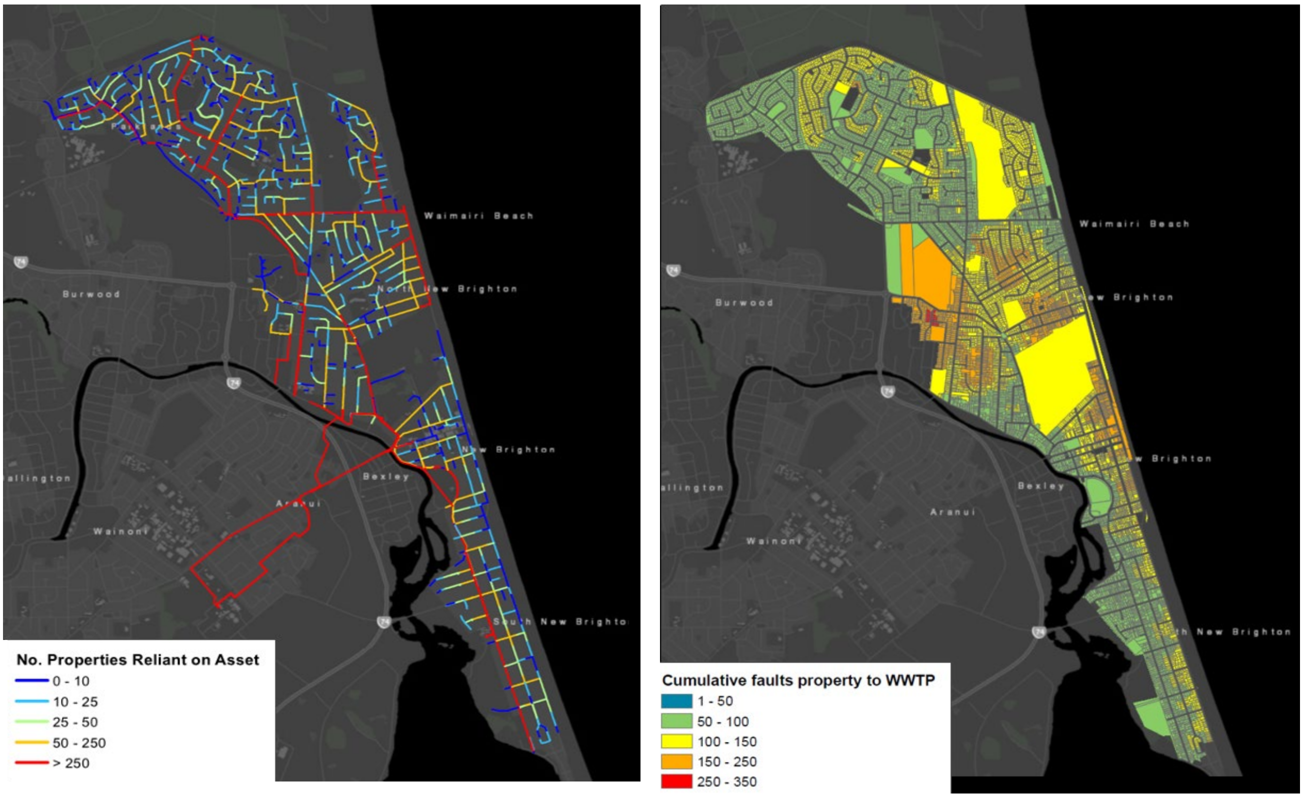

Figure 5: Example of output from assessment of asset criticality, pipe fault index as applied to an eastern area of Christchurch (Beca study completed for Christchurch City Council)

2.6 Simplified resilience assessment and asset prioritisation ranking for resilience improvement

2.6.1 Simplified resilience index

A simplified resilience index can be computed for each asset to establish a simplified prioritisation ranking for resilience.

Simplified resilience index	=	**Simplified relative damage factor**	**X**	**Asset criticality rating** *or* **Proportion of network equivalent customers relying on asset for function**

2.6.2 Asset prioritisation ranking

Assets with a high resilience index have higher influence on overall network performance than assets with a lower resilience index. Renewal of assets with a high resilience index improving the resilience of the individual asset provides greater benefit to improving network resilience with time. Figure 6 provides an example of prioritisation ranking based on a calculated resilience index.

Additional sophistication can be incorporated into the assessment through Monte Carlo simulation of individual asset failure using network tracing to identify alternative supply routes and repeating the assessment to determine damage factors and resilience indices. Undertaking many analyses for assets across the network allows an estimation of probabilities of adverse consequences for loss of service. Such assessment is most beneficial for three waters networks that have high adaptability due to the presence of pipelines that link catchments and/or the presence of ring mains, such as in water supply networks.

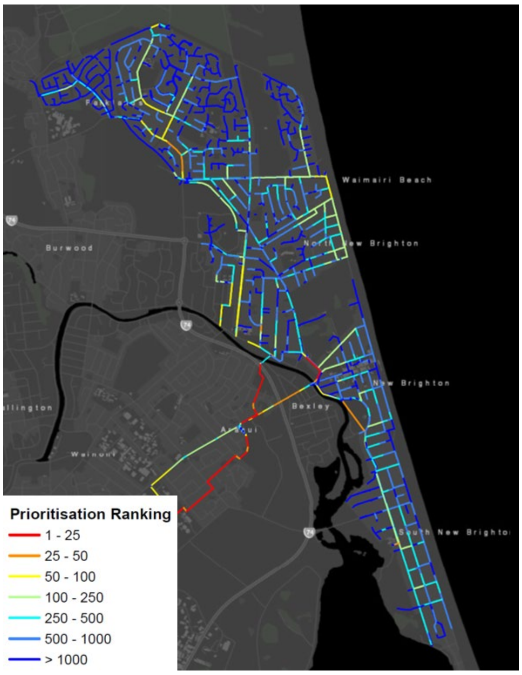

Figure 6: Example of output from assessment of prioritisation ranking developed from resilience index (Beca study complete for Christchurch City Council)

2.6.3 Assessment review

Outputs of a Simplified resilience assessment must be checked and calibrated against anticipated outcomes. This is due to the simplistic nature of the assessment and the assumptions applied, which have the potential to result in a wide variance in outcomes.

Outputs should be simplified when presenting to avoid portraying a level of accuracy beyond the limits of the assessment and assumptions. Uncertainty in model outputs must be considered and incorporated into the assessment where the specific estimated values are relied upon.

Sensitivity analysis, undertaken by varying base assumptions in the analysis, is recommended in order to estimate the uncertainty of the analysis.

2.6.4 Attribute examples for Simplified assessment

Table 4 provides hazard-specific examples of key attributes and actions across the different phases of the Simplified assessment for different hazard scenarios. Note that this list is not exhaustive and should be extended as appropriate to account for specific network and location characteristics.

Table 4: Summary of key actions for different hazards.

<table>
<tr><th>Hazard</th><th>Characterise Hazard</th><th>Damage Assessment</th><th>Consequence Assessment</th></tr>
<tr><td>Earthquake</td><td>▪ Adopt liquefaction studies to inform risk of land settlement and lateral spread.
▪ Where detailed studies are not available, review geology, geomorphology and analyse geotechnical investigation data for estimation of potential liquefaction risk and ground deformation.
▪ Compile known fault information, including return period for fault rupture.
▪ Develop broad contour maps of possible ground deformation hazard zoning (semi-qualitative supported by engineering judgment and experience).</td><td>▪ Estimate relative risk of damage to assets from earthquake strong ground motion (shaking) and ground deformation. Consider asset material type (pipe) and broad anticipated seismic performance of the ground. Estimates can be supported by experience such as the 2010-2011 Canterbury earthquakes. Refer Opus (2017A) technical Note 5 & 6, Cubrinovski et al. 2014.
▪ Table 1 provides a summary of typical relative performances for different pipe types for pressure and gravity networks.
▪ Allocate simplified relative damage factor for each asset.</td><td rowspan="3">Simplified
Assessment of asset criticality by considering diameter of pipeline.

Detailed
▪ Undertake assessment for simplified approach as a first pass (see above).
▪ Criticality can be refined though considering knowledge of customers in the community that rely upon continued network service for safety and security, and have high importance to the community (e.g. Equivalent Standard Customers described in Table 3).
▪ Identify critical nodes vulnerable to damage and assess effects of damage on level of service and timeframes for reinstating level of service to acceptable levels.
▪ Analytical assessment of network connectivity, to associate asset with customers. Determine the proportion of the community that is reliant on asset for service. Where possible, adoption of a Standard Equivalent Customer is recommended to allow a broader assessment of asset criticality considering the spatial location within the network and both the proportion and importance of the sector of the community the asset services.
▪ Review of outputs by network operators. Manually incorporate network knowledge to incorporate broader knowledge and experience of the network into the analytical assessment.</td></tr>
<tr><td>Landslides</td><td>▪ Review areas of historic instability along critical three waters assets alignments, and records of asset damage where available.
▪ Understand high level vulnerability of different geologies to instability, in different topography and spatial environments. Identify dominant triggers for instability for the area (over steep slopes, discontinuities, effect of water, earthquake shaking).
▪ Walkover inspections and/or review of aerial photos by suitably experienced geotechnical professional along critical pipelines and network assets, to identify past instability.
▪ Assessment of typical landslide characteristics; depth of ground deformation, rate of movement (catastrophic/creep), rockfall hazard.</td><td>▪ Focus assessment on damage of critical assets that pass through areas of moderate to high risk of instability.
▪ Assume that landslide severs asset where crossing anticipated slip surface, requiring replacement. For large scale landslips ground deformation will adversely affect level and alignment of pipe within landslide mass, assess the effect of this where relevant.
▪ Damage will require localised repair or full replacement, depending on the anticipated characteristics of the anticipated landslides.
▪ Allocate simplified relative damage factor for each asset. Table 1 can be used to inform assessment adopting a ground deformation severity of “high” to “severe”.</td></tr>
<tr><td>Flooding</td><td>▪ Flooding could be associated with estuarine or coastal inundation, river flooding, or flooding associated with stormwater overland flow.
▪ Map flood zone and anticipated flood levels, and water depths for assessment event return periods.</td><td>▪ Review elevations of power and communication systems relative to flood water levels to identify plant and equipment and control systems vulnerable to damage.
▪ Identify assets vulnerable to localised erosion, and review risk and potential scale and nature of damage.</td></tr>
</table>

Hazard	Characterise Hazard	Damage Assessment	Consequence Assessment
Erosion	▪ Identify where three waters assets are exposed to potential erosion. Often associated with other hazards such as flooding. ▪ Review risk of erosion affecting the asset considering factors including: setback from waterway, hydraulic conditions within the waterway, existing condition of bank (stable/past evidence of erosion).	▪ If erosion is not mitigated to protect asset, assume that assets are lost where located within potential erosion zone.	
Tsunami	▪ Compile Tsunami studies and spatially map extent of Tsunami inundation overlaying with three waters network. ▪ Estimate depth of inundation, likely impact velocity/ force and extents of damage for selected Tsunami scenario.	▪ Consider effects of Tsunami floodwater and debris impact on above ground structures. ▪ Assess potential for blockage/sedimentation of below ground assets. ▪ Review risk of erosion along coastal/waterway margins. ▪ Consider the damage to associated infrastructure that the assets rely upon for operation, e.g., power, communications and road access.	
Volcanic eruption	▪ Collate and spatially map hazards (lahar, lava flow, ash) and severity/risk overlaying with network.	▪ Judgement estimate of damage to assets that is based on the assets' exposure to hazards, consequential effects and long-term feasibility for asset. ▪ Strategies for assessing damage for erosion, and flooding can be adopted for lahar or flood/scour impacts. ▪ Assess the effect of ash on short-term level of service, such as siltation of wastewater and stormwater networks. ▪ Review vulnerability of water supply network, and supply sources, to contamination (ash, volcanic fluid discharges, and gas). ▪ Review risk of ash accumulation resulting in structural damage to structures due to surcharge exceeding design allowances.	

2.7 Technical resilience monitoring

A technical resilience review should be undertaken to check improvements in resilience levels after renewals of three waters assets or the construction of assets that strengthen the network. This can be executed by identifying improved assets and recalculating the resilience index for these assets and the entire network.

The level of sophistication for resilience assessment should be reassessed periodically, considering the needs of the community as it develops, the quality of input data available, and the resources allocated for resilience assessment. Also, the assessment should be repeated where the knowledge of hazards changes or hazard characteristics change with time or spatially across the network.

The outcomes from monitoring and evaluation can be used to underpin short- and long-term asset management planning, considering land development and insurance purposes. The results can be fed into the Evidence Based Investment Decision Making process for the Three Waters Pipe Network Programme under development by the University of Canterbury Quake Centre, Water NZ and IPWEA.

Benchmarking of resilience indices between communities is possible where a similar assessment methodology has been followed and common assumptions applied. However, caution is recommended as biases can occur between communities of different size and composition. It is recommended that reviews with time should focus on tracking changes in the resilience index for a network rather than gross reported values.

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Guideline for Assessing Technical Resilience of Three Waters Networks

Simplified Assessment Method

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