Natural Hazard Risk Management for Road Networks

Part I: Risk Management Strategies

Transfund New Zealand Research Report No. 217

Natural Hazard Risk Management for Road Networks

Part I: Risk Management Strategies

P. Brabhaharan, M.J. Fleming, R. Lynch
Opus International Consultants,
Wellington, New Zealand

Transfund New Zealand Research Report No. 217

ISBN 0–478–25075–4
ISSN 1174–0574

PO Box 2331, Lambton Quay, Wellington, New Zealand
Telephone 64-4-473 0220; Facsimile 64-4-499 0733

Brabhaharan, P., Fleming, M.J., Lynch, R. 2001. Natural hazard risk management for road networks. Part I: Risk management strategies. *Transfund New Zealand Research Report 217.* 75pp.

Keywords: natural hazard, New Zealand, roads risk, (risk) management, mitigation

An Important Note for the Reader

Acknowledgments

This research has been carried out by Opus International Consultants for Transfund New Zealand, under the Transfund research funding scheme.

In addition to the Transfund research funds, the following have assisted in the research, and their contribution is gratefully acknowledged.

- Environment Canterbury provided additional funding for this research, which enabled the case study of the risks associated with the Kaikoura section of State Highway 1 to be carried out. We thank Mr Peter Kingsbury of Environment Canterbury for his support, and also for his comments on the risk management approach.

- Wellington City Council enabled some of the risk management approaches to be developed as part of the risk study for the Wellington City road network carried out for the Road Asset Management section. We thank Mr Deven Singh of Wellington City Council for this contribution, and also for his comments on the risk management approaches and peer review comments.

- Upper Hutt City Council commissioned a study by Opus International Consultants to assess risk management for their rural road network. The risk–economic analyses presented are illustrated using the Upper Hutt study. We thank Mr Patrick Hanaray of Upper Hutt City Council for this commission, and for permission to present a section of the results from that study as a case study.

- Opus International Consultants facilitated development of some of the risk management methods, using GIS, as in-house research.

- Dr Neil Britton and Mr Henry Dowler of the Ministry for Emergency Management provided valuable comments on the risk management for road networks.

- Mr Anthony Brennand of the Wellington Regional Council provided comments on the prioritisation of transportation corridors.

- Mr Ian McChesney and Mr Richard Ball of Environment Canterbury provided comments on the prioritisation of the road corridors.

Contents

Appendices

Executive Summary

Road networks are lifelines for the community and are essential for the economic well-being of New Zealand. Natural hazard events can cause widespread damage to transportation networks, leading to significant repair costs to road controlling authorities, access difficulties for emergency services, and disruption to road users and the community at large.

There is a lack of systematic methods available to consider the impact of natural hazards on road networks, and to develop strategies for effective management of the risk. A systematic approach to developing such a strategy would enable prioritisation of mitigation, preparedness planning, and help in managing the network. Research has been carried out by Opus International Consultants (Opus) in 1999–2000, and this report outlines methods for developing appropriate strategies to manage the risk.

Past risk management initiatives, both in New Zealand and overseas, have been reviewed. Generally, the approach to risk management of road networks has been reactive. Risk has been considered on a more proactive basis for nodal structures such as bridges, and a seismic screening programme is in progress to address the earthquake risk to bridges. Risk has also been considered for specific sections of roads. The only known attempt to consider risk to the network has been the recent Transfund-sponsored research on risks to the Central North Island state highway network. However, this too considers mainly damage to nodal structures such as bridges. The situation is similar in overseas studies. Recently, geographical information systems (GIS) have been used to consider the risk to traffic networks, but again only the risk from failure of bridges.

In assessing the risk to roads, it is necessary to assess the hazards that affect the roads and their consequences for the road network and the community. This will enable the derivation of risk as a combination of the likelihood of the hazard and its consequences.

In managing risk to the road network, it is important to consider the level of service expected by the community and the target level of service that a road controlling authority is willing or able to provide. This will help in determining an acceptable level of risk for the road network. It is prudent to consider different levels of acceptable risk depending on the importance of links in the network.

The road links in a network can be prioritised by considering a range of factors, and this enables risk management to be considered according to priority. This will facilitate a rational approach to risk management given the resources available.

In situations where a risk of a significant number of deaths from natural hazard events exists, then a frequency–number of fatalities chart will help consideration of the risk in the context of wider risks faced by the community, and the levels of risk considered to be "tolerable" or "intolerable" in other risk situations.

Risk–economic analyses will help in considering the economic benefits of risk mitigation through the derivation of benefits from mitigation and comparison with its costs. This will help in prioritising risk mitigation and also provide economic justification. However, several intangible factors also need to be considered when deciding on risk management, and the use of a scoring system to prioritise risk mitigation is proposed.

Risk management analysis is difficult given the spatially distributed risks affecting lifelines such as road networks. The traffic impacts depend on the characteristics of the network. A spatial approach to risk analysis and risk–economics of mitigation has been developed using GIS, and this is demonstrated in two case studies, one for a rural road network and the other for a state highway.

The case study for the Upper Hutt rural road network suggests that mitigating risk on rural roads affected by significant hazards may not generally be financially justifiable, considering damage and disruption costs. It shows that the benefits of improving some aspects of the roads, such as drainage through culverts, may be financially justifiable. However, such rural roads may provide the sole access to small communities, and this factor needs to be considered.

The case study for the Kaikoura Coast section of State Highway 1 indicates that risk mitigation could be financially justified for some sections of roads, in this case those affected by coastal hazards.

Guidelines are provided for developing a risk management strategy for road networks.

The management of road risks requires consideration at different levels, from regional transport planning through asset-management practices to individual project analyses. It is also important that this is built into emergency preparedness planning. At present, policy directions to facilitate the management of risk in a rational manner are limited. Further research into how this may be developed at various levels, from regional transport policy to individual project evaluation, would be valuable. This would provide a framework which relevant authorities can develop into active policies to improve the resilience of the road networks, and hence the community, to natural hazards.

Abstract

Road networks are lifelines for the community and are essential for the economic well-being of New Zealand. Significant natural hazard events can also cause widespread disruption to transportation, leading to significant repair costs to road controlling authorities, access difficulties for emergency services, and disruption to road users, tourists and the community at large.

As there is a lack of systematic methods available to consider natural hazards that can affect road networks, and to develop methods for managing the risk, research on a strategy to prioritise mitigation, preparedness planning, and management of the road network was carried out by Opus International Consultants (Opus) in 1999–2000. The report outlines methods for developing appropriate strategies to manage the risk.

1. Introduction

Road networks are lifelines for the community and are essential for the economic well-being of New Zealand. Natural hazards such as earthquakes, storms, floods, volcanic eruption, snow, wind and slope failures are prevalent in New Zealand, and cause considerable damage to road networks from time to time. Major natural-hazard events can also cause widespread disruption to transportation, leading to significant repair costs to road controlling authorities, access difficulties for emergency services, and disruption to road users and the community at large. The consequential effects on businesses and the economy can be very significant. Road networks are also crucial in enabling the community to survive in the aftermath of a major natural disaster, and to recover from it.

Lifeline studies in several regions have highlighted the risk to road networks from natural hazards, and have illustrated the interdependencies between transportation networks and other lifelines. The potential effects are seen as enormous and very costly to prevent. Yet overseas and local events have shown that management of natural-hazard risk through mitigation and preparedness is valuable for the survival of the community in a major event and for recovery afterwards.

There is a lack of systematic methods available to consider natural hazards that can affect road networks, and to develop strategies for effective management of the risk. A systematic approach to developing such a strategy would enable prioritisation of mitigation, preparedness planning, and help in managing the network. Such a strategy can be built into the road controlling authority's asset management plan.

This research was carried out by Opus in 1999–2000. It considered past research and initiatives in New Zealand and overseas to manage the natural-hazard risk to road networks, and this report outlines methods for developing appropriate strategies to manage the risk. It also illustrates some of the techniques developed, by applying them in case studies. A recommendation is made to develop these further, to enable their incorporation into Transfund New Zealand's policies and procedures.

2. Risk Management Framework

2.1 The Joint Australia/New Zealand Standard

The process of risk management is well developed and documented.Yet risk management is relatively poorly understood in the general roading industry.

Recently, risk management processes have been incorporated into a Joint Australia/New Zealand Standard on Risk Management, AS/NZS 4360:1999 (Standards Australia 1999). This standard provides a useful framework for the management of risk, and provides some important definitions.

2.2 Definitions

Selected definitions from AS/NZS 4360:1999 follow.

Term	**Definition**
Event	an incident or situation which occurs in a particular place during a particular interval of time.
Hazard	a source of potential harm or a situation with a potential to cause a loss.
Likelihood	used as a qualitative description of probability or frequency.
Probability	the likelihood of a specific event or outcome, measured by the ratio of specific events or outcomes to the total number of possible events or outcomes. Probability is expressed as a number between 0 and 1, with 0 indicating an impossible event or outcome and 1 indicating that an event or outcome is certain.
Consequence	the outcome of an event, expressed qualitatively or quantitatively, being a loss, injury, disadvantage or gain. There may be a range of possible outcomes associated with an event.
Cost	of activities, both direct and indirect, involving any negative impact, including money, time, labour, disruption, goodwill, political and intangible losses.
Loss	any negative consequence, financial or otherwise.
Mitigation	appropriate action for dealing with risk.
Risk	the chance of something happening that will have an impact upon objectives. It is measured in terms of consequences and likelihood.
Risk assessment	the overall process of risk analysis and risk evaluation.

Term	Definition
Risk evaluation	the process used to determine risk management priorities by comparing the level of risk against predetermined standards, target risk levels or other criteria.
Risk acceptance	an informed decision to accept the consequences and the likelihood of a particular risk.
Risk avoidance	an informed decision not to become involved in a risk situation.
Risk treatment	selection and implementation of appropriate options for dealing with risk.
Risk management	the culture, processes and structures that are directed towards the effective management of potential opportunities and adverse effects.
Risk management process	the systematic application of management policies, procedures and practices to the tasks of establishing the context of, identifying, analysing, evaluating, treating, monitoring and communicating risk.

2.3 Risk Management Process

A structured approach will enable rational consideration of the risks and will facilitate making appropriate decisions. AS/NZS 4360:1999 presents a commonly used process for risk management, which is shown in Figure 2.1.

2.4 Derivation of Risk

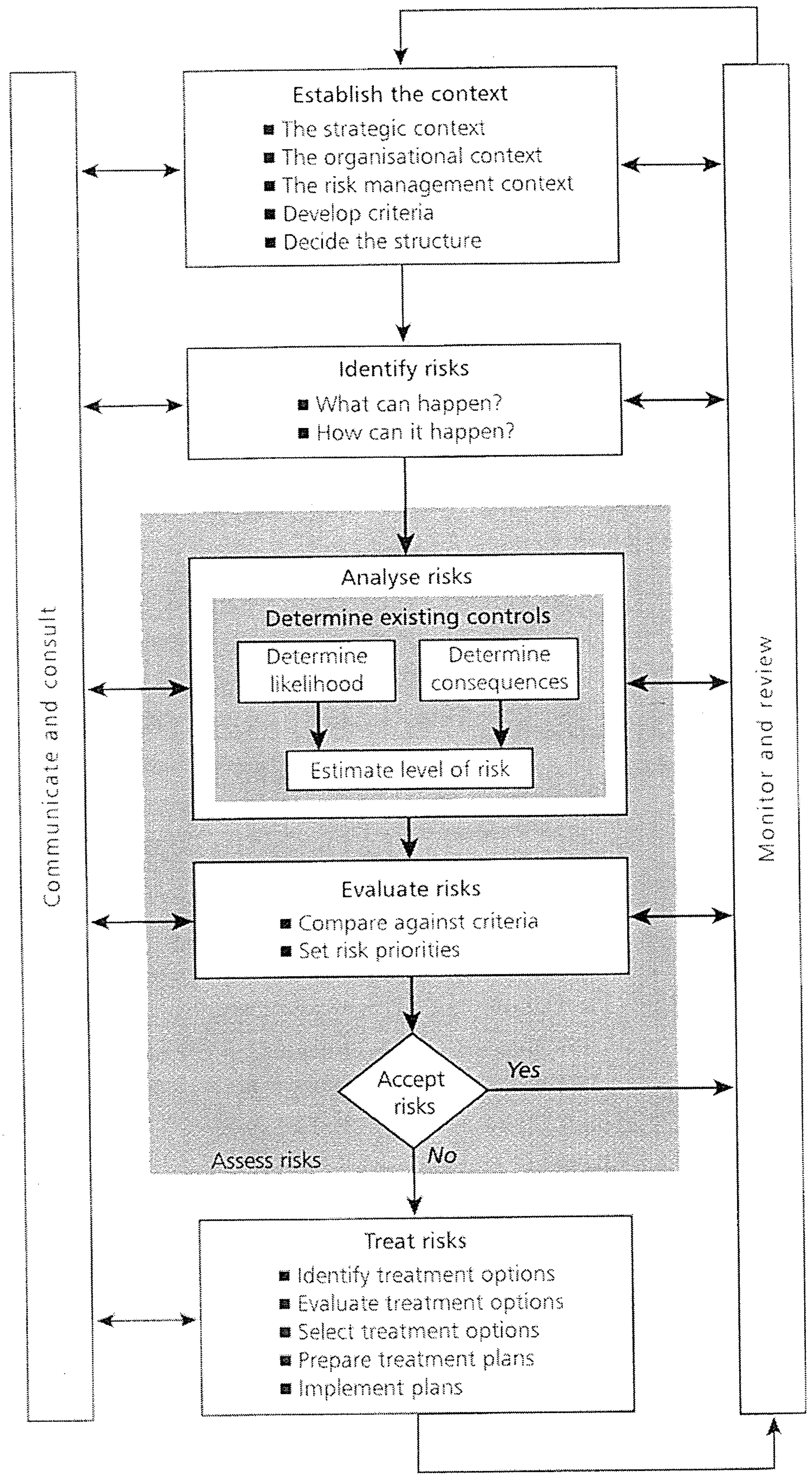
The risk associated with any hazard is derived from a combination of the likelihood of the hazard and its consequences, that is:

$$\text{Risk} = \text{Likelihood of hazard} \times \text{Consequences}$$

Risk can be derived qualitatively or quantitatively, depending on the information available and the purpose. In a qualitative derivation, the likelihood is described in terms such as rare, unlikely, possible, likely and almost certain, and the consequences as insignificant, minor, moderate, major and catastrophic. Derivation of the level of risk (low, moderate, high and extreme) from such a qualitative approach is presented in AS/NZS 4360:1999.

Risk can also be derived quantitatively, often using a probabilistic approach. In quantitative risk assessment, the likelihood can be specified in terms of the probability of the occurrence of the hazard over a specified period (say, design life) or as an annual probability. The consequences may be specified quantitatively, in terms of monetary loss (dollars) or as numerical factors to represent the consequences.

Figure 2.1 Risk management process



2.5 Risk Evaluation

An important step in risk management is the evaluation of risk to assess whether it is acceptable or requires some form of risk treatment. Risk evaluation may be by comparison with specific criteria developed for the purpose or by prioritising the risks for treatment.

2.6 Risk Treatment

Once risks have been evaluated, various risk treatment options can be considered. These include:

- avoidance (e.g. relocate road to lower risk corridor),
- acceptance (e.g. decide that the likely frequency of damage is acceptable),
- transfer (e.g. insure for the risk, where the risk is transferred to the insurer),
- reduce likelihood (this is often not an option for most natural hazards),
- mitigation (e.g. strengthen bridge to reduce the consequences of an earthquake),
- preparedness (e.g. reduce consequences of damage to road through emergency preparedness, by enabling quick reaction to reinstate access).

3. Review of Key Literature

3.1 Literature Search

A search of the literature was carried out, using the resources of TeLIS (Technical Library and Information Service, Opus), to obtain literature on risk management for road networks. Literature sourced locally, as well as from overseas, was reviewed.

Considering the major effects of natural hazards on roads, there has been relatively little research into the management of natural hazard risks affecting road networks. Much of the existing research has been carried out during the past five years.

A considerable volume of research literature exists on prioritising, assessing and retrofitting bridges for seismic performance. It appears that little research has been directed at improving the performance of the roads themselves, because it was considered that there was redundancy in the road network and roads can be repaired relatively easily (Cooper 1981). This may be valid in comparison with nodal structures such as bridges. However, the level of redundancy in the road networks is inadequate, given the New Zealand context. This has been highlighted by a number of storm events, for example Cyclone Bola in 1987 and in Central Otago in 1999. It is important to consider the impact of natural hazards on the road network, rather than bridge structures in isolation.

The National Science Foundation sponsored an assessment of research into natural hazards and its applications, and found that the research has recently been more focused on earthquake engineering than on other hazards (Heaney et al. 2000). In the USA, the Army Corps of Engineers gets much of the flood-related financial support and very little extramural research is carried out. The situation is somewhat similar in New Zealand, with much of the focus being on earthquake research. However, there is some ongoing research into other hazards such as volcanic eruption and floods.

3.2 Natural Hazards and Impacts on Roads

Numerous papers provide information on natural hazards and their impact on roads, often based on case histories. The World Road Association, previously known as the Permanent International Association of Road Congresses (PIARC), set up Group G2 to work specifically on natural hazards and their impact on roads, as an input to the International Decade for Natural Disaster Reduction (IDNDR).

The group produced a comprehensive report (World Road Association 1996), which documents:

- previous natural disasters affecting roads,
- various natural hazards and their impact on roads,
- possible mitigation measures,
- emergency response.

Following this report, the group focused on an updated international survey, international seminars, a review of seismic codes and guidelines, and emergency planning and management. A final report presents the results of these initiatives (World Road Association 1999).

In New Zealand, the most comprehensive assessment of the identification and mapping of natural hazards has been completed for earthquake hazards in the Wellington Region (Brabhaharan 2000). Similar studies are currently being undertaken for the Canterbury Region, and more broad-scale studies have been completed in Auckland. The effect of earthquakes and other natural hazards on roads and other lifelines have been assessed for a number of areas, notably in Wellington and Christchurch (Centre for Advanced Engineering 1991, 1995). These studies were carried out on a broad regional scale.

3.3 Bridge Risk Assessment

In 1991, a US–Japan workshop was held on earthquake disaster prevention for lifeline systems (National Institute of Standards and Technology 1992). The section on transportation lifelines concentrated on bridges, with reports on Caltrans' seismic retrofit programme in the USA (Maroney & Gates 1992), and the seismic inspection and strengthening programme in Japan (Kawashima et al. 1992). There have been several reports and papers published on bridge seismic screening, prioritisation and retrofit.

In New Zealand, a seismic screening procedure for state highway bridges was developed by Opus for Transit New Zealand (Works Consultancy Services (WCS) 1996b). A seismic screening methodology was also developed at the University of Canterbury (Maffei 1997). The Opus (1998) approach has been adopted by Transit New Zealand (1998), and the bridges along New Zealand's state highways are being screened systematically (Chapman et al. 2000). Following on from the screening programme, the seismic performance of some bridges has been assessed in further detail.

The vulnerability of bridges to other natural hazards, such as flood-induced scour, is considered on a more ad hoc basis. For example, the Hutt City Council considered the vulnerability of Melling Bridge in Lower Hutt to scour from flooding and earthquakes (Opus 1999). Other natural hazards such as floods are also considered where the bridges come under scrutiny as part of road improvements to reduce traffic accidents or to improve geometric alignment.

The seismic performance of major bridges such as the Thorndon Overbridge in Wellington and the Auckland Harbour Bridge has been assessed and the bridges retrofitted during the past decade. The importance of these bridges to the network and the economic consequences of failure were considered as part of the assessment.

A more network approach to the assessment of bridges has been proposed by Basoz & Kiremidjian (1995), who demonstrated the use of Geographical Information Systems (GIS) for bridge prioritisation. GIS has facilitated using the combination of seismicity, bridge vulnerability and traffic origin–destination (O–D) information to assess the risk. This allowed Basoz & Kiremidjian (1997) to consider the effect of the seismic performance of bridges on the road network.

3.4 Road Network Reliability

3.4.1 Importance of Routes

Montgomery Watson New Zealand (1999) considered the relative importance of New Zealand's state highway network outside urban areas, and selected other critical links. They assessed the relative importance of the routes considering commerce, mobility, lifeline (or health and welfare), and tourism factors. The risk was considered in terms of the return period of impacts and duration of potential closures. On that basis they prioritised the links in New Zealand's state highway network in terms of importance. They also considered four of those links in further detail.

3.4.2 Network Analyses

Several theoretical studies have considered the reliability of transportation links and networks. Du & Nicholson (1993) considered a theoretical framework for assessing degradable transportation systems. Researchers in Japan have considered the effect of earthquake disruption on urban transportation networks (Nozaki & Sugita 2000, Chunguang & Huiying 2000, Nojima & Sugito 2000).

Nojima & Sugito (2000) developed a model to simulate and evaluate post-earthquake performance using Monte Carlo simulation of damage and a modified incremental assignment method for traffic. They considered the effect on O–D trips and enabled identification of vulnerable O–D pairs. Kawakami (2000) used a similar method to assess road networks and evaluate the post-disaster role of structures. The method is applied to the highway system in Tokyo.

3.4.3 Effect on Emergency Services

Nozaki & Sugita (2000) considered the traffic demand from post-earthquake emergency disaster recovery activities and the potential for damage to network links in assessing the network, using a parameter termed "structural performance index". They demonstrated the use of this model to assess the effectiveness of structural (retrofit) and non-structural (traffic control) measures. Chunguang & Huiying (2000) presented an assessment of the reliability of a road network by considering the probability of damage to various components of the network using a Monte Carlo simulation. They demonstrated the use of this approach in considering the location of emergency service resources, such as ambulances.

By studying aerial photographs taken after the 1995 Great Hanshin–Awaji (Kobe) earthquake, Li & Tsukaguchi (1996) assessed the areas that were inaccessible for search and rescue activities. They considered the importance of the local network in facilitating emergency access.

3.4.4 Disruption costs

Mori et al. (1998) evaluated actual traffic data during different periods after the 1995 Kobe earthquake. This was compared with pre-earthquake traffic data to assess disruption costs caused by failed sections of the Chugoku Expressway, calculated as a combination of additional travel-time costs and additional operating costs. The costs were assessed as ¥5.66 billion. They also considered the improvement that may have been achieved by an alternative expressway that provides redundancy to the network.

Weseman et al. (1996) assessed the cost of delays caused by freeway closures after the 1994 Northridge earthquake in Los Angeles. They considered four freeway closures, and assessed delay costs using detailed traffic counts, surveys and travel time (delay) data as well as computer simulation using an EMME/2 model. They assessed the direct transportation-related costs as exceeding US$1.6 million per day.

Hendrickson et al. (1980) considered losses to users from earthquake-damaged road networks. They assessed a net user benefit, or the "value" of the transportation network to users, as the difference between the total user benefit and the cost of the trip. The effect of disruption from an earthquake was assessed as a decrease in total net user benefit. Hence the total loss from the earthquake was assessed as:

$$\text{Total loss} = \text{Repair or replacement cost} + \text{Loss in user benefits}$$

This, together with a component damage probability matrix (earthquake-damaged road link capacity and the associated probability of damage states for different earthquake intensities), was used to derive the total cost of earthquake damage. They compared this with the retrofit cost for that component.

Werner et al. (1997) proposed seismic risk analysis of a highway system to estimate the loss from earthquakes. A GIS was suggested with four modules:

- system module with network and traffic data,
- hazards module with seismicity, topography and soils data,
- component module with structural, functionality and loss/repair cost data,
- socio-economic module with loss, emergency response and societal effects data.

They demonstrated this model using a simplified deterministic analysis for four earthquake scenarios (considering only the ground-shaking effects) for a section of the road network in Memphis, Tennessee, USA, and considering only bridges on the road network. MINUTP traffic forecasting software was used to assess traffic impact. Only direct losses (repair cost) and traffic disruption costs were considered.

Gordon et al. (1997) outlined a framework for assessing the total economic impact from the effect of earthquakes on transportation (bridges only considered), using input/output models. They included changes in traffic demand after the earthquake.

The total economic impact was considered as:

Total economic impact = Total direct impact + Total indirect impact + Total induced impact

where:

Total direct impact	=	Reduction in final demand accounted for by earthquake losses to industrial capacity
Total indirect impact	=	Additional reductions in production of commodities other than labour due to inter-industry linkages in the economy
Total induced impact	=	Additional reductions in production driven by endogenous changes in labour requirements.

However, the practical use of this model for risk assessment of a road network was not demonstrated.

3.5 Risk Management

3.5.1 Road Networks

Augusti et al. (1994) described the use of a dynamic programming optimisation procedure to assess the reliability (that is, maintaining connection between origin and destination), evaluate optimal intervention (retrofit of bridges) and reduce the seismic risks to highway networks. The method allowed intervention, for a given amount of total resources, to be distributed to maximise reliability.

Opus carried out a risk analysis for the Upper Hutt City Council's rural road network, comprising the Akatarawa, Whitemans, Kaitoke and Moonshine valley areas (Brabhaharan 2000). A risk management framework was developed, based on hazard characterisation, loss estimation and risk–economic analysis with the aid of a GIS base model. The study considered all natural hazards, and characterised and mapped the hazards and the potential impact on the roads. The analysis comprised an assessment of the total economic costs, which were derived as:

Total economic costs = Damage reinstatement costs + Traffic disruption costs

over a 20-year period, considering the probabilities of various intensities of each hazard. In this instance, earthquake and storm were the dominant hazards, and consequent liquefaction, slope failure, erosion and flooding were considered. Mitigation measures that may be appropriate over the network were developed and costed, and the benefits from mitigation were derived as savings in damage and disruption costs. This enabled calculation of benefit/cost ratios and prioritisation of risk mitigation measures. Various risk management measures were considered and the financial benefit from various levels of risk mitigation expenditure was evaluated.

Dalziell et al. (1999) studied the hazards affecting the road network in the Central North Island of New Zealand. They considered the state highway network in the area, and assessed the risk to the Desert Road section of State Highway 1, with computer-aided traffic analyses using a SATURN model to consider the impact on traffic. The study included consideration of volcanic eruption, earthquakes, snow and ice as well as traffic accidents.

Bakir et al. (2000) described a systems approach to balance risks in managing the risks to lifelines. This was demonstrated for nodes in a water supply system in Christchurch.

3.5.2 Road Projects

Road projects are undertaken to improve the road network. Butcher (1984) considered State Highway 73, between Christchurch and Kumara in the South Island of New Zealand, as a case study of risk analysis in the economic evaluation of road improvements. He presented a detailed discussion of risk assessment applicable to road projects, and advocated the use of probabilistic cost–benefit analysis, incorporating the risks and associated uncertainty. The need to consider closure costs, considering the presence of alternative routes and the proportion of trips that may be cancelled, was noted. He suggested that the closure costs should consider route availability and, where appropriate, projects should be considered jointly. This approach implicitly indicated the need to consider road links or networks when assessing risks.

Riddolls & Grocott (1999) applied risk assessment techniques to demonstrate the optimisation of slope failure maintenance programmes, through a case study of a site on the Arthur's Pass road along SH73. A spreadsheet program was developed to facilitate analysis.

Koorey & Mitchell (1999) considered the effect of road network link reliability on the benefit/cost ratios of roading projects. They reviewed Transfund New Zealand's current *Project Evaluation Manual* (*PEM*) with respect to the treatment of risk and reliability of road links, and noted the limited guidance it gave on risk evaluation. They provided examples for calculating the reliability of road links and simple networks, and for incorporation into benefit/cost calculations. They also suggested procedures for incorporating these into *PEM*.

4. Natural Hazards and Their Effects on Roads

4.1 Range of Natural Hazards

A variety of natural hazards can pose a risk to roads. Natural hazards are particularly important in New Zealand, given its steep terrain, climatic conditions and location on a tectonic plate boundary of the Pacific and Indo-Australian plates. The predominant natural hazards that are important in New Zealand and associated hazards are summarised in Table 4.1.

Table 4.1 Natural hazards and their consequences.

Primary hazard	**Consequential hazards**
Landslides	Overslips, underslips, mudflow
Earthquakes	Ground shaking, fault rupture, liquefaction, slope failures
Storms	Flooding, wind, coastal erosion, scour, slope failures, storm surge
Tsunami	Tsunami, seiche
Volcanic eruption	Ash and pyroclastic fall, lava flow, lahars, geothermal activity
Snow and ice	Ice, snow, avalanche
Soft ground	Slumping
Wild fire	Forest fire

The World Road Association (1996) provided a comprehensive description of natural hazards and their impact on roads. The identification and primary consequences of the main types of natural hazard in New Zealand are summarised below. Opus assessed the overall asset damage to New Zealand's state highway network from earthquakes and volcanic eruption (WCS 1990).

4.2 Landslides or Slope Failures

Slope failures are a major hazard to roads in New Zealand, given the steep terrain over a large proportion of the country. Slope failures occur from time to time, leading to significant reinstatement costs. More widespread slope failures are triggered either by storms (and periods of wet weather) or by earthquakes.

The annual emergency works expenditure on work funded by Transfund New Zealand alone is $21 million. A significant part of this is for reinstating slope failures. This emergency works budget is exceeded when storm events occur, as in 1998 and 1999. The expenditure in 1999 was $53 million.

Slope-failure hazard maps have been prepared for the Auckland Region (Auckland Regional Council 1997). Opus developed and used a methodology to map earthquake-induced slope-failure hazards in the Wellington Region (Brabhaharan 2000). The method comprised identifying factors that contribute to slope hazards, and integrating the factor values with appropriate weighting for the different factors. The system was calibrated by reference to past failures and consideration of specific cases in more detail.

The generic slope hazard maps are not likely to reflect the slope-failure hazards adequately along all the road corridors where cut-and-fill slopes are located, unless these are mapped in detail. Further site-specific mapping of the hazard is often required along road corridors. This would enable the specific hazards and their impact on the road to be assessed.

The impact of slope failures affecting roads is summarised in Table 4.2, which also comments on the relative ease of reinstatement after damage caused by different types of slope failure.

Table 4.2 Impact of slope failures on roads

Type of failure	Impact
Overslips	Soil and rock from above the slope (cuttings or hillsides) fall onto the road. This can be removed by earth-moving equipment relatively quickly unless very large, but may require stabilisation of the remaining slope.
Underslips	The slope (or supporting retaining wall) on the downhill side of the road carriageway fails, often removing part or whole of the pavement. This can particularly affect steep sidling fills, which have in the past been formed in developing roads in steep terrain. Reinstatement often requires a structural solution, such as a retaining structure or rock revetment, and is often more costly than removal of overslips and can take time to construct.
Overall failure	Road corridors formed along steep or unstable hillsides can be completely removed by large landslides. These can be very extensive and time-consuming to reconstruct.
Mudflow	Mudflows can occur where soft materials and significant surface or groundwater flow occur, and can lead to flow of mud across the road causing disruption or traffic accident hazards. This is more likely in storms, or earthquakes associated with wet weather conditions.

4.3 Earthquakes

4.3.1 Consequential Hazards

Earthquakes can affect all areas of New Zealand, with a low hazard in Northland. Earthquakes can lead to the following effects:

- fault rupture,
- ground shaking,
- slope failure,
- liquefaction.

4.3.2 Fault Rupture

Shallow earthquakes are often associated with the rupture of faults at the surface, with horizontal and or vertical displacements ranging from hundreds of millimetres to several metres. Roads and associated structures located along faults can be subject to collapse or severe deformation, leading to severe misalignment if the movement is several metres. The major faults in New Zealand have been mapped by geologists associated with the Institute of Geological and Nuclear Sciences (IGNS) in New Zealand, and have been published in geology maps and hazard reports. There is also an ongoing effort to refine the location and characteristics of active faults. More detailed fault maps to a scale of 1:25 000 have been published in some regions, including Wellington (Wellington Regional Council (WRC) 1991).

4.3.3 Ground Shaking

The peak ground acceleration maps have been developed to present the general variation in the earthquake ground-shaking hazard across New Zealand. Ground shaking can cause damage to road structures such as bridges and retaining walls. Retaining walls can displace or deform without significant effect on the road, or they can collapse, leading to full or partial road closure. Ground shaking can also lead to failure of road embankments, particularly if underlain by poor ground.

For important road structures, a more detailed site-specific hazard study can be carried out. This should also take into account the ground conditions at the site, and the potential for amplification of ground motions, particularly where soft or deep sediments are present.

Records from earthquakes overseas have indicated that ground shaking is enhanced close to the earthquake epicentre or fault rupture. This may need to be considered when assessing the earthquake performance of important structures.

4.3.4 Slope Failure

Ground shaking can cause the failure of slopes, which may range from small rock falls and slumps to major rockslides and landslides. An associated phenomenon is the failure of slopes supported by retaining structures. The impact of different types of slope failure on roads is the same as that described for slope failures in Table 4.2.

Earthquake-induced slope-failure hazard maps have been prepared for the Wellington Region (WRC 1995). However, these represent the overall major slope hazards and do not necessarily adequately reflect the slope-failure hazards along road corridors where cut-and-fill slopes are located. Further site-specific mapping of the hazard is often required along road corridors, as discussed in Section 4.2 of this report.

4.3.5 Liquefaction

Liquefaction is a phenomenon where loose saturated cohesionless soils such as sands and silts subjected to strong ground shaking, as from earthquakes, experience an increase in porewater pressures and hence loss of shear strength. This can cause the soil to behave like a liquid, with consequent ground deformation.

Liquefaction could lead to:

- sand boils (where water and sand are ejected out of the ground) and associated flooding,
- subsidence of the ground,
- flotation of buried structures such as manholes,
- foundation failure of structures or embankments built on liquefiable ground,
- failure of slopes in liquefiable ground,
- lateral spreading of ground towards free surfaces such as river or coastal banks,
- rupture of buried pipelines due to ground deformation.

Liquefaction hazards in the Wellington Region were mapped by Opus in reasonable detail (Brabhaharan et al. 1994) and published by WRC (1993). These maps also show the likely ground damage from liquefaction. A method for mapping liquefaction hazards was developed during this study and is presented in Brabhaharan et al. (1994).

The areas prone to liquefaction in New Zealand are predominantly coastal areas, along the lower reaches of river flood plains, and reclaimed land. In some regions, an indication of possible susceptibility to liquefaction has been mapped, based on their outline geology.

The main types of liquefaction-induced ground damage that can affect roads are:

- near free surfaces, such as along watercourses and foreshores:
  - ground subsidence leading to cracking of pavement,
  - lateral spreading of roads towards banks, leading to severe damage,
  - lateral spreading of embankments built on liquefiable ground,
  - additional thrust on bridge abutments and piers.
- in flat areas:
  - flotation of manholes and pipes,
  - lateral spreading of embankments built on liquefiable ground,
  - subsidence leading to cracking of pavement,
  - additional down-drag on piles supporting bridges or walls.

- on liquefiable sloping ground:
  – slope failures along liquefied layers in the ground,
  – foundation failure of structures.

In general, roads on flat ground and at-grade will suffer deformation and cracking, but may still provide access.

4.4 Storms

Storms are climatic events associated with strong wind and heavy or prolonged rainfall, which can lead to flooding, scour, storm surge and coastal erosion. The heavy rainfall can also lead to slope failures (see Section 4.2). Slope failures associated with storms can include slope erosion and slumping as well as mud and debris flows.

Flooding can be one of the main consequences of storms. Flood hazards associated with major rivers in New Zealand have generally been considered by regional councils or unitary authorities, particularly in urban areas. Flood hazard information, and possibly maps, is available from such councils. Flood hazards can be assessed from long-term hydrology (rainfall, river flow/stage) data. A significant amount of data has also been collected on behalf of the Electricity Corporation of New Zealand (ECNZ) and its component or privatised electricity generation companies, and provides valuable information in areas where hydro-electricity developments are in place or were planned.

Flood protection in the form of bank stabilisation and stop banks may be present, particularly in urban areas. These may also provide protection to roads, which are often located alongside rivers.

Winds generally cause little damage to roads in New Zealand, but can cause trees to fall and block roads, causing disruption. Suspension bridges, which are rare in New Zealand, are vulnerable to wind. Winds in exposed locations can cause a hazard to road users, particularly through high trucks or towed vehicles tipping over.

Storm surge and waves associated with storms, as well as ongoing coastal wave action, pose a coastal erosion hazard. Coastal erosion has been considered only on an ad-hoc basis in New Zealand, with assessments focusing on areas where it poses a significant risk to residential development.

4.5 Tsunami

A tsunami is a tidal wave that is generated near shore or offshore (sometimes at a considerable distance) by either a sub-sea earthquake associated with sea-floor displacement, or a sub-sea landslide, which may in turn be triggered by an earthquake. It could also be associated with a sub-sea or near-shore volcanic eruption. Tidal waves can range from several hundreds of millimetres to several metres in height and can arrive at the shore with significant speed and cause widespread destruction to coastal areas within their reach.

Exposed coastal roads may be prone to tsunamis, which can cause inundation, wash out road users and erode the road formation. Coastal roads are vulnerable to tsunami originating far away in the Pacific Ocean. Exposed coastal areas can also be vulnerable to tsunami from nearby fault rupture or volcanic eruption.

Seiche is an associated phenomenon where a body of water, such as a basin or harbour, sloshes from side to side in response to a strong local earthquake. The effect is more likely to be inundation of coastal areas and flooding, rather than a tidal wave and associated destruction. Seiche is possible in places like Wellington Harbour. For example, a study by Gilmour & Stanton (1990) indicated the area around Wellington Harbour that may be affected by seiche, with the height of inundation being less than one metre. Seiche could also be a hazard for roads along the shores of large lakes such as Taupo.

Seiche may cause flooding for a short time and some limited erosion to roads.

4.6 Volcanic Eruption

Volcanic eruption is a particular hazard in the Central North Island, Taranaki, and the Bay of Plenty. There are also many volcanoes in Auckland, although they have a much lower probability of eruption. The most common hazard from volcanic eruption in New Zealand is ash fall, as well as associated lahar flows and flooding from rupture of the rims of crater lakes, such as on Mount Ruapehu.

IGNS has collated volcanic information and published volcanic hazard information. Dalziell et al. (1999) presented a good summary of the impact of volcanic hazards on roads in the Central North Island.

4.7 Snow and Ice

Snow and ice cause significant disruption to roads in mountainous areas of New Zealand during winter. Ice affects roads and forms black ice, posing an accident hazard for vehicles. This is prevalent in much of the South Island and large sections of the Central North Island, particularly where the temperature drops to near zero degrees Celsius or lower, and where the road is not exposed to significant sunlight.

Snow regularly affects the Desert Road section of SH1 in the Central North Island and the highways that cross the Southern Alps in the South Island, in particular the Arthur's Pass section of SH73, as well as the Milford Road (SH93). It also occasionally affects roads in other areas such as Otago and Canterbury as well as the Rimutaka Hill Road near Wellington and the Taupo–Napier Road. The roads are often closed when there is heavy snow, or vehicles may need to use chains when there is light snow. Grit and de-icing chemicals in conjunction with snow-ploughs can be used to control snow and allow vehicular access.

Avalanches are a significant hazard to road users in mountainous terrain that is subject to heavy snow. For example, the section of Milford Road near Homer Tunnel is particularly subject to avalanche hazards. Avalanche control measures such as controlled blasting are taken to reduce the hazard when it is considered to be high.

4.8 Soft Ground

Road embankments on soft ground may be prone to failure or ongoing deformation. Failures may often occur during or soon after construction, but also after particularly adverse conditions, such as storms or flooding leading to saturation and increased porewater pressures, or floodwater draw-down. Failure can also occur owing to loss or reduction in strength during earthquakes.

4.9 Wild Fire

Wild fires happen from time to time and are caused by high temperatures and drought, often during summer. Such fires cause little damage to the roads themselves, although removal of vegetation by fire could lead to greater slope instability in subsequent wet periods.

Wild fires pose a hazard to road users. Roads may also be impassable due to the risk from a nearby fire, and traffic can be disrupted.

Wild-fire hazards can be assessed and mapped by considering the nature of the vegetation, topography, aspect (exposure to sun), and rainfall patterns. WRC (1998) has mapped wild-fire hazards in the Wellington region.

5. Likelihood of Hazard Impact on Roads

One of the difficult considerations in the assessment of risk is the likelihood of the possible impacts on the road network. This is often a two-stage process that requires assessment of:

- the likelihood of the hazard event, as natural hazards can occur with different levels of intensity and the likelihood of different levels needs to be assessed, and
- the likelihood of the adverse effect or impact on the road, given the particular hazard event.

Assessment of the likelihood of the natural-hazard impact on the road is therefore a combination of both:

Likelihood of natural-hazard impact = Likelihood of hazard event x Likelihood of effects

In a quantitative analysis, the probabilities of the events and their effects will be used to represent the likelihood. For natural-hazard events, the likelihood of the events is often represented as a "return period" and may be converted to either:

- a probability of exceedance over a period of time – 25 years would be consistent with the *PEM*, which uses a period of 25 years for assessment of road projects, or
- an annual probability of occurrence.

Return periods for various levels of hazard events are often available for earthquakes, floods and volcanic eruptions, and have been estimated by scientists of the relevant disciplines. This may be difficult for some of the other natural hazards, such as storms, and require further judgement.

Another issue that needs to be considered in the assessment of climate-related effects such as storms and their consequences (floods, landslides and coastal erosion) is the postulated effects of long-term trends, such as El Niño, and changes, such as global warming and sea-level rise. At this time there are few established trends on which to base assessments and these may require subjective judgements pending further research.

6. Consequences to Road Network

It is important to consider the consequences of natural hazard events for the roads, particularly in deciding on an appropriate risk management strategy. The main consequences of natural hazards to roads are summarised in Table 6.1.

Table 6.1 Consequences of natural hazards

Consequence	Outline
Damage repair/ reinstatement cost	Damage to a road section from a natural hazard such as an earthquake-induced slope failure will need to be repaired. The repair cost could be significant, particularly in steep terrain and where the area is developed, requiring structural solutions.
Potential loss of life	Depending on the nature of the failure, the time of occurrence and the possible prior indication of failure, large failures could lead to loss of life – for example, a large avalanche or overslip onto a road when there is traffic. However, most failures are not expected to cause significant loss of life.
Loss of access for emergency services	Roads are important for emergency services access in the aftermath of a major event such as an earthquake. The loss of access can have consequential effects, such as impeding fire services in putting out fires or the inability to transport injured people to hospitals quickly.
Loss of service	Road failures can impair traffic flow, leading to loss of the services provided by the road to the community. Where the community is completely cut off by the failure, there is a total loss of service. Road failures can also affect public transportation using the route.
Impairment of road network	Failure along some sections of roads could impair the road network as a whole by diverting traffic onto other roads and causing congestion. This leads to economic loss. The impact on the network of failure on a particular road is important from a network management perspective.
Traffic congestion	Even if no physical damage to the road network occurs, congestion invariably follows an event, and the limited traffic flow is one form of economic (opportunity) loss.
Disruption to community	Failures impeding or cutting off road links leads to disruption to the community by impeding the ability of people to go about their activities, and are likely to cause consequential costs to the community.
Economic loss from business disruption	When roads are impeded or blocked by failure, this leads to traffic delays, prevents people from going to work and can severely affect businesses that depend on the road network for transportation. This leads to economic costs to businesses.

Consequence	Outline
Damage to adjoining property	This is particularly important in urban areas where properties are close to road corridors. Slope failures affecting the road corridor can also cause severe damage to properties. For example, failure of a road cutting could undermine properties at the top, leading to legal liability and costs.
Damage to services along road corridor	Other lifelines and services such as gas, electricity, water supply and telecommunications are often located along roads. Failure of the road could also lead to failure of these services, with consequential disruption to them. Damage to sewers can give rise to environmental and public health concerns.
Traffic safety hazard	Snow, icing, flooding or mudflow slope failures may not close the road, but could cause traffic safety hazards and congestion.
Intangible impacts	Roads are an important lifeline for communities. Disruption to roads can lead to significant criticism and adverse publicity for road controlling authorities.

Some of the consequences are inter-related. The consequences in Table 6.1 are categorised into key consequences in Table 6.2. A risk management strategy has to consider these consequences and their importance in decision-making. It is necessary to quantify or qualitatively classify the consequential impacts so that they can be incorporated into a decision-making framework. Parameters representing the consequences of road failure are also listed in Table 6.2.

Table 6.2 Parameters representing key consequences of natural hazards

Consequence category	Representative parameters
Direct damage repair cost	Damage repair cost
Damage to adjacent property or services	Cost of collateral damage to adjacent property
Loss or disruption of service	Traffic volumes Availability of alternative routes Disruption cost
Indirect losses to community	Key emergency service access? Indirect economic costs from business disruption
Injury and death	Social and economic cost
Intangible impacts	Political and social importance of routes

The relative importance of these categories depends on the emphasis placed on the various aspects of the consequences. For example, if high emphasis is placed on asset financial management, then the direct damage costs will be the most important. Alternatively, from an emergency management perspective, the loss or disruption of service would be very important. Road controlling authorities have a responsibility to provide road networks that meet these different requirements, and will have to consider these factors according to their socio-economic perspective and the primary function of particular routes.

It is important to consider the consequences of the failures in prioritising any mitigation. It would be useful to consider the impact of any mitigation on the network as a whole in addition to local effects. This is because, where a particular link has a number of vulnerable areas, the impact of mitigation of a particular section may have little benefit, whereas a similar mitigation at another location could lead to a significant reduction of risk for the network.

7. Assessment of Risk to Road Network

7.1 Derivation of Risk

The risk can be assessed as the summation of the likelihood of the various natural-hazard effects on the road multiplied by the consequences.

$$\text{Risk} = \Sigma \text{ (Likelihood of hazard x Consequences)}$$

However, some of the consequences are difficult to quantify and may be considered using a scoring system (see Section 9.3).

7.2 Spatial Assessment of Risk

Since road networks are geographically spread over lengths of tens of kilometres, it would be difficult to assess the overall risk to the network. Considering individual locations may be both time-consuming and not representative of the overall network.

The current risk assessment methods do not provide an appropriate framework for considering risks to a geographically spread-out road network, with wide variations of risk along the road. Riddolls & Grocott (1999) developed a methodology for assessing slope failure risk which, although useful for considering a specific section of road, does not lend itself to assessing spatially distributed risks. Dalziell et al. (1999) presented a case study evaluating the risk to the state highway network in the Central North Island. They considered nodal risks (earthquake effects on bridges) and spatially more or less uniformly distributed risks from volcanic eruption, snow and ice. Their method is difficult to apply to spatially varying hazards over a road network, such as landslides, earthquake-induced damage, coastal erosion or avalanches.

7.3 GIS-based Approach

A risk assessment approach based on a GIS can be used to derive the overall risk, as well as present the spatial distribution and variation of risk. Such an approach has been developed as part of several road network risk studies for Wellington City Council and Upper Hutt City Council, Opus in-house research (Brabhaharan 2000) and this Transfund research project. This GIS-based approach to risk assessment and management is discussed in Section 10 of this report.

8. Risk Management Approaches

8.1 Introduction

Managing the risk to the road network from natural hazards is prudent. Risk management measures can be incorporated into the asset management for the road network.

8.2 Level of Service

Once the risk to the road network has been assessed, it is important to consider the assessed risk in relation to the level of service that the road controlling authority will provide for road users. The level of service may be influenced by:

- government legislation or requirements,
- community expectations,
- road user demand,
- legal obligations or potential for liability.

This is one of the important issues that have to be addressed by the road controlling authority. Different levels of service may be appropriate for different classes of roads, reflecting their importance, or even for key routes, depending on their use. It is useful to consider the level of service in terms of:

- current level of service: that provided by the road links in the present network, and
- target level of service: that desired to be provided by the road controlling authority.

In determining these levels, issues that need to be considered include:

- perceived level of service: that perceived by users and ratepayers, and
- expected level of service: that expected by ratepayers and road users.

The target level of service, from a natural-hazard risk perspective, may be set in terms of:

- frequency and duration of disruption,
- distribution of disruption,
- impairment of the network: that is, disruption of the efficiency of the network,
- consequential impacts on the community.

The target level of service chosen will have an important bearing on the level of risk mitigation that may be appropriate. Often it is difficult to decide what an appropriate level of service is; and to some extent this will also depend on the funds available for the road network.

8.3 Acceptable Level of Risk

Once a level of service has been set, this can be used as a criterion to determine an "acceptable level of risk". This is a very subjective criterion and is difficult to achieve in practice within a short timeframe. Often it would seem unacceptable to accept a level of risk that has significant effects on the road network. It may be prudent to consider an "acceptable level of risk" which changes with time: that is, a target risk reduction programme can be set to achieve an acceptable level of risk within, say, five years, with an ongoing programme to progressively reduce this "acceptable level of risk" in the future. The intermediate level of risk may be better called "achievable level of risk", recognising that this is not optimal but a compromise as to what can be practically achieved, until the "acceptable level of risk" desired by the community can be achieved.

8.4 Risk Management Approach

Different approaches can be considered to manage the risk associated with a road network, including:

1. reactive approach,
2. emergency preparedness,
3. planned post-event remediation,
4. preventative mitigation,
5. development of less vulnerable routes,
6. network planning and redundancy.

These approaches are discussed below. Often it may be appropriate to consider a combination of them.

8.4.1 Reactive Approach

This is the current approach in New Zealand, and is essentially one of accepting the risk and reacting to the damage. Although the risk has generally not been systematically identified and mapped for New Zealand roads, except in a few recent instances, the risk has been implicitly accepted. While significant earthquakes have not occurred for some time, storm events occur from time to time and the resulting damage is dealt with. This is an acceptable response where the risk is low or "acceptable". It may also be adopted if the risk is high and extensive along the route (and the likely location of damage difficult to determine with certainty), making mitigation of a significant proportion of the route very costly. However, alternative routes need to be available.

8.4.2 Emergency Preparedness

The risk can be managed by creating awareness of the impact of hazard events on the road network, and developing plans for emergency preparedness so that failures can be dealt with. This approach includes plans for the labour, plant and materials necessary for reinstating the roads, the programme and responsibilities, as well as co-ordination with other parties. The Wellington City Council (1995) study, *Road re-opening scenario after the major earthquake*, is an example of a step towards such an approach. This important method of risk management is likely to be part of any risk management strategy, as all the risk is unlikely to be mitigated.

8.4.3 Planned Post-event Remediation

This is a more prepared improvement on emergency preparedness. The actual type of failure likely at particular sites is assessed and remediation schemes developed so that the damage can be readily repaired after an event. For example, where there is a risk of an underslip leading to loss of the road formation, proactive assessment would enable a remediation design to be developed and retained so that a failure may be quickly repaired after the event. This avoids the need for emergency reinstatement, which in itself may increase the risk of further failure, and then investigation and design of permanent remediation, which may take some time to implement. This is particularly valuable where mitigation is as costly as remediation, and the short-term consequences of road failure are "acceptable".

8.4.4 Preventative Mitigation

Mitigation measures can be planned and carried out in advance, to reduce the likelihood of road failure or its consequences when natural hazard events occur. Mitigation may not completely eliminate the risk, but may help lower it to an "acceptable" level or to a level that may be managed by other measures. A preventative mitigation programme could be developed as part of the risk management strategy and implemented over a period of years, gradually reducing the risk to the road network. An example would be strengthening or anchoring a retaining wall which is assessed to be vulnerable to failure in earthquake or storm events. This is a proactive risk management strategy. However, preventative mitigation could be costly or even impractical, particularly in steep terrain where potential mitigation measures are difficult.

8.4.5 Development of Less Vulnerable Routes

Some road links may have a high risk of failure which may be impractical or very costly to mitigate. At the same time, the road may serve as a vital link in the network. In such circumstances, it may be prudent to consider, plan and develop a less vulnerable route to replace or supplement the link. An example would be to develop an alternative road link at a higher terrace level where the existing section of road along a river flood plain is prone to frequent flooding and damage.

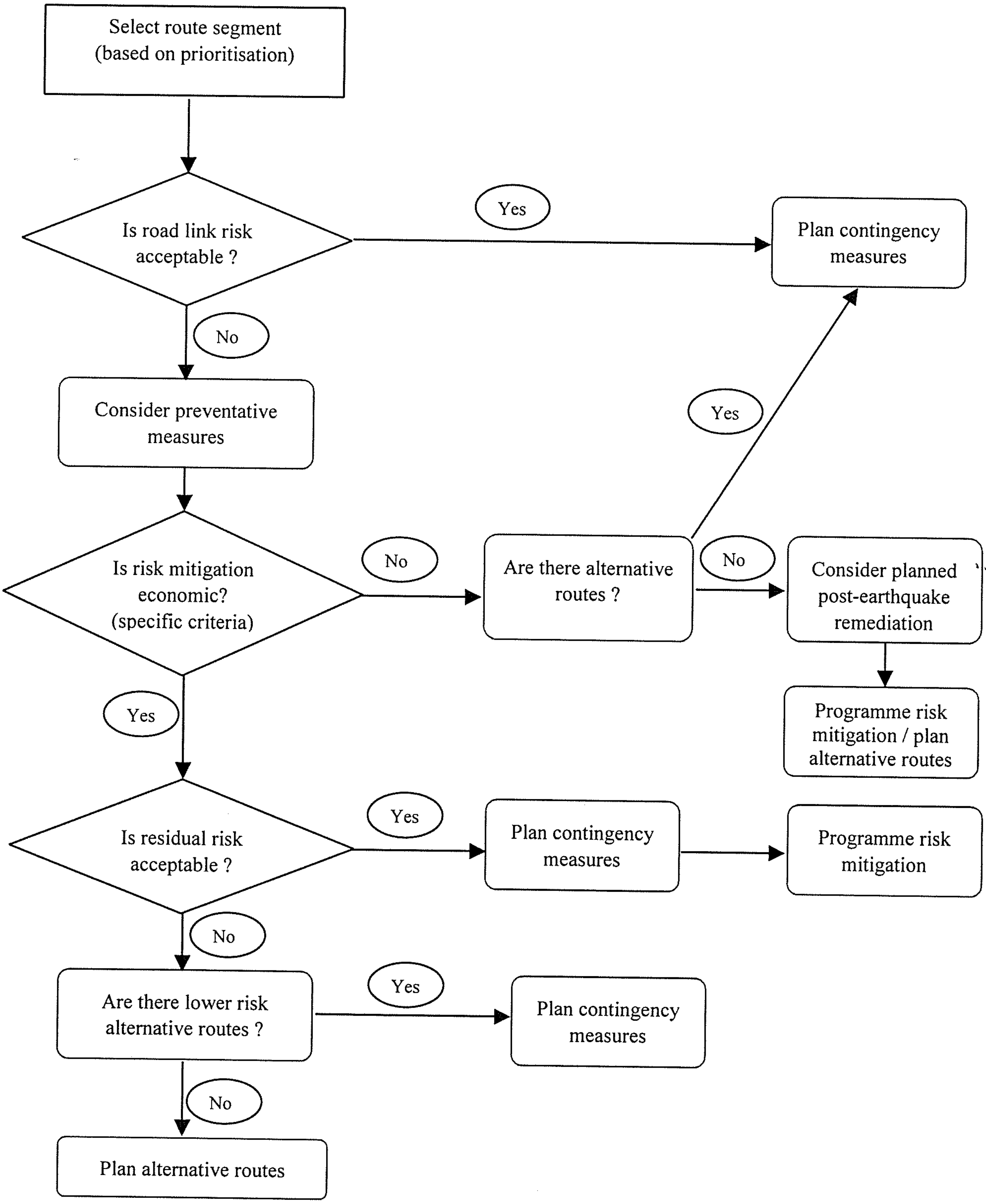
8.4.6 Network Planning and Redundancy

The overall network is likely to have links that present a significant risk with high mitigation costs. To manage this, it would be prudent to consider the overall network and plan for it to provide redundancies in the road links which give alternative means of access. In the long term, such network-wide consideration of risk and access would help ensure that the network as a whole provides the necessary transportation capacity in the event of natural hazards.

8.5 Selection of Risk Management Approach

A flow chart can be used to consider what approach to risk management is appropriate for a particular road link. Figure 8.1 presents a systematic approach to considering and selecting appropriate approaches to managing the risk to a road link.

Figure 8.1 Flowchart for selection of risk management approach



9. Risk Management Methods

9.1 Introduction

Several methods can be used to develop a risk management strategy for the road network. In fact, a combination of options can be used to consider different aspects such as network efficiency, level of service and economics. The methods which may be appropriate for different road networks are:

- prioritisation of road links,
- scoring system (for vulnerable local road sections),
- frequency–number of fatalities (F–N) chart,
- risk–economic analyses.

9.2 Prioritisation of Road Links

Risks to the road network may be widespread, and it will be difficult to assess and undertake risk management for the whole network. Prioritisation will determine the order of importance of the road links forming the road network, and hence target the assessment and prioritisation of risk management measures. This will help in implementing risk mitigation measures to reduce the vulnerability of the network where that is most beneficial.

The factors which influence the prioritisation of links are:

1. **Route class factor** (F_c): whether the link is principal, arterial, collector or local,
2. **Traffic volume factor** (F_t): based on the annual average daily traffic (AADT),
3. **Importance factor** (F_i): whether there are any alternative routes, and whether they are close or distant,
4. **Emergency services route factor** (F_e): whether the route is important for emergency services access after a major event,
5. **Public transport route factor** (F_{pub}): where the route is important for public transport services,
6. **Commercial use factor** (F_{com}): the importance of the route to commercial use that is vital to the functioning of the economy, including tourism,
7. **Overall risk factor** (F_{risk}): whether the road link has high or widespread risks (difficult and costly to mitigate), localised risks (a small investment significantly improves security) or low risk (which may be acceptable and has limited impact on the road).

Hence the road-link priority rating (F_p) is:

$$F_p = F_c + F_t + F_i + F_e + F_{pub} + F_{com} + F_{risk}$$

The factors that may be appropriate for road link prioritisation are presented in Table 9.1. These are indicative only and are subject to consideration by each road controlling authority. A weighting may be applied to give greater or lesser prominence to certain factors. The factors and weightings will depend on the relative importance that the road controlling authority places on different issues, and may vary according to the particular road network and the community it serves.

Using weightings, the priority ratings can be derived as:

$$F_p = F_c.W_c + F_t.W_t + F_i.W_i + F_e.W_e + F_{pub}.W_{pub} + F_{com}.W_{com} + F_{risk}.W_{risk}$$

Table 9.1 Road link prioritisation factors

Factor	Categories	Factor Value	Weighting
Route class factor F_c	Principal/state highway	2	W_c
	Arterial	1.5	
	Collector	1	
	Other local roads	0.5	
Traffic volume factor F_t	AADT > 16 000	2	W_t
	AADT 8000 – 16 000	1.5	
	AADT 2000 – 8000	1	
	AADT 200 – 2000	0.5	
Importance factor F_i	No alternative access	2	W_i
	Distant alternative access	1.5	
	Close alternative access	1	
	Close secure alternative access	0.5	
Emergency services route factor F_e	Primary emergency service route	2	W_e
	Secondary emergency service route	1	
	Not critical for emergency services	0.5	
Public transport route factor F_{pub}	Primary public transport route	2	W_p
	Secondary public transport route	0.5	
	Not a public transport route	0	
Commercial use factor F_{com}	Heavy commercial use	2	W_{com}
	Moderate use	1	
	Mainly non-commercial use	0.5	
Overall risk factor F_{risk}	High widespread risks	1#	W_{risk}
	High localised risks	2#	
	Low widespread risks	0.5	
	Low localised risks	0	

A higher factor is applied for high localised risks where mitigation would be more practical, in contrast to high widespread risks where mitigation would be expensive and developing alternative routes may be more prudent.

9.3 Scoring System

A scoring system can be used to prioritise the risk mitigation work identified for particular sections of road within the network. It is used in a manner similar to the road link prioritisation discussed in Section 9.2, but is applied to a particular section of road requiring risk mitigation rather than to the whole road link. The scoring system enables various factors to be considered more systematically and the combined influence of these factors to be considered in deciding on the prioritisation of risk mitigation. The scoring system is presented in Table 9.2.

(Note that with Factor 1, Potential loss of life, where there is a potential for significant loss of life it may be necessary to consider whether the risk is tolerable. If it is not tolerable, then risk mitigation or proactive management may be required regardless of the other factors. An approach such as that shown in Figure 9.1 may be used to compare the risk with other common risks and consider whether it is acceptable based on published criteria.)

The scores can be used as a basis for prioritising risk management measures for the various sections of road at risk. The weightings for the factors can be determined by the road controlling authority according to its emphasis on different factors, which will depend on the community served by the particular network.

The scoring system has the advantage of enabling consideration of various factors that are difficult to quantify. However, it is subjective.

9.4 Frequency–Number of Fatalities Chart

Some locations in the network may pose a high risk to road users or other people.

Natural hazards may give rise to failure of the road, and associated loss of life, particularly if it is a route used by a large volume of traffic or people in concentrations, e.g. tourist buses. An example would be an avalanche hazard where the avalanche could lead to a large number of fatalities.

There may be situations where the risk is difficult to mitigate, and it is recognised that it would be impractical to remove the risk of fatalities. Then the objective would be to reduce the risk to a "tolerable level". In such situations, it may be appropriate to consider the risk through societal risk criteria, such as using a frequency–number of fatalities (F–N) chart, where the frequency and number of fatalities are presented graphically. This will give a good understanding of the relationship between the potential number of fatalities and the associated frequency. A typical F–N chart is presented in Figure 9.1, which is based on the UK Health and Safety Executive and is taken from a paper presented at an international workshop on Landslide Risk Assessment (Fell & Hartford 1997).

Table 9.2 Prioritisation for mitigation of vulnerable road sections

Asset critical factor (F)				Weighting	Score F.W
	Factor description	**Categories**	**Rating**		
1	Potential loss of life F_{life}	High Medium Low None	10 7 3 0	W_{life}	
2	Loss of service F_{traf}	AADT > 20000 AADT 10 000 – 20 000 AADT 2000 – 10 000 AADT 500 – 2000	10 7 5 3	W_{traf}	
3	Importance factor F_{imp}	No alternative access Distant alternative access Nearby alternative access Nearby secure alternative access	10 7 5 1	W_{imp}	
4	Emergency services route factor F_{emer}	Primary emergency service route Secondary emergency service route Not critical for emergency services	10 5 0		
5	Damage to property F_{prop}	Catastrophic Major Minor None	10 7 3 0	W_{prop}	
6	Damage to utilities F_{util}	High Moderate Low None	10 7 3 0	W_{util}	
7	Outage from service F_{outage}	> 6 months 1 month – 6 months 1 week – 1 month 1 day – 1 week < 1 day	10 7 5 3 1	W_{outage}	
8	Reinstatement costs F_{cost}	> \$1 000 000 \$200 000 – \$1 000 000 \$50 000 – \$200 000 < \$50 000	10 7 5 1	W_{cost}	
9	Public transport route F_{public}	Major Moderate No public transport	10 5 1	W_{public}	
TOTAL					$\Sigma F.W$

For example, a high number of fatalities at a very low frequency may be "tolerable", whereas the same number of fatalities at a higher frequency would be "intolerable". The F–N chart enables a subjective assessment of the risks to determine whether they are tolerable compared with other risk situations. It should be noted that the tolerance levels in Figure 9.1 have been developed for dams and hazardous industries, and the tolerance levels for roads may be different. However, the chart provides a framework and can be modified to suit the risk perceptions of natural hazards affecting roads in New Zealand.

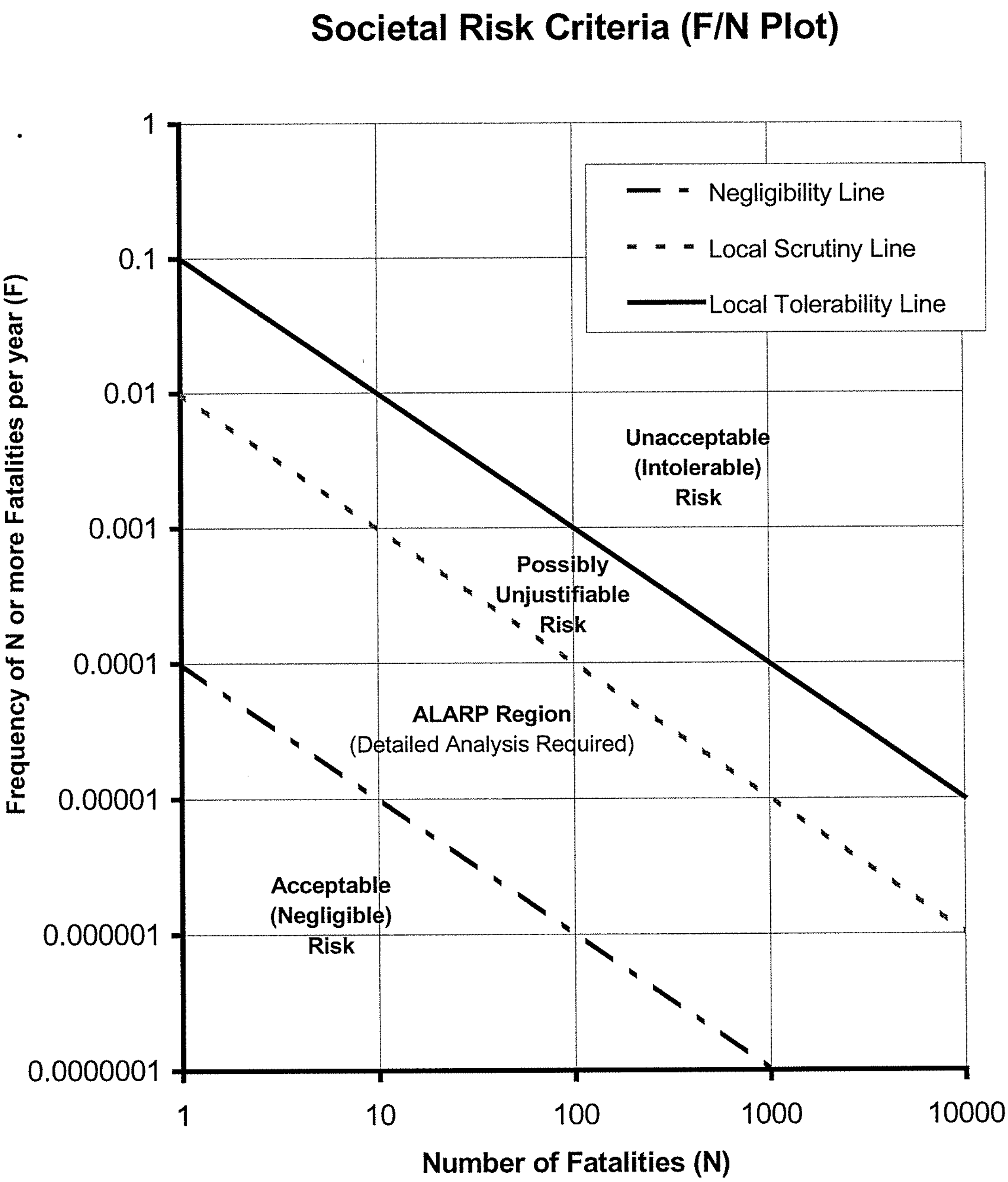
9.5 Risk–Economic Analyses

Risk–economic analyses can be used to assist in prioritising mitigation measures based on financial criteria. The mapped risks, together with potential damage costs for various hazard events, mitigation costs, and damage costs if mitigation is implemented, can be used to derive benefit/cost ratios for risk mitigation measures. Traffic disruption costs can also be included with the damage costs to represent the total direct costs of damage to the roads. This method, using a GIS as an aid, is discussed in Section 10 of this report.

Risk mitigation measures can be programmed based on the benefit/cost ratios. This can be built into the asset management programme for the road network, and the beneficial effect of the risk mitigation expenditure over a period of time can be assessed. This will help quantify the financial benefits of expenditure on a programme of mitigation measures.

Risk–economic analyses will also enable the economics of mitigation to be judged against Transfund New Zealand funding criteria.

Figure 9.1 Frequency–Number of fatalities (F–N) chart (after Fell & Hartford 1997)



10. GIS-based Risk Management

10.1 General Approach

Geographical information systems (GIS) provide a useful platform for collating information on the spatially spread-out hazards associated with the road network, assessing the risk and developing risk management measures. A GIS-based risk assessment methodology has therefore been developed to facilitate this. It is based on a desk study, data collection, site reconnaissance by specialist staff, GIS mapping and use of GIS methods to facilitate assessment of risks, damage costs, mitigation costs and benefit/cost of mitigation. The approach is outlined below.

10.2 Desk Study & Data Collection

Collection and collation of useful data for the risk assessment:

- geology (published and unpublished geological maps and reports),
- terrain (contour and aerial photographs),
- hazards (earthquake, flood, slope failure, volcanic, coastal hazards, etc. if available),
- traffic volumes,
- road asset information (which may be held by the road controlling authority),
- damage costs from past events,
- remedial measures and costs from past road works.

Depending on the hazard information available, a more detailed study may be required.

10.3 Hazard & Risk Characterisation

10.3.1 Site Reconnaissance

A site reconnaissance by appropriate specialists to assess the potential hazards will be useful to complement the data from the desk study.

10.3.2 Road Characterisation

Based on the information collected, the road can be characterised to represent the:

- type and level of hazards and risks,
- likely types of failures and damage,
- consequences to the road network in terms of damage and disruption,
- appropriate methods of mitigation.

Road sections and supporting structures (such as retaining walls) are included in the characterisation. Bridges are excluded, as they need to be assessed separately, but should be included in the final risk management decision-making.

10.3.3 Road Risk Characterisation Mapping

The characterisation of the risk to the road is then mapped onto a GIS database, using base GIS maps of the road network. The GIS risk maps facilitate subsequent analyses of the risk.

10.4 Consequences

The likely consequences of natural hazards are then assessed in terms of their impact on the road network. This is carried out for:

- each natural hazard (e.g. earthquake, storms), and
- different levels of events (e.g. storms of say 5-, 10-, 20-, 50- and 100-year return periods).

The consequences are assessed in terms of both the damage and the potential disruption to or outage from service, both during the hazard (say, a landslide blocking a road) and during reinstatement (say, construction of a retaining wall to support the road).

10.5 Damage Costs

The direct costs of damage for various risk categories are based on an estimate of the resources required to reinstate the road (e.g. slip clearance, culvert and headwall replacements, and retaining wall construction). The road damage repair costs can be estimated as unit costs per metre length of road for each road category and event, based on:

- typical sizes of failures likely in each event,
- length of road likely to be affected,
- probability of damage,
- likely reinstatement costs.

Records from previous damage repairs would help put together reliable estimates of damage costs.

10.6 Disruption Costs

10.6.1 Road Closure Period

The likely period of closure for each road category and event can be estimated based on the:

- likely period of closure until the road can be cleared,
- likely period of closure for failures requiring investigation, decision on options, design and reinstatement construction,
- estimated duration of the hazard making the road impassable (e.g. flooding).

Road closure periods may vary, based on full or part closure, or a short period of full closure followed by part closure if temporary one-lane traffic access can be established.

10.6.2 Traffic Disruption Costs

The traffic disruption costs are the difference in travel costs between normal travel along the route and travel after an event, including detours. These costs can be estimated based on the traffic volume information available. The costs per day can be assessed based on:

- whether both lanes are likely to be affected or at least one lane will be available,
- traffic along each road segment,
- alternative routes, assuming detour during the period of disruption,
- reduced traffic speed or delay if traffic light control is required where one-lane access is available,
- travel time costs, vehicle operating costs and cost of carbon dioxide emissions, according to *PEM* criteria,
- costs reflecting the effect of loss of access for "no exit" roads or where alternative access is a considerable distance away,
- consequential "business interruption" costs (although these are often very difficult to calculate unless more detailed economic modelling is undertaken).

10.7 Mitigation Measures and Costs

Careful consideration as to what proactive mitigation measures are appropriate and practical for the road is crucial to the analysis of mitigation and consequent savings in damage costs.

The type of mitigation will vary, depending on the nature of the hazard. Parametric costs for each type and size of mitigation should be assessed.

10.8 Total Economic Costs of Damage

The total economic costs of damage related to the various events can be estimated for each section of road, both left and right sides, using the parametric damage costs and the lengths of road held in the GIS database. The total economic cost includes the damage reinstatement cost as well as the traffic disruption cost, but does not include consequential costs such as business interruption costs.

10.9 Risk–Economic Analyses

10.9.1 Total Economic Cost

The estimated total economic cost can be calculated for different event levels for each of the hazards being considered. For example, for storm damage, it may be appropriate to consider 5-, 10-, 20-, 50-, 100- and 500-year return periods.

10.9.2 Expected Economic Value of Damage Over Time

The expected economic value of damage over the next 25 years can be estimated by combining the damage costs calculated for each event with the associated probabilities.

10.9.3 Mitigation Measures and Benefit/Cost Ratio

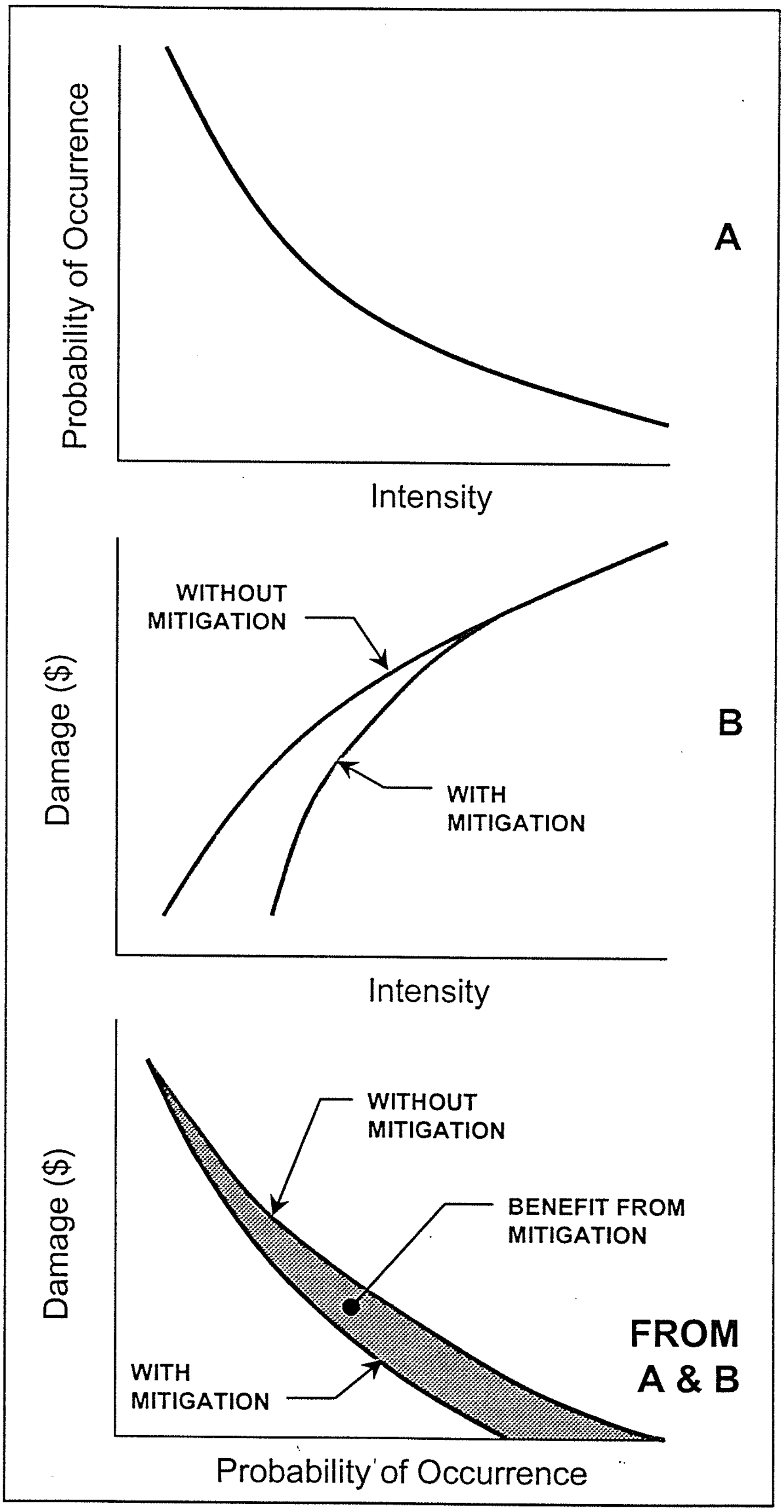
The mitigation measures can be assessed for the different categories of road, and the unit costs per metre section of road can be used to derive the total mitigation costs for the various sections of the road network.

The damage and disruption costs, assessed as discussed in Sections 10.5 and 10.6, can then be reassessed, assuming that mitigation has been carried out. The damage costs with and without mitigation, and similarly the disruption costs with and without mitigation, can be calculated and used to derive the savings in damage and disruption costs if mitigation was implemented. These savings can then be annualised using the annual probabilities of the events, and summed for the various sizes of events, for each of the hazards. The derivation of the saving from mitigation is illustrated in Figure 10.1. The total savings in damage and disruption costs can thus be calculated, and the net present value over 25 years derived using a discounting factor based on an appropriate interest rate.

A benefit/cost ratio can thus be calculated as the ratio of the net present value of the total annual savings and the mitigation cost. This can be derived for each section of road. The benefit/cost ratio can be used as a tool:

- to decide on the appropriate risk management method,
- to prioritise mitigation,
- to economically justify risk mitigation,
- in asset management planning.

Figure 10.1 Derivation of benefits of mitigation



11. Developing a Risk Management Strategy

11.1 Introduction

This section provides an outline for developing a risk management strategy for road networks in New Zealand. Details of each step in the process are given in the previous sections of this report. Case studies on the use of GIS to carry out hazard and risk assessment, as well as risk–economic analysis to assist with risk management, are presented in Appendices A and B.

11.2 Collate Road Asset Data

The first step is to collate data on the road assets covered by the network. This could include:

- network map,
- bridges and other nodal structures,
- other structures such as retaining walls and culverts,
- traffic data (volumes and O–D data if available).

It would be ideal to map this onto a GIS database, to facilitate further hazard and risk assessment, as well as present risk management priorities. The National Traffic Database (WCS 1996a) provides traffic information on New Zealand roads.

11.3 Identify Hazards & Potential Impacts

Natural hazards that may affect the road network should be identified, and their potential impacts on the road considered.

11.4 Assess Risks

The risk to the road network from the natural hazards identified may be assessed, and quantified in terms of potential damage costs, disruption to traffic, and possible effects on both adjacent property and people (both road users and neighbours) in terms of injury or loss of life.

The risk assessment may be carried out for:

- bridge structures, and
- the road network.

GIS would facilitate efficient risk assessment for the road network. The bridge seismic screening programme (Transit New Zealand, 1998) may provide a useful methodology for the risk assessment of bridges.

11.5 Consider Service Levels

With the knowledge of the risks to the road network, reviewing the current and target levels of service associated with the network would be prudent. Reviewing the level of service perceived by road users and ratepayers compared with the expected level of service may also be prudent.

These considerations will help in deciding appropriate levels of risk mitigation when considering risk management options.

11.6 Prioritise Road Links

Road networks prone to significant natural-hazard risks need to be considered in a progressive and rational manner. Mitigation of the risk for the whole network is likely to be impractical and inappropriate in the short term. Prioritisation of the road links forming the network will enable the risk to be addressed progressively and systematically.

A scoring system to prioritise the road links in the network is shown in Table 9.1 and this may be used to derive an overall priority ranking.

11.7 Consider Societal Risk Criteria

Where the risk of death from natural-hazard effects on the road is significant, it would be prudent to consider the frequency and potential loss of life in relation to other hazards faced by the community.

The typical Frequency–Number of Fatalities chart in Figure 9.1 will help in assessing whether the risk is "tolerable" in terms of risks considered to be tolerable or intolerable in other international risk situations. This chart could be developed to reflect society's perceptions of risk to roads in New Zealand.

11.8 Apply Risk–Economic Analysis

Risk–economic analysis will help in considering the spatial distribution of risks, mitigation and the benefits/costs of mitigation throughout the network. This will provide a framework for prioritising mitigation at specific sites and justifying the mitigation economically. The proposed risk–economic analysis considers damage reinstatement costs and disruption costs. Using GIS is an effective way to address the spatially distributed risks associated with a road network, and also present a visual distribution of risks and priority areas for risk mitigation. Case studies showing output from such analyses are presented in Appendices A and B.

11.9 Prioritise Risk Mitigation

It should be borne in mind that, in addition to the damage and disruption, other intangible factors affect road risk, and these may be incorporated with further development. They can be considered using a scoring system with different ratings for various factors, and deriving an overall priority rating for a particular risk location. A typical rating system is shown in Table 9.2.

11.10 Risk Management Approach

The risks associated with roads can be managed through several different approaches, as described in Section 8.4 of this report.

As all these approaches are suitable for road networks, it is important to develop a risk management strategy that incorporates a combination of them, depending on the risk, the network characteristics and performance expectations.

A flow chart showing how various risk management approaches can be considered is given in Figure 8.1.

12. Implementation of Risk Management – the Future

Achieving a road network that is resilient to natural hazards requires risk to be considered at all levels of road transportation planning and road asset management. The methods of risk management provided in this report will help.

However, to achieve this systematically, it is important to incorporate risk analysis and management into existing or new policies and procedures. It also requires action by a range of institutions from regional authorities involved in land transport planning to road controlling authorities, road network designers and designers of specific road projects.

Further research is proposed to consider how this can be incorporated into procedures, policy and manuals. One example is Transit New Zealand's *PEM*, which currently provides some assistance on natural-hazard risk.

Such procedures will help authorities and practitioners to consider and implement risk management in routine transportation-related planning, management and design operations.

13. References

Auckland Regional Council. 1997. Auckland Engineering Lifelines Project, Stage one report.

Augusti, G., Borri, A., Ciampoli, M. 1994. Optimal allocation of resources in reduction of the seismic risk of highway networks. *Engineering Structure 16(7):* 485-92.

Bakir, S.A., Elms, D.G., Lamb, J. 2000. Risk management and lifeline engineering. *Proceedings of the 12th World Conference on Earthquake Engineering, Auckland.*

Basoz, N., Kiremidjian, A.S. 1995. Use of geographic information systems for bridge prioritisation. *Proceedings of 5th International Conference on Seismic Zonation, Nice, France, 1:* 17-24.

Basoz, N., Kiremidjian, A.S. 1997. Risk assessment of bridges and highway systems from the Northridge earthquake. *Proceedings of the 2nd National Seismic Conference on Bridges and Highways, 8-11 July, 1997:* 65-79. FHWA, Sacramento, California, USA.

Brabhaharan, P., Hastie, W.J., Kingsbury, P.A. 1994. Liquefaction hazard mapping techniques developed for the Wellington Region, New Zealand. *Proceedings of NZNSEE Technical Conference, Wairakei, 18-20 March, 1994:* 140-9.

Brabhaharan, P. 2000. Earthquake ground damage hazard studies and their use in risk management in the Wellington Region, New Zealand. *Proceedings of the 12th World Conference on Earthquake Engineering, Auckland.*

Butcher, G.V. 1984. *State Highway 73 from Christchurch to Kumara. A case study of the use of risk analysis in the economic evaluation of roading improvements.* Administration Committee of the Road Research Unit. 132 pp.

Cagle, J., Waddops, A. 1998. Planning for a new type of natural disaster – El Niño phenomenon brings innovative approaches. *Public Roads*, July-August 1998.

Centre for Advanced Engineering. 1991. *Lifelines in earthquakes: Wellington case study. Project report.* Christchurch: University of Canterbury. 210pp.

Centre for Advanced Engineering. 1995. Wellington after the quake: the challenge of rebuilding cities. *Proceedings of a Conference Held in Wellington, New Zealand, 27-29 March 1995.* 284pp.

Chapman, H.E., Oakden, G.J., Lauder, M.K. 2000. Seismic screening of bridges in New Zealand. *Proceedings of 12th World Conference on Earthquake Engineering, Auckland.*

Chunguang, L. & Huiying, G. 2000. Reliability analyses of transportation system. *Proceedings of 12th World Conference on Earthquake Engineering, Auckland.*

Cooper, J.D. 1981. Mitigation of earthquake damage on eastern highway systems. *Public Roads 45 (3):* 113-23.

Dalziell, E.P., Nicholson, A.J., Wilkinson, D.L. 1999. Risk assessment methods for road network evaluation. *Transfund New Zealand Research Report No. 148.* 212 pp.

Du, Z., Nicholson, A.J. 1993. Degradable transportation systems performance, sensitivity and reliability analysis. *Department of Civil Engineering Research Report 93-8.* University of Canterbury, Christchurch, New Zealand.

Fell, R., Hartford, D. 1997. Landslide risk management. *Proceedings of the International Workshop on Landslide Risk Assessment, Honolulu, Hawaii, USA:* 51-110.

Gilmour, A., Stanton, B. 1990. Tsunami hazard in Wellington Region. *Regional Natural Disaster Reduction Plan – Seismic Hazard.* Wellington: Wellington Regional Council.

Gordon, P., Moore II, J.E., Richardson, H.W., Shinozuka, M., Cho, K.Y., Cho, S.B., Kim, B.S., Kim, G.Y. 1997. An integrated model of bridge performance, highway networks, and the spatial metropolitan economy: towards a general model of how losses due to earthquake impacts on lifelines affect the economy. NCEER technical report. *Earthquake Engineering Frontiers in Transportation 97-0005:* 515–25.

Heaney, J.P, Peterka, J., Wright, L.T. 2000. Research needs for engineering aspects of natural disasters. *Journal of Infrastructure Systems 6(1):* 4-14.

Hendrickson, C., Oppenheim, I.J., Siddarthan, K. 1980. User losses in earthquake damaged roadway networks. *Journal of the Technical Councils of ASCE. Proceedings of the American Society of Civil Engineers 106 (TC1).*

Kawakami, H. 2000. Earthquake performance of highway system in Tokyo. *Proceedings of the 12th World Conference on Earthquake Engineering, Auckland.*

Kawashima, K., Unjoh, S., Iida, H. 1992. Seismic inspection and seismic strengthening of highway bridges in Japan. Pp.91-124 in *Proceedings of the Fourth US–Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems, Los Angeles, August 1991.* R.T. Eguchi (Ed.), *National Institute of Standards and Technology Special Publication 840.*

Koorey, G.F., Mitchell, T.J. 1999. The effect of link reliability on benefit/cost ratios. *Transfund New Zealand Research Report No. 159.*

Li, Y., Tsukaguchi, H. 1996. A study on the capability of local road network against the Great Hanbin-Awaji earthquake disaster. Pp. H70-75 in *Proceedings of the International Conference on Urban Engineering in Asian Cities in the 21st Century, 20-23 November, 1996.*

Maffei, J. 1997. Seismic evaluation and retrofit technology for bridges. *Transfund New Zealand Research Report No. 77.* 100pp.

Maroney, B., Gates, J. 1992. Seismic risk identification and prioritization in the CALTRANS seismic retrofit program. Pp.55-76 in *Proceedings of the Fourth US–Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems, Los Angeles, August 1991.* R.T. Eguchi (Ed.), *National Institute of Standards and Technology Special Publication 840.*

Montgomery Watson New Zealand. 1999. The security of New Zealand's strategic roading system. *Transfund New Zealand Research Report No. 147.* 70 pp.

Mori, Y., Iida, I., Kim, J. 1998. Analysis of traffic flow and improvement planning of expressway network after the Great Hanshin–Awaji Earthquake. Pp.395-401 in *Proceedings of 9th Road Engineering Association of Asia and Australasia* [REAAA] *Conference, Wellington, New Zealand*, Vol.2.

National Institute of Standards & Technology. 1992. *Proceedings of the Fourth US–Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems.* R.T.Eguchi (Ed.), *National Institute of Standards and Technology Special Publication 840.*

Nojima, N., Sugito, M. 2000. Simulation and evaluation of post-earthquake functional performance of transportation network. *Proceedings of the 12th World Conference on Earthquake Engineering, Auckland.*

Nozaki, T., Sugita, H. 2000. A method to determine seismic performance of highway network option. *Proceedings of the 12th World Conference on Earthquake Engineering, Auckland.*

Opus International Consultants (Opus). 1998. Seismic Screening of Bridges. Report prepared by Howard Chapman for Transfund New Zealand.

Opus International Consultants (Opus). 1999. Melling Bridge – assessment of vulnerability. Report prepared for the Hutt City Council. Opus contract no. AD16-63P-2613.

Riddolls & Grocott. 1999. Risk assessment techniques for optimising slope-failure preventative maintenance programmes. *Transfund New Zealand Research Report No. 134.* 178 pp. + appendices.

Standards Australia. 1999. Risk Management. AS/NZS4360:1999. Joint Australian/New Zealand Standard.

Transfund New Zealand. 1999. *Project Evaluation Manual.* Wellington: Transfund New Zealand.

Transit New Zealand. 1998. *Manual for Seismic Screening of Bridges*, 2nd revision (SM110). Wellington: Transit New Zealand.

Wellington City Council. 1995. Road reopening scenario after the major earthquake. Wellington City Council Roading Department, Wellington, New Zealand.

Wellington Regional Council. 1991. Map series of: Wellington Fault; Ohariu Fault; Shepards Gully, Pukerua and Wairarapa Faults.

Wellington Regional Council. 1993. Seismic Hazard Map Series: Liquefaction hazard, Map Sheet 1, Wellington: WRC/PP-T-93/76.

Wellington Regional Council. 1995. Seismic Hazard Map Series: Earthquake-induced slope hazard, Map Sheet 1, Wellington: WRC/PP-T-95/06.

Wellington Regional Council. 1998. Wild Fire Hazard Study. Report and Maps: WRC/RP-G-98/12.

Werner, S.D., Taylor, C.E., Moore II, J.E. 1997. Loss estimation due to seismic risks to highway systems. *Earthquake Spectra 13(4):* 585-604.

Weseman, L., Hamilton, T., Tabazer, S., Bare, G. 1996. Cost-of-delay studies for freeway closures caused by Northridge earthquake. Pp. 67-75 in *Environmental, Social, and Economic Effects of Transportation. Transportation Research Record 1559*. Washington, D.C.: National Academy Press.

Works Consultancy Services. 1990. Risk management: asset damage due to earthquake or volcanic eruption. Report to Transit New Zealand. Works Consultancy Services, Wellington, New Zealand.

Works Consultancy Services. 1996a. National traffic database: content and operation of database. *Transit New Zealand Research Report No. 53.* 47 pp.

Works Consultancy Services. 1996b. Seismic assessment of New Zealand highway bridges: development and testing of preliminary screening procedures. *Transit New Zealand Research Report No. 58.*

World Road Association. 1996. Natural disaster reduction for roads: comprehensive report. Permanent International Association of Road Congresses Committee on Road Management: PIARC–72.01.B–1995. 219pp.

World Road Association. 1999. Natural disaster reduction for roads: final report. Permanent International Association of Road Congresses Working Group on Natural Disaster Reduction: 72.02.B.

Appendix A

Case Study: Upper Hutt Rural Road Risk Analysis

A case study is presented of the risk analysis carried out for the rural road network, covering 74 km, in the Upper Hutt City Council district. This work was carried out for the Upper Hutt City Council in 1999.

The analysis covered the rural areas of:

- Whitemans Valley,
- Moonshine Valley,
- Akatarawa Valley,
- Kaitoke Area.

These rural roads run through some steep terrain and areas subject to flooding. The study was carried out with the aid of an ArcINFO GIS, generally as described in Section 10 of this report. The study also considered the culverts along these roads and their vulnerability to natural hazards, and consequential impacts on the roads.

The study covered all natural hazards. A preliminary review identified that earthquakes and storms are the predominant hazards that are likely to affect the roads significantly. Hence the detailed study concentrated on these two hazards.

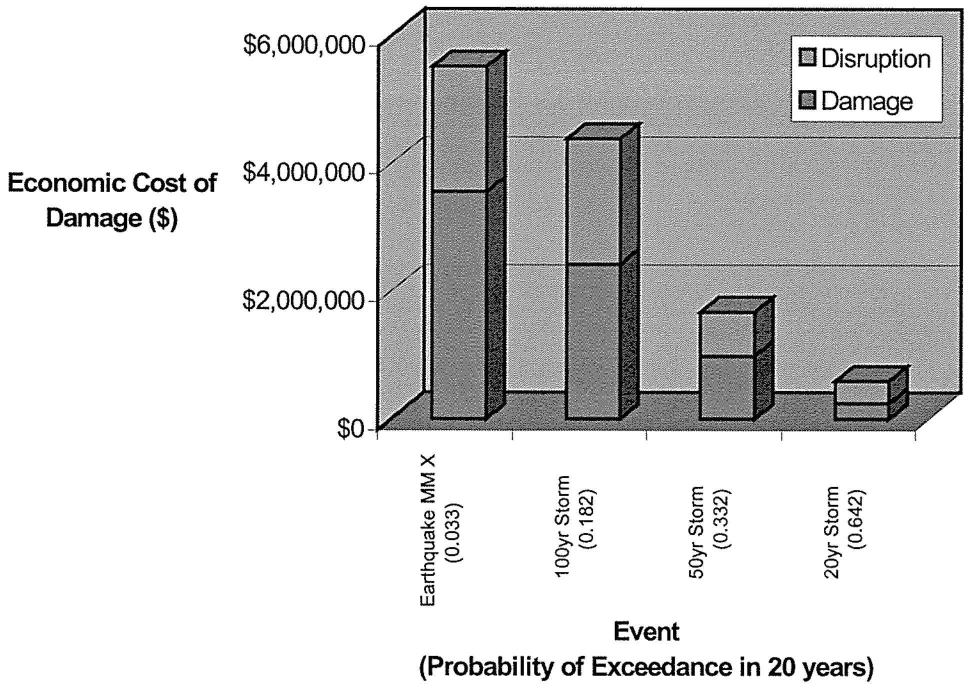
Traffic analysis was carried out using simplistic assumptions of disruption and alternative routes, rather than detailed traffic modelling, as this was considered prudent for roads with low volumes of traffic.

A section of the results from the study is presented here.

The characterisation of the Akatarawa Road section of the network is shown on the GIS map presented in Figure A1 on page 63. This map shows the range of categories representing the vulnerability of the road to earthquake- and storm-induced failures. The colours represent different hazard categories used in mapping the road network. These are described in Table A1.

The assessed damage costs are presented in chart form on page 60, while Figure A2 on page 65 shows the benefit/cost ratios for mitigation of the road, derived as described in Section 10 of this report. It shows that the benefits from mitigation of this rural road are small, which is not surprising given the high risks associated with the Akatarawa Road in steep terrain, and the associated high costs or low benefits from mitigation. In addition, given that the roads have low volumes of traffic, the disruption costs are not very high, although still significant.

Chart showing total economic costs of damage, Akatarawa Valley



On the other hand, Figure A3 on page 67 shows that mitigation for some of the culverts can have a high benefit/cost ratio. This is because:

- the mitigation of culverts, by replacement of headwall/outlet improvements, is of relatively low cost, and
- the benefits of culvert mitigation are high, because it also reduces the damage from surface run-off overflow leading to erosion and instability of sidling fills on the downhill slope.

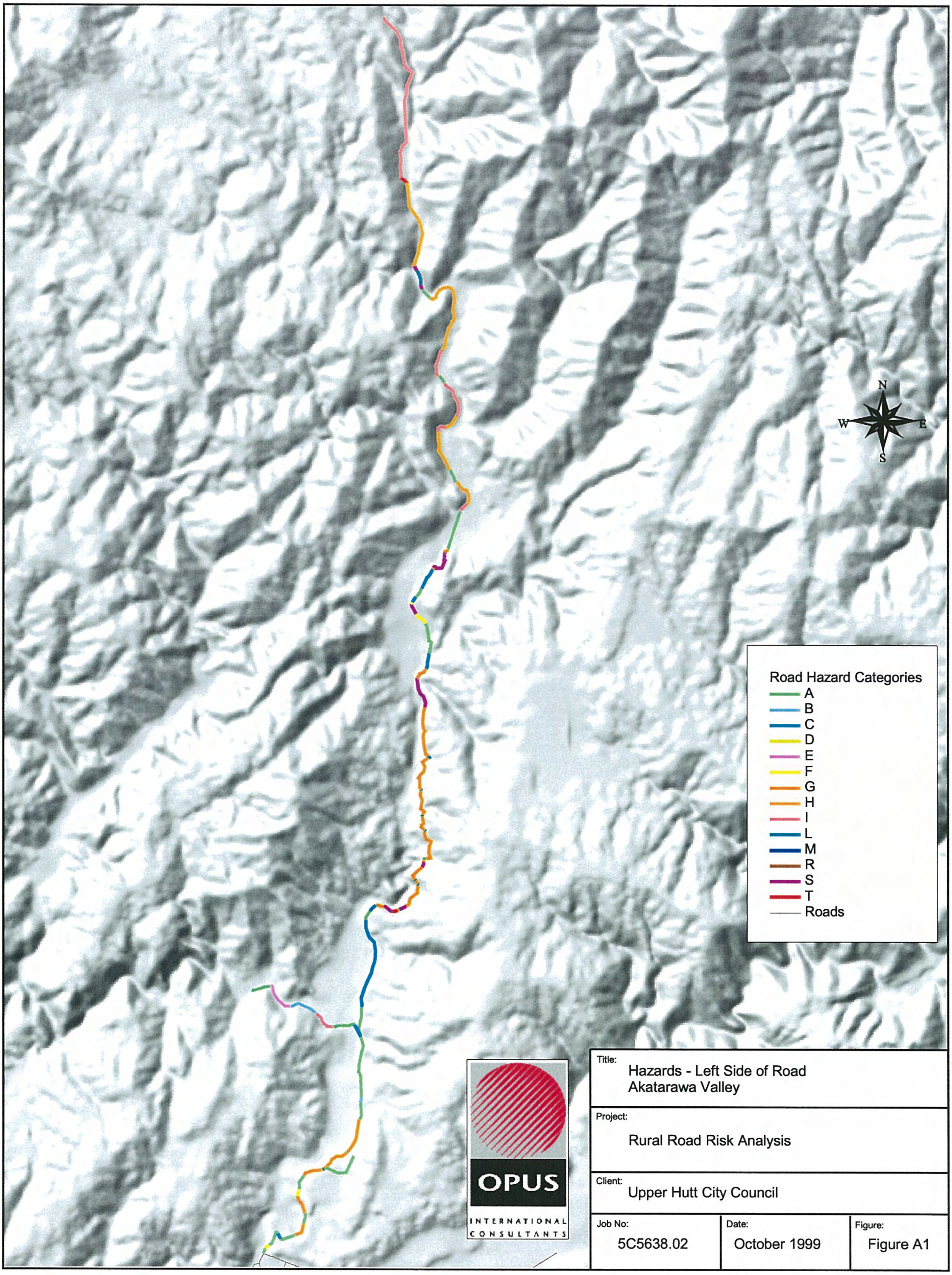
The risk analysis showed that culvert risks are worth mitigating, and their assessment and mitigation can be incorporated into the asset management plan.

Mitigation of the road in mountainous terrain was not economically justified. However, since some of these roads are the sole access for a number of properties, mitigation of the most vulnerable areas may be considered. For the other sections, two approaches could be considered:

- Carry out emergency response planning so that the failures can be reinstated as quickly as possible after damage.
- When damage does occur during small events, carry out engineered reinstatement, which will gradually improve the resilience of the road through improved performance during subsequent events. This will help gradually to improve the road network.

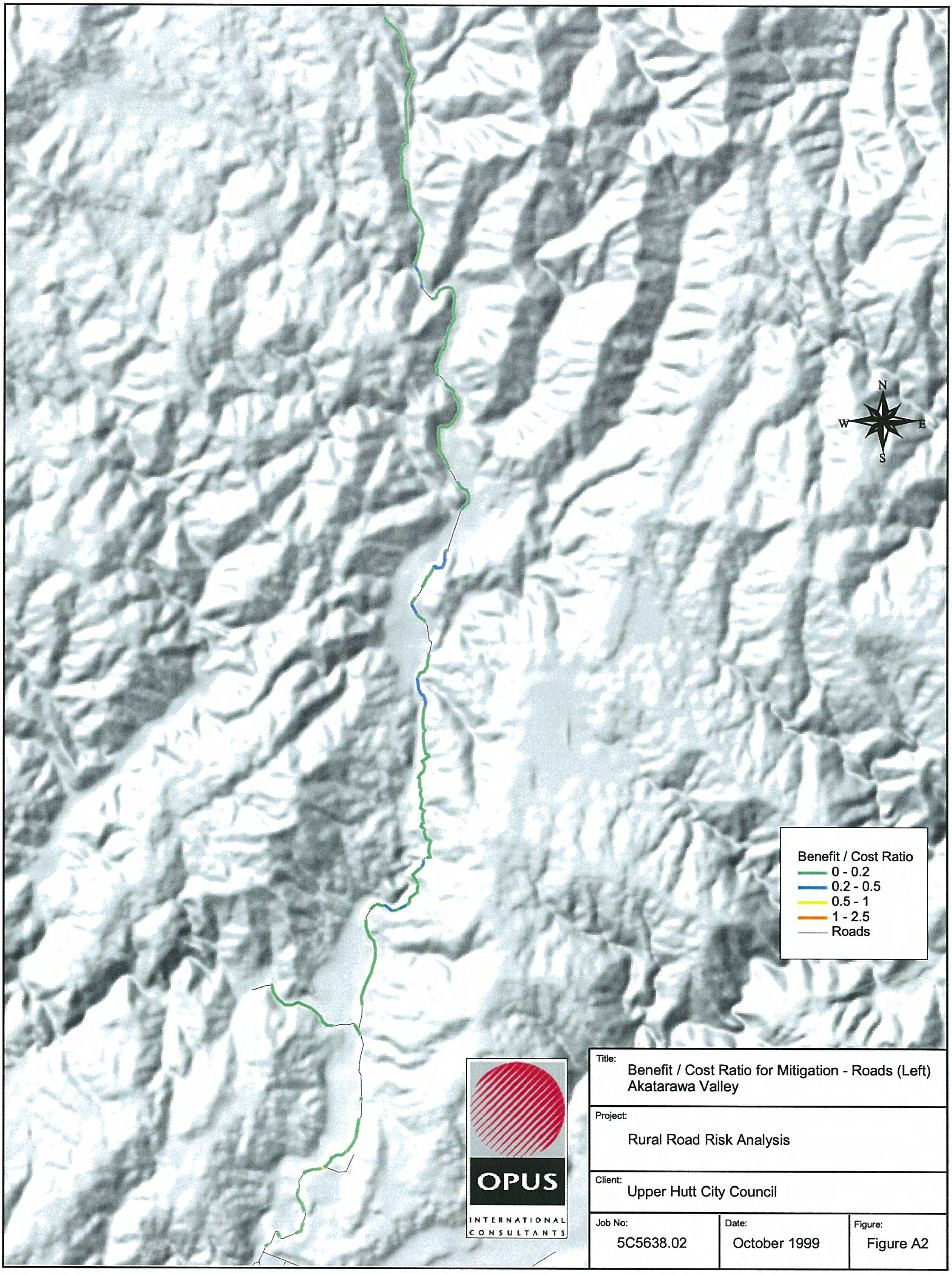
Table A1 Road characterisation by failure-type category

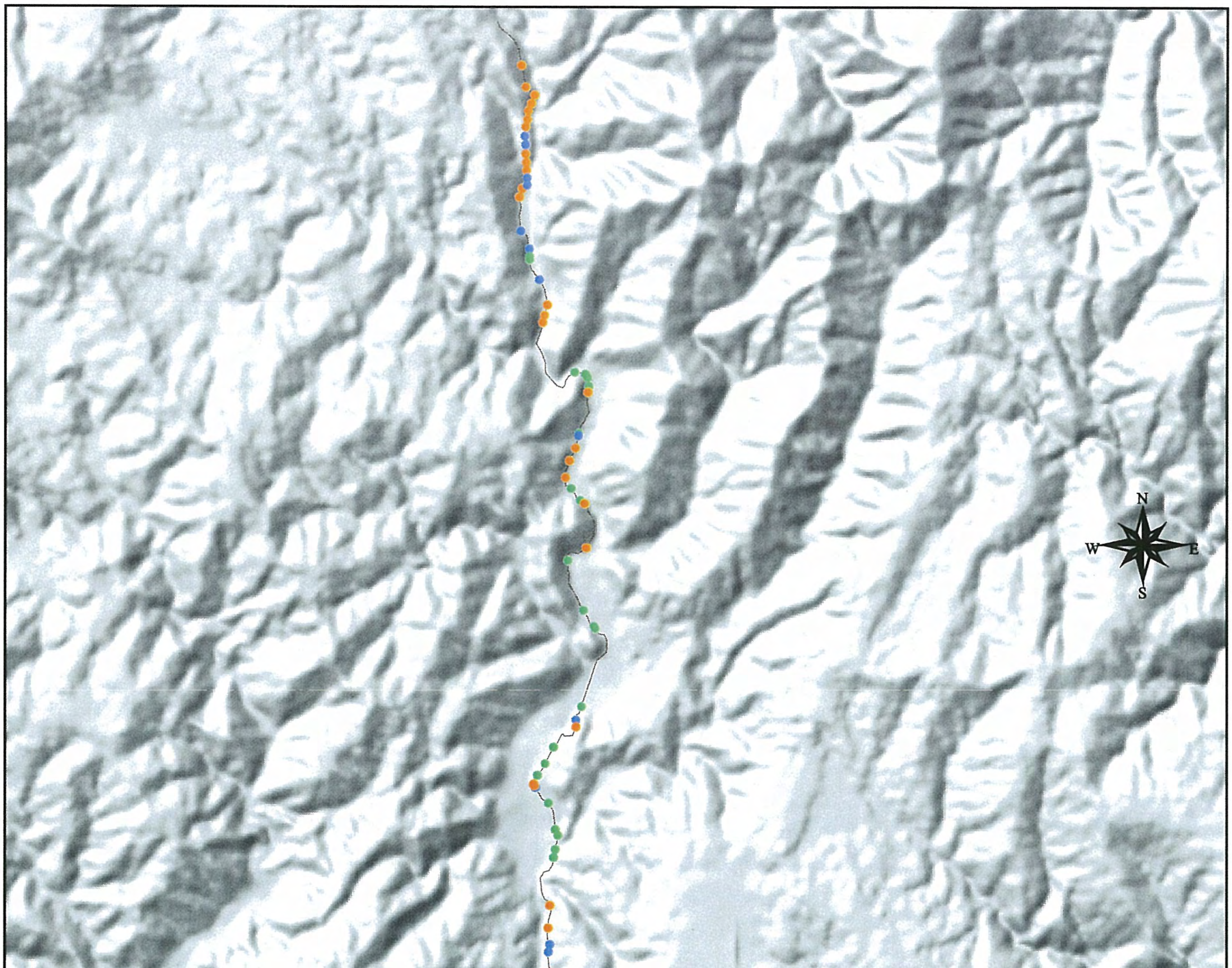
Category	Description
A	Generally flat with no significant cuts, fills or retaining walls likely to affect road.
B	Slopes **above** road, where failure of slope could encroach onto road but is unlikely to disrupt traffic lanes. Slopes generally less than 5 m high.
C	Slopes **below** road, where failure of slope could encroach onto road but is unlikely to disrupt traffic lanes. Slopes generally less than 5 m high.
D	Slopes **above** road, generally **stable**, where failure of slope is unlikely to block more than half road width. Slopes generally 5–10 m high.
E	Slopes **above** road, generally **unstable**, where failure of slope could block full road width. Slopes generally 5–10 m high.
F	Slopes **below** road, generally **stable**, where failure of slope is unlikely to remove more than half road width. Slopes generally 5–10 m high.
G	Slopes **below** road, generally **unstable**, where failure of slope could remove full road width. Slopes generally 5–10 m high.
H	Slopes **above** road in steep terrain, often with road cuttings, generally **stable**, where failure of slope is unlikely to block more than half road width, except in extreme earthquakes. Slopes generally greater than 10 m high.
I	Slopes **above** road in steep terrain, often with road cuttings, generally **unstable**, where failure of slope could block full road width. Slopes generally greater than 10 m high.
J	Gully slope **above** road in steep terrain, often associated with high storm run-off. Failure of slope is unlikely to block more than half road width. Could discharge significant water and debris onto road.
K	Gully slope **below** road in steep terrain. Often associated with culvert outlet. Failure of slope could remove part of road width. Likely to have loose sidling fill slope prone to erosion and failure when exposed to storm run-off.
L	**Retaining walls**, generally **unengineered** railway iron or crib walls up to 3 m high, in gully slope **below** road in steep terrain. Often with culvert. Failure of wall/overall slope is unlikely to remove more than half road width.
M	**Retaining walls**, generally **engineered** anchored soldier piles or gabions up to 3 m high, in gully slope **below** road. Often associated with culvert outlet. Failure of wall/slope is unlikely to remove more than half road width
N	**Retaining walls**, generally **unengineered** railway iron or crib walls up to 3 m high, **below** road in steep terrain. Failure of wall/slope is unlikely to remove more than half road width.
O	**Retaining walls**, generally **unengineered** railway iron or crib walls 3–6 m high, **below** road in steep terrain. Failure of wall/slope could remove full road width.
P	**Retaining walls**, generally **engineered** anchored soldier piles or gabions up to 3 m high, **below** road in steep terrain. Failure of wall/slope is unlikely to remove more than half road width.
Q	**Retaining walls**, generally **engineered** anchored soldier piles or gabions 3–6 m high, **below** road in steep terrain. Failure of wall/slope could remove full road width.
R	**Retaining walls**, generally **engineered** & 3–6 m high, **above** road (e.g. railway over-bridge abutments). Failure of wall/slope unlikely to block more than half road width.
S	Slopes **below** road, currently **stable**, with potential for stream undercutting at toe, where failure of slope could remove full road width. Slopes generally > 10 m high.
T	Slopes **below** road, generally **unstable**, with ongoing stream undercutting at toe, where failure of slope could remove full road width. Slopes generally > 10 m high.



OPUS INTERNATIONAL CONSULTANTS

Title: Hazards - Left Side of Road Akatarawa Valley		
Project: Rural Road Risk Analysis		
Client: Upper Hutt City Council		
Job No: 5C5638.02	Date: October 1999	Figure: Figure A1


N
W
E
S
Benefit / Cost Ratio
0 - 0.2
0.2 - 0.5
0.5 - 1
1 - 2.5
Roads
OPUS
INTERNATIONAL CONSULTANTS
Title:
Benefit / Cost Ratio for Mitigation - Roads (Left)
Akatarawa Valley
Project:
Rural Road Risk Analysis
Client:
Upper Hutt City Council
Job No:
5C5638.02
Date:
October 1999
Figure:
Figure A2



Title:	Benefit / Cost Ratio for Mitigation - Culverts Akatarawa Valley
Project:	Rural Road Risk Analysis
Client:	Upper Hutt City Council

Job No:	Date:	Figure:
5C5638.02	October 1999	Figure A3

Appendix B

Case Study: State Highway 1 along Kaikoura Coast

A case study, supported by Environment Canterbury, was carried out in 2000 of a section of SH1 along the Kaikoura Coast, covering 74 km of road. This was chosen to illustrate the application of the risk analysis for:

- a state highway,
- a road exposed to storm- and earthquake-induced slope failure, as well as coastal hazards,
- a main transport corridor from the North Island to Christchurch and much of the South Island.

The case study covered the section of State Highway 1 from Ward (north of the Kaikoura Coast) to the Conway River Bridge at Hundalee (south of the Kaikoura Coast). The highway runs along the coast, between the coast and steep hillsides or cliffs. There are also a number of fords and tunnels within this section. It is exposed to a range of natural hazards, the main ones being:

- earthquakes, causing
  – slope failures
  – rock falls.
- storms, causing
  – slope failures,
  – coastal erosion,
  – flooding.

The risk study was carried out with the aid of an ArcINFO GIS, generally as described in Section 10 of this report.

A site reconnaissance was carried out by Opus's engineering geologist to map the natural hazards affecting this section of state highway. The hazards were reviewed, and damage costs and mitigation measures were developed by a geotechnical engineer and a coastal engineer.

The road characterisation for a typical section of the study area is shown on the GIS maps presented in Figure B1 on page 71. The map shows the range of categories representing the vulnerability of the road to the natural hazards being considered. These are described in Table B1 on page 70.

Traffic analysis was carried out using simplistic assumptions of disruption and alternative routes, rather than detailed traffic modelling, as this was considered prudent for a linear section of road with limited alternative routes. The alternative route in the event of disruption north of Kaikoura township is along SH63 and SH7, from Blenheim to Waipara, bypassing the whole section. In the event of disruption south of Kaikoura township, the traffic can be re-routed through SH70 and SH7 from

Kaikoura to Waipara. These routes were considered for the assessment of disruption costs.

Disruption from half-road closures, with only one lane being available, and full closure of both lanes was considered, depending of the extent of road damage likely.

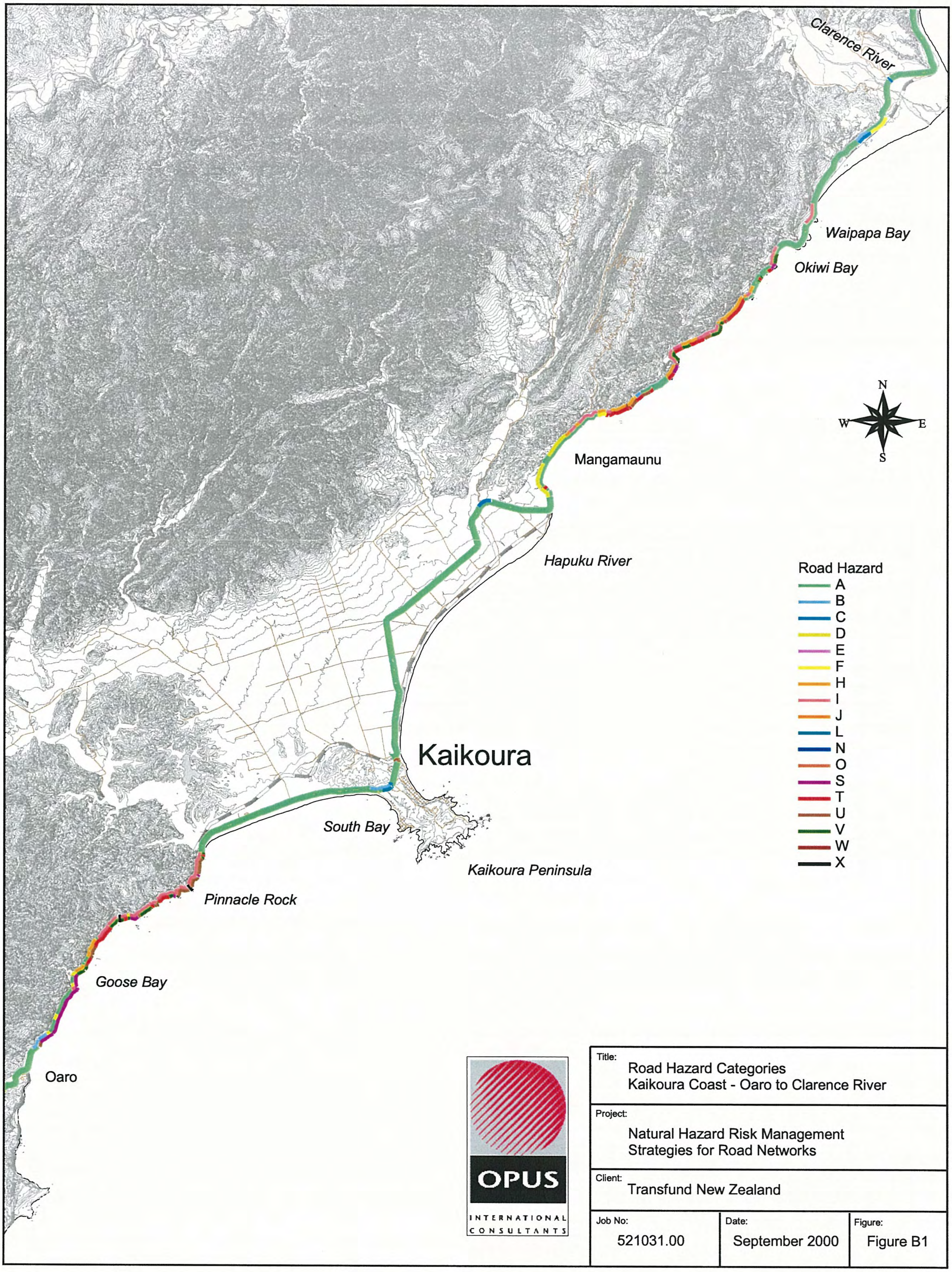
Figure B2 on page 73 shows the benefit/cost ratios for mitigation of the road, derived as described in Section 10 of this report. This is presented for a section of the study area to illustrate the techniques and results. Figure B2 shows that the benefits of mitigation of the coastal hazards significantly exceed the costs in several coastal sections of the highway. This shows that mitigation of the coastal hazards is worthwhile, given the direct financial benefits from savings in damage and disruption costs.

This, together with the primary importance of the highway for North Island–South Island traffic, makes risk mitigation a worthwhile proposition. It may be also be prudent to consider mitigation of some of the other sections that do not have a high benefit/cost ratio.

The risk assessment also shows the vulnerability of this important highway to natural hazards, some of which are impractical to mitigate, except at very high cost. This highlights the need for appropriate risk management planning, and consideration of alternative routes, for the long term.

Table B1 Road characterisation by failure-type category

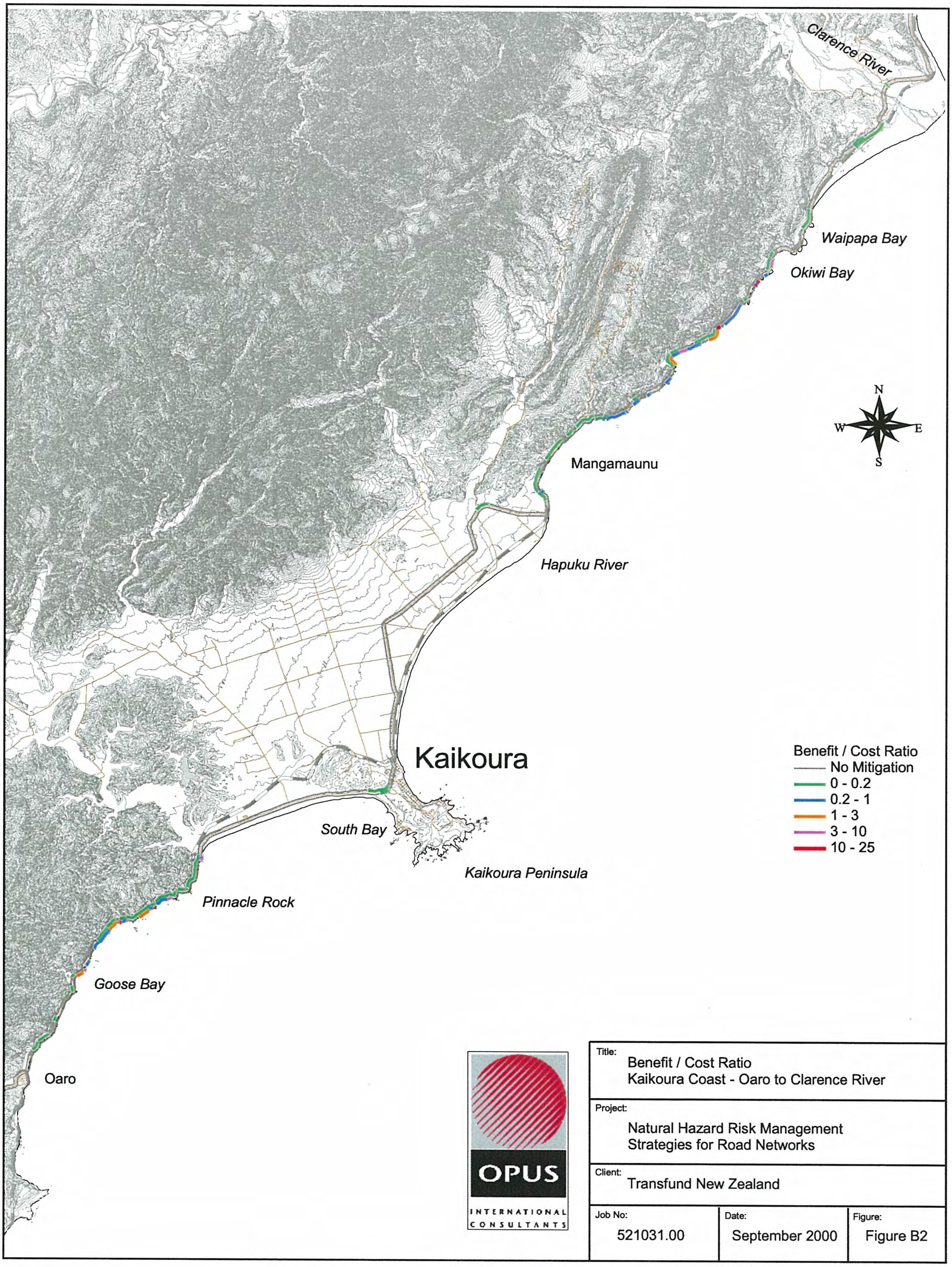
Category	Description
A	Flat, no significant cuts or fills likely to affect road. No retaining walls.
B	Slopes above road, up to 5 m high, generally stable.
C	Slopes below road, up to 5 m high, generally stable.
D	Slopes above road, 5-10 m high, generally stable.
E	Slopes above road, 5-10 m high, generally unstable.
F	Slopes below road, 5-10 m high, generally stable.
G	Slopes below road, 5-10 m high, generally unstable.
H	Slopes above road, > 10 m high, generally stable (colluvium).
I	Slopes above road, > 10 m high, generally unstable.
J	Steep rock faces above road.
K	Gully slope below road in steep terrain.
L	Gully with retaining wall below road, up to 3 m high (unengineered, with crib walls).
M	Gully with retaining wall below road, up to 3 m high (engineered walls).
N	Retaining walls below road, up to 3 m high (unengineered timber pole walls), in landslide area.
O	Retaining walls below road, 3-6 m high (unengineered, with crib walls).
P	Retaining walls below road, up to 3 m high (engineered walls).
Q	Retaining walls below road, 3-6 m high (engineered walls).
R	Retaining walls above road, 3-6 m high (railway abutments etc.).
S	Coastal slopes below road, stable or away from road.
T	Coastal erosion at toe of slope.
U	Coastal walls, generally stable.
V	Coastal walls/revetments actively undercut.
W	Unstable landslide (above road).
X	Tunnels.



OPUS INTERNATIONAL CONSULTANTS

Title:	Road Hazard Categories Kaikoura Coast - Oaro to Clarence River
Project:	Natural Hazard Risk Management Strategies for Road Networks
Client:	Transfund New Zealand

Job No:	Date:	Figure:
521031.00	September 2000	Figure B1



Title: Benefit / Cost Ratio
Kaikoura Coast - Oaro to Clarence River

Project: Natural Hazard Risk Management Strategies for Road Networks

Client: Transfund New Zealand

Job No:	Date:	Figure:
521031.00	September 2000	Figure B2