Infrastructure Resilience

What does it mean for my agency / organisation?

Version 2.2

15 March 2013

THIS DOCUMENT IS NOT NEW ZEALAND GOVERNMENT POLICY

In memory of Bruce Henderson who contributed greatly to the development of this work.

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1 Executive Summary

THIS DOCUMENT IS NOT NEW ZEALAND GOVERNMENT POLICY. The objective of this updated version on Infrastructure Resilience is to further inform the Infrastructure Recovery Technical Standards and Guidelines (IRTSG) which provide guidance and direction to the Stronger Christchurch Infrastructure Reconstruction Team (SCIRT). This document is focused on the technical aspects of infrastructure resilience, in support of community resilience. While the focus is not on community resilience, infrastructure does include consideration of the natural environment.

Simply put, ***infrastructure resilience is the ability of a system to withstand or quickly recover from significant disruption***. Resilience does not guarantee uninterrupted service, but should promise quick restoration of service, recognising that there is a high cost for any large interruption. To achieve this, the infrastructure must be robust, yet flexible.

Quick restoration of service is highly desired following any disruption, recognising that “quick” can mean different things to different people. This document provides a target schedule for the restoration of various services from a design level event (in Christchurch this is nominally a seismic event which creates ground acceleration of 0.4g). Clearly the extent of damage has a significant influence over the ability to achieve targets. It must be noted that this design level event may be the significant service restoration event for some asset owners whilst other events will be more pressing for other asset groups (e.g wind and snow may be more important design events for power distribution networks).

To construct resilience, this paper outlines indicative metrics for each infrastructure type. While some infrastructure is well represented in this draft, others require addition input and coordination. This document provides an outline definition of the following:

- Existing Materials / Infrastructure
- Modern Materials / Infrastructure
- Resilience Measures
- Improvements (Beyond those covered above)

However, it is understood that the large challenges ahead of the reconstruction, could easily apply to other locations, or have occurred from any other major disruption - whether natural or man-made, urban or rural, sudden or over time, expected or not. Communication and expectation management is a key element of implementation, with more frequent engagement than business as usual.

The application of resilience must start with an assessment of the hazards which exist within the region. While many hazards exist within greater Christchurch and the wider Canterbury region, seismic hazards are presently considered the greatest risk. The risks should be periodically reviewed.

While the concept of resilience can be viewed in the context of an individual pipe or other material, it is more appropriate to consider that an infrastructure network is a complex system, and that resilience should more appropriately apply to the whole system. However, it is important to understand that various components of a system may have different criticality. Thereafter, the interdependencies between systems require further investigation (e.g. the dependence of wastewater systems on electrical power and telecommunications), preferably in conjunction with Lifeline

Utilities work, and in consideration of external factors such as economic and social development

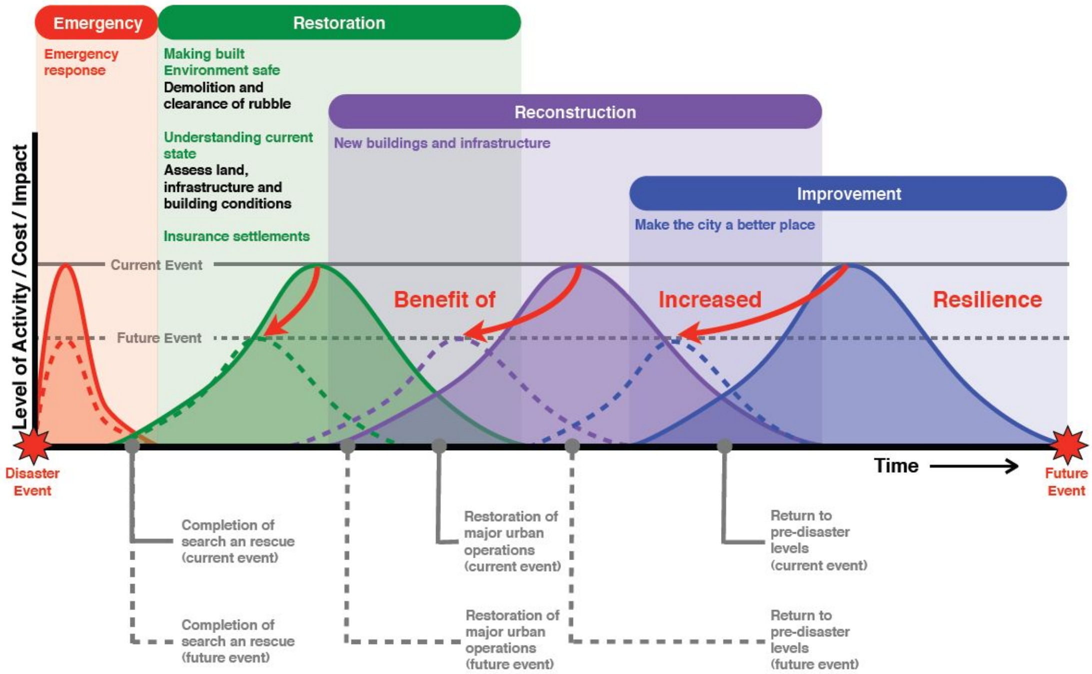
Reconstruction is front of mind for many residents in Canterbury at present, although preparation for the future is close behind. The importance of preparation cannot be understated in any dialogue on resilience, and extends to the human/social dimensions – arguably the most important component. Intentional development of measures to mitigate risk prior to a “significant disruption,” is strongly encouraged.

The next steps identified in Section 10 provide an indicative draft of the work ahead, and further versions of this document will be released as more information is made available from the rebuild of infrastructure and associated research.

2 Introduction & Background

2.1 Introduction

Disasters are inevitable. However, proactive preparation greatly increases the chances that affected communities can not only survive a natural or man-made disaster, but can quickly rebound and rebuild – often for the better. While preparation comes before a disaster event, the emergency response, restoration, reconstruction and improvement cycles follow, and are conceptually shown below, recognising that all aspects of recovery cannot be captured in a simple linear diagram.. Early implementation and overlap of these representative cycles would be very advantageous. To accelerate the recovery process, it requires enabled governance, adequate funding, and organisational or community collaboration.



2.1.1 Emergency Response

Civil defence mechanisms are usually enacted immediately upon an alarm of potential or actual catastrophic events. However, this document does not address the vital processes and roles played by various public and private agencies who serve valiantly during times of significant community distress.

2.1.2 Restoration

The restoration process involves making the built environment safe, and supports the basic needs of a community. Although this process is a critical step in the recovery process by protecting the community from secondary disasters in the aftermath (e.g. epidemic illness), it is not the focus of this document. This phase is also an ideal time to conduct planning efforts in advance of the reconstruction works.

2.1.3 Reconstruction

The future resilience of infrastructure, indeed the built environment, is largely determined by the pro-active decisions which are made before a disaster event, or certainly during the recovery and reconstruction process. This phase of recovery is usually accomplished by a host of technical personnel covering a wide range of disciplines, and supported by many others within the agencies and organisations engaged on this complex task. An additional complexity is multiple funding sources, and the numerous stakeholders involved in decision making. This document primarily addresses the opportunity to include resilience into this reconstruction phase of the recovery, and preferably into future asset replacement programmes. Ideally, all infrastructure would be required to incorporate appropriate levels of resilience (from a community, service and infrastructure perspective), commensurate with criticality to the service network, and in consideration of NPV comparisons for whole-of-life costs based on vulnerability and risk.

2.1.4 Improvement

The context of improvement shown above is in making a community a better place to live. Improvements have a more specific meaning in the context of infrastructure resilience, as more fully described in the Section on Resilience Metrics.

2.2 Background

The United Nations (UN) has engaged in emergency response and restoration efforts in many countries since its establishment, with various levels of success. They have formally defined Resilience as:

"The capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organising itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures." [1]

Resilience is like World Peace - everybody wants it, but most people don't know how to achieve it.

The UN have further said ***"reducing disaster risk and re-enforcing resilience is increasingly seen as part of a new development paradigm where well-being and equity are core values and human and natural assets central to planning and decision making."*** [2]

While there are many definitions for Resilience, the United States Agency for International Development (USAID) simply put it: ***"Resilience means having the tools to withstand adversity, whether caused by man or by force of nature."*** [3]

Within the Resilient Organisations research programme, ***"Resilience is the ability to survive a crisis and to thrive in a world of uncertainty."*** One academic has described resilience as ***"The intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions."***[4] This view is consistent with the Ministry of Civil Defence and Emergency Management National Plan.

The Recovery Strategy for Greater Christchurch, Section 4, includes the statutory goal, pursuant to s.15 of the Canterbury Earthquake Recovery Act 2001, to:

[1] UN International Strategy for Disaster Reduction. Geneva 2004.
[2] UN Hyogo Framework for Action 2005-2015 (HFA) – Building the Resilience of Nations and Communities to Disasters.
[3] http://www.usaid.gov/resilience/
[4] Dr. Ir. Ron McDowall.

5. Develop resilient, cost effective, accessible and integrated infrastructure, buildings, housing and transport networks – by:
    5.3 Rebuilding infrastructure and buildings in a resilient, cost-effective and energy efficient manner

One of the 2011 National Infrastructure Plan guiding principles is:

> Resilience: National Infrastructure networks are able to deal with significant disruption and changing circumstances.

For the purpose of this paper, ***Infrastructure resilience is the ability of a system to withstand or quickly recover from significant disruption***. While the exact semantics of a definition can be debated, the important concepts are as follow:

- Service interruptions are expected
- Quick restoration of service is required
- Infrastructure networks must be robust
- Infrastructure networks must be flexible

Resilient infrastructure requires deliberate choice early in the development of the construction / reconstruction process. The opportunities for Resilience can be lost if these factors are not considered prior to implementation. While quick restoration of service is demanded, any options that minimise the impact on the environment should be considered.

Commonly decisions are made based on funding and finance factors, whereas the definitions described above require a different approach than traditional Return on Investment views.

Infrastructure Resilience is the ability of a system to withstand or quickly recover from significant disruption

3 Hazards in Greater Christchurch

The greater Christchurch and surrounding rural area has experienced and remains vulnerable to a wide range of natural hazards, similar to many other parts of New Zealand and the world. A natural hazard is defined as a natural process with the potential to cause harm or loss to humans or the built environment, and is usually described in terms of the potential area affected and the likelihood of occurrence. While the focus of this chapter is on the hazards that exist, separate work into the consequences is an equally important consideration. “Risk” is a combination of hazard probability and consequence for a forecasted future event however, the scope of this report does not address consequences or risk. This section summarises known potential hazards that Greater Christchurch needs to consider when making resilience decisions for the rebuild of infrastructure. It should not be considered an exhaustive summary. Also some of the hazards listed are not necessarily independent of others and can occur at the same time. This needs to be taken into account when assessing the risk and the likely extent of the impact. Comprehensive risk evaluation is essential for effective asset management, whether large scale reconstruction or simple ongoing asset renewal.

3.1.1 Earthquake hazards

Earthquake hazards include surface fault rupture, ground shaking, liquefaction, lateral spread, rockfall, cliff collapse, landslides, differential settlement, and tsunamis. While the moment magnitude is commonly used as a measure of earthquake size and energy, it is the ground shaking at the site of interest which has the greatest effect on damage – generally damage decreases with distance from the earthquake source, but this can vary considerably depending on soil and rock strength, directivity of earthquake waves, and whether ground deformation occurs.

Surface fault rupture of the Greendale Fault occurred in the September 2010 Darfield (Canterbury) earthquake offsetting fences, roads and railway and damaging several houses. The Ministry for the Environment has produced guidelines for development on or near active fault traces, and these are now being applied to the Greendale Fault. While there are known active faults buried under the Canterbury Plains, there are no mapped active fault traces at the ground surface in the greater Christchurch urban area.

The ground shaking hazard due to long-lived aftershock activity in the greater Christchurch area has increased as a result of the Canterbury earthquake sequence of 2010-2011, but will decrease to near pre-earthquake levels again over the next few decades. The likelihood of other faults in the wider Canterbury region generating major earthquakes has not changed and these faults still represent some hazard to Christchurch. The latest earthquake forecast calculations for the Canterbury region from GNS Science are summarized in the Table below. Ground shaking at a particular location is also highly dependent on local soil conditions and topographic effects. The ground shaking hazard for structures is addressed through the Building Code, which is focused on life saftey, however this does not take into account local site effects.

Moment Magnitude	5 Year Probability (%)	20 Year Probability (%)	50 Year Probability (%)
5.0 – 5.4	99	100	100
5.5 – 5.9	75	97	100
6.0 – 6.4	34	64	83
6.5 – 6.9	11	27	51
7.0+	4	13	21

Note: Probability as of February 2013

Much of Christchurch, coastal Waimakariri district and low lying areas of Selwyn district are susceptible to liquefaction. While liquefaction is generally not a risk to life, it has caused enormous economic loss and social disruption in the Canterbury earthquakes. The Department of Building and Housing (now Building and Housing Group of MBIE) has defined *technical categories* for urban areas affected by the earthquakes, and has issued guidance for rebuilding in these areas to reduce potential damage from future liquefaction. The University of Canterbury, through the Natrual Hazards Research Platform has been providing advice to the Stronger Christchurch Infrastructure Rebuild Team and Christchurch City Council for infrastructure rebuilding. Environment Canterbury and the Natural Hazards Research Platform have completed a review of the liquefaction susceptibility in the greater Christchurch area (from Southbridge to Amberley Beach) to help inform future development. Based on the seismic sequence following September 2010, the design event for infrastructure is considered any event which achieves ground acceleration of 0.4g. For infrastructure modeling purposes, it has been projected that two design event earthquakes would be experienced within Christchurch over the next ten years, This section of the document should be reviewed and updated as often as new information is available.

It must be noted that the criteria for earthquake strengthening in the building code is not based on resistance to peak ground acceleration at present, but is addressed in terms of hazard related “Z-factor”. There is also a factor for serviceability in the code – the “R factor” which must also be considered under earthquake loading. This document does not address existing codes or standards, nor any proposed changes in code requirements. However, code review and code compliance are vital aspects of hazard response, and should be periodically reviewed, especially upon receipt of new information.

Proposed building safety ratings such as the one shown below, should be closely monitored in relation to infrastructure planning, reconstruction, renewals, and standards or codes. Further work on an infrastructure equivalent is recommended.

-	Earthquake Prone
⋆	33%-67% code
⋆⋆	67%-100% code
⋆⋆⋆	Full code compliance – IL2 (regular buildings)
⋆⋆⋆⋆	Full code compliance – IL3 (1.3 times code – important buildings)
⋆⋆⋆⋆⋆	Full code compliance – IL4 (1.8 times code – essential facilities)

3.1.2 Flood hazard

The greater Christchurch area has several potential flood sources.

The major rivers in the area, the Waimakariri, Selwyn and Ashley rivers can flood after heavy rain in the Southern Alps or the foothills. The main areas potentially affected by these rivers are the lower Selwyn floodplain, Christchurch city, Kaiapoi and Waikuku. The Waimakariri Flood Protection System currently has a capacity of 4,700 cumecs (approximately a 500 year return period or 0.2% AEP flood flow). The construction of secondary stopbanks, and other measures, as part of the Waimakariri Flood Protection Project, will bring the total system capacity up to 6,500 cumecs (approximately a 10,000 year return period or 0.01 AEP flood flow) once completed (2022). Stopbanks on the Ashley River from the Okuku River confluence to the sea have a capacity of 3,000-3,500 cumecs (approximately a 100 year return period or 1% AEP flood flow). Stopbanks on the lower Selwyn River have a capacity of 550 cumecs (approximately a 50 year return period or 2% AEP flood flow). Note that these capacities are theoretical design capacities, however in braided rivers stopbank failure can occur under design events due to lateral erosion of the stopbanks. The consequences of failed stopbanks could be devastating.

Local spring-fed streams, such as the Halswell, Heathcote, Avon, Styx and Cust, can overtop their banks after intense or long-duration coastal rain. The Cust River has a stopbank capacity equivalent to a ~50 year return period. The Halswell Drainage System is purely managed as a drainage scheme to benefit farming activities. The scheme does not include any flood control measures, and flooding of adjacent low-lying areas occurs on average every 2-3 years. There are a range of flood mitigation measures within the Heathcote, Avon and Styx catchments, including retention basins, a tidal barrage on the Heathcote River and some minor stopbanks. Flooding, particularly on the Heathcote River floodplain typically occurs every 3-5 years. Siltation and land form changes as a result of seismic activity, could alter the capacity of these streams and drainage systems. CCC have undertaken flood modelling of these rivers to account for the subsidence, changes in the form of channels and ground tilting that occurred with the recent sequence of earthquakes. This new flood level information is being used to set floor levels of re-built houses at appropriate levels according to the new topography and flooding level estimates.

Localised surface flooding and ponding can also occur after intense local rainfall. This may be exacerbated by land form changes as a result of recent seismic events.

Development can increase flood hazard by creating impervious areas and quicker runoff into drainage systems, and by changing flood flow paths. The flood hazard is also likely to increase with climate change due to both increased rainfall intensities and sea level rise in tidal areas.

The proposed Regional Policy Statement contains policies to avoid new development in high flood hazard areas (where water depth (m) x velocity (m/s) is greater than or equal to 1, or where depth is greater than 1 metre) in the 500 year return period (0.2% AEP) event. Where the flood hazard is lower, another policy requires new development to be built to a minimum floor level based on the 200 year return period (0.5% AEP) flood event. Many territorial authorities in Canterbury, including Christchurch and Waimakariri, have already adopted a 200 year return period (0.5% AEP) floor level standard, greater than the 50 year (2% AEP) standard required under the Building Act (which is generally accepted by hazard planners and economists as being too low). District Plan provisions should be adapted where necessary.

Environment Canterbury manages the Ashley, Waimakariri, Cust, Halswell and Selwyn rivers. Post earthquake remodelling of the Halswell and Ashley floodplanes indicates that there has been only minor changes in flood hazard associated with these rivers due to the recent seismic activity, within the uncertainty of the modelling. Christchurch City Council manages the Styx, Avon and Heathcote rivers and smaller tributaries. They have undertaken flood modelling of these rivers to account for the subsidence, changes in the form of channels and ground tilting that occurred with the recent sequence of earthquakes, and they may have more current information on these rivers.

3.1.3 Tsunami hazard

The current probabilistic tsunami hazard calculations for Pegasus Bay and Banks Peninsula (Berryman, 2005) gives wave heights at coast of ~2 m for the 100 year return period and ~4 m for the 500 year return period from all tsunami sources. These calculations are currently being reviewed by GNS Science.

The largest contributor to greater Christchurch's tsunami hazard is a distant source tsunami from South or Central America, being the most likely and largest tsunami source for the area. Recent modelling of a "worst case" distant source tsunami (based on the 1868 Peru tsunami) indicates sea level elevations at the coast above ambient level of 1-1.5 metres for much of the North Canterbury and southern Banks Peninsula coastline. However, within Pegasus Bay, Lyttelton Harbour and northern Banks Peninsula wave heights are amplified to over 4.5 metres in places. Depending on the tide stage at the time of the largest surges this is likely to cause flooding in Waikuku Beach, Woodend Beach, Kairaki/Pines Beach, Brooklands/Spencerville, New Brighton, Southshore, Bromley, Ferrymead, Heathcote, McCormacks Bay, Redcliffs, Moncks Bay, Sumner, Taylors Mistake and low lying parts of Lyttelton Harbour, Port Levy, Pigeon Bay, Little Akaloa, Okains Bay and Le Bons Bay. Water velocities in the range of 3-18 km/hr would entrain debris and sediment and increase potential damage to infrastructure.

A regional source tsunami may reach the Pegasus Bay coastline from the Hikurangi subduction zone (off the eastern coast of the North Island) within 1-3 hours. While this scenario has not yet been modelled in detail for the Canterbury coast, it is likely to generate sea level elevations at the coast above ambient level of 1-2 metres for much of the Canterbury coastline, although there may be localised amplification of waves. The return period for this event is in the range of 1,000-2,000 years.

There are known active faults in Pegasus Bay but they are thought to be very unlikely to generate a significant local source tsunami. The worst case modelled sea level elevations at the coast above ambient level are in the order of 1-2 metres from a local source tsunami. The Kaikoura Canyon landslide tsunami scenario will not affect Pegasus Bay. However, multihazard interaction could exacerbate the consequences.

GNS Science is currently updating the probabilistic wave height at coast calculations for the whole New Zealand coast for different return periods. Environment Canterbury also have funding in place for further research into tsunami hazards in North Canterbury, and from the Hikurangi subduction zone over the next three years. There are currently no land use planning provisions in place in Canterbury to address tsunami risk (mostly because of incomplete data), although the New Zealand Coastal Policy Statement has a policy stating that tsunami hazards must be taken into account in coastal planning. District Plan provisions should be adapted where necessary.

The NIWA model for the South American scenario has been remodeled to take account of 50 year sea level rise predictions as well as modelling the impact on key infrastructural assets (bridges, CWTP clarifiers and oxidation ponds in the estuary and lower Avon/Heathcote Rivers). While primarily developed for evacuation planning, this modelling may indicate additional loads that need to be accounted for in the rebuild/repair of existing assets. Consideration of longer term sea level changes may be warranted.

3.1.4 Coastal erosion and storm surge hazards

The southern Pegasus Bay coastline is generally in a state of long term slow accretion (growth). This long term stability is periodically interrupted by major storm events combining large waves and elevated water levels (storm surge) which cause significant coastal erosion. The northern margin of the estuary, where the Avon river discharges, subsided by 0.2m to 0.5m as a result of the earthquakes. This makes this part of the estuary more susceptible to these elevated water levels. Locations with sufficient sand dune volumes and good sand dune vegetation cover are able to adequately withstand such events and recover quickly. Areas with no dunes or inadequate dune volumes (carparks, surf clubs, access ways) are much more susceptible to coastal storm damage and inundation.

Major damaging storms occur as “storms in series” where runs of large storms occur within several weeks of each other and don’t give the beaches significant time to recover between storm events. Significant “storms in series” events occur on southern Pegasus Bay at roughly 10-15 year cycles.

The southern end of the South Brighton Spit is most vulnerable to coastal storm events. Spit tips are amongst the most dynamic and changeable of all landforms and South Brighton Spit undergoes periodic and dramatic changes in shoreline position often as a result of coastal storm events.

The coastal margins of the Avon-Heathcote Estuary/Ihutai are susceptible to elevated water levels during periods of low air pressure (inverted barometer effect), particularly when storm systems coincide with high astronomical tides.

3.1.5 Landslide and rockfall hazards

The steep volcanic rock slopes and faces of the Port Hills and Banks Peninsula are susceptible to rockfalls. These, along with entire cliff collapses, were widespread between Cashmere/Governors Bay and Godley Head during the February 2011 Christchurch earthquake and subsequent aftershocks. The repeated exposure to seismic activity in the area has caused a general weakening of rock faces, and has increased the susceptibility to and frequency of rockfall. Smaller, isolated rockfalls also occasionally occur during intense rainfall or with no apparent trigger.

The loess (thick wind-blown silty soil) overlying the volcanic rock is susceptible to tunnel-gully collapses and occasionally large deep-seated landslides. These types of landslide are most often triggered by rainfall, particularly after unusually wet winters. Activities on slopes, such as clearing vegetation and constructing roads and buildings, can increase the likelihood of landslides, particularly when drainage is not adequate.

3.1.6 Wind hazard

Strong winds are a hazard within the greater Christchurch region. Historically, the most severe winds have been associated with north-westerly downslope windstorms.

The 150 year return period mean wind speeds over flat locations is 70 knots (130 km/h), with gusts of 110 knots (200 km/h) and lulls of 50 knots (93 km/h). The 500 year return period gust speeds are 122 knots (225 km/h). In elevated areas such as Banks Peninsula even stronger localised winds may occur due to local topographic speed-up effects like channeling.

Weak tornadoes with speeds of 90-110 knots (180-200 km/h) are rare in the greater Christchurch area but have on occasion caused localised wind damage. Damaging winds in the greater Christchurch area can also be associated with strong thunderstorms and extra-tropical cyclones.

3.1.7 Snow hazard

Snow and ice presents an occasional hazard within the greater Christchurch area through the impact on transportation, the potential damage to overhead lines, and the potential damage to building structures. Transport services will be affected most years to a greater or lesser extent – particularly in the Port Hills Region. Approximately every ten years this will be more extensive, limiting transport for several hours to days across the city, and interrupting services provided by overhead lines. Potential exists for building snow loadings to exceed design specifications in the very rare occurrence that a heavy snowfall is followed by rainfall.

Overhead lines are at risk of failure in the event of heavy snowfalls in the absence of wind, and from the very rare occurrence of freezing immediately after a wet-snow/sleet event.

No return periods have been calculated for the various hazard severities but as an indication, significant snow storms that caused widespread utility interruption occurred in 1967, 1973, 1992, 1996, 2002, 2006, 2011.

3.1.8 Changing Sea Level (Sea Level Rise)

Over the foreseeable future, climate change will result in sea level rise.

Sea level rise is being factored into the flood floor levels and the design of tidal flood defences. At present the Ministry for the Environment recommends planning for a 0.5 metre sea level rise over the next 80-90 years relative to the 1980-1999 average. However, MfE also recommend assessing potential consequences from a range of possible higher sea level rise value and at the very least a 0.8 meter rise relative to the 1980-1999 average. For planning and decision timeframes beyond 2100 an additional allowance of 0.1 metres per year should be used.

Sea level rise is significant where it interacts with and exacerbates existing hazards. This is most obvious at the coast, with accelerated erosion and increased tsunami hazard. However, less obviously, rising sealevel also causes the groundwater table to sit at a higher level, even at some distance from the coast. This may increase inland flooding hazard and liquefaction susceptibility. Rising sea levels will also push saline water further up the rivers and gradually change the plants and other organisms to more saline tolerant species

Also mention potential impacts to groundwater sources – sea water intrusion.

3.1.9 Volcanic hazard

There are no active volcanoes in the South Island. Canterbury's volcanic hazard is restricted to the small possibility of ash fall from a large North Island volcanic eruption in unfavourable wind conditions.

3.1.10 Other hazards

Infrastructure planning should take into account the potential for intense solar activity to disrupt electricity and communication networks. While the likelihood of this in any particular year is relatively low, the consequences on infrastructure networks are potentially high.

Debris effects should be considered as a potential secondary hazard. Where possible, terminal areas for debris should be kept clear,, or alternatively channelized paths for debris should be considered.

3.1.11 Technological Hazards

While the focus of this document is on natural hazards, man-made technological hazards should also be considered. Simply put, it is essential that all hazards are considered - whether known or projected.

- Terrorism
- Infrastructure failure (including indirect failure i.e. consequences of inability to cope with results of natural hazard)
- Work force strike
- Endemic/pandemic

3.1.12 Integration of Risk Data into Recovery Design Solutions

The range of hazards discussed above should be handled through a standard design process that incorporates the latest learnings and design codes. This process should ensure new and repaired assets are resilient to all known or projected risks.

Where assets are repaired, the repair should incorporate resilient measures as applicable. It is envisaged that the "entire asset" could be bought up to new design codes in line with the relevant asset management plan governing the renewal of that type of asset. While short term repairs may not achieve the desired level of resilience, it is important to note that critical infrastructure should not be left in a vulnerable state.

4 Lifelines and Lessons Learned

Prior to the seismic sequence which started in September 2010, the Christchurch Engineering Lifelines Group were key contributors to a publication titled Risks & Realities, as facilitated by the Centre for Advanced Engineering. A 'Lessons Learned' addendum has been commissioned which draws on a large variety of studies on post-earthquake and other natural disasters that occurred since the publication of Risk & Realities.

4.1 Lessons Learned Project

The objective was to capture, consolidate and enable information sharing. This work should establish a base of infrastructure learnings to act as a starting point for further research.

The project involved:

- Consolidation of locatable lessons material.
- Review and extraction of key themes.
- Identification of gaps in documented material.
- Identification of areas where further work would add benefit.

4.1.1 Assembling the Lessons

Canterbury lifeline organisations and a range of other parties were asked to provide studies with relevant lessons which could be shared. Over 120 documents were contributed, of which 100 were considered to be highly valuable. A limitation is the originals authors' subjective view. Recognising that it was outside the scope of the project to test specific observations; no judgment could be placed on consolidating differences between authors.

4.1.2 Findings

The findings of the project suggested that the learning's fall into five categories:

- Decision-Making for Resilience-Enhancement Infrastructure
- Technical / Asset-Related Learning's
- Organisational Performance
- Regulatory environment
- Outage Consequences

The categories can be seen as different aspects of the learning cycle process.

Following the work undertaken by the Lifelines Group, Local Authorities and other Utility providers put specific projects in place within their investment programmes to address the dependence and or vulnerability of key infrastructure

Another example of strong decision making for enhanced resilience was the result of incorporating changes on the basis of the lifelines work. Orion New Zealand experienced a tangible benefit from their paradigm shift. "Since publication of *Risks and Realities*, Orion has invested in network resilience, learning from the lessons of events such as the 1987 Edgecumbe earthquake as well as from engineering and geotechnical assessments. Seismic strengthening costing $6 million is estimated to have saved Orion $30 to $50 million in direct asset replacement costs. The financial benefits of the seismic strengthening programme have substantially exceeded the implementation costs. The balance between costs and benefits is even more pronounced when societal benefits (i.e. gains to the community that don't appear in Orion's accounts" are taken into account."[5]

The Lesson Learnt project has observed that "The Canterbury Lifeline Utilities Group has facilitated collective learning activity. These steps point to a very healthy learning culture within the Christchurch lifelines community."

There were reservations in revealing intra-company information for building resilience enhancing infrastructure. In some cases this was due to the timeframe, as organizations had little to no formal documentation available, however others were hesitant about sharing what they perceived to be confidential internal knowledge.

4.1.3 Resilience Related Recommendations

There were several recommendations, however those relevant to resilience include:

1. Commissioning a review of overseas and New Zealand literature on resilience-enhancing decision-making as a process, to develop user-friendly material amenable to decision-making.
2. Further investigation of data gathering techniques. These should be aligned across all disciplines to provide consistent information to assist with designing resilience infrastructure.
3. Develop an RFP aimed at applying modeling techniques used in the Los Angeles water network to both water networks and other infrastructure in New Zealand, with a view to better targeted resilience planning.
4. Continued liaison between the Canterbury Lifeline Utilities Group, SCIRT and CERA for sharing future lessons.

4.2 Other Projects

In a separate report, the Christchurch City Council identified 15 major themes and suggestions for improvements following the emergency response phase associated with the 2010-2011 earthquakes. The majority of these lessons learned involve active and effective communication (e.g. Coordination, Structure & Delegations, Relationships, Information Communication Technology, Call Centre, and Welfare Centre)[6].

4.3 Related Work

Service Restoration curves are planned to be developed for the four major earthquake events to hit Christchurch being 4 September 2010, 22 February, 13 June and 23 December 2011 subject to the provision of research funding. These curves will be compared against similar curves from Northridge Earthquake (Los Angeles) 1994 (figure 3) and the Great Eastern Japan Earthquake 2011 (figures 4 & 5). Curves for major storm and flooding events may also be considered down track but currently the earthquake restoration curve is viewed as the service interruption defining event especially for the City's infrastructure assets. From these curves it is proposed to develop target infrastructure service restoration curves for each asset type. Evaluation of the curves will enable:

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[5] Resilience Lessons: Orion's 2010 and 2011 Earthquake Experience; Kestrel Group

[6] Capturing and Learning Points from the Christchurch Earthquakes 2010-2011: Accomplishments, Suggested Improvements, and Transferable Knowledge; Christchurch City Council

- Identification of pre-planning objectives that can shorten immediate response activity (e.g. length of boil water notice); and
- Impact of changes in technical standards on resilience of networks. This will help guide best investment options and any future adjustment to technical standards as more research work is completed.

On-going communication with authorities experiencing large events internationally will help target investment and adjust curves as best practice innovations are implemented into networks.

The sample curves detailed below provide two distinct types of information. The top example from 1994 Northridge event illustrates the various elements of service and asset capability restoration. Such curves span a much longer time frame and reflect effectiveness of the response and rebuild phases of an emergency event.

Resilience measures will be targeted to improve responsiveness to future design events to improve all aspects of service and asset restoration.

The second type of curve is simpler to compile and provides a clear picture for the wider community on how quickly service is targeted to be restored. The critical element to understand in the definition of these curves is what is defined as “the service level” e.g. for wastewater does it mean access to a sanitary fixture such as a portable toilet, chemical toilet etc. or does it mean reconnection to a flowing reticulated service.

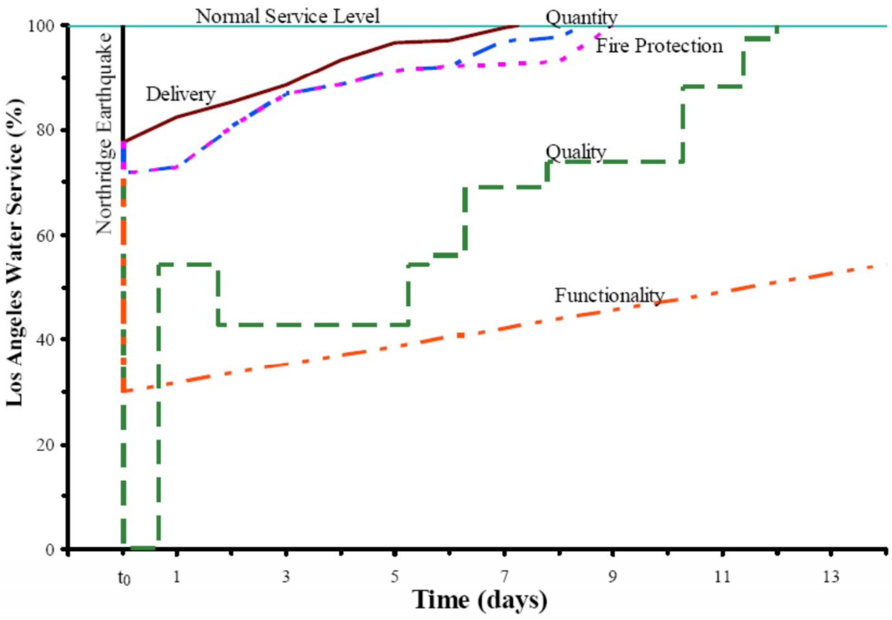


Figure 3. Los Angeles water system service restorations following the 1994 Northridge earthquake.

Future versions of this document will detail what each of the service, quality, quantity and functionality terms mean. It will be important these are aligned with international benchmarks to allow accurate comparison of restoration time frames from different events.

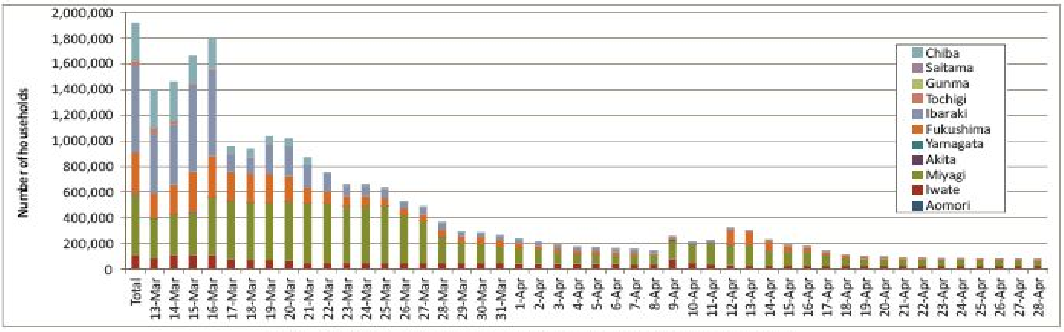


Fig. 4 Number of households without water supply

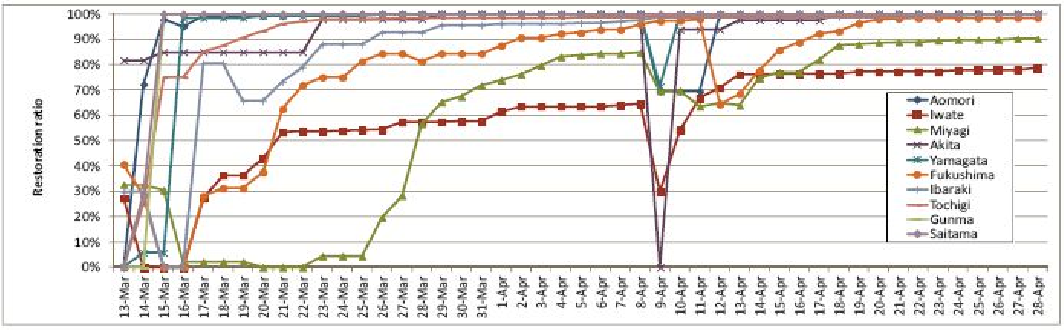


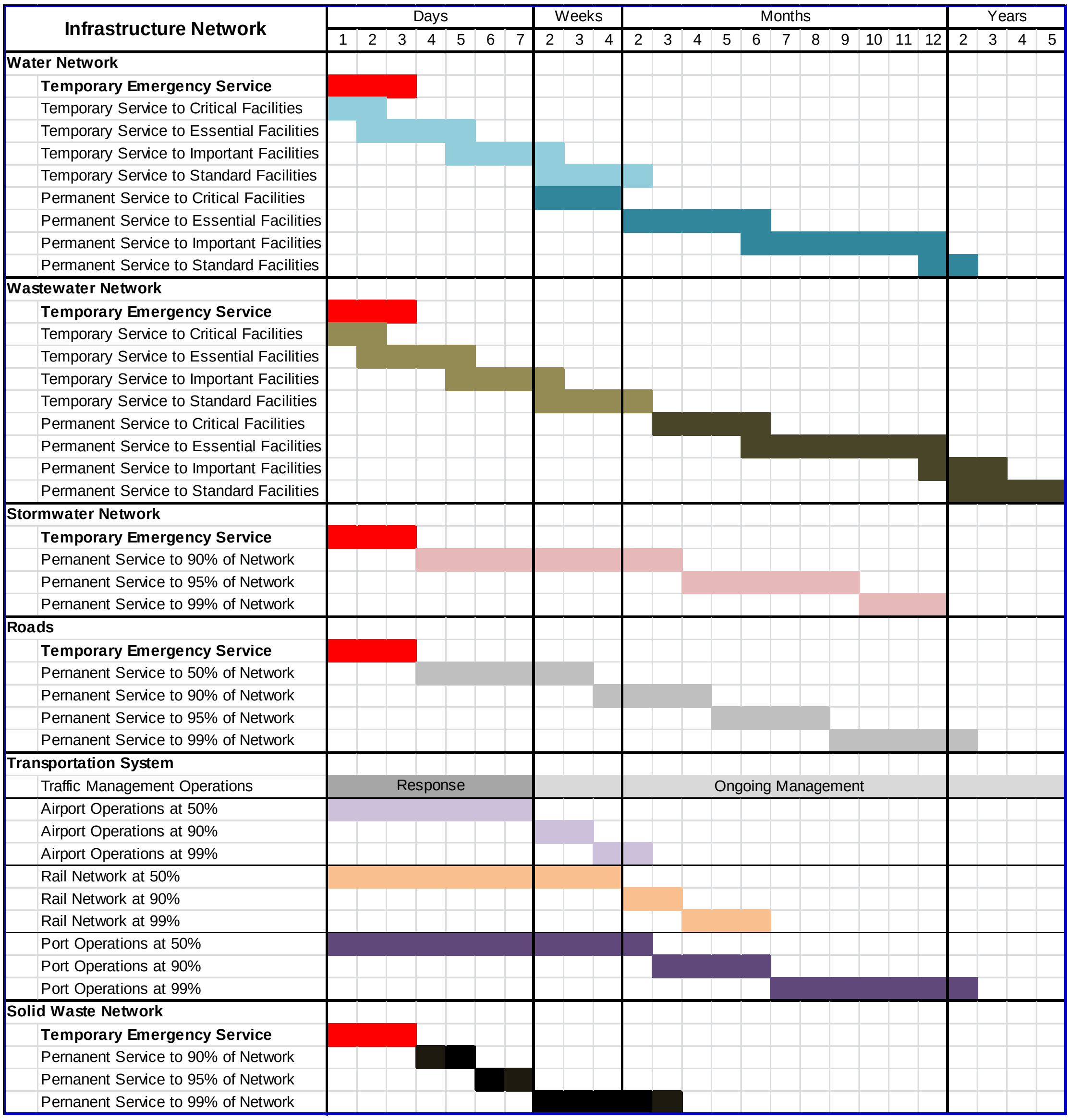
Fig. 5 Restoration curves of water supply function in affected prefectures

It is anticipated that this work will be of national importance as New Zealand is entering the first cycle of replacement of long life assets (underground water, wastewater and storm water). Establishment of reference standards will assist with national guidelines on resilience measures. Japan has benefited from such work conducted after the Kobe earthquake.

5 Target Service Restoration Standards

Indicative restoration table and associated target service restoration times have been prepared by numerous organisations and agencies to address the appropriate target for restoration of service. All such timelines commence at the time of a significant disruption. The following table is a broad representation of data presented in other publications and represents restoration of service from a design level earthquake (nominally an earthquake generating ground acceleration of 0.4g). Restoration to lesser events would be expected in less time:[7] This table is focused on public infrastructure, but could be extended to other commercial assets. Further work is required in developing this level of projected response, and should be considered at both the national, regional, and local levels – from strategic to detailed planning. This table would be a target against which actual responses could be measured.

[7] Source of information derived from Christchurch City Council and Risk and Realities



Where;
Critical Facilities – includes emergency response
Essential Facilities – includes lifelines infrastructure (also includes MESHT – Medical, Emergency, Schools, Hospitals, & major Transportation
Important Facilities – includes high priority facilities and infrastructure
Standard Facilities - includes everything else, including residential dwellings.

While the above table provides guidance on public infrastructure, it can be extended to include lifeline and commercial infrastructure such as telecommunications, electrical power supply, food and banking services.

Further work to apply research into practice is strongly recommended. Models have been developed in California, Italy and Japan, and should be trialled in Canterbury, with an understanding that the lessons learned will confirm methodologies, outputs, and be expandable to other regions and nations.

6 National Infrastructure Plan

Resilience is one of the six guiding principles of the National Infrastructure Plan (NIP) 2011, as developed by the National Infrastructure Unit (NIU) with the New Zealand Treasury. The NIP specifically defines Resilience as:
"National Infrastructure networks are able to deal with significant disruption and changing circumstances."

Work by the NIU has further developed the concepts of engagement, attributes and indicators. Each of these elements is briefly described below.

6.1.1 Engagement

To achieve appropriate levels of Resilience, engagement is required across public and private sectors, extending from strategic leadership to active implementation. and users of infrastructure. Infrastructure will fail so all stakeholders are necessarily part of the resilience balance, which in turn is strongly influenced by funding available for new investment and on-going operations.

6.1.2 Attributes

The application of Resilience to any system, agency or organisation can be broken into eight key attributes, as follow:

Service Delivery – There is a focus on national, business and community needs in the immediate and longer term.

Adaptation – National infrastructure has the capacity to withstand disruption, absorb disturbance, act effectively in times of crisis, and recognises changing conditions over time.

Community Preparedness – Infrastructure providers and users understand the infrastructure outage risks and take steps to mitigate these. Aspects of timing, duration, regularity, intensity, and impact tolerance vary over time and between communities.

Responsibility – Individual and collaborative responsibilities are clear between owners, operators, users, policy-makers and regulators. Responsibility gaps are addressed.

Interdependencies – A systems approach applies to identification and management of risk (including consideration of interdependencies, supply chain and weakest link vulnerabilities).

Financial Strength – There is financial capacity to deal with investment, significant disruption and changing circumstances. This includes: available funds, the awareness of financiers and insurers, continuing capital investment and maintenance expenditure.

Continuous – On-going resilience activities provide assurance and draws attention to emerging issues, recognising that that infrastructure resilience will always be a work in progress.

Organisational Performance – Leadership and culture are conducive to resilience, including; Resilience Ethos, Situational Awareness, Management of Keystone Vulnerabilities and Adaptive Capacity. Future skills requirements are being addressed.

As indicated above, resilience is just one part of a series of overarching guidance principles within the NIP:

1. Investment analysis
2. Resilience
3. Funding mechanics
4. Accountability & performance
5. Regulation and
6. Coordination.

6.1.3 Indicators

Not all elements of national infrastructure are expected to have high levels of resilience. The NIU has developed simple traffic light charts that can be applied to all elements of infrastructure to map out expected levels of resilience and the currently assessed levels of resilience. When applying these from a national perspective, shortcomings are identified and lead to priority areas for attention. It is essential to understand which portions of any network require the greatest levels of resilience, based on criticality, vulnerability, and risk.

Traffic light charts alone are insufficient as all elements of infrastructure have certain vulnerabilities even when overall assessed as having an appropriate level of resilience. To ensure a comprehensive assessment and to better ensure consideration of interdependencies, the concept of “pinch points” and “hotspots” are also applied. Pinch points are vulnerabilities within sectors and hotspots are generally geographic areas where co-location of infrastructure exists.

In many cases the indicated resilience is simply a result of a subjective assessment of perceived performance or risk within the system components. Increasingly robust metrics are required to more effectively track the resilience of individual and collective infrastructure systems.

7 Systems / Network Approach

The rebuild of Christchurch's horizontal infrastructure is a significant undertaking with unique challenges attached to it. Decision-making in the planning design, funding and construction is complex. Considerations will include dimensions such as:

- Speed of repair
- Level of disruption caused by the rebuilding
- Seismic (and other natural hazards) design criteria
- Impact of further aftershocks
- Consequence of future events
- Projected levels of loss (including consideration of different types of loss)
- Future shape of Christchurch
- Affordability of options
- Whole-of-life considerations, including projected future events
- Insurability of rebuilt infrastructure

Infrastructure can be seen as a system. Systems are collections of parts that together have a common purpose. The common purpose of transportation infrastructure, for example, is to carry people and freight across New Zealand. Similar infrastructure exists for electrical power, water, waste disposal, fire protection, communications and law enforcement. Because each of these infrastructure systems are almost always separately owned and managed but dependent to varying degrees on other infrastructure, the whole is commonly considered a '*system of systems*'[8]. In system analysis it is also recognized that there is a difference between the level of service offered to residents, and the proportion of physical infrastructure (ie population density is a consideration in any system). Further, the scalability of network systems is also a consideration for infrastructure resilience.

A number of systems link together to form Christchurch's core critical infrastructure, such as roads and bridges, water supply, wastewater treatment, flood-protection structures, telecommunications, and the national power grid. Understanding the linkages and cross-boundary relationships is critical to achieving a resilient response to the rebuild. The interdependencies between public and commercial assets require special attention in the form of planning and ongoing coordination.

The inter-connections of our infrastructure systems in the urban Christchurch environment are therefore complex and it is proposed that a system level approach is needed when making rebuild decisions. A systems approach includes designs that anticipate future events and their consequences, construction that is adaptable to future conditions, and the operation and maintenance of the project throughout its life cycle. The Canterbury Lifelines group has been working of infrastructure interdependencies over the last few years and this work will continue, as have lifelines groups in other regions nationally and internationally.

The four guiding principles, developed by American Society for Civil Engineers, after the levee failures in New Orleans9, to inform the planning, funding, design, construction, and operation of critical infrastructure systems, were:

[8] *Scott Jackson, 2010, Architecting Resilient Systems: Accident Avoidance and Survival and Recovery from Disruptions, John Wiley & Sons.*

[9] ASCE Critical Infrastructure Guidance Task Committee, 2009, Guiding principles for the nation's critical infrastructure.

- **Quantify, communicate, and manage risk –** transparency in assessing and responding to risk.
- **Employ an integrated systems approach** – understanding the complex interdependencies between and within systems.
- **Exercise sound leadership, management, and stewardship in decision-making processes** – recognising the importance of collaboration among stakeholders.
- **Adapt critical infrastructure in response to dynamic conditions and practice** – design solutions having the flexibility to change as conditions and knowledge evolve.

Together these guiding principles created a framework within which the effectiveness, adaptability and resilience of critical infrastructure systems are assessed and managed. Effective application of similar principles would go a long way to ensuring Christchurch's infrastructure systems are resilient and sustainable throughout their life cycle.

While not explicitly stated in the ASCE principles, it is implied that leadership and management will ensure that solutions are based on desired outcomes. While this can be dictated by leadership, it is best when outcomes can be collaboratively agreed upon by all key stakeholders.

Much work is being done to develop the concepts of acceptable risk following the Canterbury earthquakes. Outcomes should be added in updates of this document.

7.1.1 Interdependencies

No infrastructure system under consideration here operates totally independently. The interdependence may be through functionality (e.g. power needed to run wastewater pumps), co-location (e.g. telecommunication cables attached to bridges) or shared use (e.g. kerbing to discharge land drainage and road run-off). Therefore to support rebuild decision-making and to develop mitigation opportunities across the various systems a clear understanding of Christchurch's infrastructure interdependencies is needed. Scoping of the interdependencies will also assist to identify pinch points and hotspots. These may require more careful attention in determining the correct resilient response in the rebuild. Drawing on the initial work completed by the Christchurch Engineering Lifelines Group Report Risks & Realities a matrix of the infrastructure dependencies between systems needs to be developed. Critical to this work will be understanding modes of operation, failure mechanisms and order of effects. It may become evident that a simple matrix documenting system interdependencies provides an overview only and to fully explore the system complexities and vulnerabilities a dynamic model is needed. To effectively accomplish this work, emphasis needs to be focused on the development of shared information, data, and mapping. This collated data can then be used together in planning the management of risk, understanding that shared risk may reduce the collective exposure.

7.1.2 Decision-making to date

To progress the rebuild the Christchurch City Council has been considering how infrastructure components can be adaptive and making these decisions in terms of the water and wastewater projects. The focus has largely been as follows:

- **Building resilience into design in a pragmatic fashion**
  CCC recognised that there was a chance of further damage in future seismic events and built this into their design and construction plans. Some of the

solutions chosen were relatively simple and cheap (wrapping joins to avoid material entering pipes, changing to HDPE pressure sewer pipes), while other approaches were more structural.

- **Learning through trial and error**
  Unlike for buildings, design codes and standards for sewerage systems are not especially well developed. Lessons from the performance of rebuilt infrastructure from the June and December earthquakes have been incorporated into future building and design systems. Lessons learned from both the USA and Japanese earthquakes are being incorporated into standards as they are applicable to the Christchurch situation.

- **Including some key performance targets**
  The CCC are targeting a restoration service target that the sewerage systems could be operating 3 weeks after a future seismic event. This assisted the CCC to focus on what parts of the system would be more difficult to repair (thus implying more resilient design) as opposed to parts of the system that could be repaired relatively quickly if a future event were to occur. Price, quality, and schedule components must be carefully considered in the development of performance targets. The appropriate period for service restoration is directly related to the extent of disruption. Public tolerance is expected for a period of time, although this also has a relation to the extent of damage. The matching of the technical solution to the risk condition is a key strategy being taken to improve system performance.

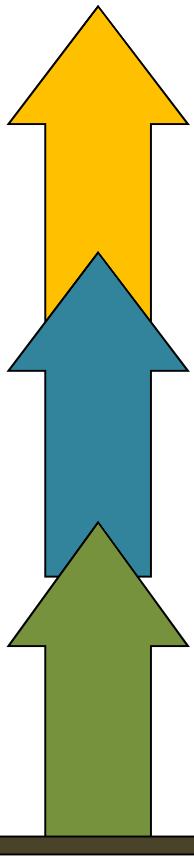
- **Pricing options**
  Cost is always a factor, but the CCC did not use this as the sole determinant for decision-making. As time passes and full extent of damage emerges affordability will become increasingly important at both a local and national level. It will be important to monitor the cost of more resilient solutions against the “like for like” replacement option. Current evidence is that increased resilience does not always come at increased cost particularly in an NPV evaluation that recognises the risk of future events. This is particularly true for deep gravity sewer solutions.

7.1.3 The Results

The repairs that the CCC have made to the sewerage (including repairs to the CWTP) and water supply systems performed well in the June and December earthquakes, and the estimated cost premium over a “normal” rebuild has not been especially significant (pending review, it appears that the cumulative effect of choosing resilient options has not increased the overall programme cost, even while some individual project are more costly). Ongoing documentation of resilience responses through the rebuild will be critical to developing long term understanding of the value of the investments. This knowledge will then inform the development of new asset management plans and Long Term Plans for infrastructure investment.

8 Resilience Metrics

While resilience can be a national aspiration, the goal is to develop discreet metrics that allow measurement and monitoring of progress. Further, to enable robust decision making, it is important to provide adequate categorisation of cost during the development of various design solutions. For the purpose of this paper, the following general definitions have been applied:



Improvements: Provides an increased level of service or capacity beyond that provided by the measures indicated below. This includes replacing infrastructure nearing the end of service life while the opportunity is available and/or providing additional capacity in infrastructure for predicted growth at a reduced marginal cost. ***'Betterment'*** is a subset of improvements relating to insurance considerations.

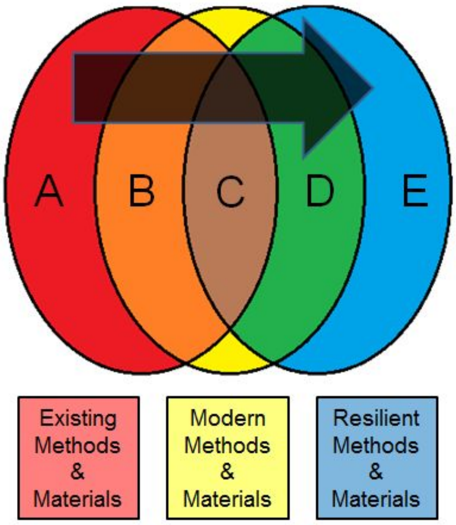
Resilience Measures: Includes additional components to ensure that modern materials can withstand, or quickly recover from, significant hazards or disruption. This further includes network system components for the same purpose, beyond a standard modern design. This includes additional levels of redundancy and network connectivity. Alternative methods of service are a key method for providing service in high hazard areas.

Modern Materials/Infrastructure: This provides improved resilience over the performance of existing infrastructure. This further includes configuration of network systems in accordance with modern design. No additional redundancy is included.

Existing Materials/Infrastructure: This provides no additional resilience over the performance of existing infrastructure. Many original materials are no longer used in underground networks.

While the application of this approach may have some traction in the post event reconstruction of Canterbury, consideration of these matters should be evaluated in other places as well. This event could provide an opportunity for establishing updated governmental positions on various aspects of infrastructure.

Infrastructure Resilience isn't a black box that gets added during the construction process, rather, it is a process method or consideration throughout the life of an asset. The following diagram shows how Infrastructure Resilience is an progressive advancement in the methods and materials.



A. Some existing methods & materials are obsolete
B. Some are not, but don't provide resilience
C. Some existing methods & are still used today, and are resilient
D. Some of the modern methods & materials provide resilience
E. Some new or additional methods & material exist (or being developed) which provides more resilient infrastructure.

Infrastructure resilience is the ability of a system to withstand or quickly recover from significant disruption

Further, it is essential that whole lifecycle costs are considered during the development of design solutions, and are a consideration for decision making. The lowest capital cost solution may not be the lowest lifecycle cost solution. Clearly the application of discount rate and depreciation period plays a large factor in the decision process. These factors should be considered further to ensure the appropriate protection for long-life critical infrastructure.

Similarly, the performance of modern materials and system components should be evaluated after subsequent hazard events to ensure the adequacy of new measures. This process is essential for ensuring the adequacy of design solutions. For hazards with very high return periods, this may prove difficult to warrant in advance of a future event. It is further noted that reconstructed infrastructure takes time to design and construct, and therefore it may take some time before an adequate amount of infrastructure is in place to measure adequacy. Since the reconstruction is starting to ramp up, and the actual performance of new materials and systems is unknown in the Christchurch context but is understood in overseas events. It is recommended that this table is updated at periodic intervals for the next three years. Due to this time lag, it is very important that Christchurch stays in touch with utilities in Japan and USA that have been implementing such measures for a longer period of time and have, in the case of Japan, been subject to more frequent large scale seismic events. The increasing collective knowledge from repeat disaster events is an invaluable resource with respect to changes that are being made to reconstruction methods. Japan has used such iterative learnings to progressively improve bridge, underground asset and building design to resist further seismic events.

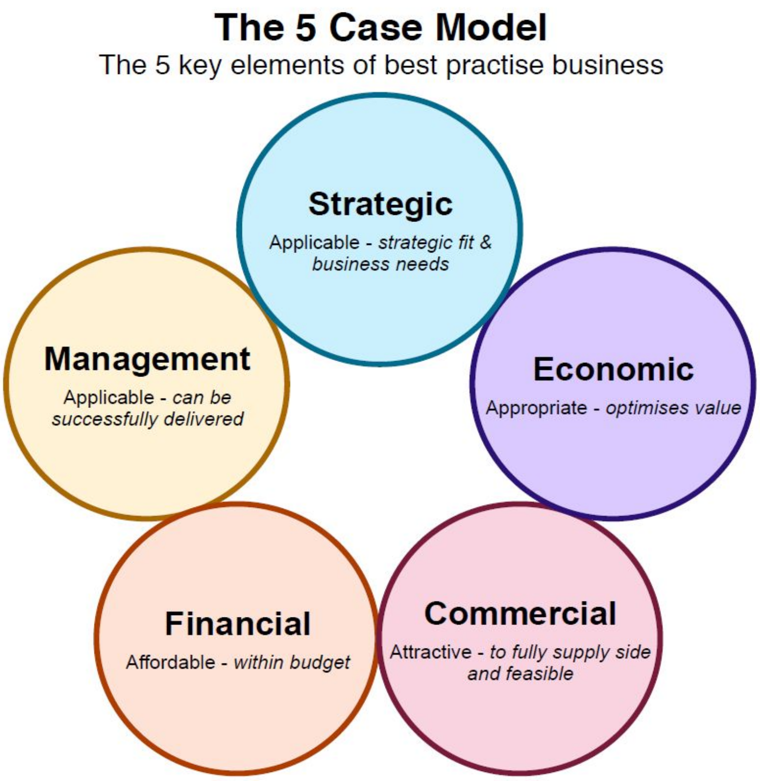
The SCIRT recovery vehicle enables a cross utility approach to the rebuild or repair of infrastructure, especially at 'hot spots' and 'pinch points'. 'Hot spots' are generally areas congested by multiple assets in the same space, while 'pinch points' are areas which limit access and constrain capacity (like a one lane bridge on a busy road). It must be recognised that the various public and private funders of the infrastructure services in Christchurch may have different priorities for investment at key infrastructure pinch points and hot spots.

Appendix A lists examples of technical changes to systems and standards CCC are making to improve resilience of infrastructure networks. The table outlines the measures which are in process of being designed and constructed following the earthquake sequence starting September 2010. These guidelines are based upon the consensus of expert opinion, observations from senior operational specialists and engineers using information about conditions, risk, and robust technology, as at the time of writing. These examples focus on infrastructure resilience solutions through agency owned assets. Promoting de-centralised systems is also another way of improving resilience.

Appendix E identifies the proposed decision making exercise required prior to implementation of resilience options.

9 Better Business Cases

Better Business Cases is a process developed by the New Zealand Treasury to inform investment decisions. Better Business Cases applies good practice and learning from Australia, New Zealand and in particular, United Kingdom. The Five Case Model developed by Courtney A Smith and Joe Flanagan in “Making sense of public sector investments”, 2001 is key to the Better Business Cases process. The Five Case Model is illustrated below and is an approach to thinking.



The Five Case Model seeks five questions that underpin investment decisions:

1. Is there a compelling case for change?
2. Does the selected option optimise value?
3. Is the potential deal achievable and attractive to the market place?
4. Is the spending proposal affordable?
5. How will the proposal be delivered successfully?

Answering the five questions above will inform investment decisions regardless of size. The application of Better Business Cases to infrastructure with optional levels of resilience is required during the decision-making process. Work has been started on a new research project, Economics of Resilience Infrastructure, and the outcomes of this work should be considered in future updates of this document.

9.1.1 When does it apply?

Cabinet has agreed the rules for Better Business Case use in the New Zealand State Sector (refer: Cabinet Paper CO (10) 2) and a number of local authorities are considering its application on specific projects. The private sector will have their own approach to assessing and prioritising investment decisions to meet specific goals for the Canterbury Earthquake recovery, although the Better Business Case process applies now for projects or programmes which are in whole or in part funded by the Crown. The philanthropic sector will likewise have their own criteria to assess and inform investment decisions.

Invariably there will be programmes and projects that are both public sector and private sector e.g. Public Private Partnerships (PPP) which will need to use Better Business Cases. There will also be private and philanthropic sector projects and programmes that will be dependent upon public sector programmes and projects being delivered first or in tandem. The public sector programmes and projects should identify (as best they can) the benefits and costs of these private and philanthropic programmes and projects to inform decision makers.

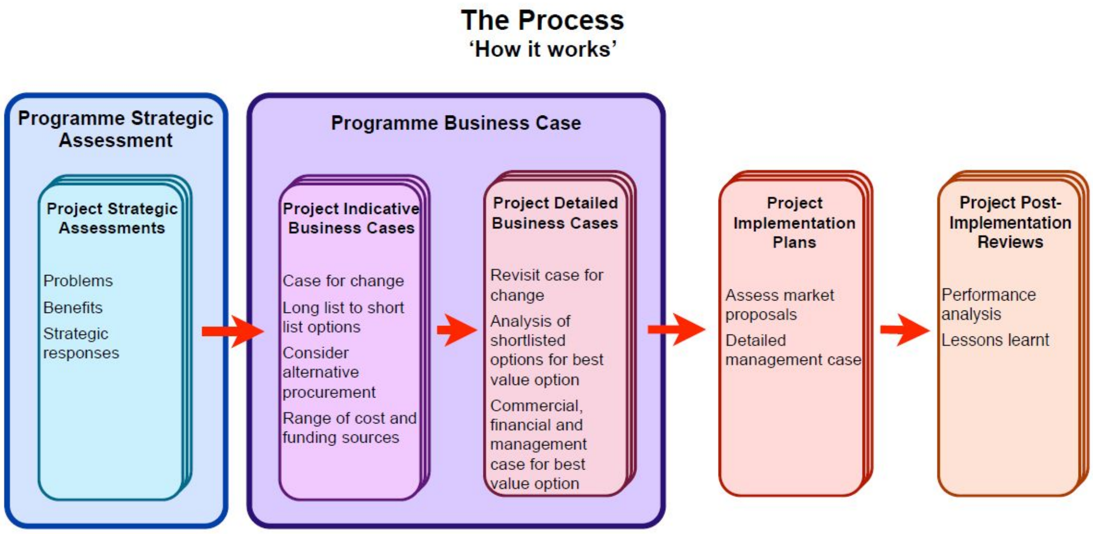
9.1.2 Benefits of using Better Business Cases

There are numerous reasons for using Better Business Cases, as identified below:

- **Scalable** – This means less work for smaller and low risk projects more work for higher risk and higher cost projects
- **Flexible** – Engage early with reviewers (CERA and Treasury) to decide on what work is required and expectations
- **Effective recovery** – Ensure we are only doing the programmes and projects that add the greatest value in achieving the recovery
- **Co-ordination** – Improves co-ordination by identifying interdependencies with other programmes and projects
- **Assurance** – Provides assurance and confidence to decision makers that an internationally recognised good practice approach has been used to present a case for an investment.
- **Prioritisation** – Inform prioritisation and sequencing of programmes and projects

9.1.3 How does it work?

The following diagram shows the process (at a high level). The first point to note is the focus of developing a programme business case. It is unlikely that there is a project that is delivered in isolation. In fact it is more than likely that projects are connected. A programme business case can help inform and can be updated over a number of years to reflect the changing shape of the programme.



Following the development of programme business case there might be the need to undertake further work (analysis) on individual projects or bundles of projects within the programme where there are greater risks or financial costs. These projects may need to go through a single or two (Indicative and Detailed Project Business Case) and a series of Gateway Reviews. This will be determined by discussions between those preparing the business cases and the reviewers. CERA will facilitate a number of seminars to raise awareness of the Better Business Case process, and its application to the recovery programme in the fourth week of each month from August 2012. The seminars, will be delivered in conjunction with the Treasury and experienced BBC practitioners and will allow business case writers (particularly those working on anchor projects or programmes) to learn more about the Better Business Case process as well as gain practical support and training. A particular focus will be working with stakeholders on the application of the application of the Better Business Case process to the key anchor programmes and projects, such as the Convention Centre, Stadium and Horizontal Infrastructure Programme.

It is anticipated that the Better Business Case model will be applied at the minimum of catchment level or across a network asset base. Where specific new assets are proposed for the purpose of increasing network resilience (e.g additional network cross connections or increased redundancy in key links) then a separate business case may be appropriate.

10 Next Steps

This document has been prepared during the midst of an earthquake recovery, after the commencement of a large scale reconstruction effort. As such, a great deal of work is still required to ensure efficient and effective implementation – and to avoid lost opportunities for incorporating resilience into the work programmes.

A preliminary outline of required actions is shown in the following table. Indicative timeframes for incorporation in Resilience documentation is:

- Version 3 completed by October 2013 (**pending approval of research funding**)
- Version 4 completed by April 2014 (**pending continuation of work**)

Identified actions to be completed	Possible lead	Expected update version number
Complete operational field crew debriefs to gain understanding of infrastructure performance.	CCC	Version 3
Conduct an integrated systems workshop to help refine decision-making frameworks using dynamic minimise, multi-criteria analysis, cost-benefit ratings and hazard/risk assessment. Consider: • How do we lift component level project considerations to a system level focus? • How do we ensure the interdependencies of systems are included in the planning and design of rebuild? • How do we establish a regional approach? • How do we quantify, manage and communicate residual risk?	CERA /Industry experts	Version 3
Development of target service restoration curves integrating world's best practice. Include an agreed definition of service – subject to approval of research funding	CCC/CERA	Version 3
Gap analysis of Christchurch service restoration curves against best practice curves including estimate of technical/ network/operational investments required to close the gaps. Subject to approval of research funding	CCC/SCIRT	Version 3/4
Engage with Japan and USA agencies in expansion of collective knowledge with respect to the success/failure of resilience measures incorporated into reconstructed infrastructure.	CCC/CERA	Version 3
Research into root cause of failures in networks and materials to further refine/define any changes needed to technical standards.	UOC/CCC/CERA	Version 3

Integration into worldwide network of disaster resilience thinking to keep abreast of developments and contribute Christchurch's lessons learned to international pool of knowledge.	Lifelines Group	Version 4
Consideration of how Christchurch's lessons learned are rolled out nationally in order to minimise future impacts in other parts on New Zealand and look to avoid "it won't happen to me mentality".	CCC	Version 3/4
Additional items identified during workshop: • Development of new asset management plans • Instigate a review of regional approach to lifelines • Develop and test cost benefit analysis within consideration of service levels	CCC	Through Local Government normal asset management planning processes
Validate Resilience Decision metrics	CERA / Industry experts	Version 3
Develop an infrastructure equivalent to Proposed building safety ratings.	TBD	TBD
There needs to be a clear link between restoration times and the community.	TBD	TBD
Confirm the direct method to show how steps taken actually improve resilience.	TBD	TBD

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Dave Brunsdon	Kestrel Group
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Helen Grant	ECan
Haydn Read	WCC
David Edmonds	Water NZ
David White	UCan MEM
Courteney Johnston	UCan MEM
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Joanne Golden	SDC
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Stephen Wright	SCIRT
Joanne Golden	SDC
Sonia Giovinazzi	UCan
Mathew Hughes	UCan
Misko Cubrinovski	UCan

Appendices:

The following tables outline the measures which are being considered for design and construction in various applications following the Canterbury earthquake sequence starting September 2010. These guidelines are based upon the consensus of expert opinion, using information about conditions, risk, and robust technology, as at the time of writing.

Four specific tables are provided below, as noted:

- **Appendix A: Modern Materials / Infrastructure** – The modern methods and materials presently in use. These may result in incremental increases in resilience.
- **Appendix B: Resilience Measures** – Those items to be considered specifically for the purposed of increasing the network resilience. These may only apply to certain critical components.
- **Appendix C: Possible System Improvements** – Possible options for increasing capacity, if appropriate or necessary. These options are out-of-scope unless approved by funding organisation. These may only apply to certain areas or components.
- **Appendix D: Commercial Table** – An indicative example for commercial infrastructure.

The final **Appendix E, Resilience Decisions**, provides consideration to methods for quantifying infrastructure priorities and funding levels for individual projects or programmes.

Appendix A: Modern Materials / Infrastructure

The following tables describes standard modern methods and materials presently in use. These specific items can be measured or seen, and may result in incremental increases in resilience. This table should be updated to include resilience considerations as part of an overall improvement in standard practice.

Reconstruction techniques which are proven successful in subsequent events should be incorporated into on-going asset replacement programmes.

TABLE A1: Modern Materials / Infrastructure		
	Water System	
PW	1.1	Use PE pipe with bolted self-restraining pipe fittings.
PW	1.2	Use computer network models to select pipe routes that avoid areas with high risk of liquefaction or lateral spread.
PW	1.3	Design systems for easy access to susceptible failure points.
PW	1.4	Design network to allow isolation of failure locations.
PW	1.5	Use computer network models to design network with adequately looped distribution (x-connections and bypass lines).
	Wastewater System	
WW	1.1	Use PVC for gravity pipe, with longer pipe lengths (fewer joints).
WW	1.2	Use steeper grades as designated by tractive force design methodology for gravity sewer pipe.
WW	1.3	Use HDPE or PE for sewer pressure pipe (welded joints).
WW	1.4	Use computer network models to select pipe routes that avoid areas with high risk of liquefaction or lateral spread where possible.
WW	1.5	Design systems for easy access to common failure points.
WW	1.6	Design below ground structures to withstand buoyancy (Includes manholes, pump stations, and any storage tanks).
WW	1.7	Use specific geotechnical designs for pump station foundations.
	Stormwater System	
ST	1.1	Select locations without high risk of liquefaction or lateral spread where possible.
ST	1.2	Use steeper grades as designated by tractive force design methodology for gravity sewer pipe.
ST	1.3	Design systems to allow easy access for maintenance and repair.
ST	1.4	Prepare and periodically update a computer model of the drainage system. (Capture changing conditions and ensure adequacy of system).
ST	1.5	Verify and apply latest guidance for percolation rates in pond systems
ST	1.6	Design new land developments to retain stormwater to predevelopment levels.
	Roads and Bridges	
RD	1.1	Bridges shall withstand Serviceability Limit State with only minor damage, and no disruption to traffic, for return periods much less than the design value.
RD	1.2	Bridges shall withstand Ultimate Limit State with repairable damage, and usable by emergency traffic (temporary repairs may be required), for return periods equivalent to the design value.
RD	1.3	Bridges shall withstand Maximum Credible Event without collapse, and usable by emergency traffic (temporary repairs are expected), for return periods much greater than the design value.
RD	1.4	Design roads and pavements in accordance with current standards.

	Transportation	
TR	1.1	Develop Greater Christchurch Transport Statement to provide guidance and dialogue between regional strategy and detailed plans.
TR	1.2	Periodic reviews of risk schedules and risk management plans.
	Solid Waste	
SW	1.1	Wheelie bin systems provided secure site storage for households and can serve as emergency human waste disposal containers.

Appendix B: Resilience Measures

The following table describes potential methods and materials that can be used for the purpose of increasing the resilience of a system. These specific items can be measured or seen, and should result in measurable increases in resilience. This table should be adopted into common practice as part of an overall improvement in infrastructure standards.

Asset owners are responsible for evaluating the applicability of the following Resilience Measures for the conditions and risk associated with their specific network, or portions thereof. The criticality of individual network components and the probability of failure should be key considerations in funding decisions.The Better Business Case process should be applied in order to ensure prudent decision making of which of these items should be incorporated into the Canterbury reconstruction. Section 9 describes the Better Business Case process.

TABLE A2: Resilience Measures		
	Water System	
PW	2.1	Install anchor blocks at connection from existing less flexible networks to new networks (prevents failure of sliding rubber pipe ring at connection).
PW	2.2	Design network to allow large scale isolation of failure locations, and large scale interconnection between zones.
PW	2.3	Operate all distribution zones at the same pressure to allow greater cross-connection and flow diversion as required.
PW	2.4	Provide flow diversion methods for routing water to/from adjacent districts.
PW	2.5	Provide cycled emergency water storage within each distribution zone.
PW	2.6	Prepare emergency treatment systems for use as required, and periodically test their installation and operation.
PW	2.7	Outer well casings made of heavy duty Oil and Gas drilling pipe to resist bending forces from “slippery” subterranean clays.
PW	2.8	Avoid sinking wells in liquefiable land or ground subject to lateral spreading. This protects production capacity by keeping wells in good ground, then route easier to repair pipes into poorer ground for local distribution to houses.
PW	2.9	Use specific geotechnical designs for pump station foundations.
PW	2.10	Fill voids between inner and outer well casings with bendonite to isolate well pipes from wellhead protection chambers.
PW	2.11	Alter flexible coupling connection to wellhead protection chambers to improve vertical and horizontal movement.
PW	2.12	Further develop SCADA and network instrumentation to allow more detailed interrogation of supply zones. Develop integration of SCADA, GIS and Water Management Platform to improve real time water loss monitoring and service availability.
	Wastewater System	
WW	2.1	Limit pipe depth to <3.5m to avoid deep repairs (laterals limited to <2.5m).
WW	2.2	Wrap PVC pipe joints with geotextile to protect against siltation if the joints open up.
WW	2.3	Use geotextile wrapped haunching in areas with a high risk of liquefaction or lateral spread.

WW	2.4	Use pressure or vacuum systems in areas with a high risk of liquefaction or lateral spread.
WW	2.5	Over excavate liquefiable material surrounding below ground structures, and replace with suitable backfill.
WW	2.6	Use gibaults and flange adapters for pipe connections to pump stations (joints sliding off are preferable to shear failure at penetration). Use flexible connections where possible.
WW	2.7	Provide bypass overflow connections at lift stations and pump stations to allow emergency bypass in case of power failure.
WW	2.8	Integrate valves into lift station or pump station structures to avoid differential settlement, shear failure, or restricted flow.
WW	2.9	Provide increased flow and load buffering within the primary wastewater treatment plant to accommodate significant hazards, disruption, or surges.
WW	2.10	Provide oversized sand/grit removal capability to enable plant to better handle future liquefaction events.
WW	2.11	Provide flow diversion methods for routing wastewater into adjacent districts for treatment and disposal.
WW	2.12	Provide emergency storage within each catchment basin where this provides overall network benefits.
WW	2.13	Analyse entire catchment basins when evaluating design solutions on a large scale (consider economy of scale and full lifecycle factors).
WW	2.14	Avoid heavy chambers adjacent to main pump station structures to minimise excessive shear and bending forces on connecting pipes.
WW	2.15	Further develop SCADA and network instrumentation to allow more detailed interrogation of WW catchments and river networks. Develop integration of SCADA, GIS and Wastewater Management Platform to improve real time infiltration monitoring and service availability
	Stormwater System	
ST	2.1	Limit pipe depth to <3.5m to avoid deep repairs.
ST	2.2	Use geotextile wrapped haunching in areas with a high risk of liquefaction or lateral spread.
ST	2.3	Provide adequate routing and storage for emergency overflows.
ST	2.4	Install open channel systems (swales) in preference to buried pipes where land availability permits . Include riparian planting and wetlands for transport and treatment of stormwater (speed of restoration of service and added benefit of pre-treatment prior to discharge in waterway).
	Roads and Bridges	
RD	2.1	Periodically evaluate bridge design capacity against the projected loads identified from lessons-learned in other similar hazard locations (including Tsunami loads where applicable).
RD	2.2	Abutments to potential lateral spread zones to have ductile piles and effective lateral propping resistance.
RD	2.3	Ensure structures within the roadway can withstand buoyancy forces (prevent manholes from popping up into the roadway).
	Transportation	
TR	2.1	Develop traffic management operations centre.
TR	2.2	Incorporate traffic management controls into network.
	Solid Waste	
SW	2.1	Enable emergency utilisation of closed landfills through resilience plans. Obtain necessary Resource Management Act approvals to facilitate this use in future events.
SW	2.2	Train personnel in safe handling of human waste in emergencies.

SW	2.3	Well managed and licensed clean-fill sites can manage some construction and demolition material in emergency.
SW	2.4	Install permanent emergency power generation at key transfer stations to ensure compactors are available in emergencies.
SW	2.5	Identify and consent emergency construction and demolition waste storage and processing sites.

Appendix C: Possible System Improvements

The following table describes potential measures that would increase the capacity of the network. These items are not included in the SCIRT work programme unless specifically added and funded. These specific items can be measured or seen, and should result in measurable increases in network capacity.

Additional work to increase the capacity of the network is outside the scope of repair or reconstruction. However, the incremental opportunity cost for increasing capacity can be much lower than pursuit of separate future projects for that purpose. The following Possible System Improvements are not included in the reconstruction scope of work, however, could be considered for approval by funders – where increased capacity is deemed appropriate and/or necessary.

TABLE A3: Possible System Improvements		
	Water System	
PW	3.1	Increase pipe sizes for additional capacity or future proofing.
PW	3.2	Replacing components nearing the end of service life while the opportunity is available (e.g. replacing pipe which doesn't meet the threshold for replacement while the area is closed for other repairs).
PW	3.3	Introduction of volumetric charging to residents (Current CCC policy does not charge for water). Metering is already installed on most residential properties and all new properties are metered. Commercial and industrial users are currently charged for water.
PW	3.4	Maintain up to date and calibrated computer network models.
	Wastewater System	
WW	3.1	Increase pipe sizes for additional capacity or future proofing.
WW	3.2	Develop satellite treatment plants in line with the growth strategy, and restrict further growth at the primary treatment site.
WW	3.3	Develop options for effluent disposal, for both short-term and long-term disruptions to the current primary disposal site.
WW	3.4	Replacing components nearing the end of service life while the opportunity is available (e.g. replacing pipe which doesn't meet the threshold for replacement while the area is closed for other repairs)
WW	3.5	Design network with adequate cross-connections to allow wastewater to get to single wastewater treatment plant via different routes or to different treatment facilities where applicable.
WW	3.6	Maintain up to date and calibrated computer network models.
	Stormwater System	
ST	3.1	Increase pipe sizes for additional capacity or future proofing.
ST	3.2	Increased treatment/buffering of storm water first flush flows in Red Zone land prior to discharge to waterways.
	Roads and Bridges	
RD	3.1	Rigid pavements with geotechnical foundation.
RD	3.2	Bridge widening.
RD	3.3	Strengthen bridges to improve load capacity.
	Transportation	
TR	3.1	Construct separation of modal conflicts.
TR	3.2	Increased passenger and freight capacity at port.
TR	3.3	Increased passenger and freight capacity at airport.
TR	3.4	Light rail public transportation system.
	Solid Waste	
SW	3.1	Provide in-city processing plants (organic and recyclable materials) to

		reduce reliance on transportation to remote landfills.
SW	3.2	Coordinate management of private and public transfer stations to handle high waste volumes in order to protect public health (highest priority to putrescible waste).
SW	3.3	Coordinate BCP's with major warehousing and retailing chains (food and beverage) critical to ensure timely disposal of perishable product.
SW	3.4	Contractors develop a national plan to provide skilled drivers for specialist vehicles in times of emergency.

Appendix D: Commercial Table

While the above tables generally focus on public infrastructure, commercial infrastructure can equally benefit from the incorporation of resilience measures into those network systems. Commercial imperatives may have already advanced these concepts into reality in certain cases, howere, the following Commercial Table provides an indicative example.

TABLE A4: Commercial Table		
Electrical Power		
	Modern Materials / Infrastructure	
EP	1.1	Provide appropriate storage for spare parts.
	Resilience Measures	
EP	2.1	Expand spare parts inventory to align with projected risk.
EP	2.2	Extend “PowerOn” system to low voltage network.
EP	2.3	Complete earthquake strengthening projects.
	Possible System Improvements	
EP	3.1	Increased source generation.
EP	3.2	Additional redundancy of transmission.
Natural Gas		
	Modern Materials / Infrastructure	
NG	1.1	On-going construction with PE pipe to current standards.
	Resilience Measures	
NG	2.1	Regular inspection and maintenance of isolation values and meters.
NG	2.2	Fully test and inspect network components prior to re-commissioning any portion closed for emergency shut-down.
	Possible System Improvements	
NG	3.1	Monitor new technologies in automated leak detection shut-off, and implement as appropriate.

Appendix E: Resilience Decisions

The decision to incorporate resilience measures into infrastructure should remain with the individual asset owners and any financial contributors, and in consideration of the work on what constitutes acceptable risk to the community. Each organisation or agency should have a process for evaluating capital and operational expenditures, together with a plan for asset replacement over time. Significant disruptions in service may require unplanned asset replacement, and may include an infusion of unscheduled funding from government and/or insurance providers – ostensibly to cover the replacement of the damaged infrastructure.

When considering replacement of assets, whether from unplanned or planned disruption, options should be considered. These options should be evaluated over an appropriate area for the network system, and not considered out of context from the surrounding environment. Further, differences in operational costs should be accounted for within each option - with a whole-of-life, Net Present Cost approach recommended for the consideration of alternatives, and subject to the work on what constitutes acceptable risk to the community. Since capital expenditure and operational costs are usually administered by different departments, both should have visibility on the numbers which are used for these calculations – and for budgetary planning.

The metrics for making decisions about investment into infrastructure resilience are not readily available. This paper provides an indicative method for consideration, and requires the following data:

$\mathbf{NPC_o}$	Net Present Cost of simple replacement of original infrastructure
$\mathbf{NPC_r}$	Net Present Cost of resilient option(s)
$\mathbf{C_r}$	Criticality (Standard = 0; Important = 0.5; Essential = 1.0)
$\mathbf{n}$	Normal asset life, in number of years
$\mathbf{n_x}$	Remaining asset life of damaged infrastructure
$\mathbf{P_n}$	Probability, as a decimal, of a significant disruption which requires asset replacement within the normal asset life

Thereafter, follow the logic steps for infrastructure reconstruction:

1. Assess damage to infrastructure.
2. Broadly prioritise damaged infrastructure into the following.
    a. IF $\mathbf{n_x < 5}$; or $\mathbf{C_r = 1.0}$; or $\mathbf{P_n > 0.65}$; then top priority
    b. IF $\mathbf{5 < n_x < 15}$; or $\mathbf{C_r = 0.5}$; or $\mathbf{P_n > 0.35}$; then second priority
    c. IF $\mathbf{n_x > 15}$; or $\mathbf{C_r = 0}$; or $\mathbf{P_n >= 0}$; then third priority
3. Set appropriate boundaries for project evaluation, preferably whole catchments, zones or neighbourhoods.
4. At Concept Design, if $\mathbf{NPC_r < NPC_o}$; then select the most resilient option, else
5. At Concept Design, if $\mathbf{NPC_r / NPC_o > (1 + C_r + P_n)}$; then select simple replacement (or prepare better business case for asset elements of strategic importance), else
6. At Concept Design, if $\mathbf{NPC_r / NPC_o < (1 + C_r + P_n)}$; then select the resilient option, and include a short-form better business case as support.

7. Following design but prior to project construction, validate the following:
    - priority
    - cost
    - funding
    - decision ratios
    - risk

    Construction should expeditiously proceed if there are no major changes identified. If there are major changes, these should be resolved prior to execution of the work.