Single Infrastructure Failures: Capturing outage information for MERIT Modelling the Economics of Resilient Infrastructure Tool

R. Buxton
L. Timar
K. C. Wright
D. Mieler
M. C. Daly

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Tony Fenwick
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Contact organisation for inquiries and correspondence is GNS Science Ltd, 1 Fairway Drive, Avalon, PO Box 30368, Lower Hutt 5040.

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R. Buxton, GNS Science, PO Box 30368, Lower Hutt, 5010
K. C. Wright, GNS Science, PO Box 30368, Lower Hutt, 5010
M. C. Daly, GNS Science, PO Box 30368, Lower Hutt, 5010
L. Timar, GNS Science, PO Box 30368, Lower Hutt, 5010
D. Mieler, GNS Science, PO Box 30368, Lower Hutt, 5010

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ABSTRACT

The Economics of Resilient Infrastructure (ERI) research programme is a four year project funded by the New Zealand Government. The aims of the project are to study and quantify the impacts of natural hazards on infrastructure and to model the economic consequences of these impacts. To this end a new software tool called MERIT (Modelling the Economics of Resilient Infrastructure) is being developed as part of the program.

This report outlines the progress undertaken to date (March 2014) as part of Research Aim 1 in the ERI programme. Research Aim 1 is focussed on the development of 'Outage Scenarios' that can be used to better inform the MERIT approach. A large part of the work in Research Aim 1 has been focussed on 'single outage' scenarios where a single critical infrastructure provider is asked to outline a credible outage scenario which may have significant impacts for the community in a study area. The study area chosen was Auckland and the infrastructure sectors concentrated on were electricity, represented by Vector and Transpower, and water supply represented by Watercare. Spatial service outage data relating to the scenarios was collected through the use of workshops, meetings and other information provided by Vector, Transpower and Watercare.

This report outlines the outage scenarios and describes the process used to generate the data in a form suitable as an input to the MERIT tool. An assessment of the suitability of the approaches used is given as well as an overview of what the next steps in the research programme will be.

KEYWORDS

Infrastructure failure, economic impacts, MERIT, Auckland, water supply, power, interdependencies

1.0 OVERVIEW

The Economics of Resilient Infrastructure research programme is funded by the New Zealand Government. Funding of $2.8m over a period of four years was granted by the New Zealand Ministry of Business, Innovation and Employment from their 2012 funding round.

The programme aims to develop a new tool (MERIT=Modelling the Economics of Resilient Infrastructure) that will be able to quantify the economic impacts of infrastructure failure and examine post disaster recovery strategies. The output of the work will be an assessment across space and through time of the economic consequences of infrastructure failure, and business response and recovery options. Furthermore, existing economic models have a very limited capability for estimating the widespread economic impacts of events causing major disruption and multiple infrastructure failures. Existing economic models have a limited ability to capture complex system behaviour due to infrastructure interdependencies, business dependencies, business adaptation and shifts in spatial patterns. Hence the need for simulation tools that allow a better understanding of how economies behave both temporally and spatially during an infrastructure failure scenario and during the recovery phase. The eventual outputs are expected to be an enhanced capability to test policies (both local and central government) and to guide investment decisions.

The project is split into four research aims:

1. Infrastructure failure scenarios;
2. Business behaviours in response to infrastructure failure;
3. Economic modelling of the impacts of infrastructure failure;
4. Informing policy and investment through stakeholder engagement.

This report provides an overview of the work carried out in the first year of the project as part of Research Aim 1 which is principally concerned with developing an understanding of infrastructure failure in terms of service outage levels, temporally and spatially, and converting this into inputs required for the economic model.

The scenarios referred to in this report are single infrastructure outage scenarios. They are generally simpler in terms of scope than would be expected from a full scale major outage due to, for example, a volcanic eruption or earthquake. Single infrastructure failures have been chosen deliberately in order to allow the team to develop confidence in the techniques and procedures being developed prior to undertaking a larger scenario which is scheduled for later in the programme.

The focus of this report is to:

1. Summarise the service outage data acquisition both temporally and spatially from the failure of two utilities (water supply and power in Auckland) for input into the economic model, and
2. Discuss the methodology used to develop the data and make preliminary comment on its utility for subsequent scenario development.

Each failure is assessed in terms of:

1. 'Business as usual' (the impacts that would occur under current response plan procedures);
2. 'Mitigation', where a mitigation measure had been introduced to the network before the event (either hypothetical or real), for example, some redundancy in the network such as an alternative water main;
3. 'Adaptation', where different adaptation measures (other than those in 'business as usual') could be introduced during response procedures that would have a different impact than usual practice, for example, different water routing decisions.

This report also summarises key findings to date and outlines next steps to be taken to develop the methodology further.

Note that the focus of this report is on the methodology used to generate the data for the economic model and not on the events themselves that caused the outages. No analysis was undertaken of the likelihood of these events. The infrastructure providers have allowed details of the scenarios to be published within a confidentiality agreement that requires limited disclosure of the causes of the failure.

2.0 SPATIALLY EXPLICIT ECONOMIC MODEL

2.1 THE MODEL

In order to collect data to calibrate the economic model, a basic understanding of the model is required in order to tailor data inputs.

The following is a brief description of the model as developed by Research Aim three. More detail can be found in Smith and McDonald (2014) (*in press*).

In economics, the general equilibrium theory of market behaviour and the extension of the theory into computable general equilibrium models (CGE) with work by Johansen (1960) means that CGE models are now a well-established technique for describing economic behaviour. Despite its widespread applicability and use, however, it is often criticised for an inability to properly deal with such things as time-path trajectories and out-of-equilibrium dynamics (Barker, 2004; Grassini, 2004; Scrieciu 2007). The problem derives from the fact that the CGE model is concerned purely with the identification of the steady states of economic equilibrium and has little or no functionality when tasked with establishing the time paths between steady states or the dynamics of non-equilibrium economic systems. In the real world, economies do not tend to have steady states of equilibrium but are constantly changing due to the influence of complex sets of destabilising forces.

The spatially explicit model incorporates elements of CGE modelling as an approach but uses them in a systems dynamics context which is a modelling framework used for analysing and simulating complex dynamic systems.

One of the key aspects of turning a standard CGE model into a dynamic model is to explicitly model supply and demand relationships. The systems models can be viewed in terms of causal diagrams which incorporate feedback loops that tend to cause the system to naturally gravitate towards some equilibrium point. The establishment of these price-related balancing feedback loops is an essential component of this type of model.

The model is divided into six modules: commodities, industries, factors, government, savings and investment, and households. Each module has the causal relationships necessary to model the behaviour of the specific economic sector.

In most CGE models a static model is converted to a dynamic model by allowing key stocks, usually related to labour and capital prices, to be varied over time. The system dynamics approach adopted here allows a similar extension. The incorporation of dynamic elements into the model requires the use of two further modules, a labour and a capital module. The model incorporates a system of “information delays”, a concept from the system dynamics approach, that serve to imitate the action of decisions made in the feedback process. In particular the ’information delay’ seeks to incorporate gradual adjustments of beliefs that happen as a result of past experiences making similar decisions. This is done by incorporating a smoothing function that retains recent information but gradually loses past information as time passes.

Only the basic structure of the modules in the proposed economic model are described here. It is expected that the model and its results will be discussed in more detail in later reports.

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3.0 SINGLE OUTAGE SCENARIOS

3.1 INTRODUCTION

In order to test the economic model with spatial infrastructure outage data, two failure scenarios were developed with partner lifeline utility networks. The scenarios produced were single utility outages affecting Auckland; the first a widespread outage in the water supply network and the second a widespread electricity outage. The scenarios were considered as independent events. Different approaches were taken to develop the outage maps for these scenarios. For the water outage, a workshop was held with key representatives (engineers, managers, planners) for the supplier, and some data inputs for the workshop were derived by quantitative network modelling by the supplier. For the electricity outage, engineers were able to produce outage data using quantitative modelling. The water supply network must be pressurised, typically flows only one way (although it can be reversed by a hydraulic system reconfiguration), and contains reservoirs which delay outages in some areas while other zones are experiencing loss of supply. The water supply must be restored following spatial constraints as water mains are recharged and pressurised.

From each single-utility outage we require the following inputs for the economic model:

1. Spatial outage data for a significantly large failure and displayed over several time-steps to show maximum impact on end users and the spatial pattern of restoration with time. Restoration follows the utility's standard business as usual response to a network failure;
2. Spatial outage data as per (1) but with a mitigation option present which influences the spatial impact on end users and/or restoration time (see Section 3.3.2);
3. Spatial outage data as per (1) but with an adaptation option applied which influences the spatial impact on end users and/or restoration time (see Section 3.3.3).

3.2 OUTAGE IMPACTS AND MANAGEMENT

From our discussions with Lifeline Utilities it became apparent that the language and units used by utilities to describe network outages would not be appropriate for developing inputs for the economic model. The terminology employed by networks typically describes the supply in measurable units at given locations. The scenarios we were seeking would create measurable changes in unit supply, spatially. However, for the economic model it was necessary to establish what effect a change in supply units would actually mean for the end user of the utility service. For example, some drops in supply can be absorbed, or redundancy and rerouting can be applied, so that a large failure in one part of the network may not necessarily have any measurable effect on users. For the economic model we needed to capture the changes in supply as described by the utility companies in terms of "tipping points" or distinct steps in time when outage or limited supply was experienced by the end users within the area of interest.

3.3 Business as Usual (BAU), Mitigation and Adaptation

One of the purposes of the economic model is to determine the changes in costs and benefits for the wider economy for different infrastructure outage scenarios. One variable input to the economic model is the level of utility supply outage or failure. This variable can be controlled by changing the magnitude of the original utility failure; however, for this project we are interested in a more complex approach. We want to determine the wider economic impacts of various mitigation or adaptation activities that lifeline utilities may undertake.

3.3.1 Business as Usual

For the purposes of this project we describe a business as usual (BAU) approach to a large outage as the accepted and planned for process and policies that a lifeline utility would follow to restore their supply during a large outage event. The BAU approach includes Standard Operating Procedures (SOPs), business continuity plans (BCPs) and technical and operation restoration responses. Business as usual does not imply no outage has occurred, rather that there are already plans and activities established for the emergency outage response.

3.3.2 Mitigation

Mitigation refers to steps that may be taken by the utility in advance of an outage, consistent with commercial objectives, to reduce outage risk. The mitigation option might be a project or installation that is currently planned or one that is possible but not likely to be introduced. Mitigation does not include regular maintenance and upgrading of networks with time. The critical elements of the mitigation option for scenario development are that the option will result in change in the spatial outage pattern and restoration time. Because these scenarios are being developed to test the economic model we can in theory include mitigation options that are currently prohibitively expensive for the lifeline utilities in terms of cost/benefit. The inclusion of these theoretical mitigation options as we develop the model is not intended to provide a business case for any particular mitigation option a utility company may be considering. However, as the model is refined, it is envisioned that it will a useful tool for some utilities to determine the wider benefits of various mitigation upgrades that are being considered. Transpower already has a framework for undertaking economic analysis of outages in place. This work may help to provide further details in support of this established system.

3.3.3 Adaptation

Adaptation refers to steps that may be required, including by authorities, to deal with outage impacts after the outage has occurred. The application of an adaptation measure in the response to a major outage also applies the ’what if’ methodology and is designed to capture response activities or measures that would not typically form part of any business as usual emergency restoration activities. Adaptation measures could include ‘blue sky’ or non-standard activities that could alter the spatial distribution of the outage, or the restoration times to return to full service, for example different water re-routing decisions.

3.4 Auckland Water Supply Outage

Watercare, a Council Controlled Organisation (CCO) is the operator of Auckland‘s water supply and waste water networks. Watercare is an active and enthusiastic contributor to planning and projects undertaken by the Auckland Engineering Lifelines Group (AELG). Watercare were approached to participate in developing a pilot scenario for model testing

and they agreed to provide us with a major, but still credible outage event for Auckland, and information on the water distribution network. Because of the complexity of the water supply network, it was agreed that a workshop of engineers, planners and supply operations managers would be necessary to produce the data we required. Prior to the workshop we provided Watercare with a list of key questions or topics for discussion that we hoped to cover during the workshop and these are included in the report as Appendix 1. The workshop timetable is outlined in Appendix 2.

3.4.1 The Auckland Water Network

Metropolitan Auckland (which now includes Pukekohe) is serviced by two major dam systems and one river source. Western sources supply 24% of demand from five Waitakere dams, through the Huia and Waitakere treatment plants. The southern sources supply a large part of the remainder of demand from two major sources, Hunua and Waikato River. Hunua's supply draws from four dams and is conveyed through the Ardmore tunnels to the 350ML/day (mega litres per day) Ardmore treatment plant, and supplies 62% of demand. The Waikato River source (11% of demand) and treatment plant is currently undergoing capacity expansion and will undergo further staged expansion to meet future regional demand growth. A small underground source at Onehunga supplies approximately 3% of demand. Treated water is delivered from these treatment plants via trunk transmission water mains and service reservoirs into Auckland with branches into the local distribution network (AELP, 2014).

3.4.2 Scenario Assumptions and Background

Watercare has previously conducted internal exercises regarding large outages within their network; therefore, much of the process of working through impacts on the wider network was not new to the workshop participants. However, we requested an extreme but still credible scenario, with far greater impact than previously considered events so as to provide some clear spatial differences in end user experience across a wider area of Auckland.

Within these parameters, Watercare based the outage scenario on a failure of both Number One and Number Two Tunnels at Ardmore. This would result in an interruption to the southern Hunua's supply into Auckland for a two week period. As a result of the tunnel failures, the Ardmore water treatment plant would be out-of-service. This scenario is highly unlikely but provides data suitable for testing the economic model.

The average consumption of water for the area serviced by Watercare is 375 ML/day. In peak periods, daily use can be as high as 490 ML/day and low demand is around 330 ML/day. Any reduction in supply below the demand amount will result in a deficit and result in water storage reservoirs being depleted.

The impact of the loss of the southern trunk supply will not be immediately noticed by water supply users in Auckland, as the system includes many reservoirs throughout the city, and these reservoirs must be depleted before the pressure loss in the network results in a loss of supply to water users.

However, the loss of 62% of the supply would result in an immediate response from Watercare using existing crisis plans and actions. Action to remedy and mitigate the impacts of such a large supply failure would be initiated before any effects were experienced by end users

During the workshop, Watercare attendees described changes in water supply using their standard supply terminology of ML/day. For the project purposes we applied a set of ’demand classes’ (see section 3.4.3) to describe spatially how users would experience the water supply failure. Each suburb would be placed in the appropriate class at several points in time following failure, to map the change in water availability throughout the City.

The following assumptions were made during the workshop process:

- That the Western water supply, Waitakere sources (via Huia (125ML/day) and Waitakere (23ML/day) supplies) were available at maximum production throughout the scenario;
- That the Waikato source would be available at maximum production (125ML/day at the time of the workshop);
- That every endeavour would be made to ensure the main trunk lines would remain full and maintain pressure (even if reservoirs were depleted). This would be managed operationally through closing off reservoir supply to keep the mains system pressurised;
- That under a water advisory, daily use across Watercare’s network would be expected to drop from 375 ML/day to 330 ML/day;
- Savings of 75ML/day or daily consumption of 300ML/day would need to be achieved to avoid reservoirs and water mains drain down;
- In order to achieve the level of savings required consumers (non-essential services) of >50m^3/day would have compulsory ’do not use water’ restrictions imposed. Domestic consumers would be asked to restrict use to the maximum extent possible;
- Water restrictions would be applied across the whole of the region;
- Supply to domestic and essential water users (for example, hospitals, care facilities, schools) would be maintained to the maximum extent possible. However, due to geographical distribution of population and service reservoirs this may not be attainable in some areas and outage will occur.
- Reservoirs will be isolated out of service when the water level drops to a trigger point of 15%, to prevent drain down and complicated recharge/refill upon service restoration.

3.4.3 Classes of water demand experience

We classify the impact on water consumers (residential, government/ non-profit and commercial) so that the impact can be displayed spatially depending on local impact due to the water failure scenario. These classes include both physical impacts on the water supply, and operational restrictions that may be imposed in response to a supply failure. The demand classes are:

1. Full water (or reduced pressure but unnoticeable to users).
2. Water restrictions are in place: For residential customers this means the area is under a water advisory e.g., ’Please use less water’. This is an advisory for household use plus a restriction on outdoor use (e.g., watering gardens and washing cars). Full restrictions e.g., ’Don’t use water’ will be applied on a site specific basis to large users (typically industrial rather than community, i.e., industry not health services, consuming >50m3/day stated incident response). These ’no use’ restrictions would need to be imposed by Auckland Civil Defence Emergency Management and then initiated directly

by affected parties. Watercare does not have the resources to impose such a restriction in a physical sense. This will be a major communications exercise coordinated by Civil Defence with the advice and assistance of WaterCare Services Ltd who will provide customer lists. This is not a physical restriction but carries authority, and if necessary physical restrictions at specific sites could be imposed.

3. No reticulated water available (or pressure so low as to be considered unusable).

3a. Reduced pressure in distribution lines (not trunk). This demand class is not a standard response (see Section 3.3.3 Adaptation). This is not seen as being practical to implement because the water pressure can only be controlled by reservoir level.

4. Water is available but not potable. Normal pressure and supply available but water must be boiled or treated before consumption. This will be a post-event situation when water mains that were drained down are 're-charged' following restoration of supply. Water mains will be recharged with potable water, however due to the risk of water mains being contaminated when drained down/empty a Boil Water Notice will be issued as a public health precaution. This is important to understand, and will have significant consequences on some industries, such as food processing, which require a very high standard of water quality.

3.4.4 Public education and information

During the workshop it became clear how critical the role of water users would be in assisting Watercare to manage a large outage. The potential level of compliance with advice from authorities to conserve water or restrict use for certain activities is unknown, but agreed to be very influential in determining how long reservoir supplies could be maintained and whether some locations would experience complete water loss.

The following points summarise the workshop conclusions regarding public consumption. With immediate water restrictions and maximum compliance (and assuming legal issues do not immediately arise):

- If demand across the region can be reduced to <300 ML/day until the Aardmore supply can be restored Watercare can avoid emptying reservoirs – therefore there should be no outright loss of supply to any suburb although the difference in storage capacity across the region does not mean this can be absolutely guaranteed;
- Achieving this target includes relying both on public and industry savings (those industries typically using >50m^3/day) made under restrictions imposed by CDEM;
- Public support is critical – a publicity campaign outlining why restricted use is necessary would be very important. Watercare reported that the Auckland public have been responsive to previous water conservation advisories (for example during drought conditions experienced in 1993/94) (pers. comm. Brian Park, 2013; Turner, 1995).

3.4.5 Water use restrictions

Because the water supply is pressurised (under a reservoir's head), the flow is maintained even when available volumes decrease. A physical restriction would therefore be required to reduce the pressure of the system. A risk associated with the physical restriction of the water supply is the limits it would place on the ability of the Fire Service to use the mains supply for fire-fighting. For this reason, a physical reduction in the supply network is not the preferred, or practical response to a supply failure[1].

Watercare suggests there is also little research or evidence to show that a reduction in supply results in behavioural change with regards to water usage. It could be that a lower pressure results in people running taps for longer and using the same amount of water, rather than moderating their water use habits. Watercare suggested that there may be case studies from overseas that could be used to determine whether the inclusion of pressure reduction as a response tool would be realistic as part of their emergency planning. However, at the time of writing this report such a response is not physically possible due to the equipment (pressure reducing valves), manpower time and financial resources required to implement such a state in the timeframe of this scenario.

The other restrictions discussed in Section 3.3.3 include placing suburbs under water use advisories whereby residential inhabitants are encouraged to reduce water use and are prohibited from certain activities (e.g., washing vehicles). Watercare has found the public to be responsive to these measures in the past. However, the reductions in use required to prevent full reservoir supply loss in this scenario are extreme and it is unknown whether they could be achieved. To prevent draining of the reservoirs, water use would need to drop to 300ML/day. The expected savings from voluntary water restrictions are likely to be (based on past events) a drop in usage from 375 ML/day to 330 ML/day. Therefore, a shortfall will likely still occur. Reservoir storage in a number of areas is small in relation to population served. It is therefore likely that in some areas e.g., East Coast Bays, it will not be possible to maintain storage and supply.

To combat this shortfall, restrictions could also be imposed on businesses which are not necessary for public health and safety. Watercare has a list of customers and priority users which includes emergency and public services (hospitals etc.). These users would not have restrictions imposed upon them, while other commercial entities could face restriction orders. These orders could be physically enforced (through shutting off supply to industrial sites) if necessary, but in the first instance would be mandatory orders from CDEM authorities.

3.5 OPERATIONAL RESPONSE TO A MAJOR FAILURE SCENARIO

3.5.1 Business as Usual Operational Response

Watercare agreed that any major failure would result in a rapid and region-wide response rather than focussing just on the most affected locations. This response would typically take the form of region-wide water use advisories; however the severity of this scenario would result in more restrictive measures being applied to water users. The possibility of reservoirs draining and loss of supply to many suburbs would require a comprehensive response.

[1] Pressure reduction is a long term capital intensive strategy for achieving water use reduction, takes extensive planning and zone management to implement with a number of implications e.g., Fire fighting capability.

These measures would take the form of water advisories for residential users to conserve water wherever possible and to have restrictions placed on water use for outdoor activities such as watering gardens or washing vehicles. This advisory would be placed over all suburbs supplied by Watercare and would be accompanied by a publicity campaign with information on water conservation and the seriousness of the problem. These measures would be in place within six hours of the major outage.

In addition to restriction advisories for residential users, CDEM authorities, would most likely place mandatory restrictions on many commercial users, particularly large industry. This restriction would not affect large campuses providing essential services such as hospitals or schools. Watercare have a database containing all of their major users throughout the region, and details of their typical water use. These large organisations can be contacted directly and advised of restrictions and in the event of non-compliance could have their supply physically shut-down. It was estimated that this restriction would be imposed within 24 hours of the failure.

It is hoped that the savings in water use arising from advisories and restrictions would be adequate to prevent depletion of reservoir supplies. To achieve this, water usage throughout the region would need to drop to 300 ML/day; the amount available after the loss of the Ardmore contribution to the southern supply. Based on past experience Watercare suggested that reductions would be likely to result in daily usage dropping to around 330/ML/day, which would mean a shortfall between available supply and usage and therefore the deficit would result in reservoir drainage.

In summary, the response by Watercare (in association with CDEM) would include the following measures:

- Time (T) = 0; Failure
- Time (T) = 6hrs; Water restriction and advisory over region with likely reduction to use of 330 ML/day
- Time (T) = 24hrs; 35 ML/day shortfall (closing commercial within 24hrs)

These time intervals were identified at the workshop as the ’tipping points’ or distinct steps in time when a change would be experienced by the end users within the areas of interest.

3.5.2 Mitigation options

Watercare are currently in the process of upgrading and expanding their network, all of the treatment reservoirs, and transmission capacities. This expansion includes an increase of supply of water from the Waikato River from 125 to 150 ML/day in 2014 and a further increase in Waikato sourced supply from 150 to 225 ML/day in 2025. As well as the increase in supply, an increase in storage capacity is underway. This involves a total of 200 ML extra storage between five reservoirs across Auckland (Redoubt Road, Runciman, Albany, Schnapper Rock and Titirangi). The assumption that this planned work is complete at the time of failure provides the opportunity to explore a mitigation option in the MERIT model. While a major objective of this additional capacity is to improve the security of supply it is largely driven by growth in demand (population). System capacity and security will always be under growth pressure in Auckland with a projected population increase to almost 2 million by 2031 (Statistics NZ, 2014).

3.5.3 Adaptation options

A 'Blue Sky' (i.e., not seriously considered currently as part of any emergency response but theoretically possible) measure was briefly discussed. This was the decision to physically switch some suburb locations on and off to preserve reservoir volumes. It was stated quite clearly that such an extreme measure would be a political decision and not made by Watercare. The Auckland Medical Officer of Health has this authority and would work with Auckland Council Civil Defence Emergency Management. Such a response could cause engineering problems and require a large labour force on site at points throughout the network to manually implement. There is a mix of remotely (trunk transmission only) and manually operated valves throughout the network (pressure zone isolations would be implemented i.e., impacting specific defined suburbs).

This measure would result in engineering problems due to air entering the system when the water mains drain down. This results in complications when re-pressurising the network when supply is restored. There is the potential for damage to the infrastructure when decreasing or increasing pressure. Locations with emergency facilities such as hospitals would have to remain supplied, while neighbouring suburbs would be without water. Homes close to emergency facilities would therefore benefit from the shadow effect of being on the same local network as the emergency facility. This inequality of service throughout the city would also make such a response politically unpalatable and would need strong public buy-in and acceptance of the gravity of the water supply issue.

3.6 IMPACTS EXPERIENCED BY WATER USERS

3.6.1 Business as usual

Because of the pressurised system, users would not notice any difference in the quality or quantity of supply from the tap under these restrictions. However, assuming behavioural change in response to advisories, it is expected that residential users would within six hours be affected by undertaking compulsory water conservation activities within homes and restricting water use.

Commercial users, particularly large, non-emergency/community users would experience significant impacts within 24 hours. The range of economic impacts that could result from loss of water supply to businesses will be explored using the MERIT economic modelling software. However, Watercare identified some obvious impacts to Auckland businesses that we mention here. There are likely to be severe impacts on the food processing industry, and any enterprise that requires large volumes of water for cooling. Employers are required to maintain a safe and healthy workplace. Water restrictions could limit the ability of many businesses to provide adequate hygiene for workers.

These impacts and advisory measures will be experienced within 24 hours after the water supply failure. However, the most severe impacts will occur due to the expected shortfall between supply and demand that results in reservoir drainage. Watercare estimates that some reservoirs in the region could be depleted 100 hours (or approx. four days) after the scenario outage at T=0. The areas which would lose supply earliest are those not serviced by the Western, Huia or Waikato supply sources. First outages would affect some eastern suburbs, and within another twenty four hours suburbs on the isthmus (including the Central Business District) and northern suburbs would also have no supply. The supply to Auckland

and North Shore hospitals would be maintained through operational decision-making to keep certain water mains supplied at the expense of others. This would partly be managed by maintaining the Western supply north rather than into the isthmus.

3.6.2 Restoration process and timeline

Within 124 hours, or approximately five days, a number of central, northern and eastern suburbs would be without reticulated water, and there are no alternate supplies of sufficient quantity to maintain even restricted levels of service. Watercare estimates that with such a severe outage, the repairs to the Ardmore tunnels would take two weeks from T=0. Following the tunnel restoration, the reticulation lines would need to be recharged and pressurised, and it is estimated that bulk water restoration, (northwards), to the first (southern) suburbs would occur after 14 days; reach the CBD after 16 days and the North Shore after 24 days.

After bulk water is restored to each suburb, a further 24 hours is required to reach full reticulation to homes, and initially the water supplied will be subject to Boil Water Notice. This is because while water supplied from treatment plants will always be potable and meet New Zealand standards, system drain down in water mains and reservoirs increases the risk of contamination. A Boil Water Notice would in this case be issued by the Medical Officer of Health in suburbs that had run out of water. Water quality will be restored through gradual flushing of the system. It is estimated that following reticulation to users, supply will be required to be boiled for up to a further 14 days, with return to potable quality following this period. Water restrictions will be lifted once bulk supply is restored and water quality can be assured to NZ Drinking Water Standards (NZDWS). Quality assurance will be confirmed by laboratory testing of water i.e., 3 consecutive days clear of bacteriological contamination. Some industries have an additional water quality testing regime which would come into effect, introducing further delays to the restoration process.

In summary, all of Watercare's residential and non-essential commercial customers in Auckland will experience some impacts on water supply. For many suburbs this will be in the form of restrictions, either voluntary or mandatory, but for some locations there will be supply outages. These outages could last between 12–20 days depending on location, and there will be a further two weeks of supply requiring Boil Water Notice following re-supply to those locations which have experienced outages. Figure 3.1 shows the timeline of water loss and restoration for the Ardmore tunnel failure scenario.

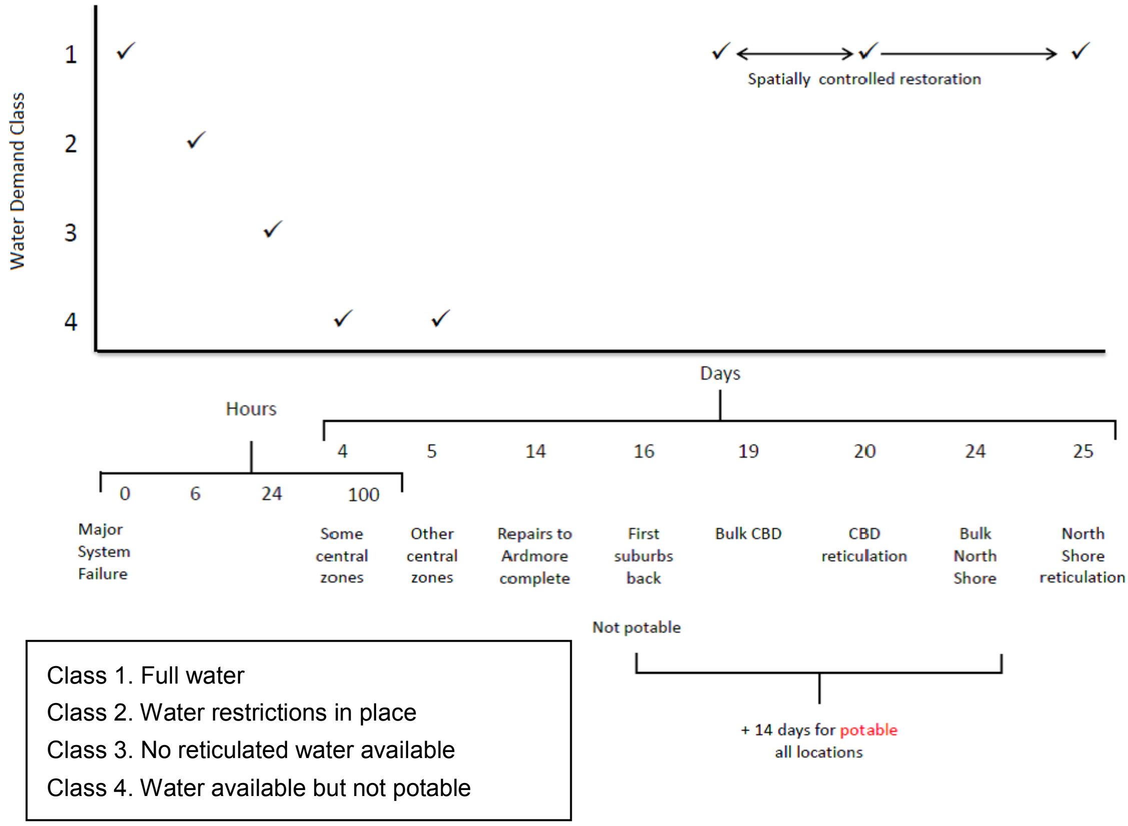

Figure 3.1 Water supply loss and restoration timeline following a major outage located at the Ardmore tunnels on the southern supply. Note: the timeline is not a linear scale.

3.6.3 Mitigation

If the program of upgrades and expansion to the network due for completion in 2025 were already in place when the scenario failure of the Ardmore tunnels occurs, the expectation is that there would be no loss of water to any suburb. However, to guarantee there is no supply loss to consumers, water advisories could still be imposed to encourage consumers to prudently manage a reduced supply. Therefore, to model the mitigation option in the MERIT model we would impose an advisory restriction across the suburbs supplied by the Watercare network. Restrictions on water use by large, industrial consumers would not be imposed unless the risk of reservoir drainage was to occur. However industrial users could be encouraged to be good corporate citizens and play their part in water conservation.

Watercare, like all Infrastructure owners will always be under pressure to maintain capacity to meet growing demand.

Although the inference of this section is that by capital expenditure the effects of this scenario can be avoided, this must be tempered since capital expenditure is usually in response to growth, security of supply and asset renewal rather than avoidance of scenarios such as that explored here. Only if analysis shows that this scenario is totally unacceptable in a public health sense and politically would dollars be spent. Which, in itself adds value to the work undertaken here.

3.6.4 Adaptation

The Blue Sky adaptation option for new water supply sources was considered to be complex and expensive to implement and would in all likelihood create significant maintenance problems within the Watercare network. For these reasons, restricting supply to certain suburbs through geographic shut-downs was not considered to be a serious option for reducing the impacts of a water supply failure. It is more likely that adaptation measures would be applied by the consumers themselves, or on a large scale by Auckland Civil Defence Emergency Management, should large amounts of emergency water be required. Options for large volume emergency water deliveries could be water delivered by truck, rail or coastal shipping, although the logistics of this may be a major hurdle and there could be possible knock-on effects where out of region sources rapidly become overtaxed. Consumer adaptation methods could include rainwater harvesting and the use of non-potable sources for some purposes.

Desalination/wastewater recycle are alternates that could alleviate capacity shortfall. These alternatives require large capital investment and long lead-time to deliver as well as a significant operating cost – and are large consumers of power. These would only be considered under conditions of extreme supply shortfall in NZ.

3.7 AUCKLAND POWER OUTAGE SCENARIO

Transpower is the electricity transmission company providing the bulk electricity supply to the Auckland area. Vector is the distribution lines company that distribute power from the main Transpower delivery points (Grid Exit Points (GXPs)) to the users. Both Transpower and Vector have been highly supportive of this work and have sought to assist in providing appropriate realistic but damaging scenarios. Large parts of this section of the report are taken from, or are substantially based upon, work prepared by representatives from Transpower and Vector and the authors thank these representatives. The documents used in this section are Todd (2013) and Welch (2013). During the concept stage it was proposed that the scenarios would be organised to satisfy Business As Usual, Mitigation, and Adaptation cases. In the case of the electricity this was difficult to organise and we received three possible failure scenarios from Transpower which were passed onto Vector to evaluate the effects of the outages at their distribution level. From the three scenario's presented, one of the scenarios produced credible outages in keeping with the intent of this exercise. Vector provided two possible outage maps for this scenario, one with alternative power generation and one without.

Vector also identified two scenarios which impact on the continuity of water and wastewater supplies. These scenarios were associated with the loss of Mangere or Takanini GXP. These would take out the Mangere Waste Water Treatment Plant and the Ardmore Water Treatment Plants respectively, additionally the loss of the Mangere GXP would directly affect Auckland International Airport with associated economic impacts. These scenarios were not developed further as part of this report, but may be at a later stage of the research programme.

3.7.1 The Auckland Electrical Network

Auckland combines high load demand with a relative lack of local generating capacity, with the result that most of Auckland's electricity is supplied from the transmission grid to the south. Otahuhu and Southdown power stations are the only local sizeable generating facilities, but can supply just 30% of Auckland's needs.

The power supply into Auckland comes from eight 220kV lines traversing three different routes and terminating in Otahuhu and Pakuranga. The transmission system within the region has three layers, Transpower 220kV system, Transpower 110kV system and the Vector distribution network (AELP, 2014).

Table 3.1 Auckland power failure scenarios.

Scenario type	Name	Transpower reference	Otahuhu generation
BAU	Loss of all 220kV north of WKM (Whakamaru)	Scenario 3	No
Mitigation	Loss of all 220kV north of WKM	Scenario 3	Yes
Additional	Mangere, Takanini GPX	N/A	N/A

3.7.2 Transpower scenarios

Transpower was approached to develop some failure scenarios that would substantially affect their transmission network, both in terms of the spatial extent and duration of the outage. Initially three failure scenarios were put forward, one involving the partial loss of a substation and two involving the loss of transmission lines.

In the steady state during normal operation, power is generated in order to match demand and transmission and distribution losses in a balanced fashion. This is to maintain system frequency at the nominal 50Hz. Power system planners and analysts use load flow programs to analyse this steady state generation/demand balance to ascertain if capacity upgrades to the transmission network are required.

During fault conditions, such as the loss of a transmission line, the generation and load balance is disrupted. This can affect the network frequency and voltages and lead to major load loss if sufficient measures are not put in place to restore this equilibrium. The Auckland region is considered to be what power system engineers call “voltage constrained”. This generalised term means that in Auckland, certain transmission asset outage conditions can result in the local voltage collapsing quickly and may result in a widespread regional outage and consequent loss of load.

For expected events, such as transformer and transmission circuit outages, the network should recover post-event to its steady state condition and is planned to do so. However, for unexpected events such as the multiple transmission line outages modelled in this scenario, there is likely to be a fast regional voltage collapse and subsequent loss of load in Auckland and Northland. It is assumed that following the event and major loss of supply, that the load can be restored in a staged manner, however, this analysis isn’t concerned with power system dynamic behaviour.

The analysis is based on what may be supplied in the steady state, post-event on a temporary basis until any damaged transmission assets are replaced or repaired.

3.7.3 Scenario 1, the loss of the Penrose substation

The basis of this scenario was a hypothetical severe wind event (tornado or similar) that severely damages the Penrose 110kV substation assets (Figure 3.2).

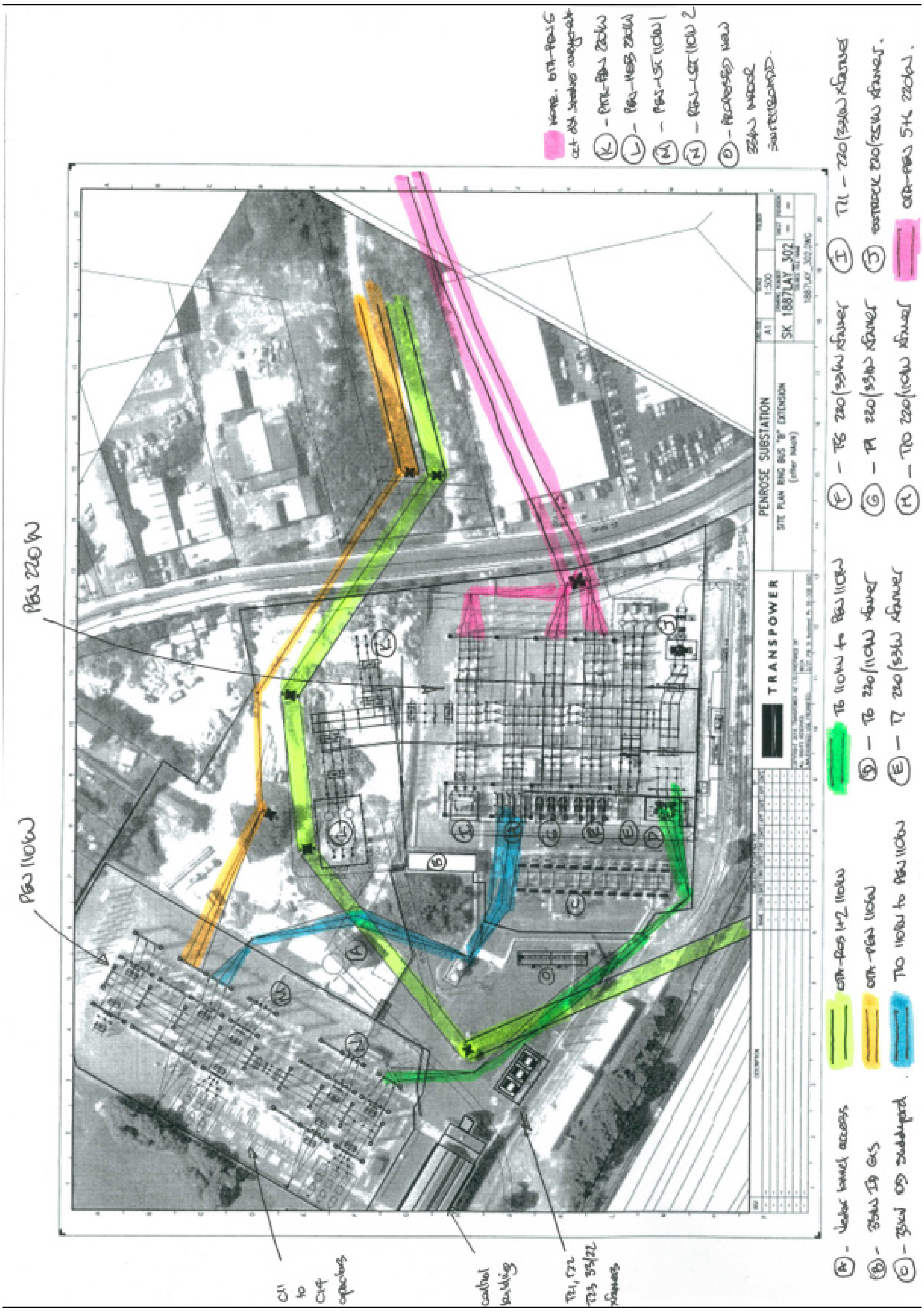

Figure 3.2 The Penrose substation with colour coding reflecting the different transmission lines. (Source: Transpower).

A substantial number of major components in the substation are expected to be affected by the hypothetical windstorm event.

The modelled result of this scenario is that there will likely be an immediate loss of the 110kV supply at Penrose. The scenario as presented assumes that the 220kV, 33kV and 22kV supplies remain operative.

Figure 3.3 shows the extent of the distribution from Penrose with the 33kV circuits shown in blue, 22kV circuits in yellow and 110kV circuits shown in grey. The grey 110kV circuits to the CBD are the ones affected by this outage scenario. However, Vector has an alternative 110kV circuit from Transpower's Roskill GXP into the Liverpool St substation and as of June 2014 will have a new Transpower GXP at Hobson St capable of supporting the CBD from the north via Transpower's GXP at Albany.

The 110kV damage at Penrose is also assumed to have damaged the 110kV supply to Roskill GXP. However, because the 220kV network remains intact, it is possible to supply Roskill (at least in part) from the north via the 110kV circuits from Henderson and Hepburn Rd GXP's.

Using desktop analysis, the load at risk includes both the Roskill (Figure 3.4) and Penrose/Liverpool St loads (Figure 3.3). This includes Roskill 22kV (150MW), Roskill 110kV (75MW) and Penrose/Liverpool St 110kV (135MW). The total load at risk is then approximately 360MW at peak, but through reconfiguration of the transmission and distribution networks, this load is expected to be restored relatively readily.

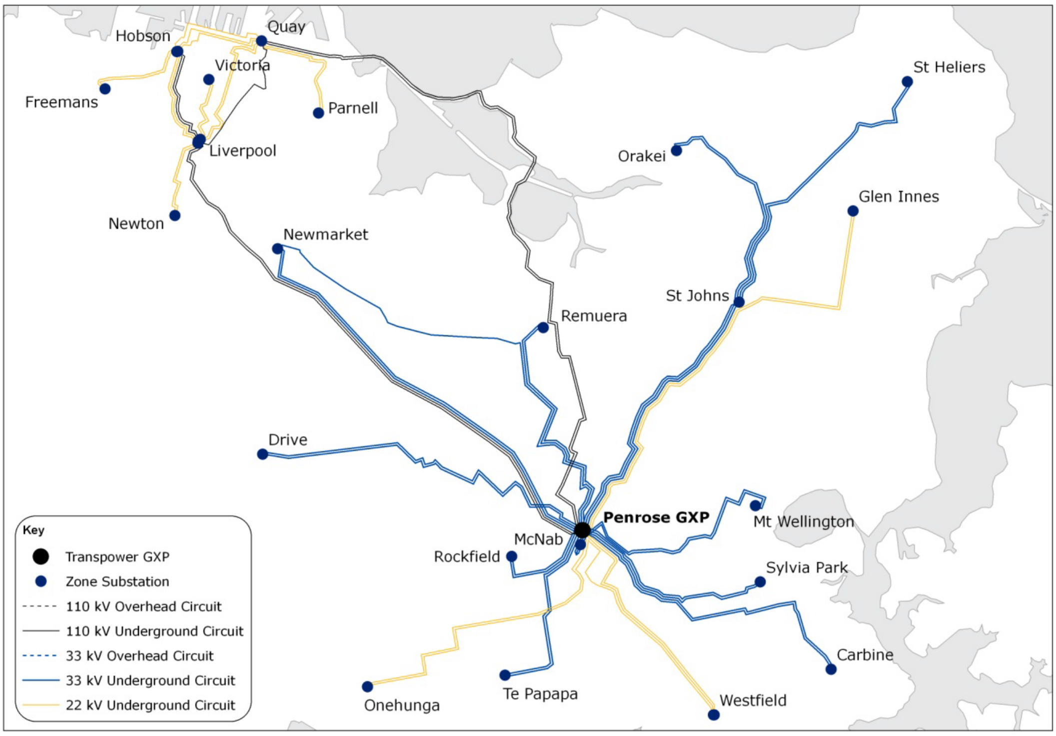

Figure 3.3 Existing and proposed supply arrangements in the Penrose area (Source: Vector 2012 Asset Management Plan – Section 5 pg. 81).

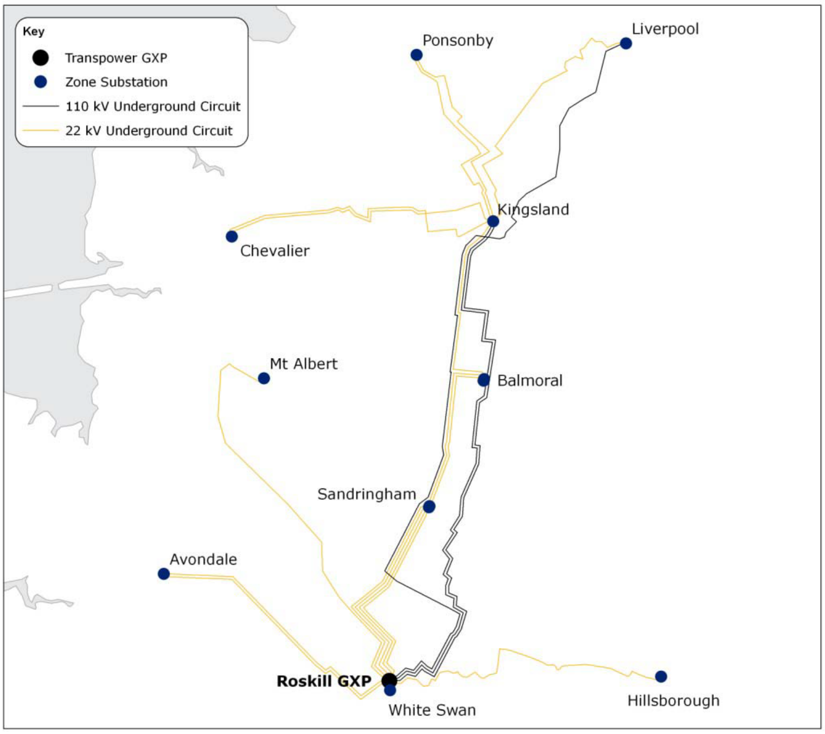

Figure 3.4 Existing and proposed supply arrangements in the Roskill area (Source: Vector 2012 Asset Management Plan – Section 5 pg. 86).

3.7.4 Scenario 2, the loss of OTAHUHU-WKM A, B and C transmission lines

In this scenario, even with the three Otahuhu-Whakamaru A, B and C lines (Figure 3.5) out of service for any length of time, the remaining transmission network can supply the Auckland and Northland regions at both N and N-1 supply security[2]. This is a surprising result and suggests that following the installation of the recent 220kV line between Whakamaru and Pakuranga, that the transmission supply security into Auckland is extremely robust[3].

In summary the modelled transmission outage event (loss of the Otahuhu-Whakamaru A, B and C lines) will result in significant lost load, probably region wide, but this will be temporary and is likely to be restored easily within a 12–24 hour period.

[2] N and N-1 denote levels of supply security. N-1 indicates that the power system is in a satisfactory operational state with 1 asset is out of service (from a pre-defined list such as circuits and transformers). N-security means that if an outage occurs the power system may not be in a satisfactory state meaning corrective action such as load shedding will have to occur. This result was obtained using the Winter Peak demand in 2016 after the NIGUP and NAAN projects in Auckland are commissioned. The demand prediction is from the Transpower 2012 Annual Planning Report.

[3] It was also assumed that only 3 coal fired units at Huntly were operating at the time and the OTAHUHU CCGT generator was out of service. This result indicates that the new 220kV and NAAN cable (post 2016) have significantly improved Auckland security of supply resilience to transmission line outage events.

Figure 3.5 Otahuhu-WKM A, B and C 220kV transmission lines highlighted and the recently commissioned BHL-WKN 220kV marked as D (Scenario 2 outage – loss of Otahuhu-WKM A,B and C) (Source: Transpower).

3.7.5 Scenario 3, the loss of all 220kV lines north from Whakamaru

This extreme scenario could be caused by one of the following circumstances:

- Forest fire at or near the Whakamaru generation station that affects all of the 220kV transmission circuits heading towards Auckland.
- Eruption of Mt Ruapehu, Mt Ngauruahoe or Mt Tongariro with significant ash emission coupled with north-westerly air flow leaving ash deposits on transmission lines. This subsequently leads to transmission line trippings and requires many assets to be cleaned.
- Eruption of Mt Taranaki with significant ash emission coupled with westerly air flow leaving ash deposits on transmission lines. This subsequently leads to transmission line trippings and requires many assets to be cleaned.

An analysis of the likelihood of these events was not undertaken.

Following this outage there will likely be a region wide voltage collapse due to circuit overloads and fast voltage drop. Only two major 220kV circuits will subsequently remain in service into Auckland, namely the Huntly-Otahuhu 220kV circuits. There are various circuit ratings along this line but they are limited to 678/688/724MVA[4] at post-event N-1 supply security and 1372/1418/1488MVA at N-security.

If we assume that post event the Huntly power station can be fully operational, and that the 110kV network is split at Bombay to allow Hamilton to be partially supplied from the 110kV network, then we can make some reasonable assumptions about what power may be supplied into the Auckland and North Albany regions.

The effect of voltage drop in the transmission network will also be factored into the calculation of likely power that may be supplied by the two remaining 220kV transmission circuits. The remaining transmission into Auckland has the following MVA ratings:

- Huntly-Otahuhu 1 and 2 circuits – 1372/1418/1488 MVA @ N security
- Huntly-Otahuhu 1 and 2 circuits – 678/688/724 MVA @ N-1 security

It will be assumed that 10% of the transmission capacity will be used to supply the GXP MVAr's[5] and to account for transmission circuit voltage drop. In the study cases used in the Transpower 2012 Annual Planning Report, the summed Auckland (AKL) and North Auckland and Northland (NAAN) regional load in 2016 has a predicted value of 1634MW and 975MW respectively.

Table 3.2 summarises the estimates of peak load and energy that may then be served for the N and N-1 post-event supply security levels (red columns), with and without the Otahuhu Closed-Cycle Gas Turbine generator (CCGT). Also, the percentage of peak demand has been calculated (green columns) and the percentage of energy that may be supplied over a typical winter peak week day (blue columns).

Figure 3.6 highlights the difference between the two estimates presented in Table 3.2.

4 Relates to Summer/Shoulder/Winter period ratings.

5 MVAr is the unit of reactive power. The natural effect of loaded transmission circuits is to affect the power system voltage "pressure" at the load end. Low voltages may require either compensation to increase voltage pressure or reduced power transfer along the circuits

Table 3.2 Results of post-event supply into the AKL and NAAN regions for transmission outage scenario 2 (Source: Transpower).

Generation conditions	Load served in AKL and NAAN regions (MW)		% peak demand (MW) able to be served at each GXP (%)		% regional energy (MWh) able to be served (%)	
	N	N-1	N	N-1	N	N-1
Without OTAHUHU CCGT	1350MW	650MW	50%	25%	75%	40%
With OTAHUHU CCGT	1730MW	1030MW	65%	40%	90%	60%

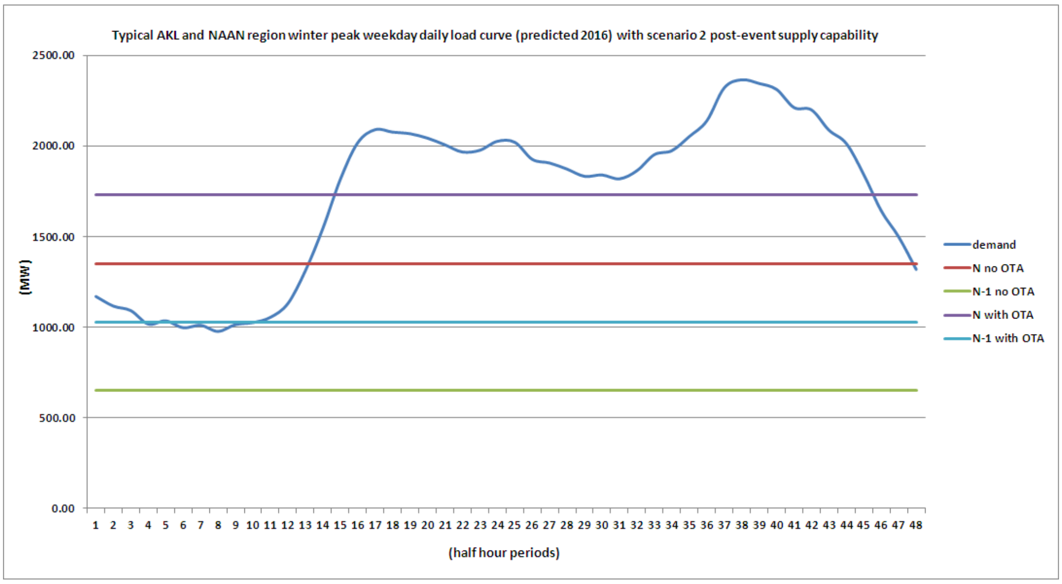

Figure 3.6 Typical 24 hour daily winter load curve for AKL and NAAN regions (Source: Transpower).

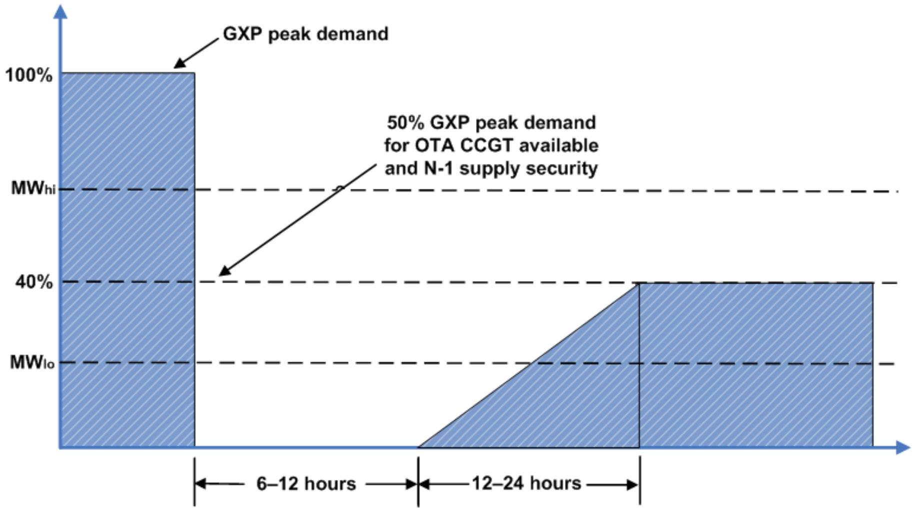

Figure 3.7 General load restoration at each GXP for Otahuhu CCGT available N-1 security level (Source: Transpower)

Figure 3.7 illustrates the general load restoration profile at each Grid Exit Point (GXP) following the modelled event.

The first 6 to 12 hours is likely to involve a major investigation by Transpower to ascertain how much of the transmission network is subsequently available. Then the System Operator in conjunction with the local generators, who operate the Otahuhu CCGT and Southdown, and the local lines companies, will start to reconnect load in a staged manner (the 12 to 24 hour period in Figure 3.7[6]). Depending on the availability of the Otahuhu CCGT and Southdown, and the transmission security level imposed by the System Operator, a certain level of coincident GXP demand will be able to be supplied.

The Hi and Lo MW levels in Figure 3.7 will be defined by the lines company (Vector, Northpower or Top Energy) and could be as high as the peak demand at each GXP to zero MW, so long as the combined MW totals do not exceed the figures in Table 3.2 (red and green columns, depending on security levels and availability of Otahuhu).

3.7.6 The Vector scenarios

Vector, the distribution company for the Auckland region, was presented with the outage scenarios devised by Transpower and asked to analyse the impacts that the scenario damage would have on their operations.

Only scenario 3 (Section 3.4.4) was identified as providing significant supply constraint issues for Vector (Figure 3.8 and Figure 3.9). Vector's strategy is to identify a list of critical customers where supply cannot be interrupted and to implement a regime of 3 hourly rolling outages. The total length of the outage would be largely dependent on the restoration of the Transpower supply to the GXPs.

Vector's list of critical customers includes critical facilities such as hospitals. Consideration of a broader civil defence emergency management response that might be required was not undertaken. Vector independently provided the network analysis which was a different approach used than the mixed network analysis and workshop approach used to generate the water supply outage data (section 3.4 above). The workshop provided a useful means to discuss wider issues such as community impacts and likely civil defence responses.

3.7.7 Mangere and/or Takanini grid exit point outage

Vector suggested that two scenarios that have implications for the continuity of supply of potable water and wastewater are the loss of either the Mangere GXP or the Takanini GXP. The loss of Mangere GXP affects the pumping capability of Watercare's Wastewater Treatment Plant at Mangere as well as the supply to the airport. Loss of supply to the Takanini GXP impacts the Ardmore Water Treatment plant.

A power failure of minutes only is sufficient to cause problem with the treatment processes at water treatment plants. Standby generators would be the only option for backup power. Ardmore & Huia WTP's have on site auto start standby generators with up to 5 days fuel storage.

[6] As an example, in 2006 when the Otahuhu substation outage occurred, it took nearly 8 hours to re-connect the 800MW load. The issue that caused the outage was, in this case identified quickly, enabling load to be restored within the 8 hour period.

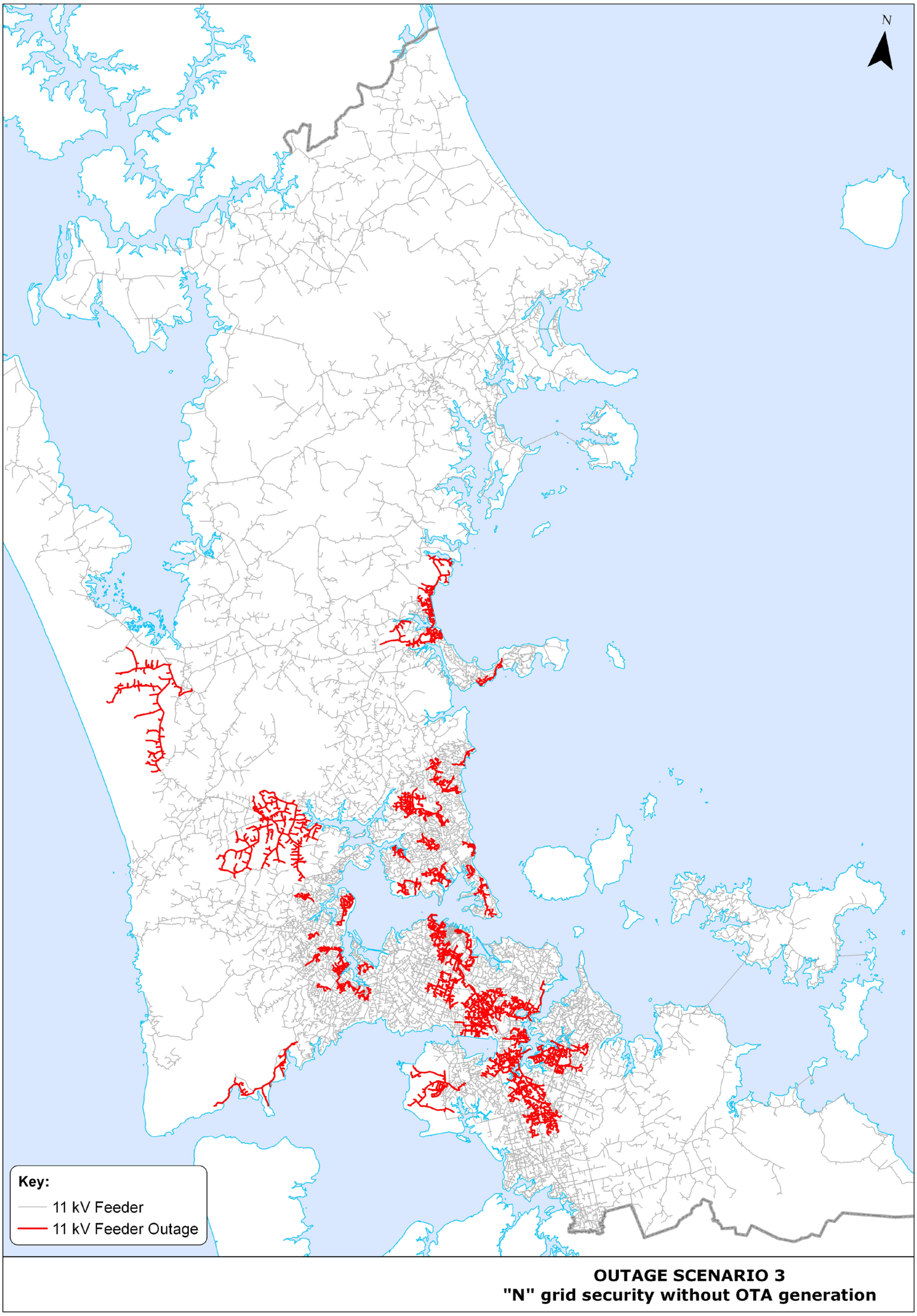

Figure 3.8 Extent of Vector electricity outages without Otahuhu generation (Source: Vector 2013).

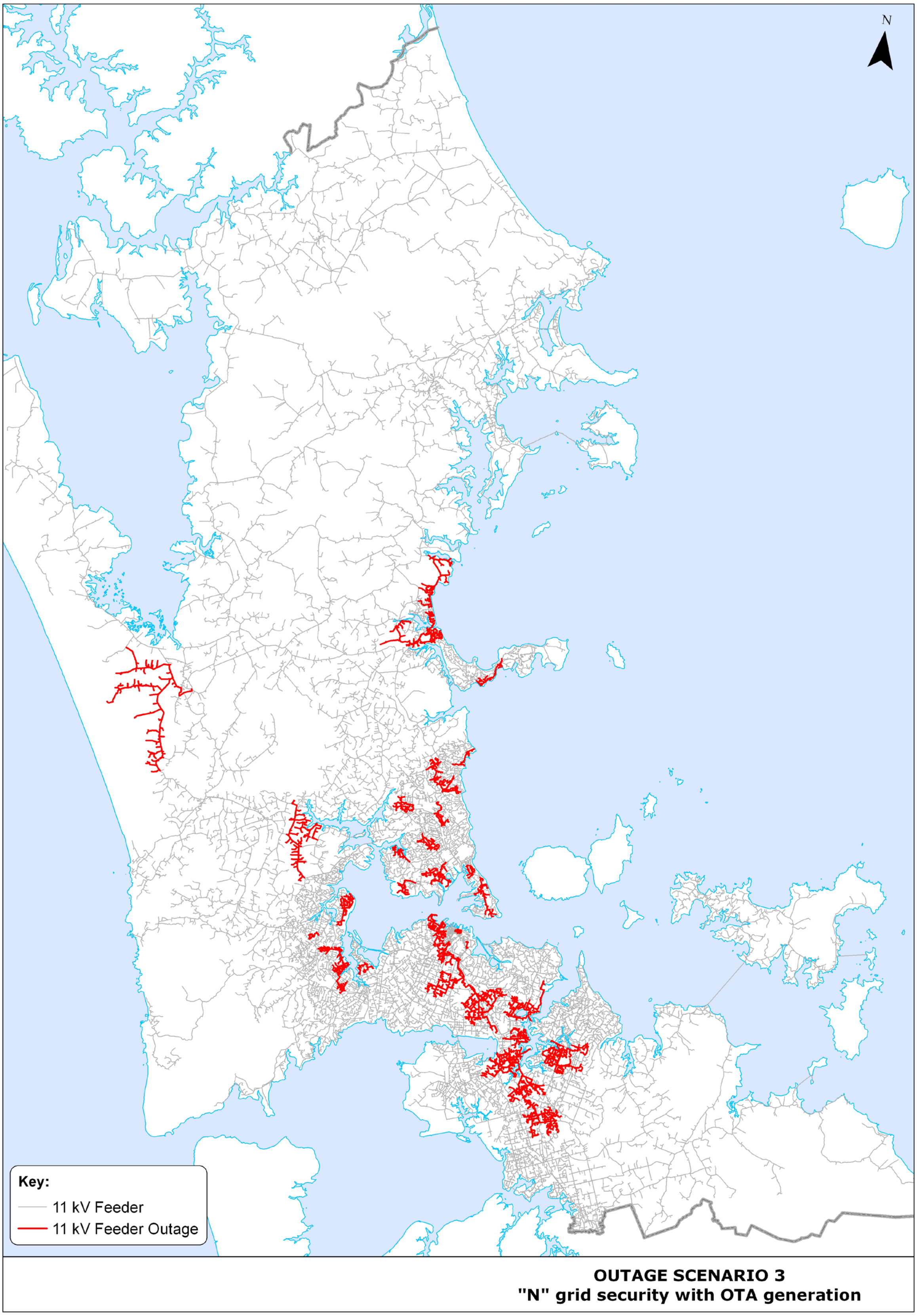

Figure 3.9 Extent of Vector's electricity outages with Otahuhu generation (Source: Vector 2013).

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4.0 SPATIAL OUTAGE DATA

The outage maps developed for each infrastructure scenario need to be captured in an appropriate GIS format for use in the spatially explicit economic model. In this section, we document the geographic data we acquired for this purpose and the major data processing steps required.

4.1 AUCKLAND WATER SUPPLY OUTAGE

The outage information for the Auckland water supply scenario was captured on physical maps during a workshop with key representatives from Watercare. These maps describe how water users in various suburbs would experience the water supply failure.

Following the workshop, we received several GIS shapefiles from Watercare. Some of these define Water District Zones and Water Balance Zones within the Auckland Region; others represent important elements of the water supply network (including transmission system trunk water mains and key facilities such as water treatment plants, reservoirs, pump stations and control valves). Finally, we were also provided with the locations of large commercial consumers of water (over $50m^3$/day). As described in the previous section, these consumers, with the exception of critical facilities, would have mandatory water restrictions placed upon them to meet the required target.

4.1.1 The classification of outage impacts

Watercare suggested that we use balance zones as the basis of modelling the water supply scenarios. These zones contain more geographic detail than the physical maps we relied on for capturing outage information during the workshop: typically, a suburb consists of several Water Balance Zones. In a few instances, a balance zone overlaps with multiple suburbs. In such cases, we used the majority classification of the zone to define the outage consumers within the zone might experience.

The assumptions underlying this scenario are discussed at length throughout section 3.3. Some of the demand classes identified in that section are indistinguishable from the perspective of the economic model. For example, a water advisory coupled with a restriction on outdoor use creates some inconvenience for water users, but has negligible economic impacts – neither households nor businesses would be affected in a measurable way, so we do not differentiate between this demand class and ‘full water’. Therefore, the outage maps we create for the model are based on a slightly different classification of impacts. The classification is as follows:

1. Potable water. This class applies when potable water is available in a balance zone (whether at full pressure or reduced pressure). As discussed above, this class also applies under a water advisory and ban on non-essential use.
2. Water subject to a Boil Water Notice. Under this class, water is available to consumers and is safe to consume after boiling. Businesses in the hospitality sector (other sectors – food processing) may be unable to operate. There are no restrictions on the quantity of water available.
3. Water restrictions. Restrictions are imposed by an authority (CDEM) and they specifically affect large water users – in this scenario consumers $>50m^3$/day. These businesses most likely will be unable to operate.

4. No water. This class applies when no reticulated water is available in a balance zone. It affects both households and businesses in the area.

4.1.2 Timeline and the specification of outages in GIS

The outage information specified by these modified demand classes was coded into the attribute table of the polygon feature class that represents the Water Balance Zones. Although the spatially explicit economic model takes a raster map as an input, coding the information directly into the feature class retains full flexibility for generating raster inputs at any desired point in time after the initial infrastructure failure.

It is worthwhile to recap key aspects of the infrastructure outage and the restoration process in terms of the modified demand classes. Table 4.1. provides illustrative examples.

All balance zones start out with potable water (class 1). Although the water advisory issued after six hours may lead to some conservation, it is not expected to measurably impact businesses or residents, so it does not affect the classification.

Restrictions are imposed on the water use of large consumers throughout the area supplied by Watercare after 24 hours. Therefore, each Water Balance Zone moves from potable water (class 1) to water restrictions (class 3) at t=24. This is the value shown for each zone in the second data column of Table 4.1.

Table 4.1 The pattern of outage experienced in three Water Balance Zones (hours) (Source: Watercare)

BALANCE ZONE	CLASS 1	CLASS 3	CLASS 4	CLASS 2	CLASS 1
Hobson	0	24	124	432	768
Konini	0	24	100	576	912
Maungawhau	0	24	-	-	432

Some centrally located balance zones lose reticulated water within a few days of the Ardmore tunnel collapse – the corresponding demand class is “no water” (class 4). For example, after only 100 hours (t=100), Konini is among the first zones to run out of water. The Hobson zone loses reticulated water a day later (t=124). Full restoration to potable water supply takes a considerable amount of time: 32 days (t=768) in Hobson and 38 days (t=912) in Konini. However, as shown by the column labelled class 2 in Table 4.1, non-potable reticulated water will already be available two weeks prior to this.

The length of time it takes to restore the water supply was specified for a few key suburbs only during the workshop. In other areas, we model restoration by staggering the recovery in a manner that is consistent with the known data points.

Several Water Balance Zones, like Maungawhau in Table 4.1, do not lose reticulated water. Potability never becomes an issue in these areas. We assume that their water restrictions are lifted as soon as reticulated water is restored to the first suburbs. This is expected to take about 16 days. Accordingly, the affected zones are reclassified from water restrictions (class 3) to potable water (class 1) at t=432.

Restrictions will remain in place until supply is restored and quality assured.

The three figures that follow provide a visual representation of the outages at selected time periods. Similar maps can easily be created (and rasterised) for any desired time period.

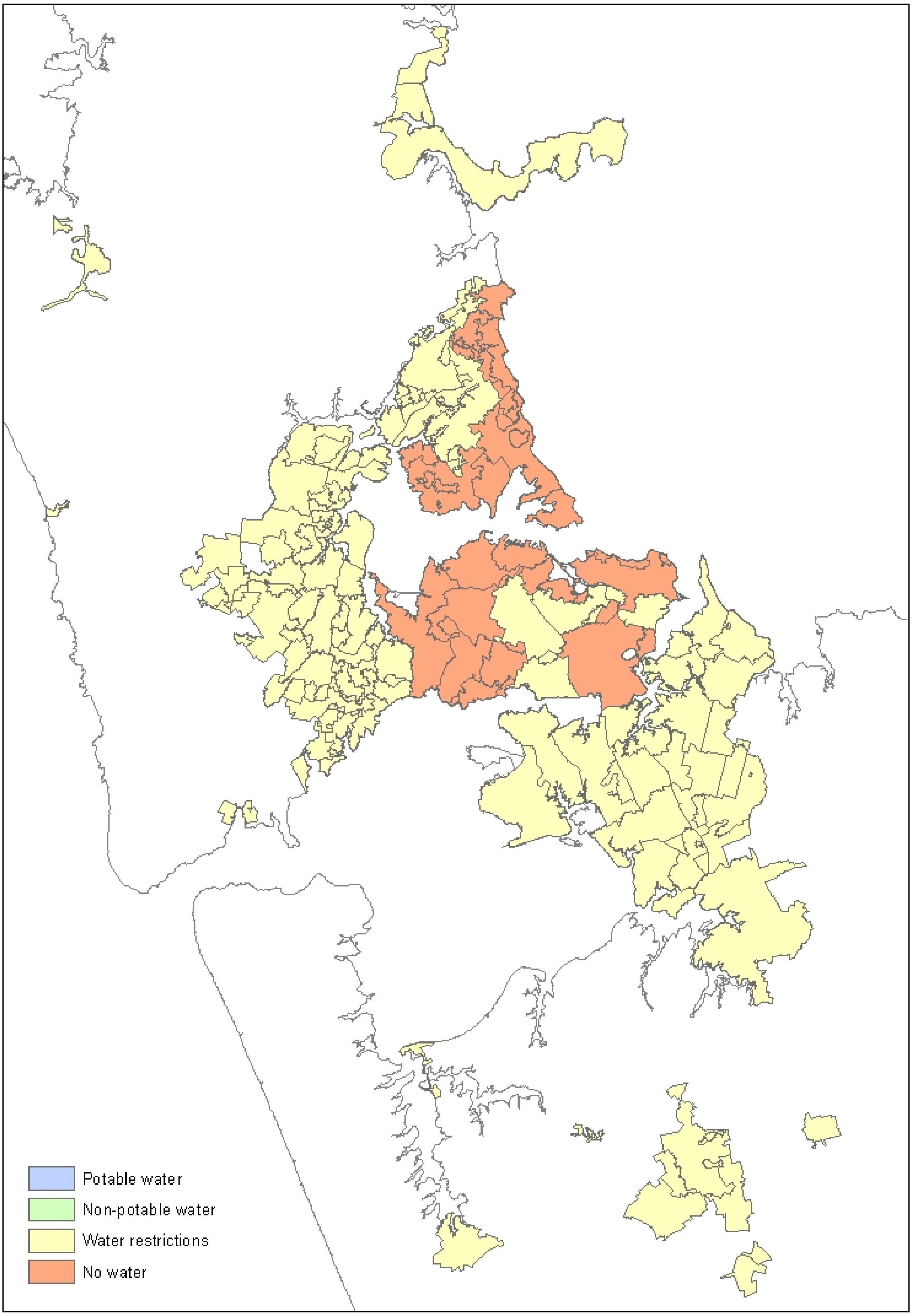

Figure 4.1 Outages five days (120 hours) after the infrastructure failure. No water is available in some central and Northern balance zones; other zones face water restrictions.

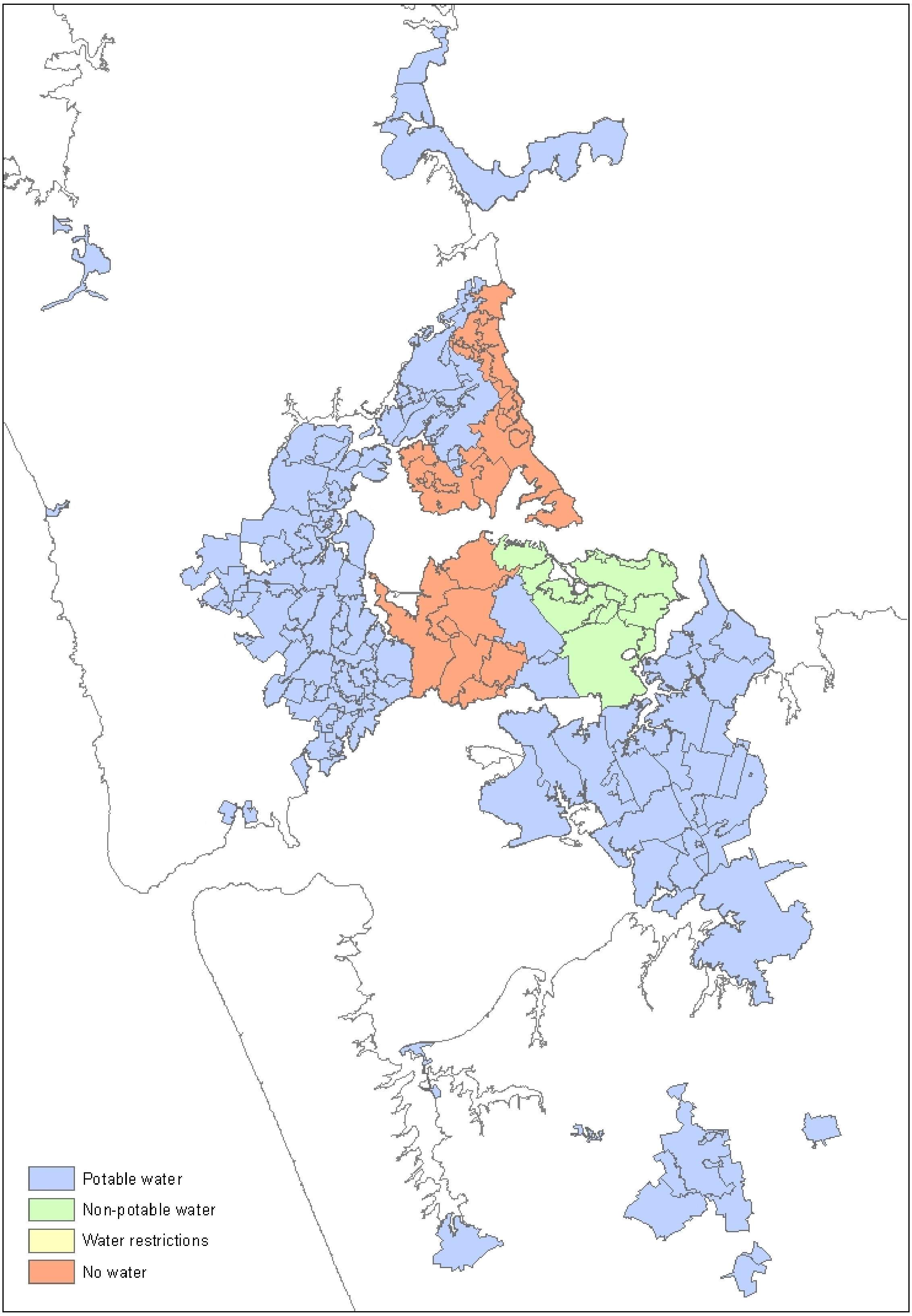

Figure 4.2 Outages approximately 3 weeks (500 hours) after the infrastructure failure. Restrictions have been lifted in all balance zones that did not lose reticulated water. Some areas have been restored to non-potable water, but Central Auckland and North Shore are still without water.

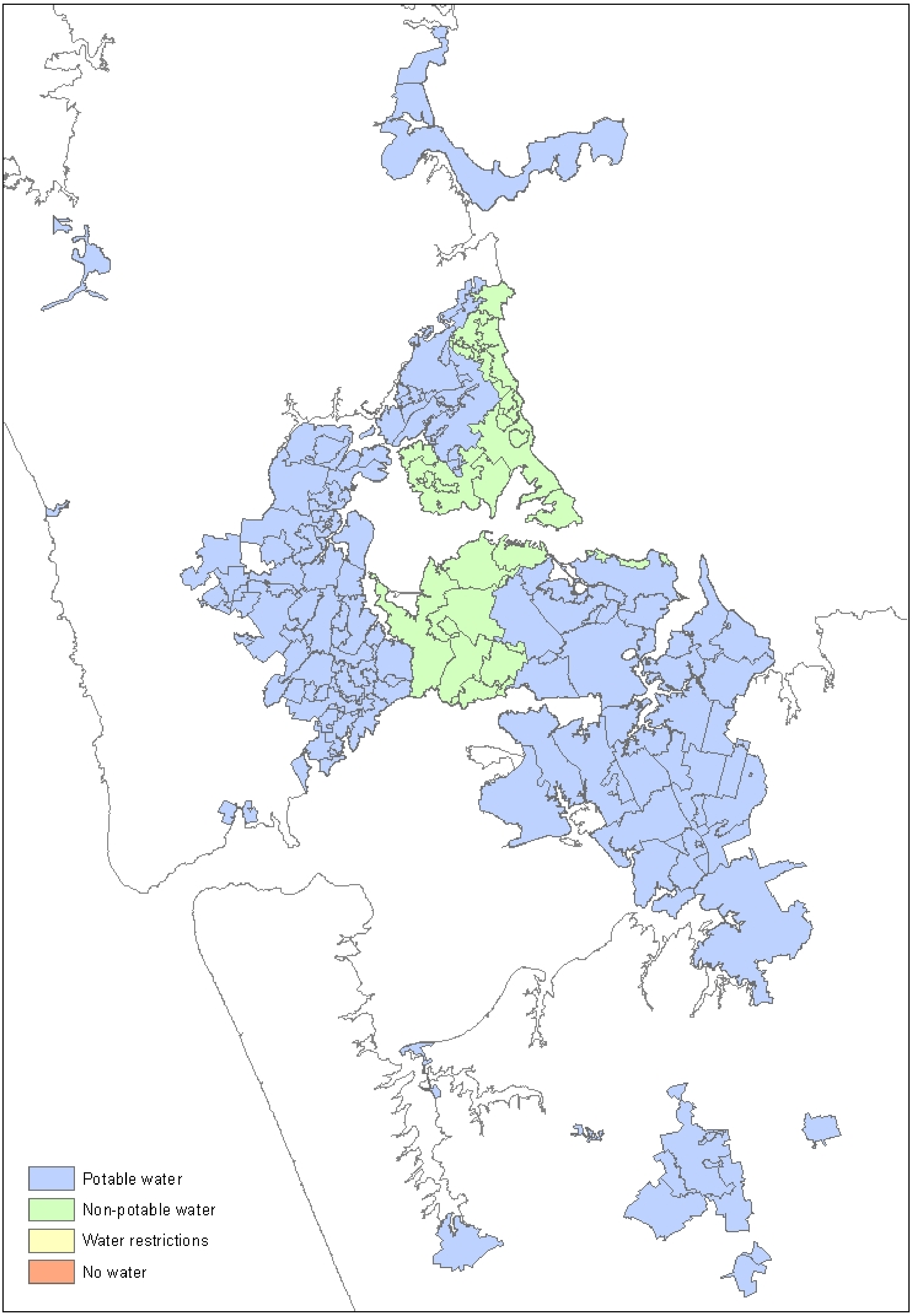

Figure 4.3 Outages approximately one month (800 hours) after the infrastructure failure. Only non-potable water is available in some areas.

4.2 AUCKLAND POWER OUTAGE

Vector, the power distribution company for the region, performed modelling for the Auckland power outage scenario in-house. The results of this modelling exercise were captured directly in GIS shapefiles. These represent the areas impacted by the 11 kV feeder outage under two scenarios: "N" grid security with and without Otahuhu generation (Figure 4.4 and Figure 4.5, respectively).

Vector's strategy to deal with the outage would require to subject these areas to a three-hour rolling outage (the total length of the outage would be largely dependent on the restoration of the Transpower supply to the grid exit points). The affected area is smaller with Otahuhu generation. All areas that are subject to the rolling blackout in the scenario with Otahuhu generation also experience the outage in the scenario without Otahuhu generation.

Because of the rolling nature of the outages and the characteristics of the restoration process, electricity customers in the affected region areas, on average, experience the same impact. Therefore, no additional data processing is needed to prepare these files for use in the spatially explicit economic model.

In addition to the above shapefiles, we also received geographic information on critical feeders from Vector; these feeders supply areas that include 'critical' customers and are therefore the last ones to be 'turned-of'" in the event of an emergency. Electricity customers in these areas are expected to be unaffected by the power outage scenarios. Finally, Vector shared with us shapefiles that represent the areas supplied by the Transpower Mangere grid exit point and the Transpower Takanini grid exit point.

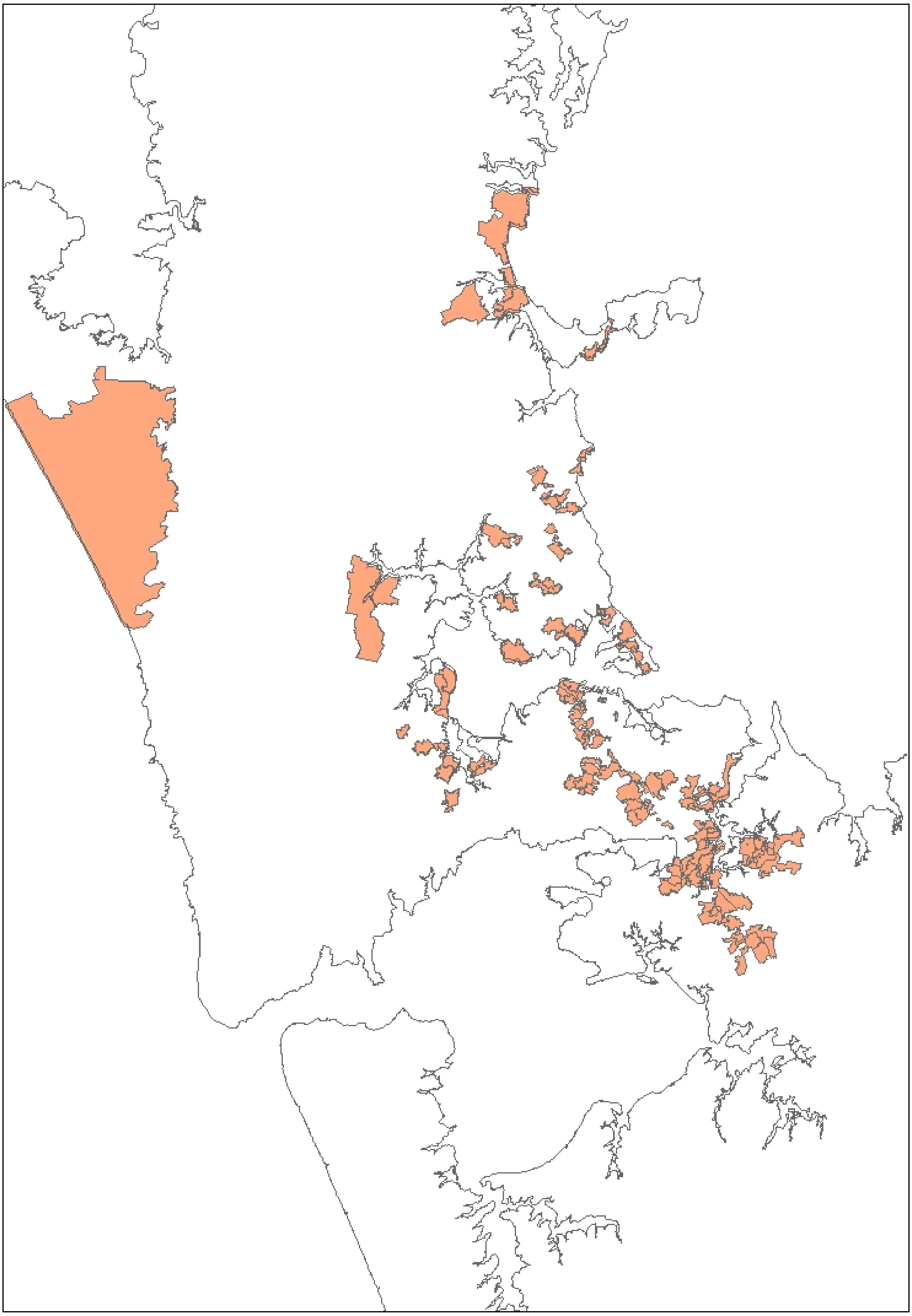

Figure 4.4 Areas affected by the rolling power outage in the scenario with Otahuhu generation (Source: Vector).

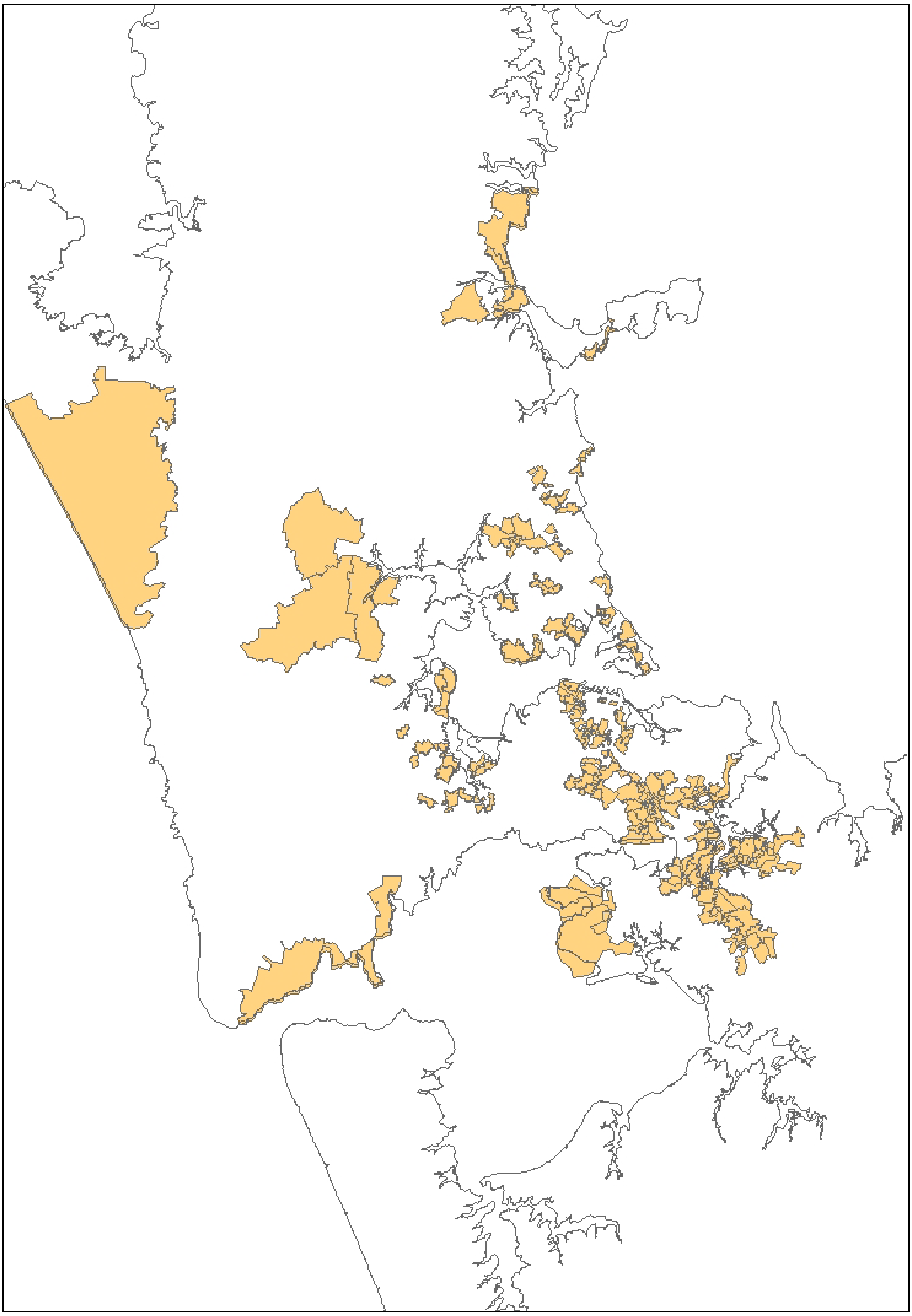

Figure 4.5 Areas affected by the rolling power outage in the scenario without Otahuhu generation (Source: Vector).

5.0 INTERDEPENDENCIES

5.1 OVERVIEW

In recent times both large natural disasters and terrorist attacks have exposed the 'stealthy fragilities' of complex inter-connected infrastructure systems. The nature of modern infrastructure networks is such that failures in some key components can initiate widespread cascading failures where the effects of the initial failures can be heavily outweighed by the final consequences.

Figure 5.1 Areas without power in New York after damage to infrastructure by Hurricane Sandy (Source: Gettyimages).

It is well known that recent large earthquake-induced tsunami have caused destruction on a huge scale resulting in a major (and ongoing) nuclear accident (Tohuku earthquake and tsunami, Japan, 2011) (Figure 5.3). Supersized storms (Hurricane Sandy, USA, 2012) have battered seemingly resilient cities resulting in major disruption and infrastructure failures (Figure 5.1 and Figure 5.2). Both these events occurred in well developed, technologically advanced nations. Modern society demands that services be provided in a fast and convenient manner often requiring the interaction of already complex systems. However, complexity and convenience can come at a price when the overall system vulnerability is increased because of the dense interconnectivity needed to achieve societal performance expectations.

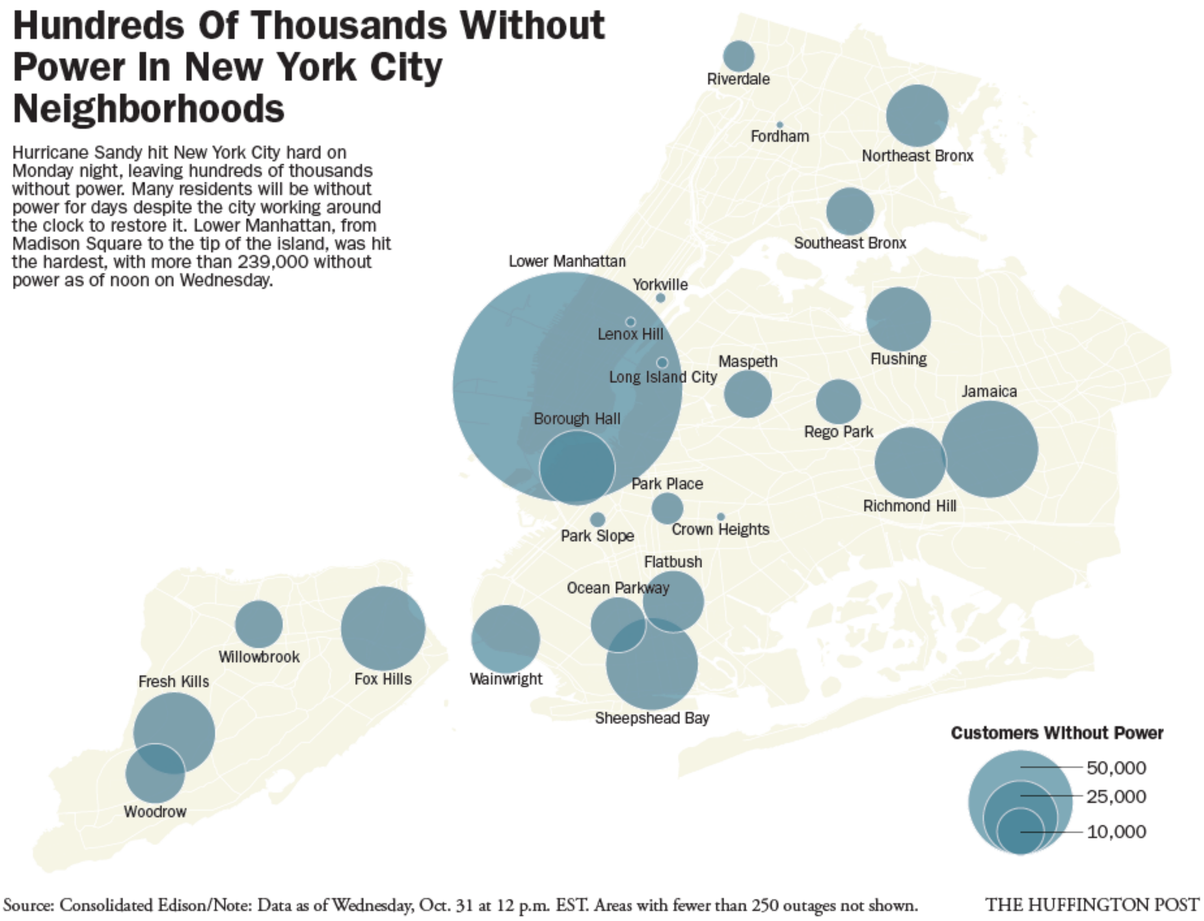

Figure 5.2 Areas of power outages in New York City, after Hurricane Sandy, 2012 (Source: The Huffington Post).

Modern society depends on a bewildering collection of complex, interwoven and critical lifelines or utilities. This includes (but is not limited to) electricity, water, gas, communications and transportation networks. The complex interactions generated by the integrated nature of many critical infrastructure networks can result in modes of failure that are difficult to model. In many cases network providers create complex models of their own network systems in isolation, completely ignoring the interaction with neighbouring systems (Buxton and Wright, 2011).

Interdependencies between critical infrastructure operators can be categorised as (Rinaldi et al., 2001):

- Physical;
- Cyber;
- Geographic; and
- Logical

Physical interdependencies exist between two infrastructure systems if the state of one system depends on the output(s) of the other. The linkage is therefore a physical linkage whereby the inputs and outputs of the two systems are bonded. This may be in terms of a consumable that is conveyed by a utility network (e.g., water, gas).

Cyber interdependencies exist if a system is dependent on information conveyed by some information infrastructure. Cyber interdependencies are relatively new and are a product of the degree of automation and computer control that exists in modern infrastructure systems. The control of infrastructure processes is usually via systems referred to as SCADA, Supervisory Control and Data Acquisition.

Figure 5.3 The Tohoku tsunami in 2011 (Source: Australian Geographic)

Infrastructure is geographically interdependent if changes in the local environment can impact on the states of all of them. Geographical interdependencies depend on the infrastructure systems being in close proximity to each other so that a hazardous event causes a correlated outage or disturbance in the interdependent systems.

Logical interdependencies between infrastructure elements exist if some mechanism other than physical, cyber or geographic exists (Ge et al., 2010). These can be in the form of logical AND relationships (if node X AND node Y fail then node Z will fail) or logical OR relationships (if node X OR node Y fail then node Z will fail).

Interdependencies can also be characterised by a proximity measure referred to as a failure order. The failure order describes the 'closeness' of a network component to a point of failure in terms of physical proximity or functional need. A first order failure may be something like an electrical power loss and the resulting failure of a cellular phone tower. More complex failures have also been observed, however, some of which exhibit feedback loops (Krimgold et al., 2006).

The complex distributed nature of the interdependent network systems means that capturing the behaviour of the systems with a reasonable level of accuracy is a challenging modelling problem. Many different approaches have been proposed. Recent work by GNS Science (Buxton and Wright, 2011) compares several modelling techniques. A study by Idaho National Laboratories (Pederson et al, 2006) undertook a review of critical infrastructure interdependencies research both in the USA and internationally. Typically the models can be based around matrices, economic models, graphical models and simulation-based approaches.

5.2 AUCKLAND SPECIFIC INTERDEPENDENCIES

The Auckland Engineering Lifelines Group (AELG) has produced many documents outlining Auckland's critical infrastructure and potential hazards that may impact on them. Several of these reports contain references to interdependencies, but from an Auckland specific point of view. Much of the following is taken from work undertaken by the AELG as part of the Auckland Engineering Lifelines Project (AELP2) which assesses the vulnerability of Auckland's infrastructure to various natural hazard events (AELP, 2014). Table 5.1 provides an overview of utility interdependencies in Auckland.

5.2.1 Electricity

The AELG identifies electricity as the service upon which most others depend during periods of normal operation. Other utilities may have on site backup generation especially at sites deemed most critical but these often have limited fuel capacity. A widespread, regional, long term electricity outage will begin to affect telecommunications, water supply, wastewater, fuel supply and traffic management.

5.2.2 Telecommunications

Most utilities could remain in operation without telecommunications but may have to modify their working procedure to use more manual operations.

5.2.3 Transportation

Short term road failures are not likely to seriously impact the operations of other utilities. Long term road failures can have larger effects.

5.2.4 Dependencies in an emergency

In the case of an emergency, telecommunications and roads become more critical. If electricity is affected then diesel supply for backup generators becomes critical as many backup generators have limited fuel capacity.

Table 5.1 An interdependency matrix produced by Auckland lifelines (Source: AELP 2014).

Dependence on	Electricity	Gas	Fuel	Tele-communications	Transport	Water / Wastewater
Electricity	Required at most facilities – generation, substations, etc.	Required at gas-fired generation plants.	Required for substation operation and vehicles.	Required for network monitoring and to coordinate emergency response.	Yes, for access to restore damaged sites.	For some cooling purposes, plus cleaning and fire fighting.
Gas	Electricity required to maintain supply at gas delivery points, though could still maintain reduced supply.	Not required.	Required for vehicles and to maintain supply at delivery points.	Required to maintain supply at delivery points.	Yes, for access to restore damaged sites.	Not required.
Fuel	Supply from Marsden to Wiri dependent on mains supply. Wiri oil depot has backup generation so can continue to fill trucks until stocks run out.	Refinery can operate without gas but environmental impacts.		Required to operate pipeline to Auckland.	Required for regional fuel distribution. Road access to Wiri particularly critical.	Fuel storage terminals cannot operate without water supply for fire fighting.
Telecom-munications	Required to operate all facilities. Most key sites have generator / battery backup. Customer phone systems usually need power.	Not required.	If power fails need diesel for generators. Need fuel for staff / contractor vehicles to respond to failures.	High level of sharing of networks, exchange of data, etc.	Yes, for access to restore damaged sites and refuel generators.	For some cooling system.
Transport	Required for traffic signal operation. Required for Ports and Airport operation though backup generation in place for critical functions.	Not required for operation, but need quick response to gas pipe failures in roads.	Not required for road network itself (only for vehicles and diesel for construction plant). Required for ships and planes. Jet fuel pipe to Auckland Airport is particularly critical.	Required to coordinate emergency response. Phone network used for networked traffic signal mgt.	Ports and airports require rail and roads to be operational to move freight and passengers.	Not required for operation, but need quick response to watermain failures in roads. Required to provide sanitary services for airport customers.
Water	Electricity required for for river/bore abstraction sources and WTPs & PS. Approx. 40% of consumers are dependant upon water supply pumped to reservoirs or direct to supply	Not required.	If power fails need diesel for generators. Need fuel for vehicles to undertake repairs and move staff.	Dependent upon cellular phone and radio telephone for SCADA network and to coordinate emergency response.	Yes, for access to geographically diverse and remote sites for operation and restoration to damaged sites.	Required to provide sanitary services for staff.
Wastewater Stormwater	Required at treatment plants and pump stations.	Required for WWTP operation but contingency plans exist.	As above.	As above.	As above.	As above.

Table 2-2: Lifeline Utility Interdependencies in Auckland

Legend:

Critical requirement to maintain service continuity during business-as usual.	Some impact on ability to function. Service response would be impaired, utility becomes more critical in an emergency.	Not required for operation.

5.3 Relevance of Interdependencies to This Project and Proposed Methodological Approach

In order to be able to model the economic impacts of infrastructure failure, infrastructure interdependencies will have to be taken into account. This presents a challenge for the modelling team as methodologies available to date for modelling interdependencies are complex, time consuming and require large amounts of data (Buxton and Wright, 2011).

At the time of writing, a workshop approach involving both Watercare and Vector was being considered to collect semi-quantitative data on the interdependencies between water and electricity that would either be suitable as inputs to the economic model, or that would inform the development of the interdependencies module of the economic model.

The proposed methodology requires a set of outage maps to be produced depicting the system outages at various times following the failure event for the water and the electricity networks (already produced and described in sections 3 and 4). The maps form the basis for a knowledge elicitation procedure, whereby a group of representatives from the participating networks provide the background knowledge for the workshop.

The next stage involves the providers identifying the key crossover points between the non-functional areas in the mapped service and their own network at t=0. These should be listed together with any existing backup capability and the endurance of the backup if it is limited. In each case, any other components or losses of service caused by the failure of the crossover should be listed and this process can be repeated for further failures. The failures can be classed in terms of an Order where 1st Order failures are the initiating failures in the

mapped service, 2nd Order are the points of key crossover and anything else is 3rd,4th, …n^{th} etc. For the purposes of the early workshops it is expected that the analysis will be limited possibly to 1st and 2nd order failures.

This process could then be repeated for t=12, t=48, t=120 and for the other options.

A set of algorithms will attempt to be developed describing the relationship between the levels of service or ‘flows’ identified during the process described above. These algorithms are intended to inform or become the basis of the interdependencies module of the economic model.

It is expected that the experience and learning gained from running such a workshop using the more limited scope of the single outage scenarios will help to better refine the process when applied to more complex scenarios later in the project.

A second methodology is under discussion at the time of writing. An operational prototype of an interdependencies model has been developed based on ecological systems models (Smith and McDonald, in prep., 2014). The model traces flow-on infrastructure impacts through time of single, cascading or multiple infrastructure failure. The focus has shifted from the workshop approach described above to development of this model which will potentially require a less intensive approach to data inputs. Some workshops may be held if deemed necessary to help calibrate algorithms derived empirically.

6.0 DISCUSSION

This report documents the work completed by Research Aim 1 of the Economics of Resilient Infrastructure research programme over the course of the first 12 months. Research Aim 1 is principally concerned with geophysical and infrastructure failure scenario definition and mapping service outage information as an input to the economic model. The major achievements of the team over the last 12 months have been;

- The establishment of links with key infrastructure provider representatives.
- The identification of suitable ’single outage’ scenarios to use as development examples allowing road-testing of techniques, procedures and principles that will be refined as the project evolves.
- The collection of GIS and other data to underpin the scenarios.
- The development of an outline interdependencies data collection technique for identifying the ’key points of crossover’ via workshopping with key infrastructure representatives.

The chosen scenarios are based on natural events that resulted in power and water outages in Auckland. The scenarios were designed by the infrastructure providers to produce both a plausible event and one that resulted in major consequences in terms of outage scale and duration.

The scenarios were further refined by workshops and meetings where the decision making processes of the operators and timelines of the failures and the reinstatement procedures were discussed.

6.1 SCENARIO DEVELOPMENT LESSONS AND HIGHLIGHTS

6.1.1 Workshop approach

The water supply failure scenario was developed in partnership with a group of key staff from Watercare. Watercare had undertaken emergency management scenario planning previously. It was highly beneficial to the research team to work with Watercare staff who had been involved in this type of planning previously, were familiar with CDEM arrangements, and were active in the Auckland Engineering Lifelines Group.

The benefits of the workshop approach for developing the water scenario are as follows:

- Free and frank discussion to capture a range of expert opinion, including knowledge of past events, emergency scenarios, and the limitations and robustness of the network;
- With some initial thought regarding a reasonable but serious outage scenario, the process of developing the draft outage and restoration maps was relatively rapid; the workshop took half a day and some extra time was provided by the key contact at Watercare before and after the workshop. Watercare also updated a hydraulic analysis using their own transmission water network model to investigate the impacts of a complete shutdown or failure of the Ardmore Water Treatment Plant and the implementation of proposed contingency measures. This enabled more accurate estimates of water availability across the network for the different demand scenarios

considered which was available during the workshop. For other Watercare staff, for the most part, their involvement and time commitment was limited to some pre-reading and to participation in the workshop;

- The research team were able to clarify terminology, impacts and assumptions using a consensus based approach with input from a key group of people with diverse expertise;
- The Watercare team were able to use the workshop as an opportunity to discuss their response to a new and previously unexplored scenario;
- Institutional knowledge – by including multiple staff members from Watercare in the workshop, the discussion and results become company knowledge, rather than relying on one staff member to share findings. Several staff members are provided with the opportunity to better explore how the company would respond to a severe problem with the network.
- Supply and demand language. It was a useful exercise for the research team and for the Watercare staff to understand the difference in terminology between how Watercare would describe changes in their network supply (ML/day) and how users would experience any change in service.

There are however, some drawbacks to the workshop approach:

- Logistics – the workshop approach requires coordinating several key staff to be available, which in turn requires commitment at senior levels to make staff available and provide them with time for workshop preparation;
- The results of the workshop were based on a set of key assumptions and group expert opinion and are largely qualitative, although provided as quantitative values. For the purpose of testing the MERIT model we do not consider this to be a significant drawback, but it should be noted;
- The workshop approach described here may not be the most efficient method to generate data for the economic model once it has been developed and available for general use. It is a valuable way to generate *test* data inputs for the model. If this approach is attempted for other infrastructure sectors (i.e., telecommunications, transport, fuel) enough time needs to be included to develop relationships and to work through confidentiality requirements with the infrastructure provider concerned. It's unlikely that such an approach would efficiently generate the data inputs required for a large multi-infrastructure failure such as those being considered in later stages of the programme.

6.1.2 Expert-developed data input approach

Both Transpower and Vector undertook network modelling in-house to generate the data inputs required. This was quicker in terms of producing the results, however, accompanying information about the assumptions made and operational decision making in response to the outage wasn't captured as a result. It may have been useful for them to have explored the implications of the scenarios with staff and the research team in greater depth.

For MERIT to be user-friendly, infrastructure providers will need a relatively straightforward way to generate data inputs, and this is most likely achieved through their own in-house network analysis models.

6.1.3 Other comments on methodology

The RA1 project team wanted to provide the MERIT model with business as usual, mitigation and adaptation scenario outputs. This proved to be a somewhat difficult approach for the utility suppliers, particularly with regards to adaptation options. These were intended to be non-standard, somewhat “blue-sky” options for assisting the restoration process. However, discussions with the providers uncovered that non-standard adaptations would likely be costly and lead to wider problems (e.g., create maintenance issues for Watercare) and it was more likely that adaptations in regards to alternate supplies would be something more likely to be introduced by those affected (e.g., supply of generators for power failure) or by civil defence emergency management (CDEM) decisions (e.g., supply of drinking water delivered by tanker truck).

The research team initially found it challenging to understand the outages both in terms of the metrics of supply which the infrastructure providers used (e.g., megalitres per day) and the metrics of demand, in terms of how the consumer might view the product or service (e.g., water on or off; water potable or not). The latter is more relevant for the economic model. For future scenarios, more work is needed beforehand to better understand the supply and demand metrics for the particular infrastructure sector being considered.

During initial discussions with the infrastructure providers, uniform time increments were being considered to enable easy cross comparisons between the various maps, i.e., mapping outages at intervals such as t=0, t=12 hours, t=24 hours, etc. We also thought this might be easier for the subsequent interdependencies analysis. However it was soon apparent that there were step changes in time after an outage event which occurred at key response decision points, and/or which depended on the network configuration (e.g., reservoir capacity) and that these were different for different networks. This may or may not have a bearing on any subsequent interdependency analysis.

6.2 NEXT STEPS

The research team are undertaking a third single infrastructure failure scenario and analysis which will explore an aspect of the transportation sector. This is a failure of the access routes (road and rail) into the Lyttelton Port due to a landslide event.

Work is underway on capturing supply and demand metrics for each infrastructure sector. This will assist with both the scenarios and also the infrastructure interface for the economic model.

Further development of the interdependencies model is underway with consideration as to how the algorithms describing stocks and flows in the model can be derived.

Finally, work has started on developing the multi-infrastructure failure events; a volcanic eruption in the Auckland Volcanic Field and an earthquake event on the Alpine Fault.

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7.0 ACKNOWLEDGEMENTS

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APPENDICES

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APPENDIX 1: KEY QUESTIONS FOR SINGLE UTILITY OUTAGE WORKSHOP

A1.1 WORKSHOP PURPOSE

(assuming no prior modelling undertaken – i.e., blank sheet approach)

To develop some data/information showing service level outages given a specified failure scenario which can be used as inputs to an economic model. The data don't have to be 'accurate' – they need to be plausible and able to be captured in an 'easy' useable form for input to the economic model. The workshop will help us work out ways to capture the information and develop the methodology. The workshop can also be used to run a 'response' exercise to a given failure scenario to help understand the assumptions and decisions made that form the basis of the service outage levels.

1. Capture service level outages spatially at 3 to 4 different time intervals (parameters and time intervals agreed prior) for:
   - a given failure scenario
   - same failure scenario but with a hypothetical (or planned) mitigation measure introduced (e.g., a redundancy in the system – additional pipeline; larger pipeline etc.)
2. Capture the assumptions and decisions made by the Watercare team as the maps are developed (i.e., what are the assumptions and decisions made that result in the mapped service level outages)

A1.2 WORKSHOP OUTPUTS

1. Ideally six–eight maps (A1 size) marked up showing areas with varying levels of service and different time intervals.
2. List of key assumptions/decisions made as each map is produced.
3. List (and map) key or 'critical' customers and qualitative implications of the outages on them.

A1.3 WORKSHOP RESOURCES

1. Six/eight maps (A1 size) pre-printed showing Auckland region and high level Watercare network (mains and pump stations, etc.) – ability to mark these up (coloured markers/ pencils).
2. Whiteboard.

A1.4 PRE-WORKSHOP DECISIONS NEEDED

1. Plausible water supply failure scenario (what element of the network has failed and for what reason?)
2. Time intervals:
    - t=0,
    - t=12 hours,
    - t=48 hours,
    - t = 7days (these will depend on the scenario).
3. How the service levels will be represented.
    - Water pressure (0%, 50% (or other nominal restriction level), 100%).
    - Water quality (potable, non-potable).

Practically this represents two maps per time increment.

- What is an appropriate scale for the outages maps? (e.g., Auckland region at A1). There is a need to capture different functional levels of service but to a relatively high level (e.g., suburb) not to drill down to house by house or street by street mapping.

A1.5 OTHER QUESTIONS/ISSUES FOR DISCUSSION/ RESOLUTION

1. Supply language and demand language clarified and transparent. How are outage levels measured and described; how will these levels of outage (failure) be experienced by an end-user of this service?
2. If outages are not usually described spatially using network maps (e.g., they are developed as tables or systems diagrams), how can we best translate the information into a spatial functional service-level map showing the area of influence and level of service for components of the network?
3. Who are the large or critical end-users within the network? How will a change in functional service (e.g., an outage or reduction in service level) affect them? Are any end-users treated differently (e.g., prioritised) by Watercare during decision making for restoration or management of outages?
4. What is the standard approach to restoration of the network to normal supply? What key thresholds of service restoration (e.g., priority suburbs locations restored first, then a gradual expansion until all areas are back at full service) might be reached before full service is restored?
5. What possible mitigation (pre-outage) measures could have reduced the outage levels – are they realistic (cost-benefit) structural improvements? What improvements are currently planned and what possible effect would their inclusion in the network have on the service levels?
6. What is one potential adaptation measure (non-standard restoration response or 'work-around') that could potentially be employed by Watercare – what difference would it make to restoration temporally and spatially and is it appropriate to include such a measure in the model? Would adaptation best be considered as a response by end users rather than as a work-around for Lifeline Utilities?

APPENDIX 2: WORKSHOP PLAN – ECONOMICS OF RESILIENT INFRASTRUCTURE PROJECT: WATERCARE OUTAGE SCENARIO

Friday July 12th 9am–1pm

9AM WELCOME AND INTRODUCTIONS (BRIAN)

9.10 BRIEF INTRODUCTION TO THE ERI PROJECT (MICHELE)

- project partners
- aim of the project
- project components (stages)

9.20 WORKSHOP PURPOSE METHOD AND GOALS (KIM)

- Supply and demand terminology – when will people notice a change at the tap?
- Marking up the maps to show changes in quantity and if possible quality
- We are looking for tipping points or thresholds when users will notice a significant change in either quality or quantity of supply- ideally we would like three maps. Initial outage, tipping point one and tipping point 2 plus an estimate of full restoration time.
- Scope: we don't need to determine how large/priority users will respond, just when they will be impacted and what this supply change might look like.
- This is semi-qualitative, does not need to be accurate, the purpose it to produce outputs which can be used to test the economic model.
- We are interested in the restoration process and response decision making as well as assumptions that are made regarding how the outage will 'play out'. - neighbourhood/suburb scale not individual household.

9.30 INTRODUCTION TO THE OUTAGE SCENARIO (BRIAN)

The outage scenario: what will cause such as significant failure?

- Outline the assumptions behind the workshop, we will identify changes in supply and mark the maps up as if Watercare was making a standard response to an emergency outage, so employing business continuity and crisis planning principles and SOPs, including adaptation measures that would be employed.
- Brief brainstorm on the tipping points – can we agree on time periods for each map before we begin?
- Identification of priority users (location, purpose and use of water e.g., health, manufacturing).
- Maps we will use: region maps and four area/zone maps for higher resolution.

10.00 ANNOTATED MAPPING (ALL WATERCARE ATTENDEES, GNS NOTE-TAKING)

- First map(s): immediately after outage T=0. Locate priority users, map the changes in water quantity (and if possible quality). Begin with all of region map and transfer to area/zone maps

Approx. 10.40 Break for coffee/tea

11.00 ANNOTATED MAPPING (CONTINUED)

- Second map: at agreed threshold when there is a significant change in supply as experienced by the end user; T=1. Locate priority users, map the changes in water quantity (and if possible quality). Use area/zone maps. Transfer the results of the four maps onto a region map for recording purposes
- Third map: at agreed threshold when there is a significant change in supply as experienced by the end user; T=3. Locate priority users, map the changes in water quantity (and if possible quality). Use area/zone maps. Transfer the results of the four maps onto a region map for recording purposes

12.30 DISCUSSION

- Mitigation strategies or infrastructure prior to T=0 that could have limited the impacts at T=0, 1 and 2? Are there any realistic options that would have limited the outage severity at T=0? If so, how much would the outage have been reduced by in terms of impact range and duration? (not a mapping exercise, theoretical and qualitative discussion only unless time allows)
- Non-standard adaptation measures. Are there any 'blue sky' response measures Watercare could take after T=0 that could change the impacts at T=1 or T=2? These would be ideas outside current response processes but need to be physically possible and not astronomically expensive e.g., installation of an additional 90km flexi pipe from Waikato River to Auckland City to fill reservoirs (this is my example and possibly ridiculous but perhaps the group can suggest at least one option). If there is an option for blue sky adaptation, how does the group think this would change the supply at T=1 and T=2?

12.50 WORKSHOP WRAP-UP (MICHELE AND BRIAN)

Final comments and follow up – where to from here?

APPENDIX 3: TERMS AND DEFINITIONS

Term	Definition	Source/Reference
Adaptation	Adjustment in natural or human systems in response to actual or expected natural hazards or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, as well as autonomous and planned adaptation.	Schmidt-Thorme et al (2007)
Business as Usual	For the purposes of this project we describe a business as usual (BAU) approach to a large outage as the accepted and planned for process and policies that a lifeline utility would follow to restore their supply during a large outage event. The BAU approach includes Standard Operating Procedures (SOPs), business continuity plans (BCPs) and technical and operational restoration responses. Business as usual does not imply no outage has occurred, rather that there are already plans and activities established for emergency outage response.	This report
Causal loop (diagram)	A causal loop diagram (CLD) is a causal diagram that aids in visualizing how interrelated variables affect one another. The diagram consists of a set of nodes representing the variables connected together. The relationships between these variables, represented by arrows, can be labelled as positive or negative.	Wikipedia (http://en.wikipedia.org/wiki/Causal_loop_diagram) accessed September 2013.
Connectivity	The state of being connected; The ability to make a connection between two or more points in a network	Wikipedia (http://en.wikipedia.org/wiki/connectivity) accessed March 2014.

Term	Definition	Source/Reference
Consequence	An impact such as economic, social or environmental damage/improvement that may result from a hazard. It may be expressed quantitatively (e.g., monetary value), by category (e.g., high, medium, low) or descriptively.	Schmidt-Thorme et al (2007)
Critical Facilities	Critical facilities are elements of the infrastructure and post-disaster functions that support essential services in a society. They include such things as transport systems, air and sea ports, electricity, water and communications systems, hospitals and health clinics, and centres for fire, police and public administration services.	UNISDR (2009)
Critical Infrastructure (also lifelines)	The physical and organizational structures that provide services that are estimated to be essential to the functioning of society. The unavailability of critical infrastructure services may have severe consequences for basic societal needs.	Brunner, E. M., and Suter, M., 2008. The International CIIP Handbook 2008/2009. An Inventory of 25 National and 7 International Critical Information Infrastructure Protection Policies. Zurich: Center for Security Studies, ETH. http://www.crn.ethz.ch/publications/crn_team/detail.cfm?id=90663. Accessed 2 Nov 2010.
Disaster	A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources.	UNISDR (2009)
Natural Hazard	Any atmospheric or earth or water related occurrence (including earthquake, tsunami, erosion, volcanic and geothermal activity, landslip, subsidence, sedimentation, wind, drought, fire, or flooding) the action of which adversely affects or may adversely affect human life, property, or other aspects of the environment.	Resource Management Act 1991

Term	Definition	Source/Reference
Interdependence	Dependence between infrastructure types, arising from a supply chain requirement (e.g., cell-site need electricity) Infrastructure systems are distinguished by their interdependency. The continued operation of an infrastructure system, such as the communications network, may be dependent on the operation of another system, such as the power system. Similarly, the ability for system owners to restore their respective systems following an earthquake (or other event) may be dependent on the condition of highways and other transportation elements.	Adapted from SPUR 2009 http://www.spur.org/files/spur-reports/SPUR_Lifelines.pdf (accessed Sept. 2013)
MERIT	Measuring the Economics of Resilient Infrastructure Tool. A tool that will be able to quantify the economic implications of vulnerabilities to infrastructure failure and examine post disaster recovery strategies	This report
Mitigation	The lessening or limitation of the adverse impacts of hazards. Comment: The adverse impacts of hazards often cannot be prevented fully, but their scale or severity can be substantially lessened by various strategies and actions. Mitigation measures encompass engineering techniques and hazard-resistant construction as well as improved environmental policies and public awareness.	UNISDR (2009)
Recovery	The co-ordinated efforts and processes used to bring about the immediate, medium-term, and long-term holistic regeneration of a community following a civil defence emergency.	NZ National CDEM Plan 2005

Term	Definition	Source/Reference
Resilience	The ability of an entity— asset, organisation, community, region — to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance.	Argonne National Lab, 2012 (http://www.dis.anl.gov/pubs/72218.pdf) Accessed Sept. 2013.
Risk	The combination of the probability of an event and its negative consequences.	UNISDR (2009)
Supply Chain	A system of organizations, people, activities, information, and resources involved in moving a product or service from supplier to customer. Supply chain activities transform natural resources, raw materials, and components into a finished product that is delivered to the end customer.	Wikipedia. http://en.wikipedia.org/wiki/Supply_chain (accessed 1 May 2014.)
Vulnerability	The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.	UNISDR (2009)

Contact details:

GNS Science
1 Fairway Drive, Avalon
Lower Hutt 5010
PO Box 30 368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600