Developing a hazard risk assessment Framework for the New Zealand State Highway Network

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Land Transport New Zealand Research Report 276

ISBN 0-478-25387-7
ISSN 1177-0600

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Seville, E.*, Metcalfe, J. 2005. Developing a hazard risk assessment framework for the New Zealand State Highway network. *Land Transport New Zealand Research Report 276. 80pp.*

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Keywords: hazard, New Zealand, risk management, risk assessment, road, road closure, State Highway

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Acknowledgments

Special thanks to Nick Gurr of Opus International Consultants, Alan Burkett of Transit NZ, and Hans Brounts of MCDEM (Ministry of Civil Defence Emergency Management) for their valuable comments on earlier drafts of this report. Thanks also go to the many people who took time to talk with our researchers and provided information for this report from organisations including NIWA (National Institute of Water and Atmospheric Research), GNS (Geological and Nuclear Sciences), Transit NZ, Transfund NZ, University of Canterbury, and NZIER (New Zealand Institute of Economic Research); many of whom have been referenced in this report.

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Executive summary

The New Zealand Civil Defence Emergency Management (CDEM) Act (2002) requires all lifelines, including the road network, to be able to function to the fullest possible extent during and after an emergency, and that lifeline providers have plans for such continuity that can be made available to the Director of CDEM if requested. To be able to meet this legislative requirement, road network managers require a comprehensive framework for identifying, evaluating and managing risks to the road network. This risk management framework needs to strike an appropriate balance between capturing the complexities of hazard risks to the road network, and the need to be cost-effective, achievable, and likely to be taken up and actively used by those people managing the road network.

This research, carried out in 2003 and 2004, focuses on the challenge of assessing road closure risk for the State Highway network. Risk, in this context, is a function of:

- the likelihood and magnitude of a hazard event,
- the vulnerability of the road network to damage from that event,
- the social, environmental and economic impacts of any damage or disruption to the road network and subsequent traffic flows,

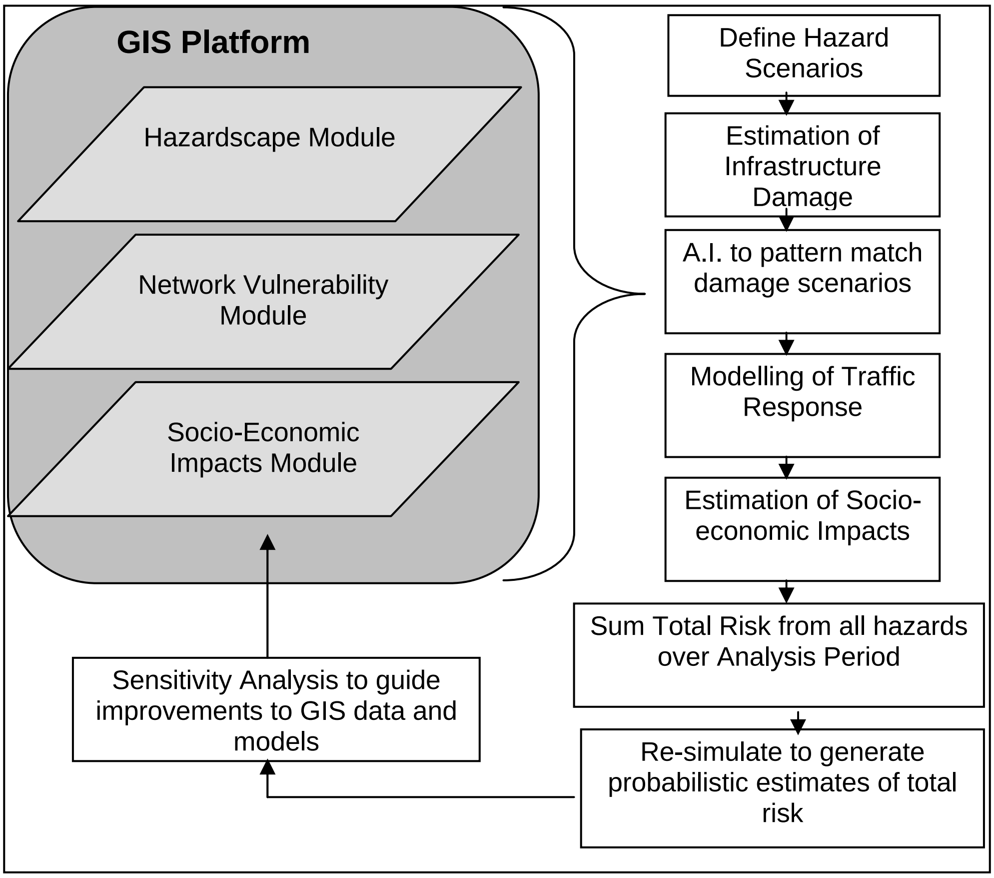
summed over the full spectrum of hazards and hazard magnitudes capable of impacting on the road network.

One of the challenges in assessing risks to networked systems is that damage to one part of the network is not statistically independent of damage on another part of the network. Analysis of risks using probabilistic hazard maps or site hazard distributions (i.e. assessing the risk at individual sites, and then summing over all sites to assess the total risk to the network) does not capture the potential impact of large scale events that cause simultaneous damage to neighbouring parts of the network.

For understanding risks to portfolios and geographically distributed networks, there has been a move towards the use of catastrophe scenarios to estimate potential losses across the system. The use of scenarios has the advantage of making it easier to visualise and communicate potential losses to decision makers, and to compare potential losses with past events. Difficulties with scenario approaches however are resource limitations to the total number of scenarios that can be considered, and challenges in selecting a representative set of scenarios to consider.

This report suggests a framework for meeting these challenges in assessing risks to the State Highway road network (see Figure on p.8). The framework uses a walkthrough scenario approach, where hazard events throughout New Zealand are randomly simulated over a long time scale (such as a 250,000 year period). This time period is then divided into a timescale suitable for analysis (such as a 100 year design life), giving a simulated data set for probabilistic analysis of total risk. The location, size, and frequency of hazard events over this period are generated using available hazard models, reflecting current scientific understanding of hazard processes. A technique is suggested to reduce the number of scenarios to be modelled during the walkthrough simulation. This technique defines a reduced number of scenario events to be simulated and assigns probabilities to those scenarios such that they are roughly consistent with the overall frequency and severity of hazard events for the area. For example, rather than indicating the likelihood of specific event A occurring, the hazard-consistent probability indicates the likelihood of events 'like A' occurring, with a similar spatial distribution of impacts. Another strategy suggested for reducing the complexity and computing requirements of the analysis is a form of Artificial Intelligence (A.I.) to pattern-match similar road closure scenarios to minimise traffic and socio-economic consequence modelling requirements.

It is recommended that some form of spatial analysis software, such as Geographic Information Systems (GIS), be used for the risk assessment. The appropriate selection of a software platform and data collection design will be very important to the overall success of the framework. A modular design, with independent layers capturing information on the hazardscape, road network characteristics, and socio-economic systems that rely on the road network will help to ensure that information is easier to update and refine. Starting with conceptually good data design is likely to save significant time and effort in later maintenance and improvement costs.



Overview of the Proposed Risk Assessment Framework

This report provides a summary of relevant hazard data available in New Zealand at the present time, and data that is expected to become available within the next few years.

Hazards that are discussed, including a summary of data availability and suggested methodology for assessing risk, include:

- seismic events,
- volcanic events,
- landslides (and avalanches),
- flooding,
- snow and ice,
- tsunamis,
- wildfire.

This report also provides an overview of socio-economic impacts of road closures that could be captured in the assessment, including a suggested approach for estimating secondary economic effects of transportation disruption.

Carrying out a full risk assessment of hazard events with the potential to close sections of the State Highway network will be a significant undertaking, but should provide key benefits. The risk assessment will provide a basis for prioritising risk management investment across the whole of the country, for all types of hazard events. It will also provide a database of information that road network managers can use to assess the risks and benefits of different road improvement projects.

To be successful, however, the risk assessment framework will need to be developed with a strong vision of how all the different components of risk will eventually be brought together into a single analysis. To be cost-effective, it also requires a collaborative approach, leveraging research initiatives underway in New Zealand to ensure that these research outputs can be effectively utilised.

If it is decided to proceed, it is recommended that:

1. A small risk assessment research steering group should be formed to provide an overview of what research is required. The whole research programme will be very multidisciplinary (involving hazard researchers, risk managers, economists, transportation planners, etc.).
2. To provide direction, continuity, and advice, it will be important to have a core group of people who are not necessarily doing the research, but who have a clear understanding of the overall research programme and how its different strands of research fit together. This group would be able to provide independent advice for evaluating research proposals on how they align with the overall objectives. They will also be a source of information and advice for researchers on how their research will fit within the overall system architecture and interface with other research programmes going on concurrently.

Abstract

Designing a comprehensive risk management framework for networked systems, such as the road network, presents significant challenges. The framework for assessing risk needs to strike an appropriate balance between capturing the complexities of hazard impacts on road network reliability, and ensuring that the framework is cost-effective, achievable, and likely to be taken up and used by those people actively managing the road network. This report, summarising research undertaking in 2003/04, suggests a framework for meeting these challenges in assessing road closure risks to the State Highway network. The framework uses a walkthrough scenario approach, where hazard events throughout New Zealand are randomly simulated over a long time scale, giving a simulated data set for probabilistic analysis of total risk. In addition, this report provides a summary of relevant hazard data available in New Zealand at the present time, and data that is expected to become available within the next few years. The report also provides an overview of socio-economic impacts of road closures that could be captured in the assessment, including a suggested approach for estimating secondary economic effects of transportation disruption.

1. Introduction

Recent flooding in the lower North Island (February 2004) illustrated the devastating effect hazard events can have on the road network, with 40-50% of the region's 9300 km road network closed by flooding. That event also illustrated the significant costs and time involved in restoring road services after such a large event, particularly when multiple sections of road are affected simultaneously.

The New Zealand Civil Defence Emergency Management (CDEM) Act 2002 requires that all lifelines (including the road network) be able to function to the fullest possible extent during and after an emergency. Lifeline providers should also have plans for ensuring this that can be made available to the Director of CDEM if requested. To be able to meet their legislative obligations under the new act, road network managers will need to have a framework in place for identifying, evaluating and actively managing risks to the road network.

The CDEM Act encourages organisations to take an all-hazards approach to their risk management. An all-hazards approach implies a need to have a consistent framework for evaluating all types of hazards to prioritise the relative risks posed by each. This presents challenges for evaluating risks across distributed networks such as the road network, as hazards occur at different locations, on different geographic scales, different time scales, and may be increasing or decreasing at different rates.

In New Zealand a number of different research programmes and databases gather information about the frequency and magnitude of hazard events, the vulnerability of infrastructure to hazards, and the socio-economic impact of road closures. Much of this information however, in its current form, does not directly assist managers to make informed decisions about how to better manage hazard risks to the road network. There are significant challenges to bring this information together to assess risks across a geographically dispersed road network, particularly to achieve a balance between a solution that captures the complexities involved and the need for it to be affordable, achievable and readily used by road network managers.

1.1 Scope of this report

The purpose of this research is to assess the feasibility of carrying out a natural hazard risk assessment for the whole of the New Zealand State Highway network. In particular it considers:

- the range of issues that need to be addressed when assessing risks to the State Highway network;
- a gap analysis of data and knowledge requirements for carrying out the risk assessment and potential options for closing these existing gaps in data and knowledge;
- a 'road map' outlining a suggested approach for carrying out an integrated hazard risk assessment for the whole of the New Zealand State Highway network.

Road network managers have multiple objectives to meet in their management of the road network, such as life safety, value for money, environmental protection, satisfying community expectations, sustainability, reputation, etc. Ideally, a risk management process should address risks to all of these objectives. In order to keep this initial project manageable we have focused on a subset of risks – the reliability of the road network in the face of hazard events.

It should be noted that although this initial report considers primarily natural hazards, it is intended that the methodology developed will be applicable to any type of hazard event with the potential to cause road closures. Similarly, it is anticipated that future developments include risk to life, safety, reputation, etc.

Developing a full risk assessment for the New Zealand State Highway network is a significant task. The purpose of this research is not to assess risks, but to explore how such an assessment could be undertaken, whether it is feasible, and to develop a framework for carrying out the assessment.

1.2 Definitions of risk

The New Zealand Risk Management Standard (AS/NZS 4360:1999) identifies eight key elements of a risk management process as shown in Figure 1.1. For the purposes of this project, we are focusing on the first and probably the most important of these elements: **Establishing the Context**. The Risk Management Standard (AS/NZS 4360:1999) describes this phase as:

> *Establish the strategic, organisational and risk management context in which the rest of the process will take place. Criteria against which risk will be evaluated should be established and the structure of the analysis defined.*

Establishing the context requires thinking about:

- Who makes decisions about hazard risk management for the road network and what type of information do they require to support and improve the decisions that they make?
- What information is already available and what information would need to be collected?
- How will that information be brought together and analysed to estimate levels of risk?
- How is that information best communicated to maximise its effectiveness?

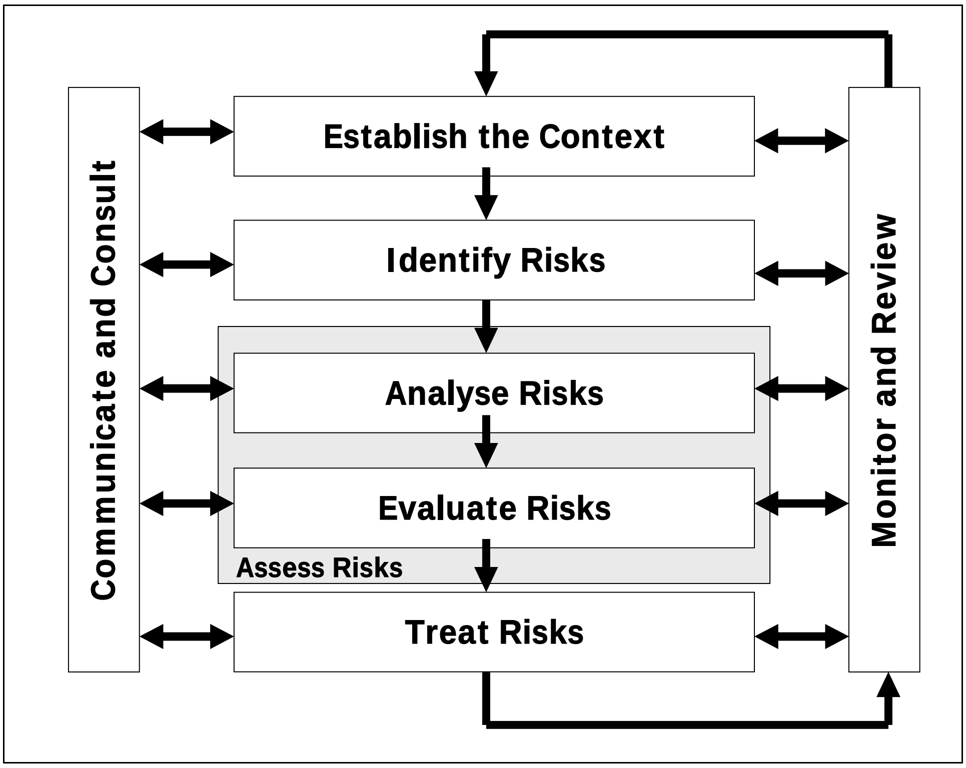


Figure 1.1 Risk management overview (taken from AS/NZS 4360:1999).

Risk is a function of both the likelihood of an event occurring, and its consequences. In the NZ Risk Assessment Standard (AS/NZS 4360:1999), risk is defined as:

> *The chance of something happening that will have an impact upon objectives. It is a measure in terms of consequences and likelihood.*

Within our context of assessing road closure risk for the road network, risk can be defined as a function of:

- the likelihood and magnitude of a hazard event,
- the vulnerability of the road network to damage from that event,
- the social, environmental and economic impacts of any damage or disruption to traffic,

summed over the full spectrum of hazard magnitudes capable of impacting on the road network (Figure 1.2).

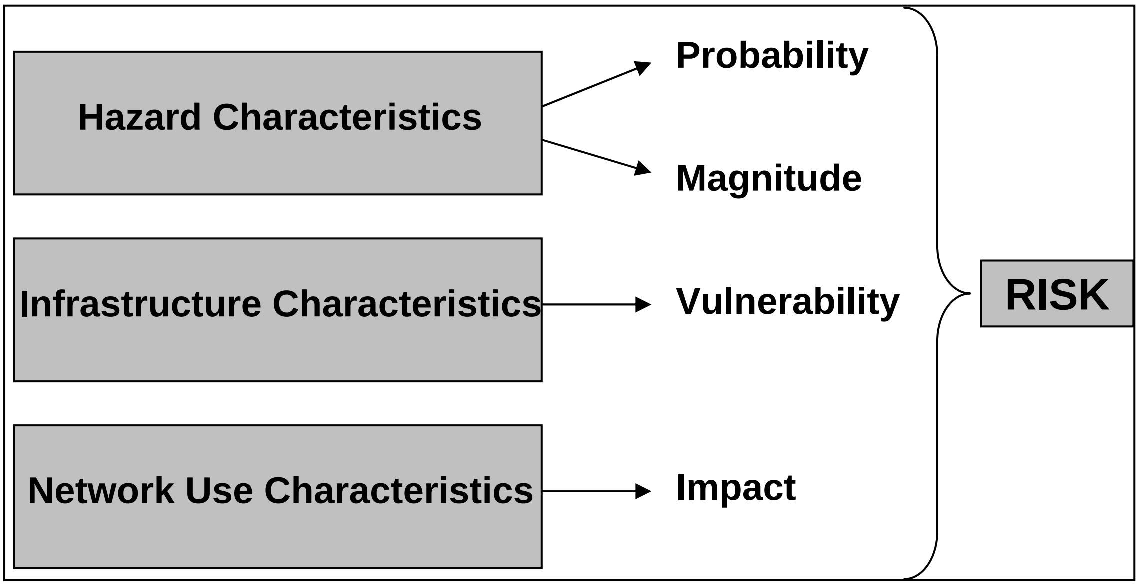


Figure 1.2 Components that are considered in the estimation of risk to network performance.

1.3 Connections with previous research

This section provides a brief overview of research undertaken in New Zealand and overseas of particular relevance to this project.

This project builds on an earlier Transfund Research Report, *Risk Assessment Methods in Road Network Evaluation* (Dalziell et al. 1999) that looked at how risk assessment methodologies could be used to assess the risks of the Desert Road being closed because of natural hazards and how those risks could be reduced. That research considered the risk of road closure from snow and ice, seismic events, volcanic eruption and lahars, and traffic accidents. It also looked at the network effects of simultaneous road closures. While Dalziell et al. (1999) showed that probabilistic risk assessment can be used successfully in road network evaluation for a small region, it did not consider how to assess risks across a geographically dispersed road network where interdependencies between closures of different road links depend on the hazard scenario event.

Transit NZ(1998) have developed and implemented a framework for evaluating seismic risk to bridges on the State Highway network. This screening process, which is discussed further in Section 3.1.2, provides a basis for prioritising seismic retrofit of bridges that includes hazard, vulnerability and importance attributes. In this project we will need to extend this approach to include all components of the State Highway network, and all hazards.

Brabhahran (2001, 2002) explored how natural hazard risk management could be implemented for the road network, suggesting natural hazard risk be considered at five levels – national, regional, local network, emergency management and project development. Brabhahran demonstrated the value of spatial analysis of risk using Geographical Information Systems (GIS) in a case study of a small scale network. In this research we extend his work to propose GIS analyses for assessing risks across the whole of the State Highway network.

Savage et al. (1998) set out a basic framework for lifeline organisations to assess economic costs and benefits of risk mitigation investments. They suggest two possible approaches. The first is a 'simple probability approach' considering a single hazard event and calculating the expected value of investment and the conditional probability value of an investment (i.e. the costs and benefits if the event happened in a particular year). The second approach is a 'hazard curve approach', which allows all possible hazard events to be included in the analysis. In this research we will be using the second approach suggested by Savage et al., as it allows all hazards to be considered and the full spectrum of event scales to be considered in the analysis.

Koorey & Mitchell (2001) investigated how road link reliabilities can be taken into account during project evaluation procedures. When currently evaluating projects, the assumption is generally made that the existing road network will continue to perform as it stands, with no closures. Secondary economic consequences of road closures are not considered, nor the relative importance of links with few alternative routes. It is intended that the risk assessment methodology outlined in this report would support the approach recommended by Koorey & Mitchell, providing estimates of link reliabilities that could be used in individual project evaluation.

In the US, the Multidisciplinary Centre for Earthquake Engineering Research (MCEER) is developing a methodology for carrying out Seismic Risk Assessments (SRA) in the US. Their methodology reflects a growing recognition that losses due to highway damage depend not only on the vulnerability of the highway components, but also on the nature of the overall highway system (Werner et al. 1997). Earthquake damage to certain highway structures such as bridges on very important or non-redundant links within the system will have greater impact on system performance than will other components. Traditional design/strengthening criteria, however, typically ignore systems issues such as these. They tend to focus primarily on the vulnerability of the infrastructure rather than on a more complete picture of risk. Where bridge importance is included as a prioritisation parameter, it is normally characterised by average annual daily traffic, detour length and route type parameters. These do not account for the systems effects associated with the loss of a given bridge, or for the combinatorial effects associated with the loss of other bridges in the highway system (Buckle 1992). The MCEER research programme aims to develop a SRA procedure that addresses these issues.

The key to the MCEER approach is a modular GIS database that contains the data and models needed to perform the SRA. This analysis tool is being developed into publicly available software called REDARS. REDARS contains four GIS modules, each describing a different component required for the seismic risk analysis. These four modules are described below:

- **Network System Module** describes the highway system and trip generation characteristics. It also includes models for analysis of traffic flows in the network pre- and post-earthquake.

- **Hazard Module** simulates the generation of earthquakes and selects their magnitude, location and frequency of occurrence. It contains input data and models to characterise system-wide ground motion, liquefaction, landslide, and surface rupture fault hazards.
- **Component Module** contains fragility curves for different components of the network such as bridges and tunnels. It also contains information relating to repair costs and serviceability after an event.
- **Socio-Economics Module** contains data and models to establish after-event costs caused by damage to the network. Currently this looks only at direct repair costs and costs to road users.

The modular GIS framework used by REDARS has several benefits. The GIS platform provides ease of data management, analysis efficiency and effective presentation of the spatial nature of analysis results. The modular nature of the database also facilitates the addition of improved data and data models as they become available.

The SRA methodology involves a four stage process. These are:

- **Initialisation of Analysis.** Selection of scenario earthquakes to be analysed, and establishing the number of simulations for each scenario earthquake.
- **Development of nth Simulation for ith Scenario Earthquake.** Estimate the earthquake ground motions and geologic hazard across the network. Evaluate direct losses and system states at various times after the earthquake. Assess the effects on travel times, travel distances, and travel paths. Evaluate impacts of impeded traffic flow in terms of indirect dollar loss, reduced access to and from emergency response centres, and certain societal impacts.
- **Incremental Simulation of Scenario Earthquakes**. Repeat steps for multiple scenario earthquakes. If the analysis is to be probabilistic, then repeat the second step to develop multiple simulations per scenario earthquake.
- **Aggregate System Analysis Results.** Results from all simulations and scenario earthquakes are aggregated and displayed. These results can focus on system wide risks or risks to individual components, depending on user needs.

The software is designed to assess seismic risk across a road network system. The costs included are currently those relating to direct repair costs of highway structures and the direct costs associated with disruptions to the network. Future developments are likely to see more advanced economic features being incorporated into the model, such as changes in traffic demand due to damage to buildings, and business losses associated with damage to the highway network (Werner et al. 2000).

REDARS represents a significant advancement in road network risk assessment capability; however, some issues prevent its direct application in New Zealand. The current scope of the software considers only seismic hazards. The approach would need to be extended significantly in the light of the 'all hazards' emphasis of the CDEM Act (2002). The software also has extensive data requirements which are likely to make its full implementation in New Zealand expensive. It does, however, provide us with an excellent source of expertise and experience in developing a GIS-based software for assessing risk to a road network.

1.4 Connections with future research initiatives

The Foundation of Research, Science and Technology (FRST) in New Zealand currently invests $11 million per annum in natural hazards research. The Institute of Geological and Nuclear Sciences (GNS) and the National Institute of Water and Atmospheric Research (NIWA) have recently secured funding from FRST for a four-year research programme to develop a Regional Riskscape Model. The model is intended to provide a consistent approach to assess risks posed by multiple natural hazards. This research programme has the potential to provide valuable information that could be used in the risk assessment for the State Highway network. The key will be to ensure that the information is presented in a format that can be used for the road network with minimal additional analysis. End-user participation within the research programme is being sought and is likely to yield significant benefits in reducing the research investment required to convert hazardscape information into a format that can be used in the risk assessment.

FRST are also funding a six-year research programme, Organisational Systems for Readiness, Response and Recovery, led by Dr Erica Seville (nee Dalziell) at the University of Canterbury. As part of that research Dr Andre Dantas will be using the road network as a case study to develop a GIS-based tool for prioritising response and recovery for networked systems. This tool is likely to have some common elements with the risk assessment tool discussed in this report, in that it is likely to include a modular GIS-based tool that contains information about the road network. It will need to interface with the Ministry of Civil Defence and Emergency Management (MCDEM) response and recovery platform, be able to assimilate actual damage information as it is received, and be able to optimise the deployment of available resources and prioritise infrastructure repairs to minimise socio-economic impacts. It makes sense to ensure that this research programme and any future Transfund research in this area are well aligned. In particular, some of the GIS modules could be common for both purposes simplifying data gathering and updating. The user interfaces should have a similar 'look and feel' so that operators are comfortable in using either programme immediately in the case of a major hazard event.

Research also proposed to FRST in the 2003/2004 funding round by GNS and the New Zealand Institute of Economic Research (NZIER) suggested looking at the economic impact of hazard events. At the time of writing it was unclear whether this research would be funded. If it is, it may provide some useful data relevant to the socio-economic impacts of community isolation.

1.5 Potential value for end users

The purpose of a risk assessment is to be able to make informed decisions about the best way to manage the risks. In this section we consider who is making those decisions, and how the risk assessment tool could be designed to maximise its potential contribution.

1.5.1 Setting national risk management priorities

The Transfund NZ Project Evaluation Manual (PEM, Transfund 1997) includes a section on how risk can be included into the standard project evaluation procedure. There are several reasons why a national risk assessment framework is required above and beyond this. These include:

- Some hazards have long return periods, and may not have occurred in recent memory. One of the challenges in successful risk management is ensuring that the full spectrum of risks has been identified. Without a formal process for looking systematically across the whole of the network it is possible that some areas of significant risk are not identified.
- Natural hazard events have the potential to cause damage simultaneously to a large number of roads. It is difficult to value the compounding effects of potential damage to individual sections without modelling the chance of simultaneous damage on the surrounding network, which is typically outside the scope of standard project evaluation procedures.
- The need for a consistent data set and methods for assessing risk to be able to compare relative risks across regions and projects for prioritising investment.

An output of the risk assessment would be annotated maps showing the profile of road closure risk across the country. Note that this would be different from standard hazard maps, as these maps would reflect *risk,* which includes not only information about the hazardscape but also the vulnerability of the infrastructure and strategic importance of the route.

1.5.2 Supporting project-based risk analysis

As discussed earlier, when currently evaluating projects, the assumption is generally made that the existing network will continue to perform as it stands, with no closures. This does not consider the economic consequences of road closures, or the relative importance of links with few alternative routes. Koorey & Mitchell (2001) recommended an approach to be included in the PEM procedure. Doing an analysis of road closure risks on a project-by-project basis may lead to duplication of effort as regions independently collect and manipulate hazard information into a useable format. It is intended that the risk assessment methodology outlined in this report would encourage greater consideration of network reliability impacts by providing easily accessible, up-to-date information about hazards and the impacts of road closures.

1.5.3 Response and recovery planning

Information collected to complete a risk assessment will also be useful to support decisions after a hazard event. In this instance, damage to the road network will have already occurred, or be happening, and it will be the role of network managers to prioritise where resources should be sent to repair the damage. The risk assessment tool will have the capability to estimate the socio-economic impact of the damage scenario, which coupled with information on resource availability and other constraints, can be used to support the co-ordination of appropriate response and recovery strategies. This is the subject of upcoming FRST-sponsored research, as discussed in Section 1.4.

2. Proposed risk assessment framework

One of the challenges in assessing risks to networked systems such as the transportation network is that damage to one part of the network is not statistically independent of damage on another part of the network. Analysis of risks to the network using site hazard distributions or probabilistic hazard maps (i.e. assessing the risk at individual sites, and then summing over all sites to assess the total risk to the network) will give misleading results as one event is more likely to cause simultaneous damage to neighbouring parts of the network.

For understanding risks to portfolios and geographically distributed networks, the move has been towards the use of catastrophe scenarios to estimate potential losses across the system. The use of scenarios has the advantage of making it easier to visualise and communicate potential losses to decision makers, and to compare potential losses with past events. Difficulties with scenario approaches, however, are deciding which scenario event(s) should be used in the analysis.

2.1 Walkthrough scenario approach

A technique that might be used to resolve this issue is the 'Walkthrough Scenario Methodology' (Taylor et al. 2001). The walkthrough approach randomly generates hazard events over a certain analysis period, defined by the user to reflect their requirements (e.g. such as the design life for a bridge). The user also selects the total duration of the random walk. For example if we are interested in a 50-year exposure time, a 250,000-year random walk will give 5000 samples of loss results for different 50-year exposure times. In each year of the walkthrough, the model will randomly generate from hazard models the number of hazard events that take place, and their size and location.

An advantage of a walkthrough scenario analysis is that it is possible to bring into the analysis a time dimension of 'when' the event takes place. Many investment decision techniques, such as benefit-cost ratios, use discounted time-series evaluations of when investment takes place v. when the benefits of that investment are achieved. Time-series evaluations are also useful where the probability or consequences of a particular event are expected to change over time, such as through increased development in certain areas, or through long-term processes such as global warming.

One difficulty in applying the walkthrough methodology across a large network such as the State Highway network is the large number of different hazard event scenarios that could take place, and the number of simulations required to achieve convergence between simulations. For example, in the Wellington area alone, there are numerous different faults, and limitless potential earthquake scenarios, of different magnitude, location and depth. Similarly for floods, there is the full spectrum of potential flood depth and velocity, and combinations of different catchments affected.

Chang et al. (2000) suggest an iterative technique for selecting a reduced number of scenario events to be simulated, and for assigning probabilities to those scenarios such that they are roughly consistent with the overall frequency and severity of hazard events for the area. For example, rather than indicating the likelihood of specific event A occurring, the hazard-consistent probability indicates the likelihood of events 'like A' occurring, with a similar spatial distribution of impacts.

The technique described in Chang et al. (2000) can be applied to analyses of urban areas. Ishikawa et al. (1997) describe a similar technique, more suitable for macro-level evaluation. In New Zealand, Rhoades & McVerry (2001) from GNS have also explored the joint probability of simultaneous damage at two or more sites. Their research looks at the spatial distribution of peak ground acceleration in the same earthquake, and techniques for estimating the ratio between joint probabilities from the same source and from different fault sources. For our purposes, we will probably want to draw on a combination of these techniques to find an appropriate level of analysis. Further research is required to better understand how existing hazardscape models might be simplified using these techniques.

2.2 Monte Carlo analysis

As highlighted by Taylor et al. (2001) it is now widely recognised that risk management needs to go beyond 'worst-case scenario' or 'probable maximum loss' type analyses. For every 'worst-case scenario' presented, an analyst can always construct an even worse scenario, and decisions based on 'worst-case' evaluations may well encourage misallocation of resources. Many hazards can occur on different scales, and it is necessary to be able to understand if the greater risk comes from smaller, more frequent events, or larger rare events.

With many hazards, there are significant uncertainties in our understanding of hazard processes and how they will impact infrastructure and society. Monte Carlo simulation is a tool for propagating uncertainties in input data through a model. The process of Monte Carlo simulation is made up of a large number of iterations. Input parameters that are uncertain are described as a probability distribution of possible values rather than a single value. Each iteration is like the successive roll of dice, generating a random combination of input parameters from their respective distributions, giving one possible model solution. This process is repeated many times, generating alternative model solutions. As the number of iterations increases it is possible to estimate the probability distribution function of the model solution.

A limitation of Monte Carlo analysis can be the number of iterations required to find a stable solution. This is likely to become an issue for this risk assessment, where the number of potential different hazard scenarios is limitless, with each having a unique impact on the road network. Chang (2000) suggested using a form of artificial intelligence (A.I.) to reduce the computing requirements for large numbers of simulations. The approach uses multi-criteria associative memory, a process in which the program identifies similarities between scenarios generated and scenarios that it has 'learnt' previously. For example, if an iteration indicates a similar pattern of road closures to a previous iteration, the model would look to the traffic-modelling results that were generated for the previous analysis rather than going through the full traffic-modelling process all over again.

2.3 Software platform

Geographic Information Systems (GIS) provide a powerful tool for analysing and communicating geospatial information, and would probably be the most appropriate platform on which to base the risk assessment. Transit NZ recently invested to digitise the centre-line co-ordinates for the whole of the State Highway network. In addition, a growing proportion of hazard information is available in GIS format and many local government organisations also use GIS databases. There are also significant amounts of information such as census data and topographical information available in GIS format through Land Information New Zealand (LINZ).

Examples of GIS being used in risk assessment include HAZUS, a powerful GIS-based software tool in use in the United States. A key characteristic of the HAZUS system is its modular design, which enables easier database management and iterative improvement. The database initially included only seismic hazard information, but has since been upgraded to include information about other hazards such as flooding, hurricane and tornado. The system is designed to operate on personal computer (PC) based GIS systems such as MapInfo and ArcView, which allows a variety of users such as emergency response organisations and government agencies to access the information.

One of the challenges will be in designing a GIS platform that maximises compatibility with other GIS databases used in New Zealand, that is capable of interfacing with traffic-modelling software, and that is user friendly. Zerger (2002) warns that GIS tools need to be developed keeping the end purpose in mind. Although this seems self-evident, the prevalent design approach has a far greater focus on facilitating the analysis of data. It is recommended that significant thought and effort is put into ensuring that the right data are collected and that the data are structured to ensure they can be moved from platform to platform as needed. Starting with conceptually good data design is likely to save significant time and effort in later maintenance and improvement costs.

2.4 Determining an appropriate level of detail

In the words of Einstein, it is important that this risk assessment methodology be "as simple as possible, but no simpler". A risk assessment is not an end unto itself. The purpose of the risk assessment is to support more effective decision making about how to better manage risks. It is proposed that development of a full risk assessment is progressed iteratively, starting with high level analyses. From those analyses areas would be identified that will benefit from more detailed analysis.

2.5 Overview of proposed methodology

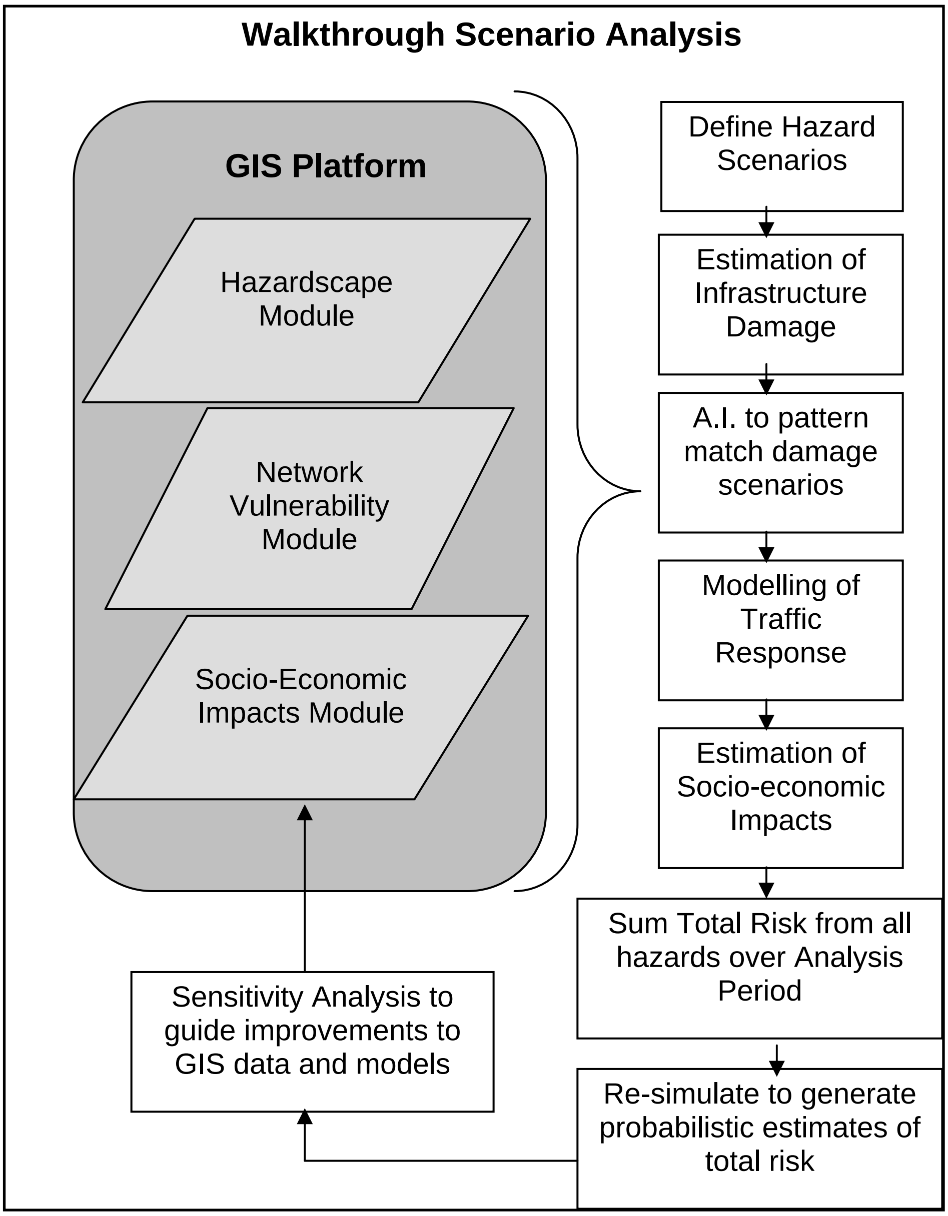


Figure 2.1 Overview of proposed risk assessment framework.

3. Hazard data availability and analysis

Information available in the research community relating to natural hazards and the transportation network can be categorised as:

- research into the underlying mechanisms of different hazard events, why they occur, their characteristics, when they happen, and the probability of them occurring in the future,
- research into the vulnerability of infrastructure to these hazard events (such as the response of bridges to seismic shaking),
- research into the effects any damage to the infrastructure has on the transportation network (the availability of roads for emergency and other vehicles following a hazard event, how traffic behaviour may respond to changes in the network, and ways to measure the costs to society of disruptions to the network).

This chapter discusses what information is available in New Zealand relating to the hazardscape and the vulnerability of the road network to these hazards.

3.1 Seismic events

New Zealand is located on the boundary of the Pacific and Australian plates making it prone to a large amount of seismic activity.

3.1.1 Probability of seismic events

Determining the probability of earthquake occurrence is not an accurate science. It relies on a mix of historical and geological data along with measurements of fault movements and observations of earthquake behaviour from New Zealand and around the world.

In 2000 GNS prepared a probabilistic seismic hazard assessment (PSHA) covering the whole of New Zealand. The PSHA predicts the location, magnitude, tectonic type or mechanism, and the frequencies that may be produced at each earthquake source. These predictions are based on geological and historical records.

The predictions of peak ground accelerations (PGAs) experienced in an earthquake are reliant on information about ground conditions within the areas affected by the earthquake. Different soil types and varying depths will cause different levels of ground acceleration as the energy produced by an earthquake is propagated up from the bedrock and through the overlying soil. The prediction model used in the GNS report uses three different classifications for site conditions. Figure 3.1 illustrates the differences in ground shaking intensity depending on the soil type at a particular site.

The outputs from the PSHA models are maps showing the distribution of PGAs across the country for given return periods and probabilities of exceedence. Figure 3.2 shows the PGA map for New Zealand with a 10% probability of exceedence over a 50-year design life.

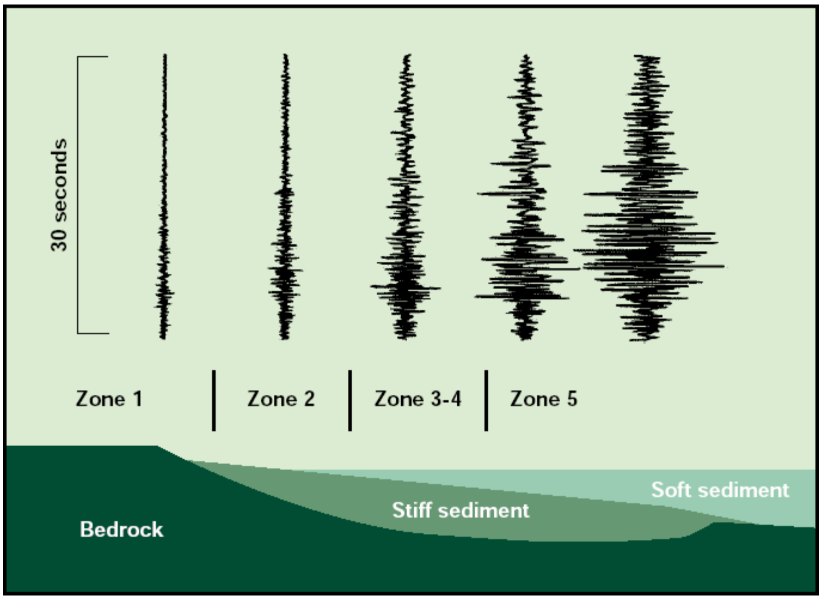


Figure 3.1 Shows how ground conditions at a site effect the amplitude and frequencies of ground motions. The GNS report uses a similar soil classification in estimating PGA experienced within New Zealand (GNS website 2003).

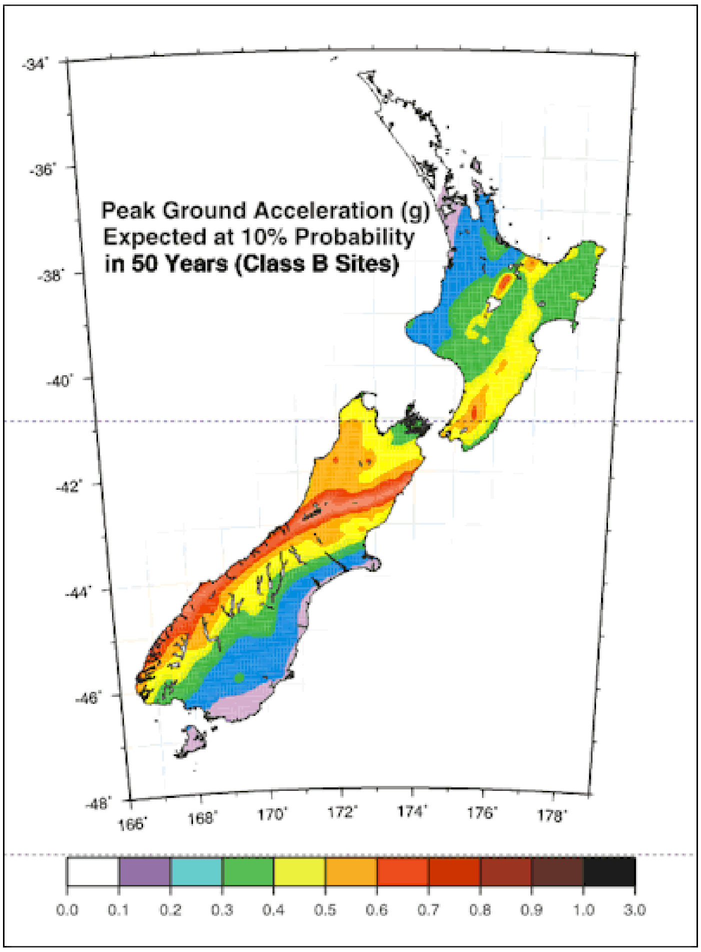


Figure 3.2 The output of the model employed in the GNS report shows the peak ground acceleration with a 10% probability of exceedence in 50 years (GNS Website 2003).

There are many uncertainties in estimating the probability of seismic events, including natural variability and limitations of our current state of knowledge. Unfortunately the PGA maps do not include information about their estimated uncertainties, so it will be necessary to discuss with GNS the degree of uncertainty that should be assumed in any risk assessment.

3.1.2 Consequences of seismic events

3.1.2.1 Bridge failure

The vulnerability of bridges is important from a network perspective. In general, because of the high cost associated with building bridges and the terrain they are commonly built in, generally redundancy is less in networks where multiple bridges are required.

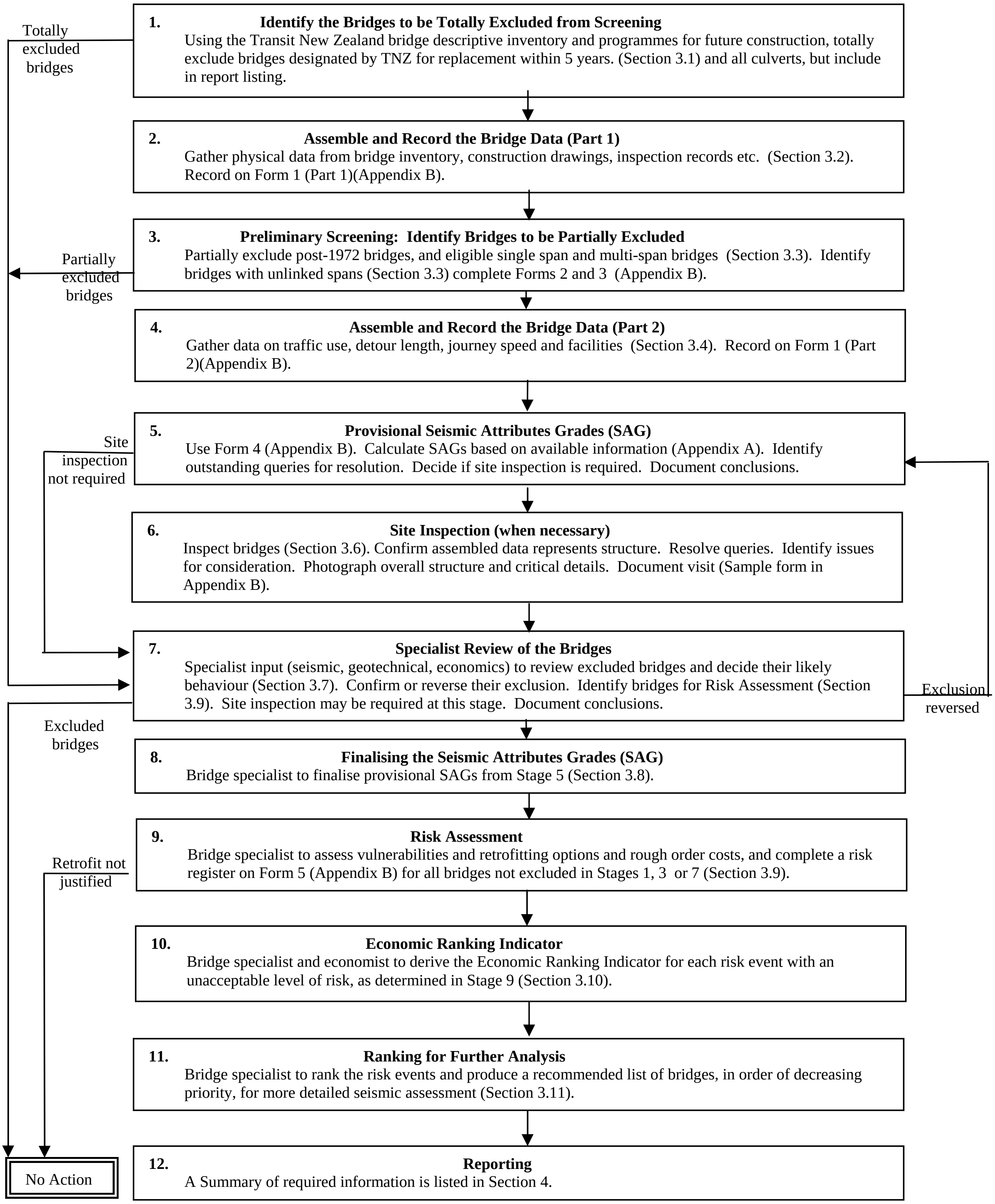
Transit NZ (1998) has developed a screening process for evaluating bridges within New Zealand with regard to seismic hazards. The process followed estimates the bridge's vulnerability, its probability of experiencing high magnitude earthquakes, and the impact to the economy if the bridge becomes unusable (see Figure 3.3). Transit's evaluation process has already been conducted for all bridges on the State Highway network.

For bridges involved in the screening process that have been assessed by an engineer, PGA values have been assigned based on their ability to trigger different failure mechanisms within the bridges. These values can be directly incorporated into the risk assessment process.

Some problems are associated with the ranking system used by Transit NZ in assessing the bridges when put in the context of a broader risk assessment process. The ranking incorporates the probability of earthquake occurrences, the vulnerability of the bridges, as well as the economic consequences of a bridge failing. These components would need to be separated out to enable consistent comparison with risks from other types of hazard. The ranking does reflect the network availability of an alternative route in the creation of the Seismic Attributes Grade (SAG) which is a significant factor in deciding relative rankings of the bridges for detailed seismic assessment. However, in assessing the available routes there is no consideration for the interdependencies that may exist between the failure of the original route and the detour route (see Figure 3.4).

Figure 3.3 Transit NZ Manual for Seismic Screening of Bridges (MSSB) outlines the process by which bridges are evaluated for retrofitting. This diagram shows the process which is followed (Transit NZ 1998).

(See p.27)



1. Identify the Bridges to be Totally Excluded from Screening
Using the Transit New Zealand bridge descriptive inventory and programmes for future construction, totally exclude bridges designated by TNZ for replacement within 5 years. (Section 3.1) and all culverts, but include in report listing.

2. Assemble and Record the Bridge Data (Part 1)
Gather physical data from bridge inventory, construction drawings, inspection records etc. (Section 3.2). Record on Form 1 (Part 1)(Appendix B).

3. Preliminary Screening: Identify Bridges to be Partially Excluded
Partially exclude post-1972 bridges, and eligible single span and multi-span bridges (Section 3.3). Identify bridges with unlinked spans (Section 3.3) complete Forms 2 and 3 (Appendix B).

4. Assemble and Record the Bridge Data (Part 2)
Gather data on traffic use, detour length, journey speed and facilities (Section 3.4). Record on Form 1 (Part 2)(Appendix B).

5. Provisional Seismic Attributes Grades (SAG)
Use Form 4 (Appendix B). Calculate SAGs based on available information (Appendix A). Identify outstanding queries for resolution. Decide if site inspection is required. Document conclusions.

6. Site Inspection (when necessary)
Inspect bridges (Section 3.6). Confirm assembled data represents structure. Resolve queries. Identify issues for consideration. Photograph overall structure and critical details. Document visit (Sample form in Appendix B).

7. Specialist Review of the Bridges
Specialist input (seismic, geotechnical, economics) to review excluded bridges and decide their likely behaviour (Section 3.7). Confirm or reverse their exclusion. Identify bridges for Risk Assessment (Section 3.9). Site inspection may be required at this stage. Document conclusions.

8. Finalising the Seismic Attributes Grades (SAG)
Bridge specialist to finalise provisional SAGs from Stage 5 (Section 3.8).

9. Risk Assessment
Bridge specialist to assess vulnerabilities and retrofitting options and rough order costs, and complete a risk register on Form 5 (Appendix B) for all bridges not excluded in Stages 1, 3 or 7 (Section 3.9).

10. Economic Ranking Indicator
Bridge specialist and economist to derive the Economic Ranking Indicator for each risk event with an unacceptable level of risk, as determined in Stage 9 (Section 3.10).

11. Ranking for Further Analysis
Bridge specialist to rank the risk events and produce a recommended list of bridges, in order of decreasing priority, for more detailed seismic assessment (Section 3.11).

12. Reporting
A Summary of required information is listed in Section 4.

Note: Stages of work will normally be undertaken by the following personnel:

Stages 1 to 5	Engineering personnel familiar with the structures
Stage 6	Experienced bridge inspector or competent bridge designer
Stage 7 to 12	Bridge engineers, geotechnical engineers and economists experienced in the seismic design of bridges.

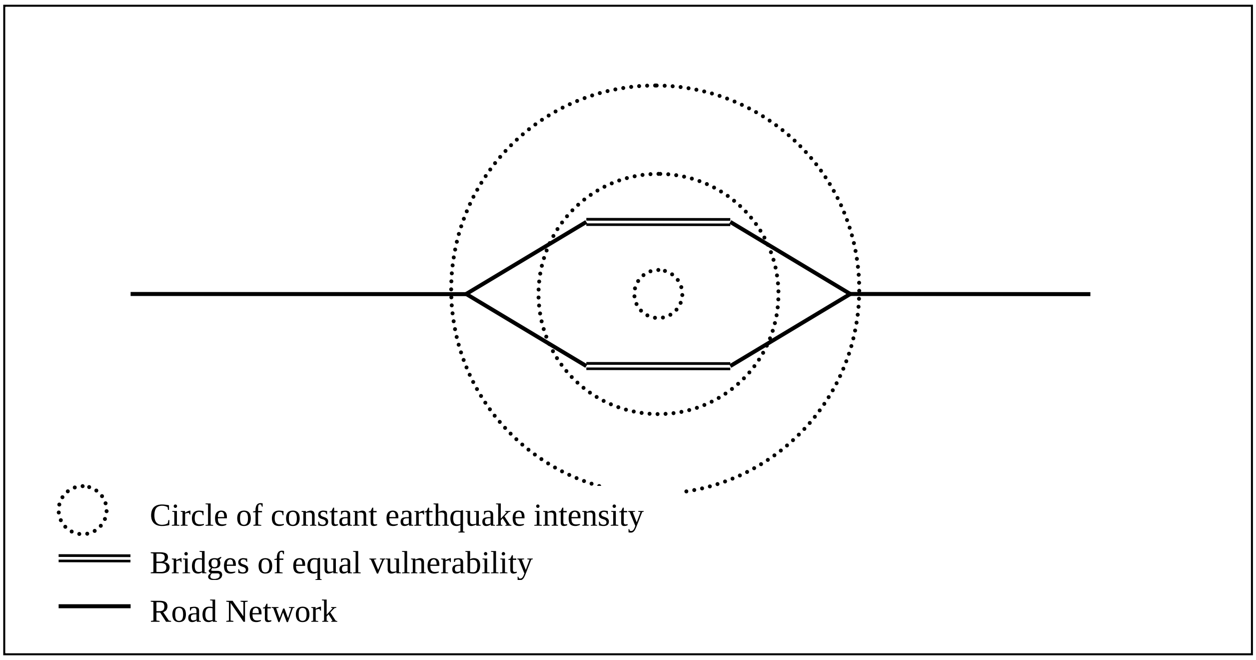


Figure 3.4 Both bridges are equally likely to fail at a given earthquake intensity. The Transit methodology assumes that failure of each bridge is independent of each other. This is unlikely to be the case in the event of a major earthquake that is centred close to the bridges.

3.1.2.2 Surface rupture

Surface rupture is the term used for disturbances to the ground surface in the event of an earthquake. It covers uplifts, vertical displacements, and separations. The size of surface ruptures varies greatly depending on the type, location, and magnitude of the earthquake and can be quite substantial. This was observed during the 1929 Murchison earthquake in which over 1,000 km^2 was uplifted by an average of one metre from its original position. Other examples of surface rupture occurred during the 1987 Edgecumbe earthquake.

Ground ruptures are located along fault lines but little is known about predicting the extent of the ruptures. The soil types along the fault are likely to play a major part, as will the extent of the fault movement. There is no doubt that ruptures can cause major damage to road carriageways but this will be relatively quick to repair unless earth-working machinery is not available or is unable to gain access to the site of rupture because of other damage to the State Highway network.

3.1.2.3 Liquefaction

Liquefaction occurs as a result of ground shaking in areas where a combination of high pore water pressures and fine particle clays are present. The ground shaking causes the soils to become saturated, consequentially losing strength and behaving in a fluid manner (see Figure 3.5). The effects of liquefaction take a number of forms:

- water ejections (high pressure fountains),
- sand boils,
- settlement,
- landslides.

A study conducted by Brabhaharan (2002) established the potential liquefaction hazard present in western Bay of Plenty. This study used prediction models from GNS to predict earthquake intensities and then compared this information with soil and water table profiles to establish the likelihood that liquefaction will occur. Similar hazard maps that have been generated for other regions could be combined to form a hazard map identifying the liquefaction potential throughout much of New Zealand.

Figure 3.5 Liquefaction occurring under roadways will make them impassable except by all-terrain vehicles. Napier earthquake 1931 (GNS website).

3.1.2.4 Rock falls

Rock falls have the potential to block a section of road, and cause impact damage to the road surface. It is not currently possible to predict the likelihood of rock falls occurring during an earthquake using models or formulas. Areas that will be susceptible to rock falls can be identified by an experienced geologist through observation. Determining the size of an earthquake that may trigger a rock fall and the size of the rock fall will not be easy. In predicting these parameters past rock fall information could be used where available. Most of this information will consist of historical records and from geological information about earthquakes that occurred both before and after colonisation of New Zealand.

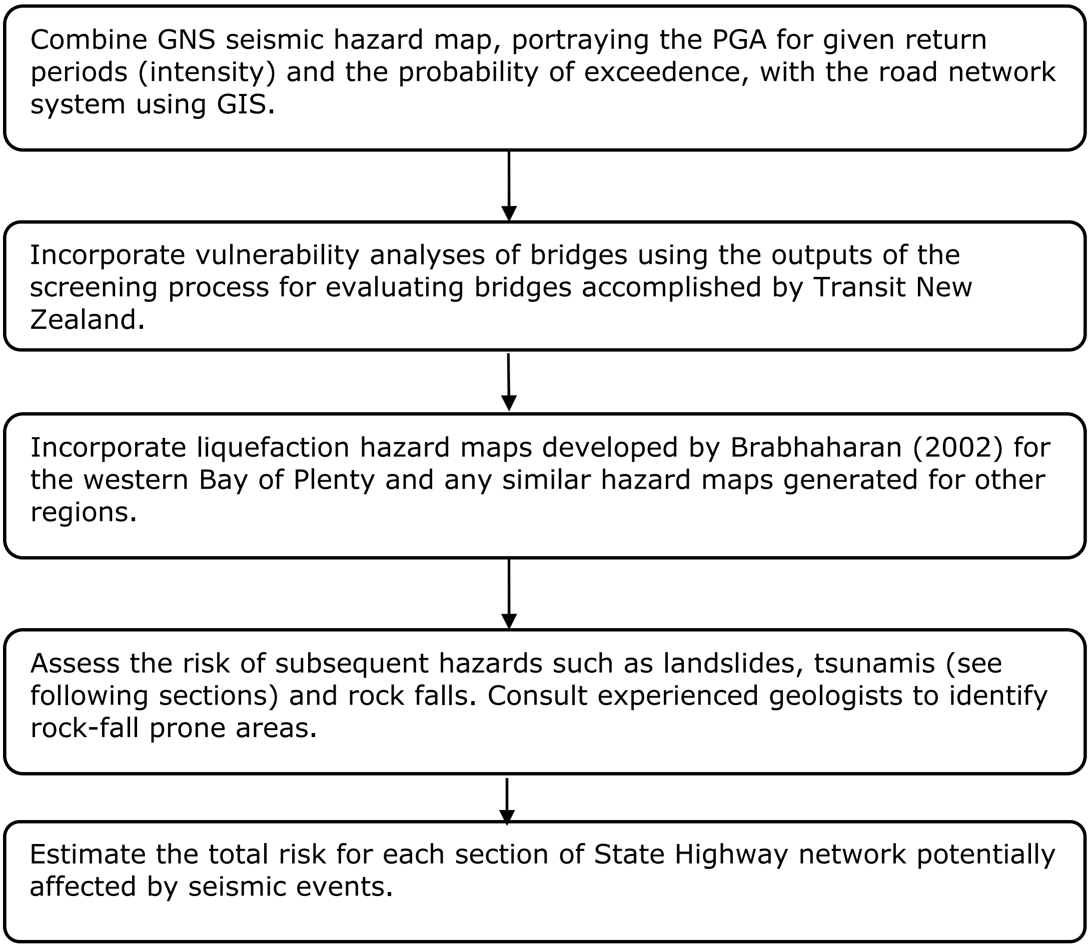
The major impact from rock falls will not be experienced during an earthquake but rather in the post-earthquake scenario. An earthquake occurring in a mountainous region will cause numerous rock falls, but a large number will also occur after the earthquake because of general instability and aftershocks. This does not pose a significant threat to the State Highway network itself but to those who may be working in the area to clear earlier rock falls and other obstructions caused by the initial earthquake. Because of this threat it may not be possible to send workers to the affected areas without first ensuring that further rock falls will not occur, hence slowing the recovery of the network.

3.1.2.5 Urban debris

The State Highway network is designed to carry large volumes of traffic at high design speeds. In order to reduce the impact that the network has on its surroundings they are, wherever possible, built outside urban environments. This means that little of the State Highway network will be subject to the possibility of closure due to urban debris. In most instances where the network passes through an urban environment there are likely to be local roads that will enable highway traffic to bypass any blockages.

3.1.2.6 Other effects

Landslides and Tsunamis can also be associated with seismic events, but these are discussed in later sections of the report.



Combine GNS seismic hazard map, portraying the PGA for given return periods (intensity) and the probability of exceedence, with the road network system using GIS.

Incorporate vulnerability analyses of bridges using the outputs of the screening process for evaluating bridges accomplished by Transit New Zealand.

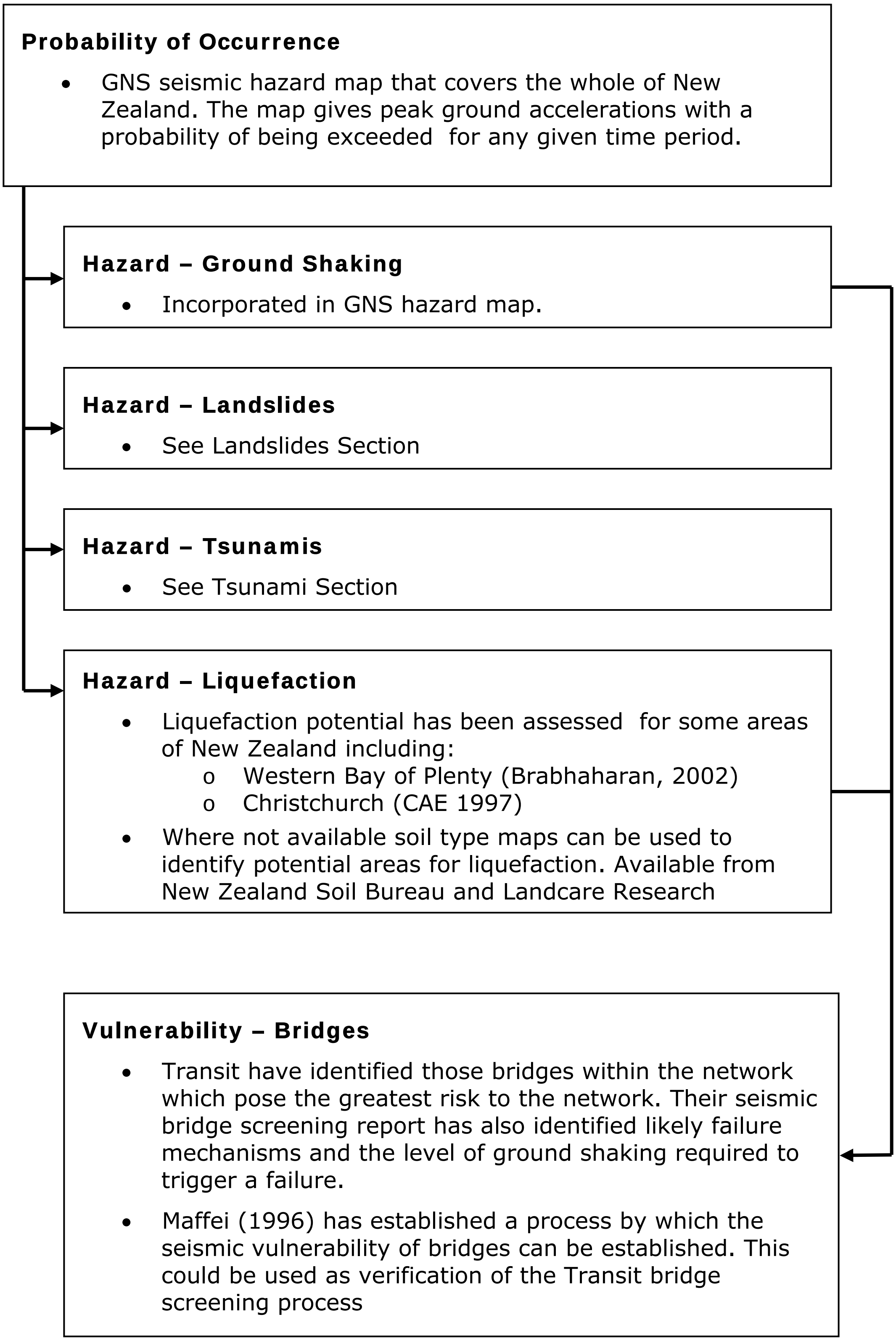
Incorporate liquefaction hazard maps developed by Brabhaharan (2002) for the western Bay of Plenty and any similar hazard maps generated for other regions.

Assess the risk of subsequent hazards such as landslides, tsunamis (see following sections) and rock falls. Consult experienced geologists to identify rock-fall prone areas.

Estimate the total risk for each section of State Highway network potentially affected by seismic events.

Figure 3.6 Proposed methodology to assess the risk caused by earthquake hazards.

3.1.3 Information availability



Probability of Occurrence

- GNS seismic hazard map that covers the whole of New Zealand. The map gives peak ground accelerations with a probability of being exceeded for any given time period.

Hazard – Ground Shaking

- Incorporated in GNS hazard map.

Hazard – Landslides

- See Landslides Section

Hazard – Tsunamis

- See Tsunami Section

Hazard – Liquefaction

- Liquefaction potential has been assessed for some areas of New Zealand including:
  - Western Bay of Plenty (Brabhaharan, 2002)
  - Christchurch (CAE 1997)
- Where not available soil type maps can be used to identify potential areas for liquefaction. Available from New Zealand Soil Bureau and Landcare Research

Vulnerability – Bridges

- Transit have identified those bridges within the network which pose the greatest risk to the network. Their seismic bridge screening report has also identified likely failure mechanisms and the level of ground shaking required to trigger a failure.
- Maffei (1996) has established a process by which the seismic vulnerability of bridges can be established. This could be used as verification of the Transit bridge screening process

3.2 Volcanic events

New Zealand is home to a number of the world's most active volcanic sites as well as a number that are, for the most part, dormant. Ruapehu, Ngauruhoe, and White Island are among the most frequently active cone volcanoes known, while Taupo and Okataina are the most productive and frequently active rhyolite volcanoes on Earth (MAF website). Auckland City lies atop a volcanic zone that is home to around 50 small volcanoes.

3.2.1 Probability of volcanic events

Prediction of the likelihood of future volcanic events is based upon geotechnical, prehistoric, and historical information. Because of the small number of eruptions that have been recorded in living memory, the importance of geotechnical and prehistoric information in predicting eruption events is paramount.

GNS has produced magnitude-probability curves for some of New Zealand's major volcanoes (GNS website, see Figure 3.7). By the end of 2004 these are expected to be available for all of New Zealand's rhyolitic volcanoes. Work is also being done to produce magnitude-probability curves for the remaining New Zealand volcanoes and this is expected to be completed by 2007 (M. Stirling pers. comm.).

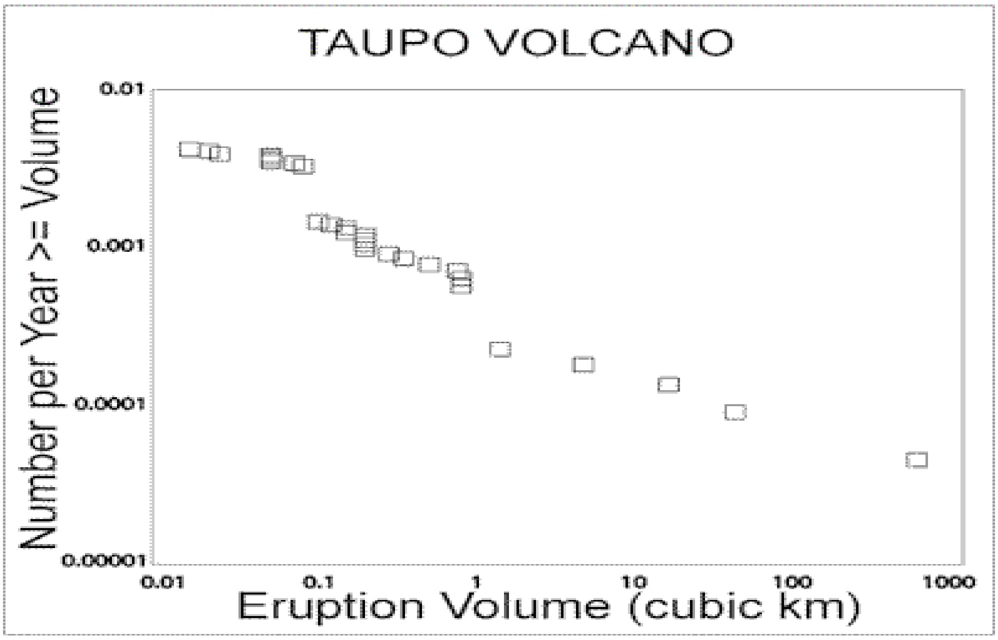


Figure 3.7 The relationship between likelihood of eruption and size for Taupo Volcano (GNS website 2003).

Information is available on the return periods of those volcanoes not currently assessed by GNS, which can be used to fill information gaps. MAF has produced a table of New Zealand volcanoes and their likely return periods and magnitudes that would be suitable for use within a risk analysis in the absence of more detailed information (Table 3.1).

Table 3.1 Likely magnitude and return periods for New Zealand volcanoes (MAF website 2003).

Volcano		Last known eruption	Future eruption size (km^3)	Estimated frequency of occurrence
Auckland		~600 years ago	small - medium (0.1-2.0)	1000-2000 years
Mayor Island		6340 years ago	small - medium (0.1-1) large (>1.0)	?1000 years ?10 000 years
White Island		1998 AD	small (<0.01) medium (0.01-0.1) large (> 0.1)	1-5 years ?100 years ?10 000 years
Tongariro Volcanic Centre	Ruapehu	1996 AD	small (0.01-0.1) medium (0.1-1.0) large (>1)	20 years 100-500 years 10 000 years
	Ngauruhoe	1975 AD	small (< 0.01) medium (0.01-0.1)	10-20 years 100-200 years
	Tongariro	1896 AD	small (<0.01) medium (0.01-0.1) large (0.1-1)	100 years 1000 years 10 000 years
Egmont/ Taranaki		1755 AD	small (<0.01) medium (0.01-0.1) large (<.1)	300-500 years 1300-1600 years 10 000 years
Taupo		181 AD	small (0.1-0.9) medium (1-10) large (10-100)	1300-1600 years 2500-5000 years 5000-10 000 years
Okataina		1886 AD	medium (1-10) large (10-20)	1500-2000 years 2000-5000 years

3.2.2 Consequences of volcanic events

3.2.2.1 Ashfall (tephra) hazards

The effects of tephra pose one of the biggest hazards to the road network from volcanic eruptions. Its many effects, while not devastating, are far reaching, difficult to remedy and mitigate. The following are some of the disruptions to the road network that can be expected during and after a tephra fall:

- poor visibility,
- slippery surfaces,
- vehicle damage,
- flooding,
- damage to unsealed road surfaces.

In the initial period following a volcanic eruption driving in areas where tephra is airborne will become difficult as a result of poor visibility caused by airborne particles. Even after the initial settlement of ash (which may take a number of days if not weeks depending on the size of the eruption) there will still be disruptions caused by the ash that falls onto the roadway and adjacent areas. In the instance where the ashfall coincides with rainfall then road surfaces will become slippery as a result. If, however, the tephra remains dry then vehicles using the roadway will be subject to large amounts of dust that can damage vehicle engines and mechanical systems.

Once tephra has settled it has the potential to create an ongoing flood hazard. Tephra fall has the potential to cause the defoliation of vegetation as well as causing the ground surface to become much less permeable. As a result the rate of run-off from areas surrounding the volcano will become much greater and has the potential to cause mudflows and flooding of road surfaces In addition, the slurry that is formed when rainwater and ash are mixed is highly abrasive and can cut channels alongside and across the roadway, eventually undermining sections of the road. These problems are compounded as a result of drains becoming blocked by tephra as well as mudflows that are sometimes generated by the increased run-off around the highways.

Unsealed road surfaces are likely to be damaged in the post-eruption clean up, where it is impossible to remove the ash from the roadway without removing a large portion of the chip. The Federal Emergency Management Authority (FEMA) has published a guide for ash clean-up based on the 1980 Mt St Helens experience (FEMA 1984).

3.2.2.2 Ashfall prediction

GNS has a stochastic computer model (ASHFALL) that can be used to estimate the likely distribution of ashfall depths resulting from a volcanic eruption. It was designed as a simple and fast program to be used in the event of a volcanic eruption (Hurst & Scott 1998) to give warning to areas likely to be affected by ashfall rather than as a modelling tool for hazard assessments. It is, however, possible to use this tool to produce hazard models of ashfall using historical wind and eruption records. Currently this tool is being used by GNS to develop tephra hazard models for all volcanoes in New Zealand but this will not be completed for several years.

ASHFALL takes into account a number of factors that influence the deposition of ash (Figure 3.8). These include:

- wind direction and speed, from the time of eruption through to deposition,
- the volume of the eruption,
- the height of the eruption,
- the particle size distribution of the ash.

The ASHFALL program requires that information be provided for both wind direction and speed at different atmospheric levels. Volcanic eruption columns can reach tens of kilometres high and cross atmospheric layers where the wind speed and direction can be vastly different from those experienced on the ground. Historic meteorological data can be used to predict the wind speed and direction that may occur during the eruption and deposition period.

Where the previous eruption height is known it is possible to make an estimate based on the rate of the eruption and the total size of the eruption (Hurst & Scott 1998). During the 1996 Ruapehu eruption observations from sources close to the volcano were used to estimate the height of the eruption, this was then used to estimate the volume of material being erupted (Hurst & Scott 1998). This enabled the eruption to be modelled within ASHFALL so that warning could be given to areas that were likely to be affected by tephra deposits.

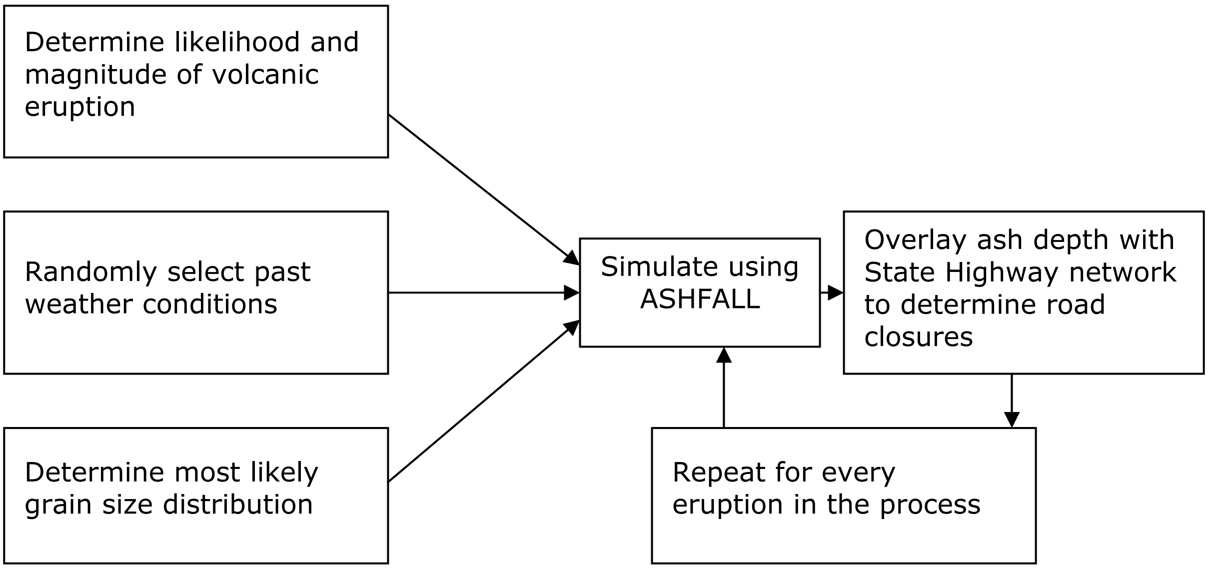


Figure 3.8 Methodology for producing ashfall hazard maps.

To determine how tephra will be deposited it is important to know the distribution of ash particle sizes. Three forces that are constantly acting on particles when airborne are: gravitation, atmospheric friction, and those generated by wind. The terminal velocity increases with both density and particle size so that smaller particles are suspended for longer and travel greater distances. Predicting the particle size distribution of volcanic ash is not entirely possible before a volcanic eruption occurs, but can be reasonably assumed to be similar to that of previous eruptions from the same volcano. As tephra moves further away from the eruption site the distribution of particles becomes more important as small particles will travel much further than larger ones(Hurst & Scott 1998).

3.2.2.3 Toxic gases

Toxic gases can be released from volcanic eruptions in large quantities. These gases are not considered to be of importance to this study for two reasons:

- The areas at risk from toxic gases are small (Tilling 1989).
- Any areas affected by toxic gases are likely to experience massive to total destruction from pyroclastic density currents, so the additional impact of toxic gases will be minimal for the purposes of this analysis.

3.2.2.4 Precautionary road closures

To fully incorporate all disruptions to the State Highway network from volcanic activity it is important to consider the non-direct impacts that volcanic activity can induce. The use of early warning systems to close roads and evacuate residents in areas that are threatened will, in itself, induce disruptions even where the volcanic activity is heightened without an actual eruption event.

To assess the effects of early evacuation it will be necessary to look at the evacuation plans for each volcano within the study (see 3.9 and Figure 3.10) along with the likelihood of false alarms.

At scientific alert level 1

- There are initial signs of possible volcanic unrest.
- There is no eruption threat and no need for a public response.
- This is a good time though to review any emergency planning you may have done.
- A public awareness campaign will be started by the Taranaki Regional Council.
- This will involve radio broadcasts to keep you up-to-date, and newspaper articles to tell you what precautions you should be taking if activity increases.

At scientific alert level 2

- There is confirmation of volcanic unrest.
- An eruption threat exists and a state of regional civil defence emergency may be declared as the risk to the community increases.
- In consultation with the Department of Conservation, the National Park will be closed.
- People will be encouraged to evacuate, or stay away from Taranaki, particularly in the high risk areas.
- At this stage, there may be no visible changes to the mountain.

At scientific alert level 3

- Minor eruptions have commenced.
- There is a real possibility of hazardous eruptions.
- Evacuation of institutions within Taranaki to neighbouring regions may be underway.
- Progressive evacuation of the Primary Hazard Zone, RED and BLUE zones will begin, based on the level of activity on the mountain.
- Evacuation may become compulsory in some areas.

At scientific alert level 4

- A hazardous local eruption is in progress.
- Large scale eruptions are now possible.
- Progressive evacuation of the RED and BLUE ZONES will continue, based on the level of activity taking place on the mountain.
- Evacuation will be compulsory.
- Bulk food supplies and transport will also be removed from the zones as they are evacuated.

At scientific alert level 5

- A large hazardous volcanic eruption is in progress.
- Residents of the ORANGE and YELLOW ZONES may also need to be relocated as necessary, and when possible.

Figure 3.9 Evacuation plan for the Taranaki region given heightened levels of activity at Mount Egmont. See Figure 3.10 for zonations.

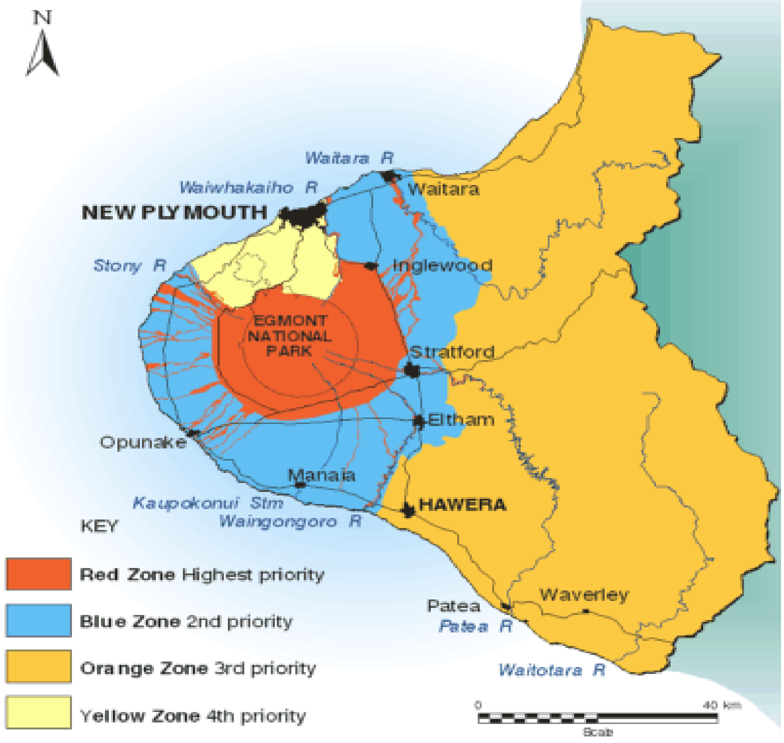


Figure 3.10 Evacuation zones for Mount Egmont (Taranaki Regional Council website 2004).

3.2.2.5 Lahars and volcanic floods

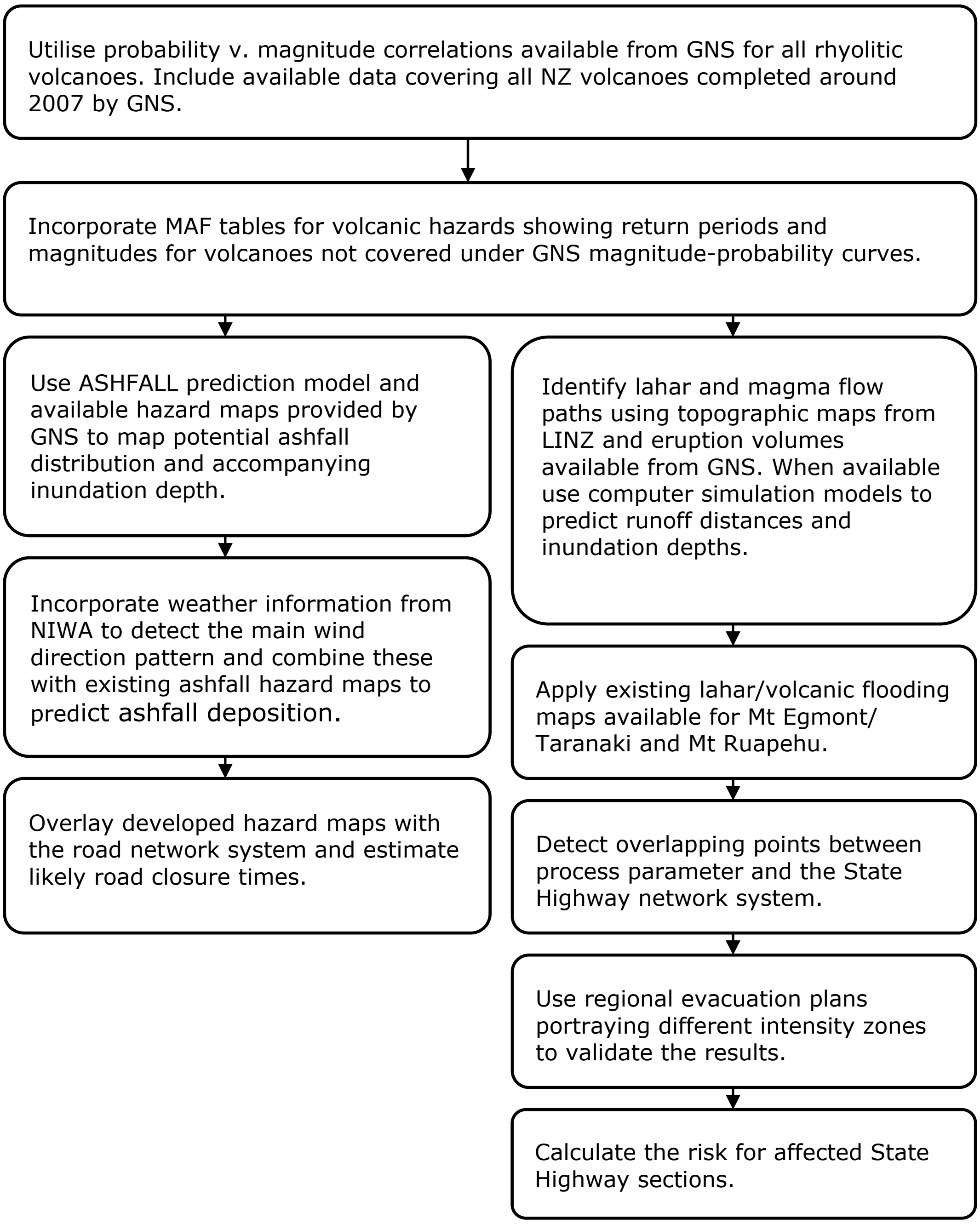
Lahars and volcanic floods are considered together for the purpose of this study as they present similar hazards for the State Highway network and are triggered by similar events. A lahar is a rapidly moving mixture of rock debris and water that originates on the slope of a volcano. Volcanic floods are similar in all aspects but have less debris incorporated in the flow and as a consequence are much less dense and corrosive than lahars (Tilling 1989). For the remainder of this report the term 'lahar' shall refer to both lahars and volcanic flooding.

Lahars are generated by a number of different mechanisms:

- volcanic eruptions releasing water from crater lakes,
- pyroclastic flows incorporating stream flows to form lahars,
- dams formed by lava flows, previous lahars, debris avalanches, pyroclastic flows, or craters failing through overflow or mass failure,
- torrential rainfall on recently deposited tephra or other unconsolidated materials causing the densification of flood waters through incorporation of material,
- rapid melting of snow and ice caused by deposition of hot ejecta.

Areas of inundation and length of lahar are a function of volume, grain-size characteristics, flow transformations, and topography (Tilling 1989). Particularly dense lahars, because of the large amount of momentum, can often surmount physical topographic barriers. In mapping the likely paths of lahars this must be taken into consideration as the effect is likely to cause areas to be inundated that may not be entirely expected.

In order to develop a probabilistic assessment of the risks posed by lahars it will be necessary to make an individual assessment of each volcano that is likely to generate lahars. Dalziell et al. (1999) used likely lahar paths that can be found in Houghton et al. (1987), or Latter et al. (1981), which include likely return periods for Ruapehu lahar events. A similar study has been conducted for Mount Egmont/Taranaki, where lahars are known to have occurred on a regular basis in the pre-historic past, by the Ministry of Civil Defence (Neall & Alloway 1991). These maps could be incorporated in the risk assessment with little need for additional work to be carried out.



Utilise probability v. magnitude correlations available from GNS for all rhyolitic volcanoes. Include available data covering all NZ volcanoes completed around 2007 by GNS.

Incorporate MAF tables for volcanic hazards showing return periods and magnitudes for volcanoes not covered under GNS magnitude-probability curves.

Use ASHFALL prediction model and available hazard maps provided by GNS to map potential ashfall distribution and accompanying inundation depth.

Incorporate weather information from NIWA to detect the main wind direction pattern and combine these with existing ashfall hazard maps to predict ashfall deposition.

Overlay developed hazard maps with the road network system and estimate likely road closure times.

Identify lahar and magma flow paths using topographic maps from LINZ and eruption volumes available from GNS. When available use computer simulation models to predict runoff distances and inundation depths.

Apply existing lahar/volcanic flooding maps available for Mt Egmont/ Taranaki and Mt Ruapehu.

Detect overlapping points between process parameter and the State Highway network system.

Use regional evacuation plans portraying different intensity zones to validate the results.

Calculate the risk for affected State Highway sections.

Figure 3.11 Proposed methodology for assessing risk caused by volcanic hazard affecting the State Highway network.

3.2.3 Information availability

Probability of Occurrence
- Extensive probability v volume relationships
  - Available from GNS in 2005: all rhyolitic volcanoes
  - Available from GNS around 2007: all volcanoes
- Rudimentary probability v volume relationships
  - Available from MAF for all volcanoes

Ashfall Hazard
- Hazard maps produced using ASHFALL models without wind variation:
  - Available from GNS in 2005:
    - All rhyolitic volcanoes
  - Available from GNS around 2007:
    - All volcanoes
- Hazard maps with wind variation are currently being worked on by GNS but no time frame has been given. These could be produced independently using the GNS volume-probability curves and weather information held by NIWA.

Magma Flows
- Area of effect needs to be identified from topographical information and eruption volumes:
  - Topographical maps available from LINZ
  - Eruption volumes available from GNS volume-probability curves

Lahar / Volcanic Flooding
- Hazard maps are available for:
  - Mount Egmont/Taranaki
  - Mount Ruapehu
  - Possibly others not yet identified
- Topographical maps are available from LINZ.

Precautionary Evacuation
- Regional Evacuation Plans have been identified for:
  - Taranaki
  - Auckland (ARC 2002)
  - Waikato
- Other regions may have plans that have not been identified but these regions cover those most at risk from volcanic eruptions.

3.3 Landslides

Landslides can be triggered by earthquakes, heavy rainfalls, and in some cases can occur through general instability with no significant trigger event (T. Davies pers. comm.).

Earthquake-induced landslides

A study of New Zealand historical data was conducted by Hancox et al. (1997) to determine if correlations exist between earthquake-induced landslide occurrence and size, and specific geological features. The study found that it should be possible to predict the size and location of landslides given the magnitude and location of an earthquake, along with the rock type, topography, and other geological data. This approach was used by Brabhaharan et al. (1994) to assess the slope failure hazard present in Wellington.

Rainfall-induced landslides

Little work has been uncovered that looks at the potential for landslides to be triggered as a direct result of rainfall. The features that have been identified as being important in determining the potential for rainfall-induced landslides are the same for those induced by earthquakes with the obvious exception that in place of considering the seismicity of the area, the heavy rainfall potential needs to be assessed.

Avalanches

For the purpose of this study avalanches will be considered similar to landslides in the form of the impacts that they can cause. Avalanches however will have different trigger mechanisms and will affect a smaller proportion of the State Highway network. Some avalanche-prone areas, such as the Milford road, have already been the subject already of risk assessments (such as Weir 1998) and it is anticipated that these studies could be directly incorporated into the full risk assessment of the State Highway network.

Geothermal-induced landslides

In some parts of New Zealand, the potential exists for geothermal-triggered landslides. Examples include the hillside above Waihi at Lake Taupo, where large landslides of this kind have occurred in the past. As there are only limited sections of State Highway vulnerable to this hazard, these would be assessed on an individual basis and included in the overall risk assessment.

3.3.1 Probability of landslides

The following is a summary of a landslide hazard mapping procedure that was utilised in the Wellington Region (Brabhaharan 2001):

- A review of historical records of earthquake-induced slope failure in the Wellington region.
- Identification of factors that contribute to slope failures during earthquakes, such as slope angle, slope modification (cut slopes), geology, past landslides, etc., and compilation of factor maps from available information and site reconnaissance by an engineering geologist.
- Integration of factors to derive slope failure hazard rating.
- Review of slope failure mechanisms and historical evidence.

- Assignment of factor values and weightings and integration to obtain a slope failure susceptibility rating:

  $$Rs = \Sigma (Fi \, . \, Wi)$$

  where:

  Rs is the failure susceptibility,

  Fi represents factor values for the factor 'I', and

  Wi represents associated weightings for factors: slope angle, slope modification, slope height, geology, past landslides and groundwater.
- Earthquake scenarios evaluated.
- Mapping of slope failure susceptibility using the factor maps and the slope failure susceptibility rating derived by combination of the factors.
- Presentation of slope failure potential for the earthquake scenarios considered. The slope failure maps were calibrated using the historical evidence of slope failures during earthquakes.

The basic procedure outlined is similar to that used in an Italian study that looked at using GIS techniques for mapping landslide hazards (Guzzetti et al. 1999). The Italian study uses a total history of landslides to calibrate the model, while the Brabhaharan study uses individual earthquake scenarios. Using individual earthquake scenarios will enable a model to more accurately delineate between landslides caused by earthquakes and those induced by heavy rainfalls. The ability to differentiate between the two triggers that lead to landslides is important as it allows the likelihood of simultaneous road closures to be assessed.

While these methods are robust and capture interdependency between the different hazards caused during earthquakes and heavy rainfall, they are also time-consuming and demand large amounts of information which may not be available for all areas. GNS have undertaken to create a 'broad brush' landslide hazard model of New Zealand to identify those areas that are most prone to landslides. The GNS landslide hazard model separates the land mass of New Zealand into areas that have similar geographic features, and consequentially, very similar landslide occurrence rates. Each area is then examined to identify historical and pre-historical landslide sites before each area is assigned a landslide risk value that is based on the number of occurred landslides. The risk value is considered to be constant across each area and is in units of frequency/km^2. Although this goes some way to identifying the risk posed to the network it does have some limitations:

- No consideration is given to how close the landslide hazard in an area is to sections of the State Highway network.
- It does not allow for interdependency in the network where multiple landslides are triggered by a single event.

The GNS model for the North Island is already available. A model for the South Island is still being developed as more investigative work will be necessary to identify landslides from historical and pre-historical events (M. Stirling pers. comm.).

A suggested approach for estimating the location and likelihood of landslides is shown in Figure 3.12.

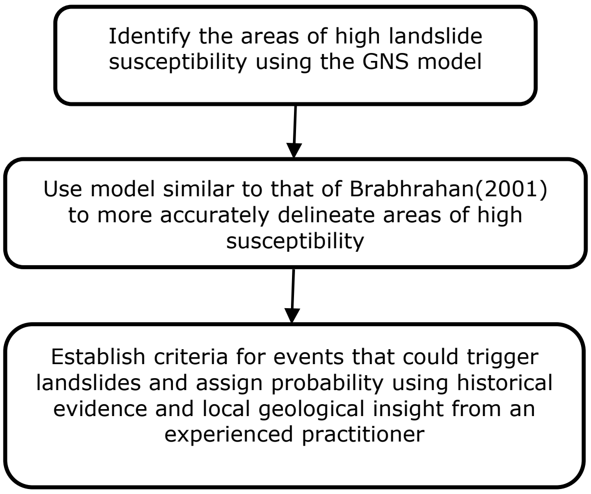


Figure 3.12 Outline of possible procedure for identifying the probability of

3.3.2 Consequences of landslides

3.3.2.1 Bridges

Landslides will affect bridges in three ways:

- They have the potential to destroy bridge structures as the amount of energy inherent with the movement can be massive enough to remove bridge piers and decks.
- The sheer mass of landslides can cause structural failures of the bridge decks if large amounts of material are deposited on the deck.
- Bridges are at risk where the landslide originates around the piers or abutments of the bridge, causing the bridge to lose stability. Bridge structures requiring cuts (a necessary part of many bridge constructions) will be particularly vulnerable to landslides as these are more unstable than naturally occurring slopes (Hancox et al. 1997).

To assess the impact that landslides may have on a bridge the characteristics of the bridge site need to be looked at. It may be possible to draw a number of conclusions about a bridge’s susceptibility by investigating bridge plans and from aerial photographs of the area. To reduce the labour requirements of this approach it may be possible to use general terrain features as a basis for assessing the vulnerability to landslides. Comparisons can then be drawn between the terrain of closely inspected bridges and bridges that undergo only a rudimentary investigation used to assign vulnerability ratings. For example, detailed analysis of one bridge in high alpine terrain with numerous cuttings could be made, and the vulnerability associated with that bridge used for other bridges in similar terrain and with similar design features (this could possibly be done using the age of bridges as the design of bridges tends to be very dependent on the best practice methods at the time of construction).

3.3.2.2 Road blockages

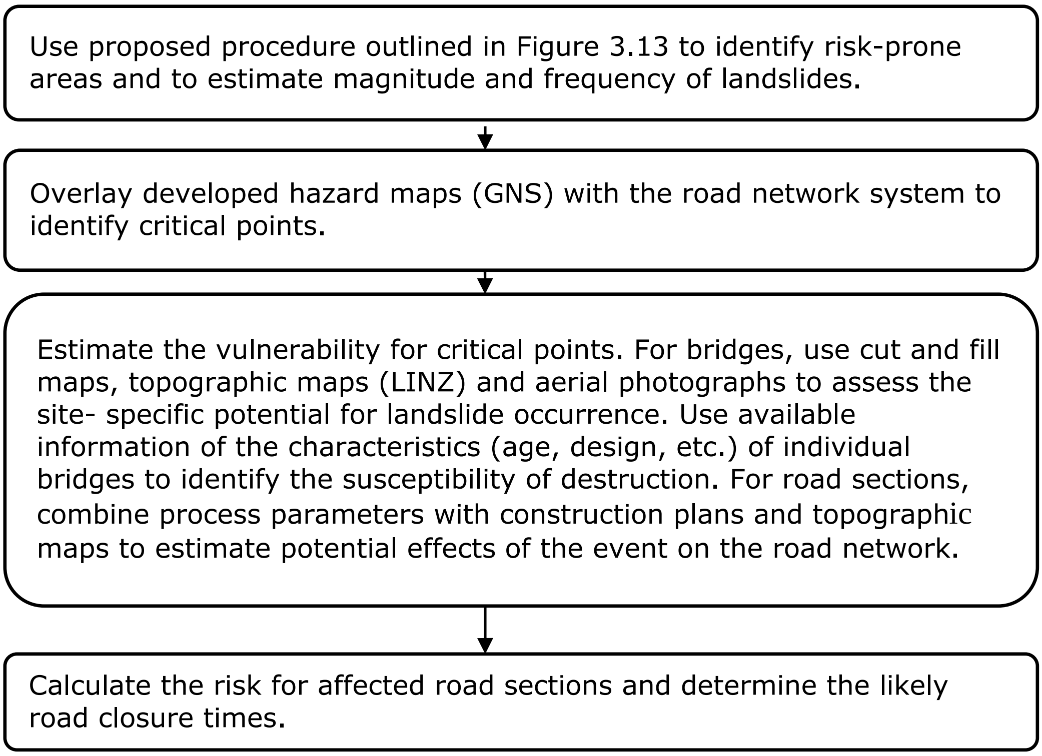
Landslides can range in size from a few cubic meters up to a number of cubic kilometres. It will be necessary to determine the amount of landslide material that is required to block a road completely, and also to identify the time and resources required to remove these blockages. In addition to the volume of material, the water content of the landslide will influence the time taken to clear the road. A 'dry' landslip is typically fairly contained and easy to remove, whereas a 'wet' landslide is more likely to flow, and be more difficult to remove. The removal of landslide material can also be complicated by the need to obtain resource consent to dump the material in certain instances.
(A. Burkett, pers. comm.)

As with bridges, roadways require extensive man-made cuts and fills to enable the laying of the road, particularly in mountainous and hilly terrain. Where cuts and fills have been made down a slope of a roadway the susceptibility of the underlying road support collapsing and leaving the roadway impassable. Where cuts have been made above the roadway there will be an increased chance that landslides will cause the blockage of roads with debris.

3.3.2.3 Indirect landslide impacts

A study by Arshad et al. (2004) utilises a GIS data system to predict the behaviour of a landslide in Westland, New Zealand. The GIS system incorporates a number of different layers containing topographical and geological data to create and interpret landslide hazards in the area. This information was then used to model the occurrence of a landslide and consequent damming of the Poerua River that occurred in 1999. Measurements carried out in a previous study (Hancox et al. 2000) were then compared with the results of the GIS model. It showed that the model provided a very accurate estimation of the size and behaviour of the landslide. Using the GIS model it was also possible to estimate the size and associated features of the dam that were created as a result of the landslide. This additional information could form a useful basis for identifying flooding hazards that are an indirect result of landslides. A similar approach could also be used for lahars.

Proposed assessment method for risk due to landslide



Use proposed procedure outlined in Figure 3.13 to identify risk-prone areas and to estimate magnitude and frequency of landslides.

Overlay developed hazard maps (GNS) with the road network system to identify critical points.

Estimate the vulnerability for critical points. For bridges, use cut and fill maps, topographic maps (LINZ) and aerial photographs to assess the site- specific potential for landslide occurrence. Use available information of the characteristics (age, design, etc.) of individual bridges to identify the susceptibility of destruction. For road sections, combine process parameters with construction plans and topographic maps to estimate potential effects of the event on the road network.

Calculate the risk for affected road sections and determine the likely road closure times.

Figure 3.13 Proposed methodology for risk and vulnerability assessment for the State Highway network potentially affected by landslides.

3.3.3 Information availability

Probability of Occurrence

- Identification of high risk areas using hazard maps:
    - North Island map produced by GNS available by 2004
    - South Island map under construction but no time frame given
- More intensive studies of high risk areas:
    - Wellington (Brabhaharan)
- GIS studies are available to provide a framework for intensive studies (Arshad et al., Brabhaharan)
    - Slope information available from GIS digital elevation map (LINZ)
    - Soil type (Land Care Research, National Soils Database)
    - Historical records are held for all past landslides in the North Island by GNS.
- Intensive studies should incorporate information from the trigger events, intense rainfall and earthquakes, on a common framework so that interdependency of hazards is captured.

Vulnerability – Bridges

- Identification of bridge susceptibility to landslide damage:
    - Cut and fill maps (From bridge drawings, aerial photographs, need to be sourced)
    - Immediate topography around bridges, digital elevation maps (LINZ)
    - Bridge maximum loading (Transit)
    - Pier resistance to lateral earth pressure (evaluated by practising bridge engineer)
- Alternative approach using classification of bridges:
    - Some structural resistance determination (unsourced)
    - General topographic region of bridge (LINZ)
    - Time of bridge construction (needs to be evaluated by practising bridge engineers)

Vulnerability – Roadway

- Identification of likely fall away areas:
    - Cut and fill maps (unsourced)
- Proximity of roadway to likely landslides (topo map from LINZ, GIS road map from Transit)
- Width of roadway available (Transit)
- Surrounding topography to determine availability of bypassing blocked roadway (LINZ – Topo map, Transit – Road Map)

3.4 Flooding

Evaluating the risks posed to the State Highway network by flooding is not easy, but doing so may reduce the costs of maintaining the network and reduce traffic disruptions that occur as a result of flooding. The current funding regime tends to encourage a reactive approach to flood risk management because repairing roads affected by floods does not require the usual project evaluation procedures. This approach minimises the amount of time taken to reopen the roadway, but puts little emphasis on Road Controlling Authorities (RCAs) to mitigate against road closures caused by flooding. Coupled with this, appropriate catchment management and other initiatives to reduce the frequency or extent of flooding may rest with multiple organisations.

3.4.1 Probability of flooding

Two different methods are proposed to evaluate the probability that a section of the State Highway network is at risk from flooding hazards. The first is a broad brush approach that provides the flood flow rates for catchments in New Zealand and associated return periods. The second is a more detailed approach to estimate inundation levels and flood flow velocities for individual catchments.

3.4.1.1 Broad brush approach

The most complete mapping of flood return periods was conducted by McKerchar and Pearson (1989), with the results of their work being published as a report: *Flood Frequency in New Zealand*. The report gives details of the methodologies employed to estimate the frequency and flow size of flooding events. It also provides maps from which these details can be estimated for catchments throughout New Zealand.

The data used to determine the annual and 100-year flood flows is based upon river flow data that spans more than half a century. During this time there have been marked changes in the way land is used in New Zealand. An increase in pasture- based farming, an increase in urban development, and a decrease in forested areas will all have contributed to a change in the way that catchments behave, thus altering flooding behaviour. The age of some of the data used may also affect the results as the accuracy of this data will not be on a par with that obtained using more accurate measurement devices.

The very nature of the contour maps also introduces uncertainty when determining the flood flow rates. There are areas on the maps for which the contours are widely spaced and as a result it is very difficult to make accurate estimates of the flow levels. There are some areas of the contour maps that are not bound by two contour lines, making it impossible to determine values in these areas.

3.4.1.2 Detailed approach

Within a catchment two important parameters must be identified to determine the effect that flooding will have on the State Highway network: the flood inundation level, and the flood velocity. To determine these parameters a detailed approach must be taken that incorporates the effects that soil type and saturation, climatic conditions, vegetation cover, topography, and rainfall patterns will have on the inundation level and the flow velocity.

The soil type and saturation state within a catchment will influence the amount of water that is available for run-off during a rain storm and also the speed with which this water travels from the outer areas of a catchment to the actual flood flow. Soils that are saturated allow for a greater amount of rainfall run-off so that flows from a catchment will be greater when soils are already in a saturated state. Similarly some soils will be able to absorb more rainfall than others causing variations in the amount of run-off that contributes to the flood flows. The degree of saturation of a soil varies depending on the amount of rainfall that has occurred in the recent past, the amount and type of vegetation in the area, and the geological makeup of the area. Because the rainfall experienced in an area is dependent on the season then so is the level of saturation in the soil and as a consequence this must be considered on a temporal scale. Climatic conditions will have a major effect on the flood flow levels and velocities, with catchments receiving snow and glacial melt experiencing large variations in river flows between seasons. The amount and type of vegetation in a catchmentwill also have major effects.

The topography of the area will influence the velocity with which run-off reaches the flood flow, the velocity of the flood flow, and also the level of inundation caused by flood flows. Steep catchments will cause run-off to travel more quickly from the outer areas of the catchment to the flood flow because of increased gravitational effect. Narrow flood paths will cause flood waters to rise more rapidly and to higher levels as the volume of water is captured in a smaller cross-sectional area.

Rain does not fall in a uniform manner but changes over both time and space. This variation causes changes in the amount of run-off that reaches the flood flow over time, which can in turn alter the peak flood flow and velocity. Models are available that can be used to estimate how rainfall changes over time and space based upon the topography of the area (Zoppou et al. 2000).

There is also a need to utilise local catchment knowledge wherever possible. It may be that a landslide will block a large flow path and hence alter the flood flow levels and velocities, or cause temporary damming that could lead to dramatic flood flows should the dam be breached.

3.4.1.3 Proposed methodology

The high resource demand of flood hazard modelling is likely to make it uneconomical to evaluate each individual catchment area. By using a screening process it will, however, be possible to model only those catchments where the flood risks to the State Highway network are significant. The proposed methodology (outlined in Figure 3.14) incorporates a screening process based upon the contour maps developed by McKerchar and Pearson (1989) that will identify areas where flood flow levels are the greatest, before more detailed analysis is undertaken. By utilising flood hazard maps already available from local and regional councils the number of catchments that will require detailed investigation can be further reduced. The methodology also incorporates two stages in which local knowledge is sought to help identify areas that are prone to flooding, which may be missed by simply numerical processes.

The contour maps developed by McKerchar and Pearson do not incorporate flood information after 1989 and will require updating to ensure the greatest accuracy. NIWA have applied for FRST funding to update these contour maps which, if accepted, will be updated within the next few years (R. Woods pers. comm.).

- Conduct an initial assessment to identify high risk areas using contour maps produced by McKerchar & Pearson:
    - Cover all catchments in which the State Highway network is located.
    - Contour maps should be used to determine flood flows for different flood return periods
- Identify catchments at significant risk from flooding
- Consult with geologists in areas of moderate risk to verify results from the broad brush assessment
- Remove from the study catchments where topography prevents roads being at risk from flooding
- Identify and incorporate available flood plans from Regional and City Councils
- Evaluate high risk areas through modelling of rainfall flows using GIS to identify inundation levels within catchment areas
- Consult local hydrologists and incorporate their understanding of the catchment behaviour
- Compare results with historical records of major flooding events to validate the process
- Develop GIS tools capable of determining flood flow velocities and apply to catchments where roadways, bridge piers, and road embankments are at risk from inundation

Figure 3.14 Proposed methodology for determining the probability that the State Highway network will be affected by flooding.

3.4.2 Consequences of flooding

3.4.2.1 Bridges

Bridges along the State Highway network are prone to several different modes of failure during a flooding event including collapse caused by scouring of the piers, hydraulic loading on the piers, hydraulic loading on the bridge deck, erosion of the abutments, as well as debris such as large trees or logs carried by the flood waters striking the piers. While bridge designs do incorporate features to reduce the chances of failure, designing bridges to withstand the most extreme flooding events is not generally a viable option. The uncertainty that surrounds return periods for different flooding events means that it is possible that the designer of a bridge ensured that the bridge could sustain floods that were believed to have a return period of 100 years where in reality the return period could be much shorter.

3.4.2.2 Roadways

Roadways that are caught in the path of floodwaters will be prone to damage or complete removal as a result of erosion of road embankments, erosion of the road subgrade and basecourse materials, or by the removal of surrounding soils that will cause a general instability in the road surface. Surface flooding on the road surface can also lead to delays in the network.

One problem associated with flooding for roadways is the effect that scour can have on road embankments. Where a road lies parallel to the flow of flood waters the effect of scour can be felt along vast stretches of the roadway, damaging not just small sections of the roadway, but large swaths of road. Repairing damage of this extent is a slow process as remedial measures can be applied only to either end of a roadway section, because of lack of accessibility to central areas. This limits the resources that may be allocated to repairing the roadway at any one time. The repair process is further slowed because of the nature of scour which can remove the earthworks on which the road was built, particularly where step embankments are affected. Earthworks are both expensive and time consuming to carry out, particularly if access to the repair site is hampered by damage to other roadways.

3.4.2.3 Debris

Debris will affect the State Highway network in two ways during flooding events. First it will act as barriers on roadways that may prevent travel until removed. And second, debris can become lodged against bridge piers which will increase the pressure applied to the piers by the flood waters because of the reduced aerodynamic nature and the increased surface area.

Proposed methodology

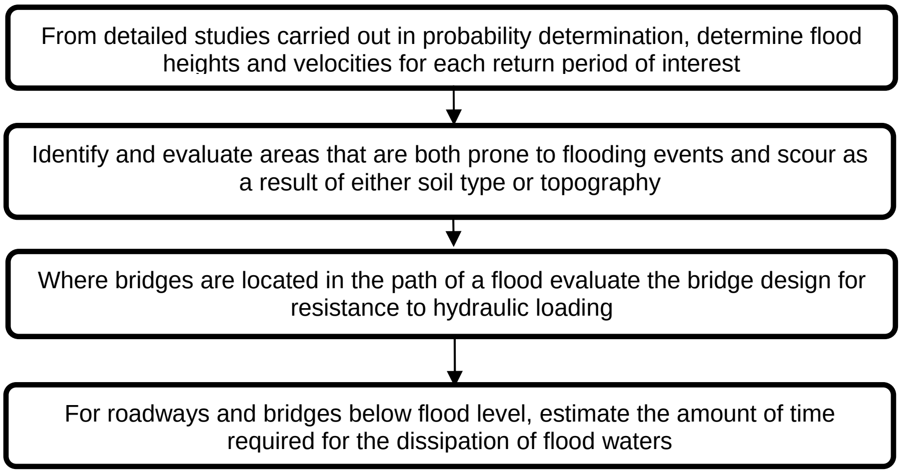


Figure 3.15 Proposed methodology for determining the vulnerability of the State Highway system to flooding events.

3.4.3 Information availability

Probability of Occurrence

- Identification of high risk areas using contour maps:
    - Contour maps generated by McKerchar and Pearson (1989) currently available
    - NIWA may be able to provide updated maps in the near future
- Further refinement of high risk areas through modelling:
    - Topographic Data – Currently available (LINZ)
    - Rainfall Data – currently available (NIWA)
        - Alternately, information provided in contour maps can be used to evaluate flood peak flows
    - State Highway information – currently available (Transit)
    - Geological information – currently available (LandCare Research, National Soils Database)
- More intensive studies of high risk areas that are already available:
    - Numerous studies have been conducted by local and district councils for populated areas

Vulnerability – Bridges

- Identification of bridge susceptibility to flood damage:
    - Immediate topography around bridges, digital elevation maps (LINZ)
    - Geological conditions around bridge approaches and piers to determine effect of scour (Transit bridge plans, LandCare Research)
    - Pier resistance to lateral pressure (evaluated by practising bridge engineer)
- Alternative approach using classification of bridges:
    - Time and type of bridge construction (Transit)
    - Geological Conditions (Transit, Land Care Research)
    - Evaluation procedure (requires further research)

Vulnerability – Roadway

- Identification of erosion susceptible areas:
    - Cut and fill maps (unsourced)
    - Geological conditions (LandCare Research)
- Surrounding topography and road location to determine the existence of alternative routes and the level of flooding to occur at roadways (LINZ – Topo map, Transit – Road Map)

3.5 Snow and ice

Snow and ice on some New Zealand roads are relatively frequent occurrences, with some roads closing several times each winter. The cost to the economy associated with snow and ice on the Desert Road in the central North Island was quantified in a study by Dalziell et al. (1999), which indicated that the road closure risk caused by snow and ice for that stretch of road was greater than any other hazard. As yet no attempt has been made to quantify the risks of road closures caused by snow or ice across the State Highway network.

Road selection

The suggestion is that the roads to be analysed should be limited to those where snow and ice are known to form on a frequent basis. Transit NZ has a database of all road closures that have occurred in the last decade along with details about the closure length and causes which could be used to identify areas of the State Highway network that require closer investigation (M.Fahy pers. comm.).

Building a generic model of conditions that result in road closures from snow and ice may be possible by comparing the conditions of the most frequently occurring road closures. If the correlation between the weather conditions and key geographical features (altitude, slope, etc.) is strong, it may be possible to use generic conditions for all roads with possible adjustment factors for roads at higher altitudes or with other easily measured variations in conditions.

3.5.1 Probability of snow and ice

There are several strategies that could be employed to estimate the probability of snow or ice conditions on the road.

3.5.1.1 Historical frequency

Estimating the frequency and duration of closures that may occur in the future is possible by looking at the frequency and duration that roads have been closed in the past as a result of snow and ice. This approach requires that each individual road closure has an adequate record and that road management and conditions affecting decisions to close the road have not changed significantly. Dalziell et al. (1999) found that these requirements are unlikely to be met, for example:

- Road conditions, such as pavement materials, road alignment, and snow and ice management have changed significantly over the last few decades, with the purchase of new types of road clearing equipment and in particular the more recent use of chemicals to prevent ice formation on the road surface (A.Burkett pers. comm.).
- The level of service and safety expected by the public has increased over time.
- The implementation of the 1992 Health and Safety in Employment Act by which Transit must abide when contractors are clearing the road.

3.5.1.2 Causative closure mechanisms

Rather than relying on historical data to assess the probability of road closures a more mechanistic approach can be used. If the weather conditions that lead to road closures today can be determined, then these weather conditions can then be used to evaluate the frequency of past road closures given the present closure criteria. This allows for historical weather information to be used, rather than historical road closure information. A much larger sample of data can then be analysed. In saying this, it is all important to realise that the closure conditions of today will not necessarily represent the closure conditions of the future.

Dalziell et al. (1999) developed a methodology for determining the closure criteria of the Desert Road, in the Central Plateau of New Zealand, based on the minimum and maximum temperatures recorded at a weather station in the nearby town of Waiouru. The humidity of the environment was also considered, but did not prove to be as significant in establishing the statistical closure criteria. It should be noted that, although Dalziell et al. did not identify humidity as a significant factor in determining if icing is present, experience from the field would indicate that it is important (N.Gurr pers. comm.), so this is an area that would benefit from further research. Other factors that could be included in the analysis include shading and topography.

These closure criteria were referred to in the Dalziell et al. (1999) study as ‘Icing Criteria’. Roads sometimes close with snow alone, particularly during whiteout conditions, or due to large snow drifts. On the Desert Road at the time of that study however, the majority of long closures were caused by ice. The use of chemicals now means this is no longer the case. The term ‘Icing Criteria’ in this context would now refer to days with potential for ice to form or for snow to settle on the road surface.

The minimum and maximum temperatures on days when ice was formed were compared with those for days when ice did not form on the road. Statistical analysis revealed that for ice to form the maximum temperature must remain below 10°C and minimum temperature must fall below 2°C. As these closure criteria are specific to the Desert Road (relative to weather conditions in Waiouru), this type of analysis would need to be carried out individually for different areas. Hence, it is suggested that this analysis focus on those sections of road that have been regularly affected by snow and ice in the past.

Transit NZ is developing thermal maps for highways affected by ice as part of their ice-prediction-forecasting technology. These maps provide relative spatial variation of minimum road surface temperatures along highways under different weather conditions. These may be of assistance when analysing closure criteria. The installation of road weather information systems over the next few years will, together with the maps, give more specific knowledge of actual network conditions (A. Burkett pers. comm.).

3.5.2 Consequences of snow and ice

The number of consecutive days where the closure criteria were met was considered to be the major contributing factor in determining the probability of road closures occurring. If the criteria were met on consecutive days then the likelihood of road closure also increased. By comparing the number of consecutive days of closure criteria being met with the number of closures, a probability of ice closing the road and the duration of that closure can be estimated. Figure 3.16 summarises the approach suggested.

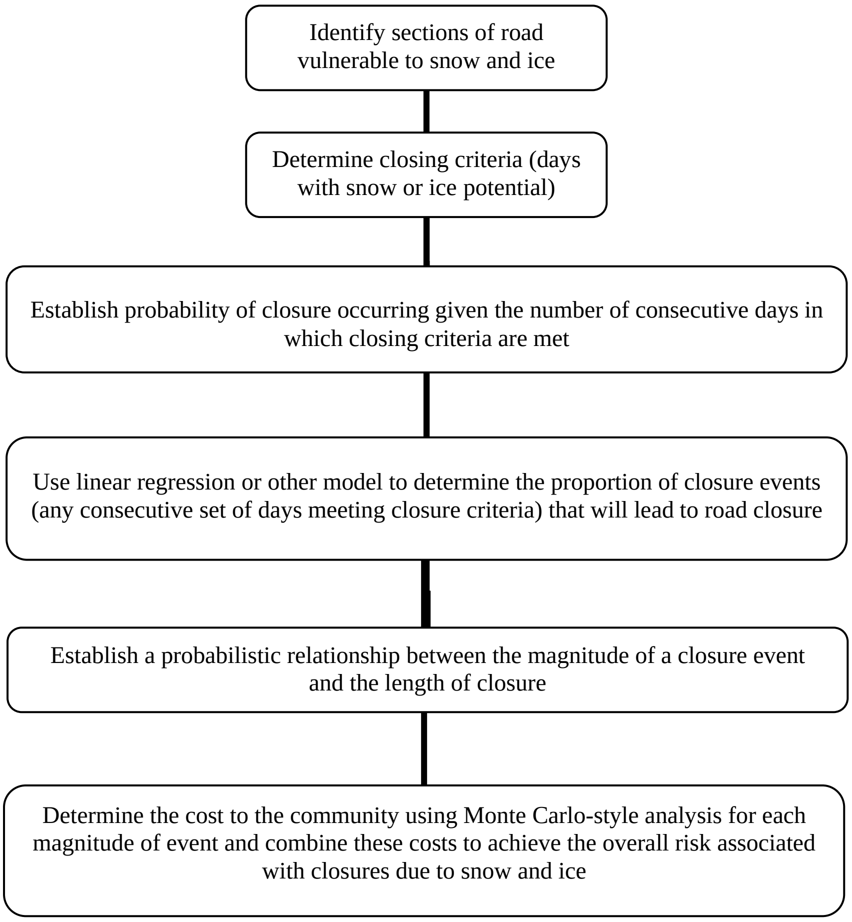


Figure 3.16 Suggested approach for estimating the likelihood and duration of road closures due to snow and ice.

3.5.3 Analysis

The effects of a single weather system may be felt over a large proportion of the country. Closure of different sections of road because of snow and ice will not necessarily be independent. This means that if a Monte Carlo analysis is to be used, it will be necessary to ensure that the temperatures generated are realistic representations of weather patterns that occur in reality. Investigations could be carried out to identify correlations between the temperatures on any given day between one location and another. This would increase the robustness of the model while taking into account the interdependency of the road network that results from the broad reach of weather patterns.

Breaking the network into segments may also be possible when conducting the Monte Carlo analysis. For this to be feasible, it must be shown that the state of the network in each area selected does not significantly affect another. Using this approach, a weather pattern for each area can be used rather than a nationwide weather pattern. This will allow for stronger correlations between ice formation and weather conditions to be established and hence a more robust definition for closure conditions will be achieved. The thermal mapping exercise being carried out by Transit NZ (Section 3.5.1) will help to determine 'climatic domains' or areas where the network may be likely to experience variable weather conditions. The intention is to establish road weather stations in each of these domains (A. Burkett pers. comm.). These road weather stations will provide significant future benefits in understanding the likelihood of concurrent road closures due to poor weather conditions.

3.5.4 Information availability

Probability of Occurrence

- Dalziell et al. (1999) procedure available for determining likelihood from weather station data.
    - Closure information available from Transit for identification of hot spots and for analysis.
    - Weather station data available from NIWA.

Vulnerability - Roadways

- Vulnerability of roadways determined by duration and severity of closure conditions.
- Identify areas where risk management strategies are already employed to reduce vulnerability from road closure (i.e. duration of closure):
    - De-icing programme information (Transit).
    - Location and usage of specialist road clearing equipment.

3.6 Tsunamis

Tsunamis are temporary oscillations in the sea level with associated periods that are longer than wind waves or swells, but shorter than those of ocean tides. Tsunamis are normally created by sudden movements or ruptures in the ocean floor that are generated from earthquakes, underwater landslides, or an underwater volcanic eruption. Large tsunamis can cause coastal flooding and erosion damage that could affect the State Highway network system in low-lying areas.

Tsunamis are classified into two groups, remote and local, with remote tsunamis being caused by earthquakes or other tsunami-generating events occurring at large distances from the coast of New Zealand. Local tsunamis are those that are generated by events close to the New Zealand shore.

The effects of remote tsunamis are, in general, small with most causing variation in sea level of less than one metre in harbour areas. On rare occasions the impact can be greater, such as was observed with the 1960 Chile tsunami which generated variations in sea level as large as 5.5 m (Figure 3.17). The largest known remote tsunami to strike New Zealand's coast occurred in 1868 after a fault movement in Chile, which generated a wave that was 8 m in height on parts of the east coast of New Zealand.

Figure 3.17 Gisborne Wharf during the 1960 Chile tsunami. The tsunami produced a maximum height of 5.5 m in Lyttelton Harbour, and also affected other harbours along the east coast, and was caused by an M9.5 earthquake in Chile. It took 15 hours for it to reach New Zealand (NIWA website 2004).

Local tsunami events are much rarer but generate much larger wave heights than remote tsunamis. The only significant recorded example of a local tsunami occurred in the Gisborne region in 1947 and generated wave heights of up to 10 m. It was thought to be triggered by a fault movement off the coast that induced an underwater landslide. The effect of local tsunamis will be much greater than remote tsunamis as the waves that are generated do not have time to dissipate and no advance warning system is in place for those people in low-lying areas.

3.6.1 Probability of tsunamis

3.6.1.1 Local tsunamis

The high level of seismicity in and around New Zealand, the large amount of underwater volcanic activity, and the susceptibility of the seabed to landslides along the New Zealand coastline indicates a significant probability for tsunamis occurring that will be similar in size to the one in 1947.

There are two ways for analysing the risk of local tsunamis that are best used in conjunction with each other. The first looks at historical and pre-historical evidence to determine the magnitude and source of a tsunami. The second looks at possible sources of tsunamis such as underwater faults, volcanoes, and landslides to analyse the probability that these sources will generate tsunamis, and then uses advanced computer models to predict the magnitude and behaviour of the tsunami.

Using historical and pre-historical information a probabilistic hazard map could be produced that would reflect how New Zealand has been affected by tsunamis in the past, and hence, how it could be affected in the future. This methodology has several problems associated with it:

- It assumes that the probability of tsunami occurrences is constant at all times.
- The record of events is small (KDELP 2003).
- The cost of investigating previous tsunami occurrences is significant and existing records are not entirely accurate (KDELP 2003).

Although the use of historical and pre-historical information is not entirely accurate in evaluating the probability of tsunami occurrence, it does provide information as to the areas of coastline that may face the greatest risk from tsunamis. To complement the historical and pre-historical information more localised evaluations can be carried out that provide a much more accurate picture of the risks posed. The first stage of a study into the hazard posed by local tsunamis to a section of the Canterbury coastline has recently been completed (KDELP 2003). This study identifies and analyses different sources that could cause a tsunami and the likely effects that will be experienced on shore. A similar study is currently being conducted for the Bay of Plenty coastline, also including a section of the Coromandel coastline, and is due for completion in mid-2005 (R. Martin pers. comm.).

The Kaikoura District Engineering Lifelines Project *Tsunami Hazard Assessment* (KDELP 2003) identifies a number of gaps in scientific knowledge that, should they be filled, would reduce some of the uncertainty in modelling local tsunamis and in producing the associated inundation maps. They are:

- the lack of definitive observational data for the past occurrence of large tsunamis in the area (though there are limited opportunities for improving this),
- a poor state of understanding of submarine landslides,
- limited resolution of land-based topographic information.

These gaps in information make it difficult to predict the exact extent to which the road network will be affected. Without observational data from previous tsunamis it is hard to calibrate the tsunami model. The lack of understanding of submarine landslides increases the uncertainty of the possible size and timing of the landslides, and the limited mapping resolution does not allow for the accurate identification of lifelines that may be affected within an inundated area. NIWA is currently investigating submarine landslides so that a greater understanding of the mechanisms that cause them can be achieved (KDELP 2003).

The Kaikoura study models four different tsunami-generating events. These events were selected to represent what was thought to be the most damaging scenarios, but because of the diversity of possible tsunami-producing events triggers that generate devastating tsunamis may not be represented in this study. The area inundated by tsunamis also varies quite considerably depending on whether they occur at high or low tide and with seasonal variations.

By combining the historical and pre-historical information with more detailed local studies of high risk areas it should be possible to estimate the likelihood and extent to which tsunamis will affect the New Zealand coastline with enough accuracy to be useful to road network managers and civil defence planners.

3.6.1.2 Remote tsunamis

In the case of remote tsunamis, defining the source of the tsunami accurately is not as important as with local tsunamis. The propagation of tsunamis across long distance means that a large variation in the source location will only cause a slight change in the angle of incidence with the New Zealand coastline.

Currently NIWA and GNS are in the process of developing a remote tsunami hazard model. The model development is in its initial stages and will not be completed until approximately 2006 (M. Stirling pers. comm.). The tsunami model will incorporate sources of tsunamis from around the 'ring of fire', starting with the Chilean fault lines, which have been known to cause tidal waves in New Zealand, and will be able to determine those areas of coastline that are most at risk from remote source tsunamis.

3.6.2 Consequences of tsunamis

A number of sections of the State Highway network run close to the coastline. This proximity to the coast puts the road network at risk of major disruptions caused by both local and remote tsunamis.

3.6.2.1 Bridges

The vulnerability of road bridges that are located close to the mouth of rivers is of particular importance in determining the impact of tsunamis. The massive upsurge of sea water that is experienced during a tsunami will follow the line of a river much further inland than in other areas. This means that while roads that are located close to the coast may not be affected, bridges that are further inland may experience the devastating force of the tsunami.

Bridges are in danger of becoming unusable via two different mechanisms in the event of a tsunami. First they are at risk from structural damage. Second, they are at risk from scour due to the high flow volumes and velocities that can occur. The effects of scour will be further amplified if the tsunami waters have entrained material further down stream, making the flow much more abrasive. Scour will not only occur in the initial movement of the tsunami but also as the land drains of the water left in its wake. The design of some bridge piers may place them more at risk than others. If the bridge has been shaped to reduce the drag that it experiences from water flowing downstream (and hence the scour) then it is likely that the upstream motion of a tsunami will have the opposite effect on these piers and actually increase the drag experienced.

3.6.2.2 Road surfaces

Tsunamis will have a markedly different effect on roadways from any of the other hazards discussed in this report. A tsunami will in some instances simply remove the entire road surface along with any underlying basecourse. In its place the receding flood water may leave debris ranging from trees and soil, through to cars and building materials.

The extent of both the damage and the area of roadway affected by a tsunami will mean long delays in re-opening sections of the State Highway network. This coupled with the small number of alternative routes available to some sections of the network that follow the coastline will lead to major disruptions to businesses and individuals who rely on the road system as a means of transportation, on top of the cost that is associated with the replacement of the roadway.

Local tsunamis, because of the limited warning time available, may also lead to fatalities in the affected areas. In areas such as Kaikoura the mountainous terrain means there are few road evacuation routes that do not follow the coastline.

Proposed methodology

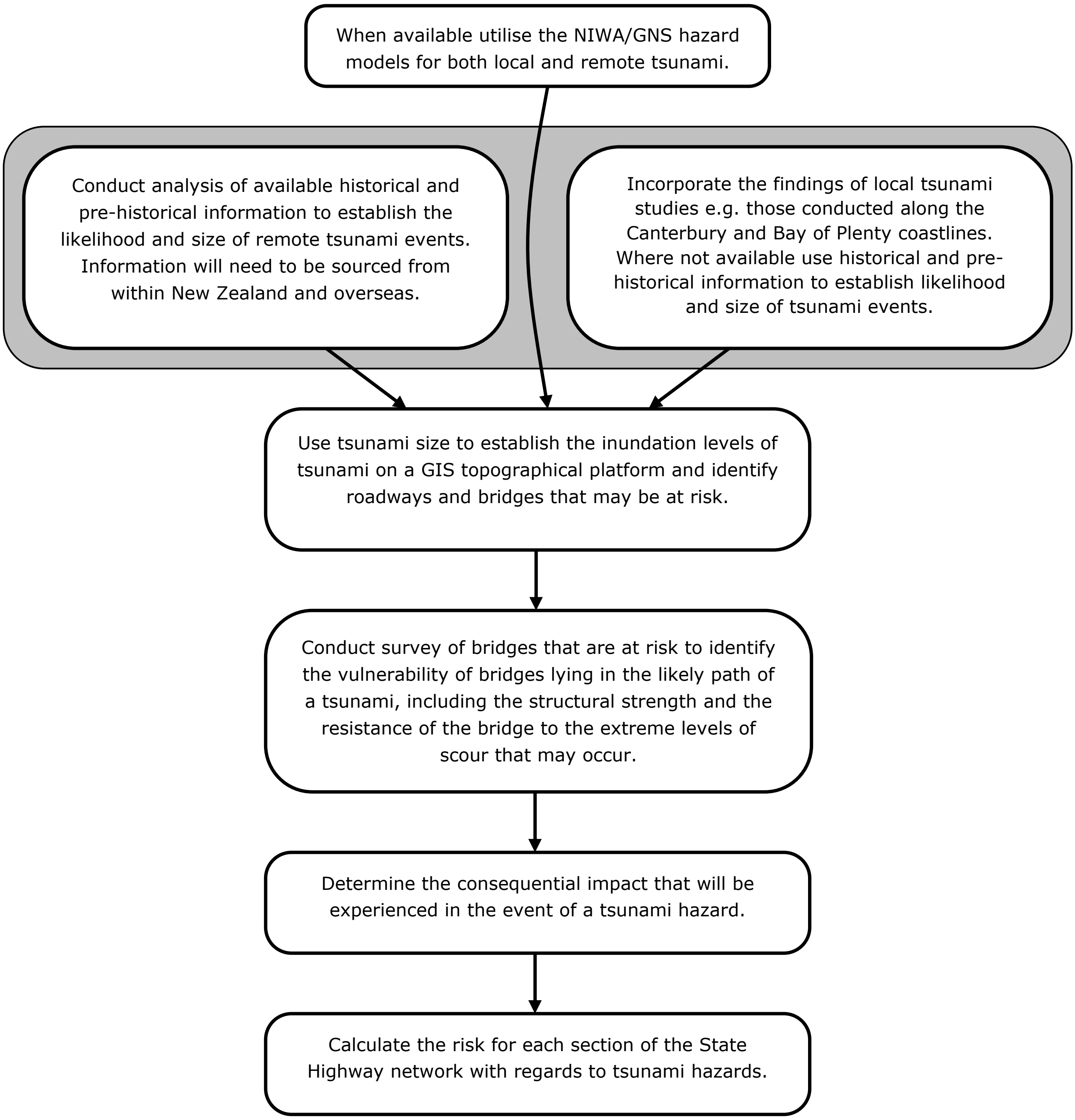


Figure 3.18 Proposed methodology for assessing the risk associated with both local and remote tsunamis within New Zealand.

3.6.3 Information availability

Probability of Occurrence – Remote Tsunami

- NIWA and GNS are currently working on the production of a Remote Tsunami Hazard Map. A total hazard map will be ready by 2006 but a substantial part which looks at the threat from tsunami originating near Chile will be completed much sooner.

Basic Approach

- Where detailed studies have not been carried out the analysis of historical information could be used to produce a basic hazard map. This information is available from newspaper reports and tsunami databases. NIWA holds information relating to previous tsunami events.

Probability of Occurrence – Local Tsunami

Complete hazard map

- NIWA and GNS are planning on producing a complete local Tsunami Hazard Map. This is expected to be completed in 2006.

Partial Hazard Maps

- Hazard maps are currently being produced for some high risk regions areas of coastline by local councils but no indication of completion times have been identified:
    - Canterbury coastline.
    - Bay of Plenty and parts of the Coromandel coastline.

Basic Approach

- Where detailed studies have not been carried out, the analysis of historical information could be used to produce a basic hazard map. This information is available from newspaper reports and tsunami databases. NIWA holds information relating to previous tsunami events.

Vulnerability – Roadways

The hazard maps being created by NIWA and GNS will provide information regarding inundation levels that will be experienced during a tsunami. This information needs to be overlayed on a network map to determine what roads will be affected.

- Highway Network map available from Transit.
- Soil Mapping to determine erosion effect from Tsunami Waves (Land Care Research).

Vulnerability – Bridges

Bridges that are used to span rivers will require analysis to determine vulnerability from waves coming up stream from tsunami events:

- Inundation available from GNS hazard maps.
- Structural resistance of bridges likely to be inundated (Determined by practising bridge engineer using bridge design available from Transit).
- Soil mapping to determine erosion effect from tsunami waves (LandCare Research).

3.7 Wildfire

On average New Zealand experiences 2500 wildfires each year which cover an area of 7000 ha. While most of these fires are small, a few occasions occur each year where wildfires grow to proportions that are uncontrollable by the New Zealand Fire Service. The New Zealand Fire Service Commission funded a report, *A fire danger climatologic for New Zealand* (Pearce et al. 2003), that identifies the regions that are most at risk from wildfires and ranks them according to the number of very high and extreme fire hazard days that occur each year.

To determine the number of wildfires that will result in road closures an investigation of historical records should be taken to determine the mean number of rural fires that have occurred each year in New Zealand. In addition to this, the number of fires that have caused the closure of sections of the State Highway network should be investigated to determine which proportion of rural fires will cause closures. In doing this, it is also advisable to identify any trends in these two areas (rural fire occurrences and road closure occurrences) to determine if the potential for fire events to impact on the State Highway network is increasing or decreasing.

Smoke is likely to be the major source of disruption to the network as it will cover a much larger area than the actual fire itself. Even if a fire lasts for a duration of weeks it is unlikely that any section of the State Highway network will be affected for the total length of this time as the fire front will be constantly moving and the wind direction will change throughout the course of the fire. This means that while multiple roads could be closed in the course of a fire it is unlikely that these closures will coincide with each other and hence the impact of wildfires will, in most areas, be minimised by the availability of alternative routes.

Fire will melt and burn the surface of the road and damage roadside furniture such as delineators, signs, barriers, etc. (M. Gurr pers. comm.). The level of service provided will be reduced accordingly until repairs and replacement are complete, but the duration of total closure is likely to be small relative to other hazards.

Where a wildfire approaches the road, the road is likely tol be closed to prevent any damage to vehicles and their occupants as a result of extreme temperatures. The effects of this on the network will not be great as it is unlikely that a fire will cross more than a single highway at any one time and the duration of wildfires is limited due to the fuel that feeds them being quickly consumed.

Proposed methodology

Identify the regions most likely at risk from wildfires by using NZ Fire Service Commission information. Incorporate historical data of road closures caused by wildfires.

Utilise weather data from NIWA to determine temporal and seasonal fire dangers. For hazard-prone sites, assess the main wind patterns to estimate potential fire and smoke movement directions.

Calculate likely road closure times and estimate total risk regarding to wildfires.

Figure 3.19 Proposed methodology for risk determination for the State Highway network in terms of wildfires.

3.7.1 Information availability

Probability of Fire Occurrence

- The New Zealand Fire Service keeps detailed information on fires that have happened within New Zealand.

Vulnerability of Roadways

The vulnerability of the roadways to wildfires will be determined using historical information

- While a great deal of information is held by the New Zealand Fire Service it is unclear at this stage whether any of this information pertains to the closure of roads during fires. If no information is available then it may be necessary to locate where the fires have occurred and assume that fires close to roadways caused closures. It is not known what distance would be appropriate in this instance or if the information is accurate enough to be used in this manner.
- Transit may have information regarding road closures that have been caused by fires.
- It may be possible to obtain similar information from overseas and use it to determine the vulnerability once it has been adapted for New Zealand conditions.

3.8 Non-natural hazard events

The description of hazards so far has focused on natural hazards. There is the potential however for road network services to be disrupted for other reasons, such as major traffic accidents, industrial accidents that affect large areas, and terrorist activities. Man-made risks that have lead to significant road closures in the past in New Zealand include: heavy commercial vehicle accidents, combustible and toxic spills (which also raise significant environmental risks), bridge strikes (incidents where vehicles, their load or equipment damage bridges) and aircraft crashes (Brown 2002). It will be necessary to undertake a comprehensive risk-identification process to ensure that all types of potential hazards are identified, and where appropriate are incorporated into any risk assessment. This is in keeping with the 'All Hazards' approach promoted through the CDEM Act (2002).

Several techniques are being developed overseas, particularly in the USA, to assess risks to critical infrastructure due to terrorist threats. Terrorist activities are in many ways more challenging from a risk management perspective, as terrorists will modify their behaviour to take account of risk management steps that have been undertaken. In essence it means that the likelihood of certain events can no longer be assumed using random game theory, but requires a form of game theory with an 'adversary'. Techniques being explored for predicting where and how terrorists may strike include Evolutionary Computing techniques which try to anticipate the way terrorists might think in terms of optimising their attack design for maximum impact (Arciszewski et al. 2003). As terrorist threats increase around the world, New Zealand will need to consider how these threats can be better understood and managed.

4. Predicting traffic disruption

In order to evaluate the impact of road closures, predicting how traffic on the network will behave in response to road closures is necessary. Estimating traffic response allows the cost associated with altered travel times, delays, the cost of cancelled trips, and the cost of trips in which the transportation mode changes to be estimated.

Numerous computer modelling programmes are available for predicting travel behaviour, but all of the available programmes rely on large amounts of data to make these predictions accurately. This chapter will discuss the different travel costs that will be incurred because of alterations in the road network, the processes by which modelling programmes evaluate these costs, and the data requirements for these models.

4.1 Traffic-modelling process

Ideally, there would be a single traffic model that included the entire State Highway network in New Zealand. Transit NZ now has available spatial information showing the centre-line location for the whole of the State Highway network in New Zealand. This information, used within a GIS environment, provides an excellent starting point for developing this kind of traffic model.

Once a GIS-based network model is in place, the next step in the traffic-modelling process will be to divide the network into different zones. Zones are created to indicate areas of interest that are likely to generate and attract trips.

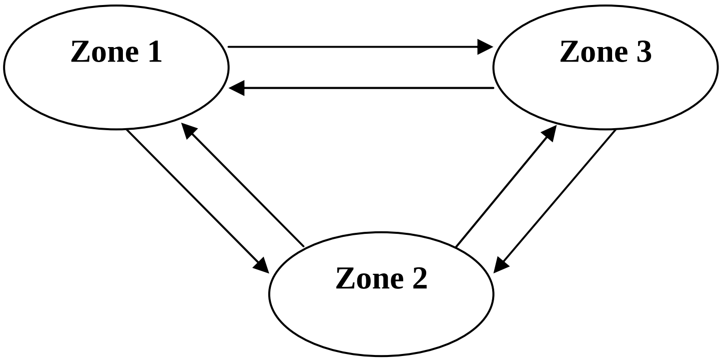


Figure 4.1 The trip distribution process determines the number of trips that occur between different zones in the traffic model. This information is then stored in an O-D (origin–destination) matrix (see Figure 4.3).

The delineation of different zones is not a straightforward process. The number of different zones, and thus the size of different zones impacts the accuracy and granularity of the model predictions. A model with a larger number of zones will have more detail, whereas a model with a smaller number of zones will have improved accuracy. The extent to which the size of zones affects accuracy is dependent on the amount of data available for generating the model. It is likely that the available data will have a large influence on the number of zones selected. In general it is not possible to split a data set for a given area but it is possible to combine areas where there are data sets available for each area to form one zone.

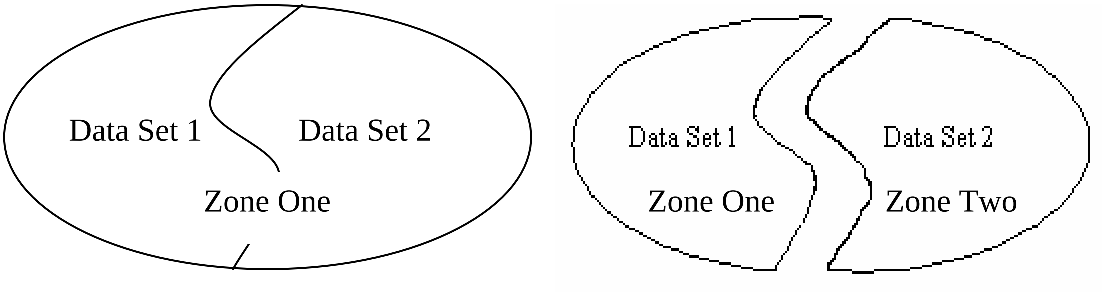


Figure 4.2 Data sets can be combined to reduce the complexity of the model or where doing so will provide better statistical estimates through increased data set size.

Traditionally, the number of trips generated and attracted by each zone is determined by a number of defining features in that zone. These features include land use, dwelling density, and numerous demographic indicators. The processes of deciding which parameters are important and what interdependencies exist between them makes generating an O-D matrix a difficult and time-consuming process, particularly as much of this information must be collected by way of surveys. There are techniques available however where a combination of surveys and traffic counts can be used to estimate the O-D matrix.

Origin-Destination Matrix		**Destinations**		
		Zone 1	**Zone 2**	**Zone 3**
Origins	**Zone 1**	T_{11}	T_{12}	T_{13}
	Zone 3	T_{21}	T_{22}	T_{23}
	Zone 3	T_{31}	T_{32}	T_{33}

Figure 4.3 The O-D matrix stores information regarding the number of trips made between different zones.

Traffic is assigned to the network in a way that minimises the cost for the trip. In rural areas, where there is no congestion, this is usually on the route of shortest distance. In urban areas the route chosen may be a function of both time taken and distance. It may be appropriate in a model for the whole of the New Zealand State Highway network to also include other factors influencing route selection such as scenic beauty. Particularly for many of our main tourist routes, the scenic beauty of certain routes is their main attraction, and people may be willing to travel further and/or longer to get to their destination via these roads.

The detail of a traffic model will vary depending on the outputs that are required and the data that is available for building the model. The detail of outputs can be increased by allowing the model to discriminate between different types of traffic, for instance between perishable freight and non-perishable freight, or by including temporal variation. By increasing the level of detail in a model there will be an increase in the amount of time required building a model and more intensive data requirements, but in doing so it may allow for much more useful information to be extracted from the modelling results. A balance must be achieved between the need for more detailed information and the cost, accuracy, and limitations of the information being used.

4.2 Data requirements

The data requirements of a traffic model vary depending on the level of accuracy and the required outputs of the model. It should be noted that the type of traffic model chosen should be made with reference to the total uncertainty in the overall risk assessment. There are several levels of detail at which the traffic model can be aimed. These and their data requirements are outlined below.

Base Model

- Annual daily traffic counts used in place of generating an O-D matrix. The accuracy of this process is dependent on the number of traffic counts available, the number of routes available, and the number of zones. The traffic counts available are very rarely enough for a unique solution to be developed so a number of possible O-D matrices are generated. It is possible to compare these matrices with previously observed/generated matrices to determine which is the most likely. Where previous matrices are not available a matrix can be estimated where each trip is equally likely so that the matrix will be most evenly distributed.
- The model is then compared with historical road closure data to determine accuracy of the model when alterations to the network occur.

Model Level 1

- As for base model but incorporate seasonal temporal variations into the model.

Model Level 2

- Develop an O-D matrix using demographic information and any readily available trip survey information.
- Assess feasibility of conducting traffic surveys in areas where there is little or no existing information.
- Compare Model with historical data during road closures to determine accuracy of the model when alterations to the network occur.

Model Level 3

- As for Level 2 but expand to include seasonal, and if appropriate, am/pm temporal variation.

Model Level 4

- Create an online database for collecting traffic and demographic information from different organisations around the country. Once established it should be able to be modified by trusted stakeholders.

The size of a model that incorporates the entire State Highway network poses a number of problems in terms of data collection, manipulation, and handling. GIS systems are continuing to be developed which are more and more capable of handling the increasing information demands of traffic models.

4.3 Computer modelling packages

Several traffic-modelling packages are available that could be used, including Transcad, Tracks, SATURN, ME-2 and QRS. Each of these packages has its different strengths and weaknesses for use in this analysis. For example, some packages are designed for modelling congested networks, others are better for understanding traffic behaviour at intersections etc. To complicate matters, there are several different packages already in use by Road Controlling Authorities (RCAs) across different regions in New Zealand. It would be useful for the package selected to interoperate with as many of these existing models as possible.

Key considerations in selecting a modelling package for use in this analysis include:

- the ability for models to be used in Monte Carlo-style analysis, where large numbers of simulations must be carried with a minimal amount of processing time;
- the accuracy of different models with regards to travel times and distances, and the implications that accuracy will have on the end users of the model;
- information requirement versus availability for the different types of models;
- ease of use of the modelling package and its ability to support other road network management activities;
- compatibility with GIS and other modelling packages that are already in use around the country.

It is important to recognise that the State Highway network sits within the greater road network across New Zealand. Where the State Highway is damaged, it may be possible for traffic to be diverted onto local roads. The modelling package will therefore also need to be able to capture the presence of these alternative routes, for example as a “pseudo network”.

4.4 Suggested approach

The development of a traffic model for the State Highway network is a major requirement towards achieving a full hazard risk assessment for the State Highway network. It is important this traffic model is well designed to ensure it provides maximum value. Selection of a modelling platform will be a matter of balancing accuracy with availability of data, and ensuring its compatibility with existing network models, and ease of use. It is also important that the model is flexible and versatile enough to be adapted over time to changing requirements. It is anticipated that a traffic model of the whole of the State Highway network will become a useful tool for other road management decision-making. In particular it would enable network effects to be included in benefit-cost ratio estimates for road improvement projects.

To give an indication of the potential costs of this work, it is estimated that a research project to develop a traffic model for the Strategic Road Network (which includes all State Highways plus some key local roads) for the South Island would be approximately $27,000 using postgraduate student researchers. This would be dependent on finding an excellent student to work on the project. Alternatively Transfund could propose a project for competitive tender to design and create the full traffic model.

It is recommended that Transfund or Transit NZ consider funding, as a first stage towards undertaking a full risk assessment, a research project to design and develop a traffic model for the whole of the State Highway network.

5. Estimating socio-economic impacts

The way Transfund allocates funds is changing, with a move towards a less prescriptive approach to the valuation of benefits and costs of road improvements. Proposals within each activity class are initially prioritised on a benefit-cost ratio basis, where the benefit-cost analysis includes all benefits and costs that can be quantified in economic terms. Project rankings are then adjusted to reflect the less tangible benefits and costs associated with that project (Transfund 2003). Transfund have confirmed that they are open to accepting economic evaluations using methodologies outside those described in the Project Evaluation Manual, providing the methodologies are consistent, justifiable and appropriate (I. Melsom pers. comm.). This means there is now an opportunity to value the impact of road closures more holistically.

5.1 Direct response and recovery costs of infrastructure

Damage to the road network will incur direct costs for reconstruction and repair, and for temporary works needed while the repairs are carried out. It should be noted that in the aftermath of a major hazard event, there will be significant pressure on limited resources and expertise for reconstruction. This will inevitably mean that repairs may take longer, or cost more than they might under normal circumstances. This should be factored into any cost estimates. A major hazard response also withdraws resources from other areas of work which affects normal work programmes (A. Burkett pers. comm.).

5.2 Additional road user costs

Closures on the road network will cause disruption to normal traffic behaviour. Drivers who normally use that route will have to divert and drivers on other parts of the network may be affected by increased congestion. This will result in additional road user costs and travel times for drivers. The Project Evaluation Manual (Transfund NZ 1997) provides standard values that can be applied for estimating these costs. It is then a relatively simple process to estimate the total additional travel cost for drivers on the network using the traffic network model.

Some drivers, however, may chose to delay or cancel their trip if they feel that the new cost of taking the trip outweighs its benefits. The extent to which drivers will alter their trip behaviour depending on the cost of the trip is known as 'driver elasticity'. It is important to account for driver elasticity in estimating the impact of road closures, as effectively, the benefits of taking the trip will be lost. For example, if commuters decide that it is not worthwhile travelling to work because it will now take them too long to get there, productivity is lost. 'Driver elasticity' is estimated as:

$$\text{Elasticity} = \frac{\%\ \text{change in number of trips made}}{\%\ \text{change in the price of trip}}$$

In particular, driver elasticity will be influenced by the level and quality of information that drivers have available to them about the current status of roads on the network (open, closed, delays, etc.), and their knowledge of alternative routes that are available.

The idea of driver elasticity is relativity new and limited data is available for estimating how variable it may be under different conditions. This is an area that would benefit from further research, particularly if the impact of road closures is shown to be sensitive to driver elasticity.

5.3 Community isolation

The Transfund Project Evaluation Manual (1997) specifies that isolation effects should only be considered where an existing link is cut; and be reported in terms of the number of residents affected, the frequency and duration of closures, the availability of alternative routes, the degree of disruption caused by closures, additional distance to community facilities by alternative routes, and the visitor and tourist potential of the area, as appropriate. It does not provide specific guidance on how these impacts could be valued.

In particular, it would be worthwhile exploring public acceptability of communities being isolated following major hazard events. It is possible that the public will be forgiving of short-term isolation as a natural consequence of a significant event. This attitude may harden after several weeks, however, particularly if it is perceived that the recovery process is being mismanaged, or if the recovery of the road network is slow in comparison with other critical infrastructure. This changing acceptability of road closures as time progresses reflects a community’s non-linear utility or valuation of road closure impacts. As large hazard events have significant potential for both short-term and long-term isolation of communities, the recommendation is that this be further researched to provide more specific guidance on how isolation impacts might be valued.

5.4 Availability of priority access routes

Another aspect that would be useful for the risk assessment to consider is the availability of priority access routes for emergency services in the aftermath of a hazard event, and whether or not the closure of these routes should be valued at a premium because of the potential for greater loss of life. Other lifeline service providers will also require access to repair damage to their systems. CAE (1997) identified that the transportation network has a significant influence on the speed of recovery of other lifeline services. Transfund would need to consider whether access routes to other key lifeline sites should also be valued at a premium if not already classed as priority access routes.

5.5 Impact on the economy

As well as directly impacting on the economy through additional road user and repair costs, road closures also have the potential to lead to indirect economic impacts. The economy relies on access and transportation as an integral part of normal operations. Any disruption to these normal operations has the potential to cause impacts beyond the immediate vicinity of the road closure. Chang (2000), for example, found striking long-term differences in the economic recovery of urban areas that suffered significant transportation losses compared with those that had transportation rapidly restored following the Kobe earthquake.

Estimating the magnitude of these economic impacts can be complex. In particular it is important that impacts are not double-counted. From Transfund NZ's perspective, it is also important to identify which of these costs will be to the detriment of the New Zealand economy as a whole, not simply a single community. Any disadvantage through lost sales in one community may be picked up by another without any net impact on the New Zealand economy. Only impacts to the New Zealand economy are included in Transfund NZ's funding process.

Estimating the scale and distribution of economic impacts across a regional or national economy is possible using models such as a Computable General Equilibrium (CGE) model. A CGE model is essentially an input/output model that represents the flow of goods and services between different sectors in the economy (between different businesses, lifeline service providers, government and households, etc.). One of the services that may be represented in a CGE model is road transportation. Using a CGE model it is possible to restrict the availability of road services, and estimate how this will impact on the flow of goods and services throughout the economy.

NZIER in association with GNS, NIWA and the University of Tasmania have used a general equilibrium model to evaluate the economic impacts of the 2002 Weather Bomb event (NZIER 2004). That study evaluated the direct and indirect costs of the Weather Bomb, giving a macroeconomic view of the event in terms of the region-wide economic effects. Another New Zealand company, Infometrics, has developed a general equilibrium model for the Horowhenua-Kapiti region (Stroombergen and Stuart 2003). That model was developed for the purpose of analysing regional economic growth strategies.

Bočkarjova et al. (2004) recently developed a CGE model for the Netherlands, exploring the economic impact and recovery time if a dike were to break causing large-scale inundation. Their research highlighted some interesting effects. For example it indicated that economic recovery of a region may be slowed in times of economic boom, when resources are already used to capacity. This is because other regions are unable to ramp up production to compensate, or to lend spare resources needed for recovery. Their research also indicates that recovery of a regional economy can be held up by 'production bottlenecks', where the slow response of a single sector slows recovery of all sectors. It is very likely that given the dependence of many industries on the road network for their everyday activities, slow recovery of the road network following a hazard event could act as a production bottleneck. With limited options for substituting road transportation with other services, this would significantly amplify the indirect economic impact of road closures.

Economic impacts from hazard events are complex, with reconstruction investment speeding the economic recovery of some sectors, yet bypassing others. Tourism is one of New Zealand's biggest export industries, contributing almost 9% of GDP (TIANZ website), but it is an industry that is susceptible to damage from bad publicity and levels of perceived risk. The impact that road closures will have on tourism is not likely to be significant unless prolonged closures cut access to a significant number of prime tourist sites, or if tourist safety is put at risk. When considering life-safety risk, particularly for a reputation-sensitive industry like tourism, societal risk may be a better indicator of priority areas than individual risk. Societal risk estimates reflect the number of people who may be simultaneously affected by a hazard event. As a society, we tend to place greater importance on hazards that affect a large number of people, and this is reflected in (or some might say, driven by) greater reporting in local and international media of these events. This issue becomes important for example when looking at the avalanche risk for tourists travelling in buses along the Milford Road. The sensitivity of the tourist industry to perceived risk means there is a need to focus on developing a sound strategy for risk communication as well as the treatment of risks.

Primary producers will be significantly affected if road closures occur during critical times such as harvesting. For example, cherry crops are only able to be picked for a two-week period before they become overripe on the trees. If workers are not available during this time or if they are delayed for even a short time then some of the crops will be lost. The impact of road closures on primary producers and some other industries may vary greatly depending on the time of year that the event occurs.

While CGE models provide a technique for estimating regional economic impacts, they also have their limitations. In particular it can be difficult to calibrate CGE models, meaning that they are better for comparing the economic impact of different scenarios, rather than predicting the absolute economic impact of a given scenario. For example significant assumptions are made in the models regarding the extent to which consumers are able to substitute goods and services when they become unavailable or too expensive. For some markets, such as petrol, plenty of historical data indicates the elasticity of consumer behaviour as prices increase. For services such as road access, less data is available, and the assumptions have greater uncertainties.

5.6 Suggested approach

The valuation of socio-economic impacts of road closures is an area where there is a great deal of potential for further research. Preliminary investigations indicate that both the capability and expertise are already present in New Zealand for developing a general equilibrium model of the New Zealand economy. For some regions, preliminary models already exist. The investment requirements would be in updating these existing models, developing regional models for areas without them, plus the development of an inter-regional model to simulate the flow of goods and services between the regions.

Regional economic models will be useful for many organisations such as other lifeline utilities, local and regional government. The recommendation is that Transfund explore opportunities for joint-funding the setting-up costs of building these economic models. NZIER have expressed an interest in building their capability in this area, and indicate that they may be interested in sharing some of the initial development costs (M. Walton pers. comm.).

6. Conclusions and recommendations

Carrying out a full risk assessment of hazard events with the potential to close sections of the State Highway network will be a significant undertaking, but should provide key benefits. The risk assessment will provide a basis for prioritising risk management investment across the whole of the country, for all types of hazard events. It will also provide a database of information that road network managers can use to assess the risks and benefits of different road improvement projects.

To be successful, however, the risk assessment framework will need to be developed with a strong vision of how all the different components of risk will eventually be brought together into a single analysis. Several key areas where research will be required include:

- Design of the overall system architecture to ensure that the modelling platform is robust and can be upgraded over time to incorporate new information as it is collected. It is recommended that an initial project is funded to design the data requirements and structure as conceptually good data design to start with will likely save significant time and effort in later maintenance and improvement costs.
- Proactive involvement with ongoing research projects, such as FRST-funded natural hazard research programmes, to maximise opportunities to leverage existing research initiatives.
- Working with the hazardscape research community to identify how existing hazard models might be characterised by a reduced set of scenario events that could be used within a Monte Carlo 'walkthrough' scenario framework.
- Development of a traffic model for the State Highway network for predicting how traffic will respond to changes in the road network. This could be later extended to the full road network if required.
- As hazard events have significant potential for both short- and long-term isolation of communities, further research is required to enable Transfund to provide more specific guidance on how isolation impacts and the availability of priority access routes for emergency services might be valued.
- A better understanding is needed of the secondary economic effects of road closure such as business disruption impacts. Transfund might explore the possibility of sharing initial costs of economic modelling with other lifeline utilities.

A complete risk assessment framework is unlikely to be successfully delivered via unco-ordinated individual research projects proposed to the Transfund research programme. Their outputs will, in general, not have enough compatibility to easily be combined into a single analysis. Similarly, a 'big bang' approach, i.e. by funding a single large research programme to carry out the assessment, may not give best value from the research investment. As highlighted in this report, many ongoing, concurrent research programmes exist in New Zealand that could be leveraged to feed into the risk assessment. Opportunities may also exist to share research costs by jointly funding research with, for example, other lifeline utilities, local and regional government organisations, or the MCDEM.

If it is decided to proceed, it is recommended that:

3. A small risk assessment research steering group should be formed to provide an overview of what research is required. The whole research programme will be very multidisciplinary (involving hazard researchers, risk managers, economists, transportation planners, etc.).
4. To provide direction, continuity, and advice, it will be important to have a core group of people who are not necessarily doing the research, but who have a clear understanding of the overall research programme and how its different strands of research fit together. This group would be able to provide independent advice for evaluating research proposals on how they align with the overall objectives. They will also be a source of information and advice for researchers on how their research will fit within the overall system architecture and interface with other research programmes going on concurrently.

To see any real progress, however, someone will need to make a strategic decision as to whether or not to invest in developing a risk assessment framework for the road network. The current Transfund research budget for natural-hazard-related research is approximately $200,000 per annum (10% of the total $2 million research budget). Although this research report has not explored in detail the actual costs of delivering all of the research required to achieve a full risk assessment framework, it is anticipated that the risk assessment framework could be delivered with greater targeting of the existing research budget within a period of 5-10 years. However it should be noted that clarification is required between Transfund NZ and Transit NZ as to where responsibility lies for funding and undertaking the risk assessment, as part of this work might be classified as fundamental research, and other parts as operational.

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