RESILIENCE ASSESSMENT GUIDELINE FOR THREE WATERS: A TECHNICAL RESILIENCE PROSPECTIVE

Miao (Melanie) Liu (Beca Ltd), Marcus Gibson (Beca Ltd), Greg Preston (University of Canterbury Quake Centre)

ABSTRACT

A guideline for assessing resilience of three waters systems (water supply, wastewater, stormwater) is developed in the New Zealand context, with a focus on asset technical resilience. The guideline takes into account of criticality of three waters assets, potential hazards, asset vulnerability and network consequence. Sponsored by the University of Canterbury Quake Centre, the guideline promotes wider understanding of network asset technical resilience and provides a framework for a consistent assessment approach, to support local governments and private sector.

It is intended that the guideline can be used as both a pre-event proactive tool and a post-event reactive tool. The guideline provides tools and strategies to assist asset owners to make rational and strategic decisions for asset management and urban planning of three waters systems. This guideline will fit into a wider framework of guidance being developed to set national good practice in three waters asset management with particular emphasis on pipe renewals.

To improve network resilience, it is important to identify critical assets that have significant influence on the level of service for a community if impaired. The guideline assists asset managers to spatially identify asset criticality within the network, asset vulnerability, and relative risk of service disruption to the community. One of the outputs of resilience assessment is a resilience prioritisation ranking of assets across the network. This can be used to allocate resources (e.g., budget, crew) on targeted asset renewals and to reduce the consequences of natural hazards on loss of the level of service.

This paper presents two tiers of assessment sophistication namely: a simplified (qualitative and semi-quantitative) and an advanced approach (quantitative modelling). This aims to provide asset managers with flexibility to undertake assessment to a level matched to the scale of the network, urban development and resources available. Opportunities for integration of technical resilience modelling into long-term improvement of network resilience as well as hazard response and planning are discussed.

KEYWORDS

Wastewater, Water Supply, Stormwater networks, Resilience Assessment, Strategic Decision Making

PRESENTER PROFILE

Greg Preston is the Manager of the Quake Centre, based at the University of Canterbury. He is actively engaged in developing guidance material for improved asset management process in the 3 Waters as part of the *Pipe Renewals* programme of work being developed in conjunction with Water NZ and IPWEA NZ. Aspects of this include the creation of a national pipe data portal, implementation of the NZ Metadata Standards in 3 Waters and the development of a framework for pipe renewal decisions-making.

Melanie is a Civil Engineer at Beca, with a focus on three waters resilience. Melanie completed her PhD research at the University of Canterbury. The focus of her research was “Decision Support Framework for Post-earthquake Restoration of Sewerage Systems” in the context of the Canterbury earthquakes. This work can underpin decision making on system restoration after a seismic event and also support system maintenance and upgrade by guiding system rehabilitation and monitoring system behaviour during business-as-usual time.

1 INTRODUCTION

Three waters systems are vulnerable to natural hazards and may suffer both physical and functional damage in the aftermath of an extreme event. Damage to individual or multiple assets can result in reduced asset functionality or the entire shut-down of elements of the network, adversely affecting the level of service experienced by the community. This could impact community health and wellbeing as well as affecting the economy on a regiona,l or even a national, scale as observed following the 2010-2011 Canterbury Earthquake Sequence.

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”, (NZTA Research Report 614, 2017)

1.1 BENEFITS OF RESILIENCE ASSESSMENT

The community and asset owners can benefit from the knowledge developed through completing a resilience assessment of the three waters systems by having:

- Improved understanding of network, potential natural hazards, vulnerable areas and consequence from a spatial perspective.
- Reduced cost on resilience improvement 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, including:
  - Improved community resilience and ability to rebound following a disaster

  - Rapid estimate of the scale of the remedial work required, e.g., costs and resources
  - Reduced risk of social and economic consequences through prior awareness and planning.
- Improved community confidence from understanding the risks and acknowledging the mitigation and recovery plans.
- Informed high-level strategic planning following events. This can expedite recovery and improve robustness in recovery planning.

The outputs from resilience assessment that can be fed into:

  - Asset management (e.g., asset upgrade and/or renewal)
  - Disaster planning for both emergency and recovery phases
  - Financial planning
  - City planning (e.g., capital work projects future, land development).

2 TECHNICAL RESILIENCE ASSESSMENT GUIDELINE

2.1 GUIDELINE OBJECTIVES

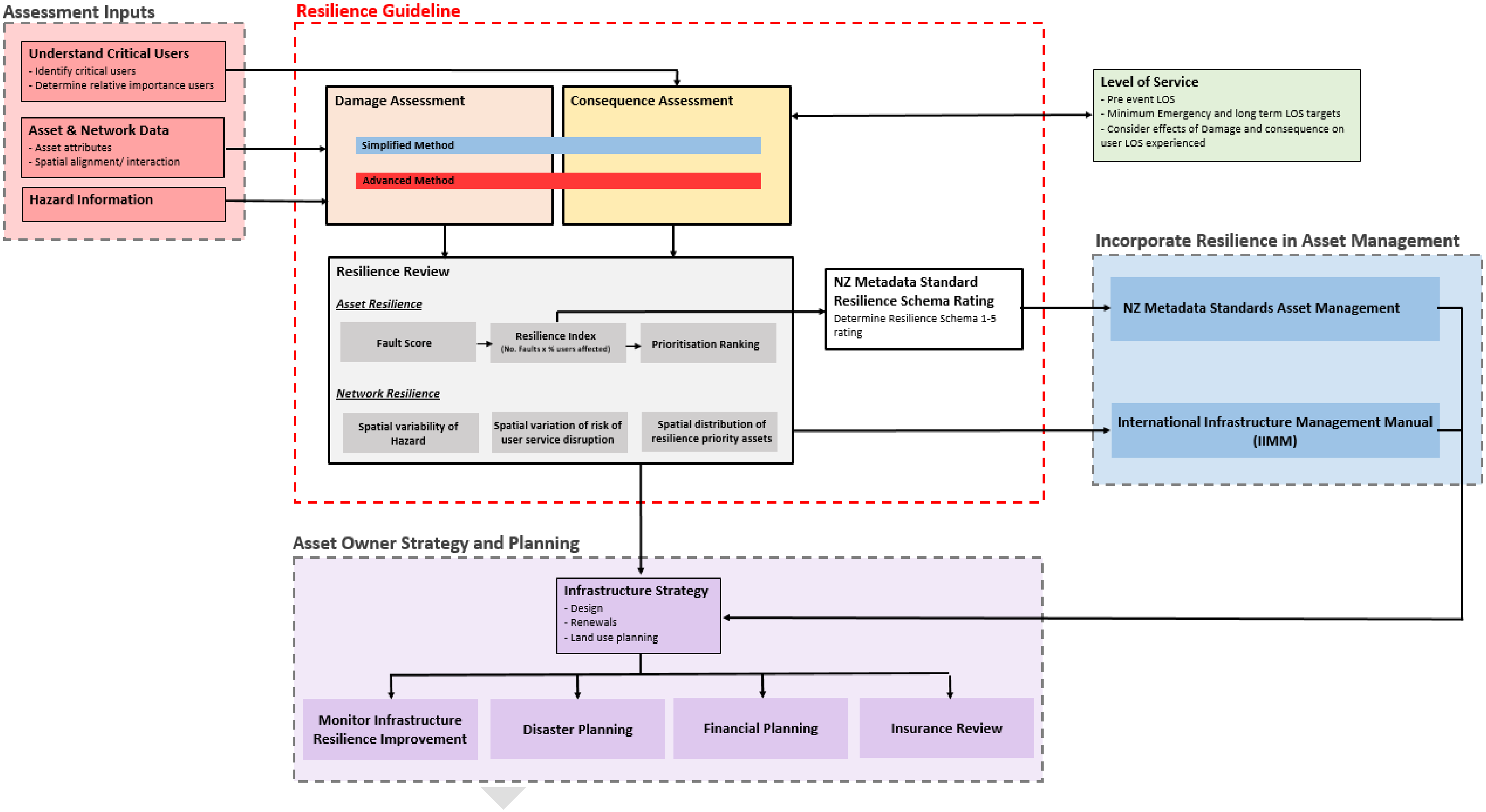
This guideline aims to promote wider understanding of network resilience and the costs and benefits of potential strategies for improving the resilience of pipe networks, to inform pipe network intervention strategies. The guideline aims to assist with developing evidence and a knowledge base for improving system resilience in preparation for natural hazards. The guideline provides tools and strategies enabling asset owners to make rational and strategic decisions for asset management and urban planning of 3 waters systems.

2.2 GUIDELINE SCOPE

It is acknowledged that resilience involves technical, organisational, social, and economic aspects. However, the guideline does not attempt to tackle resilience in its broadest sense, rather the guideline provides a framework for assessing to the technical aspects of the resilience of three waters piped networks in relation to the impact of an extreme natural hazard event. The guideline has been developed drawing on existing literature and guidance on asset management and resilience assessment frameworks, and by incorporating lessons learnt from the Canterbury Earthquake Sequence in 2010-2011. Concepts presented within this guideline for distributed assets can be incorporated into detailed assessment for discrete critical assets.

Figure 1 presents the schematic diagram of the resilience guideline and interacting activities

Figure 1: Schematic diagram presenting the Resilience Assessment Framework, including interacting activities.



3 ASSESSING SYSTEM RESILIENCE

3.1 ASSESSMENT INPUTS

3.1.1 HAZARD SCENARIOS

The region's potential natural hazards are assessed to identify predominant hazards that could significantly influence the performance of three waters systems and community. A risk register is a useful tool to keep records of relevant risk factors, including the likelihood and consequences of risk, potential mitigation approaches, and calculated risk levels. In this way, asset managers can investigate risks of interest, explore underlying strategies for mitigation, and increase awareness of potential problems that may occur. This enables territorial authorities to better prepare for and manage potential hazards by selecting hazard scenarios for resilience assessment. Selecting a hazard assessment approach to use is contingent on the purpose of the study, availability of necessary inputs, and the constraints on budget and time.

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).
- 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 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.

This technical resilience assessment guideline has been developed for extreme natural hazard events, defined specifically to comprise: earthquake, landslide, flooding, erosion, tsunami, volcanic eruption. The principles of the guideline can be applied to natural hazards that are not extreme events, but develop over time such as sea level rise.

3.1.2 NETWORK DATA WITH ATTRIBUTES

The attributes and spatial arrangement data of the three waters systems is of critical importance for resilience assessment and three waters asset management decision making. It is essential also to capture the information on asset spatial distribution relative to urban populations, because this affects the criticality of individual assets.

The critical network data inputs for resilience assessment are listed as follows:

- Database of asset information comprising spatial location and asset attributes. Recommended minimum data is listed below:
  - Asset spatial location, along with links to adjacent assets where these exist and knowledge of flow pathways.
  - Material type
  - Pipe diameter
  - Date of installation

    - Asset condition
- Location and construction details for critical components of the network, mainly focused on key structures
- Understanding of historic typical 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, treatment facilities)

3.1.3 GROUND CONDITION

The majority of three waters facilities and assets are either founded or buried within 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) and its potential interaction with three waters assets is important in terms of establishing and ranking the influence 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) provides a mechanism for storing and sharing geotechnical information nationally.
- Topographical information such as LiDAR surveys.
- Historic land use register to provide knowledge of the change of physical characteristics of land, such as historic filling (where available).

3.2 RESILIENCE ASSESSMENT PROCEDURE

Resilience assessment procedures are summarised below:

1. **Hazard scenario identification** – collate a risk register and identifying a range of natural hazards that could potentially cause damage to three waters networks and subsequently adverse consequences on community. Based on these, develop hazard scenarios for selected critical hazards affecting the network.

2. **Input Data Collation** – Source and verify quality of data inputs for the hazard assessment identified in step 1. Detailed spatial network data with asset attributes is required for assessment along with hazard scenarios and knowledge of locations of critical customers across the network.

3. **Criticality Assessment** - The criticality assessment focuses on the importance of the three waters facilities from a community perspective. It is used to identify the critical assets in three waters systems, taking into account critical customers determined by territorial authorities (e.g., hospitals and schools).

4. **Damage Assessment** – Estimate the anticipated level of damage following an extreme event to inform assessment of asset vulnerability. It is not possible to predict the specific location, fault type and consequence for distributed infrastructure. Therefore, all damage estimates are averaged and distributed, providing a risk based assessment.

5. **Consequence Assessment** – Review the asset interaction/ dependence across the network to identify asset criticality. Use this with knowledge of customers to assess likely

effects of compromised assets on risk of a reduced level or loss of service across the network. The consequence assessment focuses on the interaction and spatial arrangement of specific assets across the distributed network, and risk of individual asset loss on the level of service across the network.

6. **Resilience Review** – Combine the outputs of the damage and consequence assessment to quantify the resilience of the network, to identify spatial vulnerability and risk of loss of service on an asset basis. Feed this into a prioritisation ranking for assets across the network.

7. **Sensitivity analysis** – Re-evaluate the outcomes gained from the resilience assessment, in consideration with engineering judgement. This should be conducted and verified by experienced professionals.

3.3 SELECTING ASSESSMENT METHOD

The detail and sophistication of resilience assessment can vary substantially from judgement based assessments using high level knowledge of the network composition and spatial variance in hazard, through to detailed hazard modelling and system analysis. The level of sophistication depends on:

- Quality and completeness of input data
- Natural hazard profile
- Complexity, size and spatial arrangement of three waters systems
- Vulnerability of three waters assets to damage and anticipated duration of repair
- Ability for the community to adjust and respond to loss of services - varies with the size of community and population density
- Resources available for resilience assessment and renewals

A two-level approach of resilience assessment sophistication has been developed to accommodate different community characteristics across New Zealand, namely: simplified and advanced methods.

The simplified method is the minimum level of assessment recommended for all communities. Table 1 provides recommended sophistication for resilience assessment for the Damage and Consequence elements of the resilience assessment process. The simplified and advanced methods can be applied separately as a “mix and match” to the Damage Assessment and Consequence Assessment processes independently. For example, in a situation where hazard information is poorly defined while an excellent dataset of the network assets is available and the community has a resilient culture, the asset manager may determine that a simplified approach for damage assessment and advanced assessment for consequence assessment may provide the highest value. Advanced assessment of criticality within the consequence assessment is recommended where quality asset data is available.

Table 1 – Recommended minimum level of resilience assessment sophistication for network size

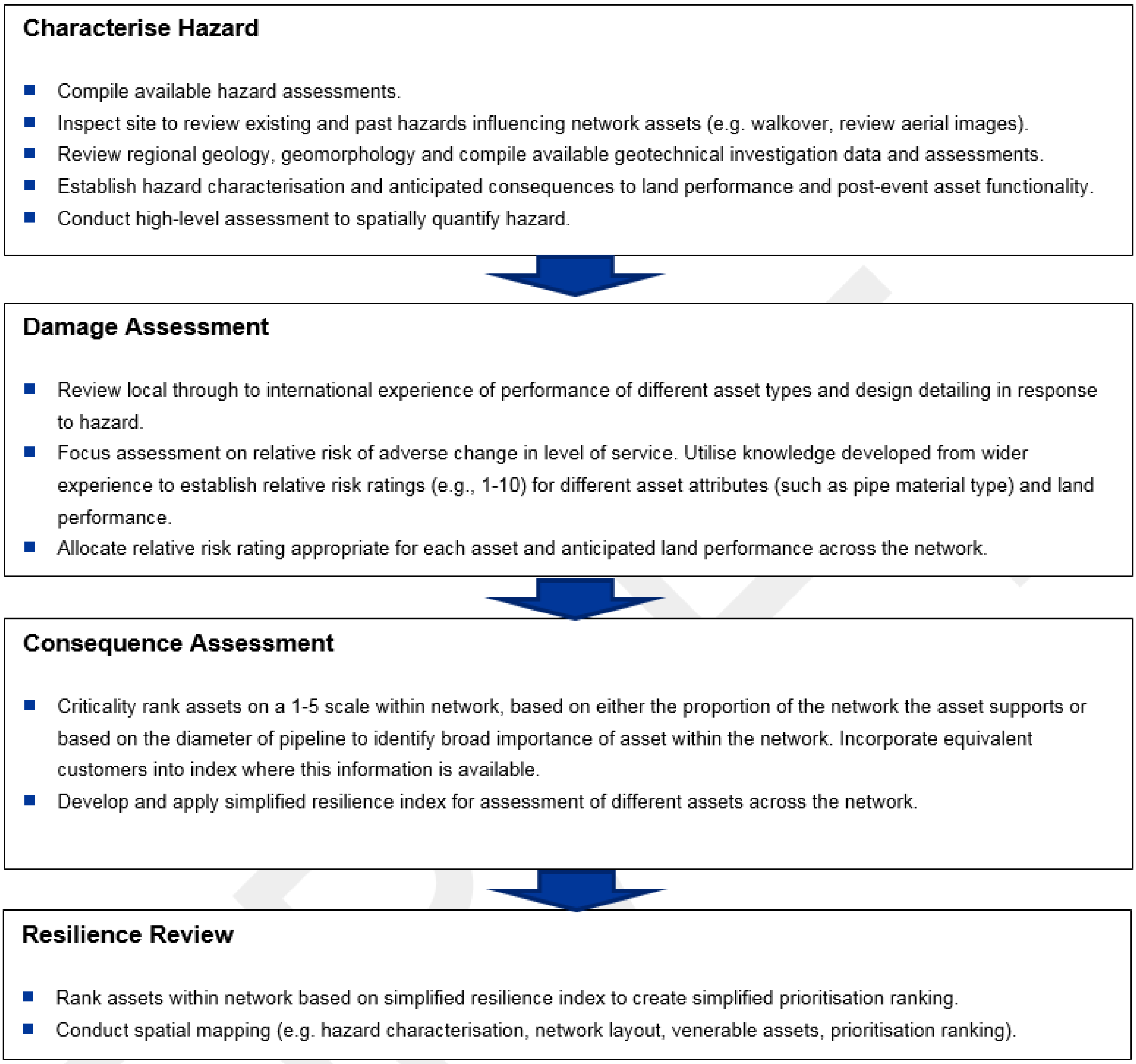
	Recommended minimum resilience assessment method sophistication					
	<10,000 Equivalent Standard Customer		10,000–300,000 Equivalent Standard Customer		>300,000 Equivalent Standard Customer	
	Damage Assessment	**Consequence Assessment**	**Damage Assessment**	**Consequence Assessment**	**Damage Assessment**	**Consequence Assessment**
Earthquake	Simplified	Simplified	Simplified	Advanced	Advanced	Advanced
Landslide	Simplified	Simplified	Simplified	Advanced	Advanced	Advanced
Flooding	Simplified	Simplified	Simplified	Advanced	Simplified	Advanced
Erosion	Simplified	Simplified	Simplified	Advanced	Simplified	Advanced
Tsunami	Simplified	Simplified	Simplified	Simplified	Simplified	Advanced
Volcanic eruption	Simplified	Simplified	Simplified	Simplified	Simplified	Advanced
Sea level rise	Simplified	Simplified	Simplified	Advanced	Simplified	Advanced

3.3.1 SIMPLIFIED RESILIENCE ASSESSMENT

The simplified resilience assessment approach is based on engineering judgement paired with a good understanding of hazard scenarios and anticipated consequences, network characteristics and vulnerabilities developed from local experience, and supported by knowledge of performance of assets during extreme events both nationally and internationally.

To provide a balanced assessment and promote development of a constructive positive challenging of assessment outcomes, the team should include: technical specialists, asset managers, and network operators and asset owners. Figure 2 provides a schematic process for the Simplified resilience assessment.

Figure 2 - Schematic process for the simplified resilience assessment



Characterise Hazard

- Compile available hazard assessments.
- Inspect site to review existing and past hazards influencing network assets (e.g. walkover, review aerial images).
- Review regional geology, geomorphology and compile available geotechnical investigation data and assessments.
- Establish hazard characterisation and anticipated consequences to land performance and post-event asset functionality.
- Conduct high-level assessment to spatially quantify hazard.

Damage Assessment

- Review local through to international experience of performance of different asset types and design detailing in response to hazard.
- Focus assessment on relative risk of adverse change in level of service. Utilise knowledge developed from wider experience to establish relative risk ratings (e.g., 1-10) for different asset attributes (such as pipe material type) and land performance.
- Allocate relative risk rating appropriate for each asset and anticipated land performance across the network.

Consequence Assessment

- Criticality rank assets on a 1-5 scale within network, based on either the proportion of the network the asset supports or based on the diameter of pipeline to identify broad importance of asset within the network. Incorporate equivalent customers into index where this information is available.
- Develop and apply simplified resilience index for assessment of different assets across the network.

Resilience Review

- Rank assets within network based on simplified resilience index to create simplified prioritisation ranking.
- Conduct spatial mapping (e.g. hazard characterisation, network layout, venerable assets, prioritisation ranking).

The Simplified method relies upon generalised and high-level hazard responses, rather than 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, Ministry of Business Innovation and Employment, local and regional councils, NZS1170, RiskScape). Damage assessment for the Simplified method focuses on broad expectations of relative asset performance based on empirical assessment of performance on a large-scale basis.

For simplified damage assessment, to utilise knowledge developed from wider experience to establish relative ratings (e.g., 1-10) for different asset attributes (such as pipe material type) and land performance.

For simplified consequence assessments, 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. Criticality can be simplified through allocating a pipe importance rating of 1 (Low) to 5 (High).

All in all, a resilience index can be computed for each asset to establish a simplified prioritisation ranking for resilience.

Simplified resilience index = [Simplified Relative Damage Ranking] x [Simplified Pipe Criticality Rating]

This approach generally provides a good simplified high level understanding of the key issues influencing network resilience and high level opportunities for improvement. However simplified assessments can struggle to provide adequate definition across network elements, or consider the complexities of distributed networks and interactions. The method of resilience assessment that asset owners have historically undertaken across New Zealand typically fits into the definition of the simplified assessment process.

3.3.2 ADVANCED RESILIENCE ASSESSMENT

The advanced resilience assessment method utilises analytical modelling to estimate severity of the damage and potential network consequence. Resilience modelling cannot replicate exact outcomes due to the challenges associated with numerous of nonlinear interacting processes. Estimates of performance are average in nature and cannot predict specific location or severity of individual defects. Output can provide a useful representation of likely network outcomes, and can be powerful in assessing likely risk of adverse consequences and vulnerability spatially across a network, superior to the simplified method. Sensitivity of the outputs can be assessed and a range of scenarios and future networks can be modelled with relative ease to identify key elements/assets, or sections of the network that would provide most benefit to overall network resilience if improved. Advanced assessment must be undertaken on a platform that facilitates spatial analysis and presentation of output, for example a geographic information system (GIS).

Conducting scenario analysis to simulate potential hazards and a range of situations is preferable for local authorities when assessing three waters resilience. In a risk-free environment, all dominant hazards and the resulting consequences on three waters facilities and service are modelled and analysed. The outcomes from the scenario analysis can be fed into the knowledge base for the decision making on three waters asset planning and upgrade.

One of the benefits of advanced assessment is that research (academic and practitioner) can be incorporated into the assessment through published empirical relationships developed based on analysis of extreme event experiences. Underlying processes and assumptions between different assessments can be maintained consistently, allowing for a detailed review of sensitivity. This means that outcomes are less likely to be biased by pre-conceived opinions, as could occur for a simplified approach.

Published functions for pipelines have varying levels of input data and analysis complexity for practitioner application. Below is a list of useful references for estimating high-level asset damage during earthquake scenarios. This list is not exhaustive and a literature review should be regularly undertaken to ensure that the resilience assessment utilises current state of knowledge.

- American Lifelines Alliance (2010),
- Opus (2017A),
- Pineda-Porras & Najafi (2010),
- O'Rourke, M., and Ayala, G. (1993),
- O'Rourke, M., and Liu, X. (1999) and
- O'Rourke et al., (2014).

Susceptibility of pipelines to damage from wave propagation or permanent ground deformation is dependent on their material properties (strength properties, failure type, ductile/brittle, condition), joint details, separation distance between joints, and ability of joints to accommodate rotation or extension, and pipe diameter. O'Rourke and Liu (1999) state that international experience indicates that damage to pipes associated with ground deformation is typically 20 times greater than that caused by wave propagation. A similar ratio of 10-20 was observed in Christchurch during the Canterbury earthquake sequence.

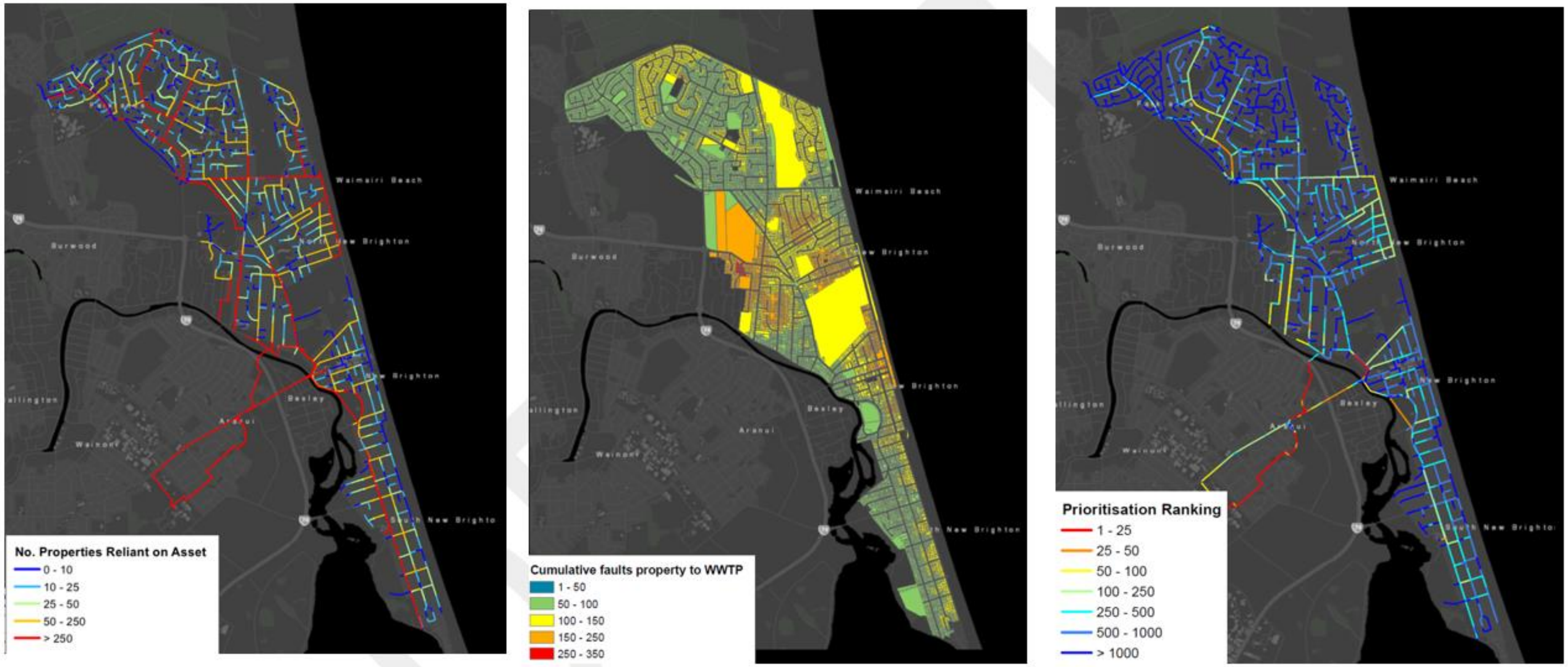
Advanced consequence assessment aims to compare the relative risk of the reduction of level of service in spatial environment by developing a range of measurement indices. Consequence assessment should consider both pipelines and node assets, such as pump stations and manholes. Asset criticality, relative risk of loss of service, and asset prioritisation are the measurement indices recommended in the guideline. The guideline contains other indices that may be applied. Figure 3 provides an example of asset criticality, relative risk of loss of service, and asset prioritisation.

- <u>Asset criticality</u> – Number of equivalent 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.

- <u>Loss of service risk</u> – Development of a pipe fault index through network, tracing and summing faults along the trace that are anticipated to influence service between the customer and treatment plant/supply node. The index acts as a proxy to indicate the relative risk of an individual property losing service relative to another property. 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.
- <u>Asset prioritisation</u> – The ranking of each asset relative to one another is determined from a risk index comprising the predicted number of faults for each pipe asset for the earthquake scenario, multiplied by the proportion of properties in the study area and catchments upstream that this asset services. Assets with a high-risk index have higher influence on overall network performance than assets with a lower risk index. Renewal of assets with a high-risk index would provide greater benefit to improvement in network resilience with time if higher priority ranking assets were renewed first.

Advanced Resilience Index = [asset faults] x [proportion of network relying on asset for function]

Figure 3. Example of output from assessment of asset criticality, relative risk of loss of service and asset prioritisation ranking (Gibson, Liu and Johnson, 2018)



4 IMPROVING SYSTEM RESILIENCE

4.1 LESSONS LEARNED FROM THE CANTERBURY EARTHQUAKE SEQUENCE (CES)

Structural damage to infrastructure leads to a reduction or loss of functionality, and hence limit the ability to provide a desired level of service. The failures of the overall network include physical failure of a critical asset or assets, functional failure of network elements, and widespread degradation of the whole network. The social consequences can be severe and continue over an extended period, as occurred following the Canterbury earthquakes. Hence, it is important to consider the resilience of critical infrastructure in life-cycle process, including planning, design, construction, operations, maintenance, and monitoring.

In order to improve three waters system resilience, the learning and knowledge gained from the resilience assessment can be fed into the following operations for three waters systems:

- Strategic planning.
- Engineering design – both renewals and new capital projects.
- Construction.
- Operations and maintenance.

The following sections provide a high-level discussion on strategies and philosophies that can be adopted to improve resilience of three waters networks, supported by real-life examples encountered during the Canterbury earthquakes in 2010-2011. It is worth noting that these sections have a primary focus on earthquake-related lessons learnt in Christchurch. However, it is acknowledged that these lessons can be applied in principle to other natural hazards.

4.2 STRATEGIC PLANNING

Three waters systems are distributed and linked. For this reason, focused projects to improve resilience of a small section of the network can often have limited ability to avoid hazard due to existing constraints in place. A long-term strategic plan may require a change of thinking with the sole focus of a more cost-efficient approach that considers all factors involved.

Resilience assessment for three waters systems provides the ability to model the benefit of different strategies, considering the wider network interfaces, rather than the traditional methods of design assessment that can only assess benefit in isolation from the wider network. In addition, the knowledge of spatial arrangement of hazard and network vulnerability spatially for lifeline assets can assist with land use planning.

Frequently, key assets within a network such as trunk mains, pump stations, and treatment facilities can be located away from areas of the greatest hazard. Avoiding a zone with high natural hazard risk provides a significant improvement in resilience by reducing the likelihood and severity of damage sustained. When hazard isolation is technically feasible and can be economically implemented, it is a preferable mitigation strategy. In the cases where three waters customers are located within a hazardous zone, alternative strategies can be explored. For example, after the 2010-2011 earthquakes, for the liquefaction and lateral spreading prone zones, the existing gravity wastewater systems have been changed to pressurised sewer or vacuum sewer systems.

The output of the resilience assessment, with a focus on spatial representation of hazards and vulnerability, provides much of the information required to develop a high-level strategy for three waters systems. It considers the objectives of the asset owner and may include, for example, change in spatial demand across the network, hazards, condition of existing assets, and opportunities for resilience improvement.

Another example can be found where strategic planning is applied to the arrangement of distributed assets. Such strategies include distributed treatment facilities, pipelines that can link different catchments allowing overflow to an alternative conveyance pathway, and pipe loop arrangements. They provide the ability for the network to adapt to change in the event of failure of some key assets. While these approaches do not reduce the risk or severity of damage, there is benefit in reducing the consequence of the damage. A pre-planned response and the ability of unaffected sections of the network to assist with providing a level of service, albeit significantly lower than described, can be satisfactory to reduce potential effects on the community and allow a managed recovery.

Planning for improved resilience needs to have a very long-term focus. It may take 30 years or more to create a suitably resilient network. Therefore, if a strategic resilience improvement plan is in place that has been informed by a robust resilience assessment the opportunity to make improvements both opportunistically and as part of a renewals/replacement programme may make significant difference at little or no extra cost. In fact, experiences overseas have shown that good resilience planning can actually reduce the capital cost of some renewals programmes whilst decreasing the overall operational expenditure.

4.3 ASSET RENEWALS

When making decisions on three waters assets renewals, it is not enough to solely consider specific three waters facilities or individual assets, but to treat the wider network, including community needs as a whole. Among other factors, ground conditions, hazard risk analysis, interdependency between three waters and other systems should be considered (Gibson & Newby, 2015). Local authorities need to think of the wider context when providing system maintenance and asset renewals.

In order to maximise the value of asset renewals, it is important to understand the advantages and disadvantages of pipe materials, including modern materials such as PVC and PE. Although the evidence collected from the Canterbury earthquake sequence shows that these ductile materials performed well during the earthquakes, they can suffer failure mechanisms which are uncommon for other pipes, for example, chemical break down. For the modern pipe materials, where to install them and how much to install is also critical, considering the cost and potential failure mechanisms. With capital works and asset renewal budgets that are generally limited, understanding pipe failure mechanisms and wisely choosing materials at the location where they are most needed and considering facilities nearby that are critical. For example, where there are waterways that could lead to lateral spread or flooding, modern ductile pipe materials should be preferentially considered and installed for critical facilities, e.g., hospitals, emergency services and schools.

4.4 DESIGN

Knowledge from resilience assessment for the wider network can feed into design of all three waters assets. This can provide a focused and consistent perspective of hazard, performance and vulnerability across a range of designers from different organisations. The resilience assessment outputs, along with resilience objectives for both the network and the specific elements of the project being designed, could form a part of the design brief.

It is important that all designers involved, from design strategy through to construction monitoring, understand the minimum level of resilience required and are up to date with current design methodologies and detailing that can be incorporated into three waters designs in order to achieve the desired resilience objectives.

4.4.1 DESIGN PROCESS FOR RESILIENCE

Assessment and consideration of resilience should be undertaken during all stages of design from the feasibility or concept stage. The higher level of resilience can be achieved for a low cost, or no extra cost, during the early planning and design phases of a project where the overall strategy is being developed. The ability to improve resilience for an asset or sector of a network decreases rapidly as the design process progresses. This relates to the 80/20 rule where most of the gains are achieved for minimum effort. Following this, costs to implement feasible improvements in resilience increase exponentially.

4.4.2 DETERMINING AN APPROPRIATE LEVEL OF RESILIENCE

In the light of risk mitigation, the key to good design is to provide an appropriate level of resilience in the right locations. Determining an appropriate level of resilience for an asset is generally achieved through applying engineering judgment, supported by numerical analysis and review of past cases. The appropriate level of resilience and performance expected from an asset, or a section of the network, must be discussed in consultation with the asset owner.

Optimising resilience is a complex engineering problem. Resilience assessment considers geotechnical hazards, anticipated consequences, and probability of natural hazard events of interest. Critical hazard scenarios are reviewed and determined, which the form the basis for resilience assessment for the design. The level of resilience adopted must be compatible with associated infrastructure and objectives of the asset owner.

4.4.3 UNDERSTANDING FAILURE MODES

It is critical to understand failure modes for three waters assets. Damage cannot be reduced through considered design detailing if the underlying mechanisms to be mitigated are not well understood.

The following examples are observations during the Canterbury earthquake in 2010-2011:

- Gravity pipelines with shallow grade are vulnerable to differential settlement and associated dips. This can affect network functionality even where structural damage does not occur.
- Pressurised pipe systems are less fragile to dips than gravity pipes. However, the functionality will be significantly reduced or totally loss as a result of structural failures (e.g., crack).
- Shallow pipes may be preferred due to the ease of construction and repair, and associated low cost. However, shallow pipes might be more vulnerable to ground deformation.
- Special attention needs to be paid on assets like pump stations. The criticality of such assets can be determined by considering the number of customers reliant upon operation of the asset, and the criticality of the customers in the community.
- Pipe and utility connections to below or above ground structures are vulnerable to damage associated with differential vertical settlement, structure rotation, or lateral stretch of the ground. Improving flexibility and ductility of connection details and pipe materials can substantially reduce damage and improve post-disaster functionality. If ductile failure reduces the residual life of the connection or level of

service is reduced, remediation can be programmed, facilitating a controlled post-disaster recovery.

Resilience assessment of critical infrastructure should consider all network components that influence the level of service experienced by customers. This may require consideration of components of the wider network that may be owned and/or operated by another party, e.g. private wastewater pipes/ laterals.

4.4.4 RESILIENCE PRIORITISATION METHOD

Design for resilience should aim to control failure mechanisms and limit the extent and/or severity of damage as best practicable to satisfy minimum functional requirements and enable timely and cost-efficient repair. A resilience prioritisation method can be implemented for in the design process the selection and additional resilience measures incorporated into infrastructure. The resilience prioritisation method can be summarised into the following key design components (Gibson, et al, 2013):

- Determine appropriate level of resilience required for the overall asset, and for sub components.
- Identify geotechnical hazards, infrastructure vulnerability and key failure mechanisms, considering influence on overall seismic performance and impact on post-disaster functionality.
- Develop engineering solutions to mitigate or limit extent and severity of damage, commencing with reducing the highest priority risks and vulnerabilities.
- Consider improvement in performance provided by each design solution and overall value provided. Initial design focus on low-cost/high-value solutions.
- Check that the completed design satisfies project objectives and resilience requirements.

4.5 CONSTRUCTION QUALITY

In order to ensure three waters assets perform as expected, construction quality is important. Construction quality refers to both quality of asset material and the standard of workmanship for installation. Poor construction quality can compromise asset performance to a large extent. Based on the observations gathered after the Canterbury earthquakes, construction quality is one of the triggers for poor performance of the damaged three waters assets.

More specifically, common errors are listed, but not limited to:

- Not installing to manufacturers and/or designers installation guidance.
- Not achieving construction tolerances.
- Over/under insertion of joints.
- Not providing adequate residual joint rotation.
- “Locking in” elements designed to be flexible. For example, at connections of pipes and service cables to structures.
- Usage of substandard or incorrect materials.
- Changes in design in the field to accommodate the conditions or site constraints without consulting designer to assess repercussions to performance.

Effective approaches can be adopted to improve the construction quality of three waters assets at both individual and organisation levels:

- Competence training: Ensure that infrastructure is installed such that design intentions are reached.
- Field briefing: Provide a basic understanding of key concepts, identified frequent problems and potential issues for business as usual and extreme events.
- Competent personnel: Selected supplier, construction monitor, and contractors.
- Construction monitoring: Involvement of design representatives and appropriate allowance and design for temporary works.

5 CONCLUSIONS

This paper presents a guideline for assessing technical resilience of three waters assets. The guideline aims to assist with developing evidence and a knowledge base for improving system resilience in preparation for natural hazards.

Two tiers of assessment methods namely: a simplified (qualitative and semi-quantitative) and an advanced approach (quantitative modelling) are presented. This can provide asset managers with ability to tailor assessment methods according to a level of details required and resources available. Rather than looking into individual facility, the guideline focuses on the interaction of network elements and the consequences of the interaction on the wider network in a geospatial environment. The implementation of the resilience assessment guideline should be undertaken by a team of professionals, with good knowledge of hazards of interest and local networks. The team should include: technical specialists, asset managers, network operators and asset owners.

This guideline provides an efficient and repeatable method for assessing resilience spatially. It can be used to track resilience improvement with time and test different renewal and planning strategies. More complete and accurate data, as well as a sensitivity check, can improve the value of resilience assessment. The guideline can be used as both a pre-event proactive tool and a post-event reactive tool. The guideline can assist asset owners to make rational and strategic decisions for asset management, urban planning, insurance, and disaster planning of three waters systems.

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