Climate Change Effects on the Land Transport Network Volume Two: Approach to Risk Management

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Executive summary

Introduction

This report is the second stage of a two-part project to identify and assess the impacts climate change may have on New Zealand’s land transport networks (road, rail, ports and coastal shipping). Stage One involved a literature review and gap analysis. Stage Two (this report), carried out between August 2008 and March 2009, examines the regional effects of climate change on the physical infrastructure of land transport systems with a focus on clarifying aspects such as:

- temporal and spatial distribution of significant climate change effects,
- which parts of the surface transport networks are most at risk,
- multimodal corridors at risk (e.g. common road/rail routes),
- when these risks may emerge, and
- what priority adaptation responses are needed to counter these effects.

A national risk profiling approach was developed to determine the likely regional effects of three high priority risks to the national land transport networks:

- heat stress (buckling) affecting the national rail network as a result of high temperatures,
- inundation of low-lying coastal land transport infrastructure (road and rail) caused by sea-level rise and storm surge (including a port risk profile study), and
- future flood risk under climate change for sections of the state highway and rail networks that are currently prone to flooding.

Scenarios have been developed for current (nominally 10-year) and future (50-year and 100-year) timeframes. Regional impacts for each mode are illustrated using GIS maps that overlay climate change predictions and transport infrastructure. Recommendations for more effective management of climate change risks are given for each study, and cover applied research, policy, design and operation as appropriate.

Rail heat stress study

The aim was to determine the impact of heat buckling on the national rail network in response to the higher and more frequent extreme temperatures expected under climate change. The study considered the regional distribution of increased heat stress, the timeframe over which this effect may emerge and appropriate adaptation measures.

The methodology comprised:

- determining the relationship between air temperature and rail temperature from a literature review;
- establishing a critical rail temperature and equivalent threshold air temperature for the onset of heat buckling under New Zealand conditions; and
- predicting the distribution of the threshold temperature and which parts of the rail network may exceed this under different climate change scenarios.

Conclusions from the national rail heat stress profile are as follows:

- Rail heat stress and track buckling is mainly a summer phenomenon with about quarter of the 4160 km of track currently subject to heat speed restrictions. Sections from Invercargill to Dunedin, Westport via Arthur's Pass, Kaikoura to Blenheim, Masterton to Hawke's Bay and Wanganui to New Plymouth are most affected, based on ONTRACK's records over the last four years.
- Regional climate change predictions using a UK heat buckling risk model for the New Zealand rail network show no speed restriction days for track in good condition, but under poor track conditions, the range was from seven days (least extreme scenario in 2040) to 49 days (most extreme in 2090). The results indicate the key influence of track maintenance in determining the risk of rail heat stress.
- Regional climate change predictions based on the number of days >30°C (the assumed critical rail temperature in New Zealand) show temperature 'hot spots' in Canterbury (from 2010), Hawke's Bay (from 2020), and Waikato and Wairarapa (by 2090). Caution is needed in assuming these areas may experience a greater risk of heat buckling, as actual design temperatures vary with track maintenance standards. Seasonal estimates suggest that the summer rail buckling season could start earlier and finish later as the effects of climate change take hold.
- The sensitivity analysis shows that for track design temperatures above 30°C, almost no increase occurs in days exceeding this threshold, even for a change in mean temperature of 3°C (an extreme climate change for New Zealand), as long as the track ballast remains in good condition. By optimising the design temperature and achieving a high standard of maintenance, climate change will probably play a minimal role in influencing the risk of heat buckling, even in areas subject to the highest temperatures.
- Managing any emerging risk of heat buckling may be met by adjusting the existing track maintenance and de-stressing regime to achieve the optimum critical (neutral) rail temperature in affected regions of the network.

Coastal inundation risk study (road and rail networks)

This study conducted a national risk profile of New Zealand's coastal road and rail networks in relation to inundation resulting from sea level rise and storm surge, based on their elevation with respect to mean sea level.

The methodology comprised mapping coastal areas using nation-wide digital satellite data of coastal elevation, overlaying the transport networks and measuring the length of low-lying (<5 m elevation) coastal networks, (the 'at risk' metric). A broad estimate of risk was determined from the total length of network within this zone. The study also looked at which multimodal (state highway and rail) coastal corridors may be at risk of inundation. Comparison with 1 m LiDAR data indicated that the 'at risk' metric derived from the satellite data underestimates the true value. For purposes of this national profile, the <5 m metric is considered to provide an acceptable first approximation of potential risk from inundation.

The following conclusions are drawn from the inundation risk study:

- Nationally, about 3.6% (160 km) of the rail network, 1.4% (222 km) of state highways and 1.6% (2112 km) of local roads, and at least 10 multimodal coastal corridors are potentially at risk from inundation.
- While national profiles show a relatively small fraction of coastal land transport networks at risk from climate change, regional impacts may be higher, depending on the distribution of at-risk sections and priority of the affected routes.
- The actual proportion of transport network at risk is expected to be smaller than the figures suggest as the inundation/storm surge risk lies in the lower half of the 0–5 m zone, and the screening profile takes no account of elevated coastal assets (e.g. those on embankments) or those protected by sea defences.
- Topographic risk profiling provides a high-level 'first cut' of coastal road and rail sections potentially vulnerable to inundation, and points to where site inspections and more detailed risk assessments should be prioritised. This will allow refinement of the actual assets at risk, taking account of local site characteristics e.g. existing sea defences.

Order of magnitude calculations of potential costs to respond to the effects of climate change on coastal inundation under a worst-case scenario, where all low-lying sections of the network identified in this study require repair/replacement, indicate the following:

- national rail network: ~ $80 million (ballast and formation replacement);
- state highway network: ~ $88 million (raising and rebuilding all affected sections);
- local road network: ~ $840 million (raising and rebuilding all affected sections).

This broad analysis does not take account of any damage to other assets (e.g. bridges) in the road/rail corridor, or the disruption cost associated with transport delays.

Several strategic coastal corridors representing high priority transport routes were identified that contain a number of contiguous low-lying sections. Closing any of these sections would cause major transport disruption because deviations inland are difficult or circuitous. Corridors particularly at risk include:

- Blenheim to Kaikoura: five individual at-risk sections on a coastal corridor containing a major trunk line (parts of which are in tunnels) and State Highway 1.
- north and south of Dunedin: six individual at-risk sections on an inter-regional coastal corridor containing a major trunk line and national state highway.

Future work to refine the risks to coastal networks from climate change could include:

- topographic mapping using high-resolution LiDAR and/or asset elevation data,
- site inspection and asset condition surveys,
- quantitative risk modelling of priority 'at-risk' sections,
- assessing resilience of existing sea defences,
- determining vulnerability of networks to other coastal hazards e.g. slips, erosion, and
- risk studies of coastal transport corridors.

Port inundation risk profile

This study conducted a national risk profile of New Zealand's ports regarding inundation resulting from sea level rise and storm surge, considering two related aspects:

- a review of port authorities' response to a survey on their perception of risk, and
- assessing the vulnerability of key coastal transport networks servicing the ports.

The methodology comprised a questionnaire to port authority executives requesting information on their port infrastructure and perceived risks from sea level rise. Five of the fifteen port authorities provided responses, which were used to determine a 'first cut' risk profile of individual port vulnerability to inundation. The risk profile was based on the elevation of current deck heights and available freeboard with respect to current and future mean sea levels. The vulnerability to inundation of coastal transport networks servicing the ports, along with the number of modal links and their importance, was used to develop a qualitative risk categorisation for each port.

The main findings are:

- New wharf deck elevations were reported to be generally higher than older structures, indicating a margin of safety is being included to offset the increased risk of overtopping. Gaps in responses on the design water level and minimum acceptable freeboard indicate that climate change may not yet be 'on the radar', despite the fact that wharves have a design life of up to 100 years.
- No perceived threat from climate change was identified by the majority of respondents. Four of the five authorities considered that a sea level rise of 0.5–0.8 m by 2100 would not have a major impact on their port operations, although one respondent (with the lowest freeboard) noted that operational impacts could emerge from increased corrosion and stormwater backflow.
- The survey responses indicate that while many port authorities acknowledge the adverse effects of sea level rise, the severity and likelihood of these effects and their timing are, for the most part, not well understood. With some exceptions, a

concerted effort to conduct climate change risk assessments and develop an adaptation response does not appear to have been made by the industry.

- The qualitative risk categorisation of New Zealand ports based on loss of connection to coastal transport links owing to inundation from sea level rise/storm surge showed a wide range in risk. At the low end is Port Taranaki, with both state highway and rail links above the nominal 5 m elevation risk threshold. At the higher end are ports serviced by multi-modal connections where the coastal transport corridors all contain multiple low-lying sections susceptible to inundation (e.g. Port Otago, South Port NZ).

Inland flood risk study

This study estimated the likely increase in flood risk of vulnerable sections of the state highway and rail networks under climate change in order to assist network operators plan for an appropriate adaptation response (e.g. planning, design, operation or maintenance).

The methodology comprised identifying current flood-prone parts of the networks based on recorded floods, establishing an Annual Recurrence Interval (ARI) for each flood, predicting future ARIs in 2040 and 2090 using a scaling factor, and plotting the flood data on a GIS map of each network. National floods affecting the rail network were retrieved from ONTRACK's incident database for July 2004 to September 2008. Similar information for the state highways was sought from each of NZTA's 24 network operation regions.

The screening method assumes that the future change in flood risk at a given location is proportional to the increase in extreme rainfall at that location and that a given increase in heavy rainfall results in a similar increase in peak river flow. These simplifying assumptions are acceptable for the purposes of this national profile, although it is noted that present day 'near misses' (i.e. sections that are likely to flood in future but which are not currently at risk) are not identified.

The following conclusions are drawn for the national rail network:

- The rail network is vulnerable to weather extremes, particularly because of weaknesses in the culvert and drainage system. The network experienced about 68 floods from July 2004 to September 2008. Regions with higher flood prevalence include the coastal section near Hauone (central Bay of Plenty), Palmerston North, Arthur's Pass and the Amberley/Rangiora area in Canterbury.
- On a regional basis, the four-year data from ONTRACK indicate more floods affecting main lines in the North Island (32) than in the South Island (20), with two North Island events exceeding a 100-year return period.
- The majority of track floods have an ARI <2 years (based on the nearest rain gauge) and are interpreted to represent flooding cause by significant rainfall further up the catchment. Such non-localised floods require catchment-based modelling to provide predictions of future recurrence under climate change.

- Research by ONTRACK has shown that 97% of expected costs from floods could be attributed to the failure of 10% of culverts, primarily as a result of frequent small flood srather than less frequent extreme weather events.
- This study has shown that climate change is set to increase the flood risk in track sections currently prone to flooding by a factor of two by 2090, in some cases.
- Further studies should investigate long-life (50- to 100-year) assets in flood-prone areas to identify their risk profile and adaptation response to ensure future flood resilience. This will entail catchment-based flood modelling and cost/benefit analysis for bridges and culverts most at risk. Design standards for new assets should consider site-specific flood flows under climate change scenarios.

Conclusions for the state highway network are as follows:

- At the time of this study, the hazards database was encountering technical difficulties which prevented data prior to July 2008 from being accessed, so the study used flood data held at the regional level.
- Responses from 16 of the 24 state highway network operations indicated that all but one region (Marlborough South) have recorded floods affecting the state highway in the past. However, a regional comparison was not possible because of uncertainty in how flood data are reported and a shortfall in data for about 30% of the network.
- The vulnerability of the state highway network to extreme weather is not well defined. While certain parts of the network are vulnerable to flooding, a national profile of flood risk or estimates of future risk (based on changes in ARI) could not be developed because of lack of adequate records of flood events and when these occurred.
- Adaptation response in the short term should focus on the systematic collation of data on extreme weather events that cause disruption/damage to the network, and more detailed flood risk studies for those parts of the network that are currently prone to flooding, as identified in this study.

Future flood studies in respect of climate change for both the rail and state highway networks could consider:

- catchment-based modelling of flood-prone areas,
- identifying sections at future flood risk (current ‘near miss’ events),
- identifying critical long-life assets at risk (bridges and major culverts),
- screening bridges for scour risk and adequate freeboard,
- assessing the resilience of existing flood defences, and
- reviewing current design standards and philosophies.

General conclusions

The three climate change studies comprise an initial high-level appraisal of the regional implications of climate change effects for the land transport sector. Recommendations are given on priority adaptation responses in terms of applied research, policy, design and operation, as well as aspects needing further consideration, in order to provide more effective management of climate change risks.

The report identifies sections of the land transport networks where more detailed studies should be prioritised under an ongoing research programme to confirm the actual risk of climate change, quantify the likely damage and cost implications, and provide the basis for a robust, cost-effective adaptation response, where needed. Future efforts should focus on the following key aspects:

- **closing gaps in transport data:** Existing asset management systems held by land transport providers in New Zealand are generally not set up to provide information to assist prediction of climate change effects on the networks. For example, high-resolution elevation datasets of transport assets are generally not available for flood or coastal inundation risks to be assessed at the local level. Such information is essential to quantify risks and maintain future network resilience.
- **better understanding of network vulnerability to extreme weather:** the vulnerability of surface transport networks to weather extremes is not well documented and the quality and retrievability of nationally consistent data varies widely. More robust systems are needed to evaluate the significance of extreme weather events and weather variability in the design, cost, mobility and safety of existing networks. Analysis of current weather events that affect transport systems will assist future forecasting of effects under climate change.
- **desirability of linking climate change to asset management:** Better integration of climate change considerations into transport providers' current asset management programmes (covering planning, design, operation and maintenance) is needed, as well as linkage to wider sustainable transport initiatives (such as priority transport corridors and lifelines perspectives).
- **importance of regional / local impact analysis:** The effects that a changing climate might have on transportation infrastructure and services are very dependent on regional climate and local site characteristics. These require local-scale modelling of such effects in order to provide the basis for cost-effective adaptation responses. Higher resolution climate models for regional and sub-regional studies would support the integration of region-specific data with transportation infrastructure information.
- **need for better risk analysis tools:** transportation planners also need new tools to address the uncertainties that are inherent in projections of climate change. Such methods are likely to be quantitative and based on a probabilistic framework with greater clarity on uncertainty for end-user risk management. Given the long timeframe of climate change (50–100 years), factors such as changing demography, land use and technology need to be taken into account in the risk analysis model.

- **an integrated transport planning approach:** This study provided an initial analysis of where climate change (e.g. risks from flood and coastal inundation) could affect parts of individual transport networks. Future studies need to consider climate change in the context of an integrated transport network. For example, the risks to ports from climate change do not depend simply on the vulnerability of the port infrastructure but also on the critical transport networks servicing the ports.

more robust economic evaluation: a wider assessment of the economic cost of climate change on surface transport is necessary, given that calculating the true economic impact of climate change is fraught with 'hidden' costs. Aside from the replacement value of infrastructure, other real costs include re-routing traffic, lost workdays and productivity, provision of temporary shelter and supplies, and potential relocation and retraining costs. Systematic collection of data relating to such impacts should be investigated in future.

Abstract

This project (undertaken in 2008/2009) aims to identify and assess the impacts climate change may have on New Zealand's land transport networks (road, rail, ports and coastal shipping), and provides recommendations, including adaptation options, to address information gaps and risks. Stage One comprised a literature review and gap analysis. Stage Two deals with regional effects of climate extremes on the networks, and considers how these vary by region, when and where these risks emerge and which parts of the land transport networks are most at risk. The study describes three national climate change profiles covering rail heat buckle from extreme temperature, flood risk from extreme rainfall and coastal inundation risk from low-lying areas sections of the networks. Data from NZTA, ONTRACK and port authorities were used to assess the current vulnerability of networks to extreme weather. Extrapolation was used to predict future effects based on modelling of climate extremes for 10-, 50- and 100-year projections using a mid-range (A1B) scenario. Regional impacts were determined from GIS maps by overlaying climate change predictions with transport infrastructure. Priority adaptation responses are discussed for each national profile in the context of design, operation, research and policy issues, and related emerging climate change research.

1 Introduction

1.1 Motivation

Experience over the last few years has demonstrated that New Zealand's land transport system is vulnerable to the impacts of extreme climatic events. Some of these events include:

- Flooding in the central and eastern North Island, February 2004, caused extensive damage and disruption to transport networks, including closing a section of State Highway (SH) 3 (Manawatu Gorge) for 2.5 months, and also significant closures on other parts of SH1, SH3, SH4, SH54 and SH57.
- Rainfall well in excess of normal levels in Northland, Auckland, Hawkes Bay, Wanganui, Wairarapa and Canterbury in 2006 caused flooding of the state highway network (Transit New Zealand 2006).
- Storms during June/July 2007 caused damage to property and infrastructure in Southland and Otago, while in Southland erosion damaged a coastal road (NIWA & GNS 2007).

The recent end-of-year climate review (NIWA 2009) cites 2008 as '…a rollercoaster year for extremes'. It was 'a year with heat waves and many new records of high temperature extremes were established.' The National Institute for Water and Atmospheric Research (NIWA) noted that the broad climate pattern over the year 'swayed from La Niña to neutral then back to La Niña.' As reported by one national newspaper (Fawkes 2009):

> *Niwa's national climate study showed a hotter than usual summer, with drought across the North Island and the tip of the South Island. But winter hit hard, with Wellington experiencing its third-wettest year since 1864, while sub-zero temperatures were felt briefly in Auckland. Less than 10 millimetres of rain a month fell in the King Country, Waikato and the Hauraki Plains between January and March. Coastal Marlborough and parts of North Canterbury also suffered. Drought spread to areas including Hawke's Bay and Wairarapa and although April and May brought showers, the drought cost the farming sector and related industries $1 billion, and the agriculture ministry reported an 11 per cent drop in sheep numbers.*
>
> *Relief in the South Island was short-lived as floods hit Marlborough and Canterbury, causing a state of emergency to be declared in Marlborough. Flooding cost the insurance industry an estimated $68 million nationally. The weather was a product of La Niña creating anticyclones to the east of New Zealand, increasing sea temperatures and driving winds from the north.*

These events serve to underscore the importance of climate to New Zealand's economy, and how extreme weather may cause extensive and costly disruptions to transport networks. The situation is set to become worse over the coming decades as climate change is predicted to increase the magnitude and frequency of weather extremes. Hence it is necessary to identify when and where climate change impacts are most likely to occur and to develop measures for appropriate adaptive responses.

Land Transport New Zealand (now the NZ Transport Agency or NZTA) engaged MWH NZ Ltd, in partnership with NIWA, to assist its understanding how, where and to what extent climate change will affect the land transport network, and what policy options and adaptation measures should be adopted in response to this risk.

The one-year project commenced in January 2008 and comprised two consecutive stages:

- Stage One: literature review and gap analysis, and
- Stage Two: approach to risk management.

The background and context to Stage One, and the purpose and scope of Stage Two are summarised below.

1.2 Background to Stage One

Stage One was concerned with reviewing the current situation, identifying gaps in the state of knowledge and prioritising which aspects need further research. This stage was completed in the first half of the project with the publication of the Stage One report (Volume One; Gardiner et al. 2009).

Work completed in this stage included:

- a **literature review** on the effects of climate change and adaptation measures for land transport networks (road, rail and ports) internationally and by New Zealand's central government agencies, local government, crown research institutes, universities and private agencies;
- an online **stakeholder questionnaire** for selected network operators, central and local government authorities, and research institutions on their research needs, adaptation responses and perceived barriers to how land transport networks are planned, designed, operated and maintained to address the effects of climate change;
- a **climate change review** summarising the likely effects for New Zealand, drawing on latest findings from analysis of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (FAR) (Perry et al. 2007);
- a **risk assessment** of the national land transport system from changing weather patterns under climate change conditions, including identification and prioritisation of risks to each mode;
- a **legislation and policy review** of effects of climate change on land transport networks in New Zealand;
- a **modal review** (road, rail and ports/coastal shipping) using the risk assessment findings to provide an initial analysis of how key climate variables can potentially impact on their design or operation; and
- a **gap analysis of information,** knowledge or practice (covering climate science, policy and individual modes) and prioritisation of further work required to enable risks of climate change on the land transport network to be better understood.

Priority issues are summarised in Chapter 10 of Volume One. A key finding was that a large amount of further investigation and study is required to produce a comprehensive

New Zealand-wide climate change impact assessment for the land transport system across all modes.

Regional considerations were discussed where broad spatial patterns of predicted climate change effects had been identified. An initial appraisal of regional implications to the land transport network of the main risks from climate change effects was described in Chapter 9 of Volume One, and is summarised below:

- extreme temperatures leading to increased heat buckling on the rail network (the highest risks predicted for the northern part of the North Island based on extreme temperature distribution);
- increased flood, erosion and slip risk caused by increased frequency/intensity of extreme rainfall (regional patterns could not be determined owing to a lack of detail on regional differences in extreme rainfall, and a lack of information about where the transport network could be disrupted by such events);
- sea level rise/storm surge: this threat is increasing nationally with a higher risk likely on the western seaboard;
- higher risk from strong winds: indicative results show higher risk to road networks and port areas in eastern coastal areas of the North and South Islands, and on the Canterbury Plains in the lee of the Southern Alps; and
- storminess (e.g. ex-tropical cyclones or mid-latitude storms): these would bring an increase in extreme rainfall and strong winds (regional implications were not able to be evaluated because of lack of information on effects of climate change on current storm patterns).

Two barriers were identified that hinder detailed regional assessment of climate change impacts on land transport networks in New Zealand:

- the uncertainty both in regional climate change predictions and downscaling of global climate models for projected changes in extreme events as required for determining impacts on transport networks at the regional level; and
- the lack of readily accessible specific transport infrastructure datasets and design standards for each of the territorial local and regional authorities, and other transport mode owners and operators.

These findings were taken into account in deciding the scope of Stage Two, as described below.

1.3 Purpose and scope of Stage Two

In line with the required project outcomes, the purpose of Stage Two (Volume Two – this report) was to conduct a broad assessment of potential climate change scenarios as they relate to risks identified as 'significant' in Stage One of this research. Scenarios were considered across a range of time horizons and geographic scales.

The focus has been on defining the probable effects on the physical infrastructure of land transport systems. Recommended adaptation measures have been identified to enable more effective management of climate change risks with an indicative assessment of cost-effectiveness. Such measures have been prioritised using multi-criteria analysis (MCA) and categorised by type, such as:

- design issues, where changes in the design of the land transport network are proposed;
- operational issues, where changes in the operation of the land transport network are proposed;
- research issues, where further applied studies are required; and
- policy issues, where recommendations would affect current policies.

As noted in Volume One's recommendations, and notwithstanding the shortcomings mentioned above, a key objective of Stage Two has been to provide a better understanding of the regional manifestations of climate change effects on land transport infrastructure in New Zealand. The intention has been to provide greater clarity on aspects such as:

- temporal and spatial distribution of significant climate change effects,
- the parts of the surface transport networks that are likely to be most at risk,
- areas where multi-modal risks may arise (e.g. common road/rail corridors), and
- broad-brush cost implications.

A national/regional profiling approach was developed for this project to determine likely regional effects. This was applied to the following three inter-related studies based on their prioritisation in Stage One as high priority risks to the national land transport network:

- **Rail heat stress study:** assess specific impact scenarios for the national rail network caused by rail buckling from high temperatures/heat wave events (see Chapter 3).
- **Coastal inundation risk study:** identify low-lying coastal land transport infrastructure (road, rail and ports) that are potentially more at risk from coastal flooding from sea level rise and storm surge; for ports, this considered available freeboard based on deck heights (see Chapter 4).
- **Inland flood risk study:** identify sections of the state highway and rail networks currently at risk of (or prone to) inland flooding as a basis for estimating the likely flood risk (based on the Average Recurrence Interval (ARI)) of these areas under different climate change scenarios (refer to Chapter 5).

The study outputs include:

- regional Geographical Information System (GIS) maps based on current understanding of climate change predictions;
- identification of the likely regional impacts for each mode, subject to availability of transport data; and
- scenarios developed for current (nominally 10-year) and future (50-year and 100-year) timeframes.

An overview of the methodology used in the national/regional profile is given in the following section.

1.4 Methodology

An overview of the methodology used in Stage Two is given below. More detailed descriptions of the national/regional profiling study methodologies and data inputs are given in the respective study chapters (Chapter 3: rail heat stress; Chapter 4: coastal inundation risk; Chapter 5: inland flooding risk).

- **Scoping Stage 2:** Volume One provided recommendations on the scope of work for Stage Two. An initial aspect of Stage Two comprised reviewing available data sources and obtaining national datasets, confirming details of the approach to be followed in the national/regional profiling studies, and developing the methodology. This included an early discussion with the NZTA on the required outcomes for the second stage, taking account of comments made on Volume One by the NZTA Board. Meetings were also held with NIWA to confirm climate change modelling requirements for the rail heat study, national topographic and sea level rise/storm surge datasets for the coastal inundation study, and inputs for the regional flood risk study (to be based on historical flood event mapping and scaling up with extreme rainfall predictions).
- **Stakeholder liaison:** Rather than adopting a formal Working Group, the project team worked directly with national land transport providers (ONTRACK, NZTA, and state highways and port authorities) to provide early input to Stage Two studies. A letter was sent to all Stage One questionnaire stakeholders who expressed interest in follow-up during Stage Two with an invitation to share their climate change research or initiatives. Meetings were subsequently held with representatives of the Ministry of Transport (MoT) and the Ministry for the Environment (MfE) to discuss the Stage One findings, and identify current and pipeline climate change projects relevant to the subject study. Contact was also made with other organisations to identify related information, including civil defence and emergency management (resilience of lifelines to weather extremes), Maritime NZ (strategic port study on effect of climate change) and regional councils (LiDAR[1] data sources and regional climate change modelling studies).
- **Assessment of network vulnerability:** Weather-related natural hazard records were sourced by NIWA from a search of the national NIWA/Institute of Geological and Nuclear Sciences (GNS) database. Records of events affecting the road and rail networks were sourced from the respective national transport providers. Data were spatially mapped and overlaid with the land transport networks in a GIS to provide a spatial output suitable for identifying the extent of transport assets currently affected by weather conditions, identifying regional patterns and providing quantitative metrics of effects.
- **Climate change modelling:** Climate change scenarios comprised a 50-year projection centred on 2040 (2030–2049) and a 100-year projection centred on 2090 (2080–2099). Scenarios for New Zealand were developed using statistical downscaling from twelve different global circulation models for a mid-range greenhouse gases emission scenario (A1B) to regional scale climate change

[1] LiDAR: Light Deflection and Ranging. A method of detecting objects and determining their position, velocity or other characteristics by analysis of pulsed laser light reflected from their surfaces.

projection patterns. (Refer to Appendix B of Volume One for further details). Extreme rainfall predictions were based on NIWA's High Intensity Rainfall Design System (HIRDS) model. Information on sea level rise/storm surge was based MfE's coastal guidance manual (MfE 2008a).

- **Climate change effects on transport infrastructure:** The general approach was to identify the current vulnerability of transport networks to weather stresses (e.g. distribution of rail buckling, flooding, etc.), identify a transport infrastructure 'trigger point' in relation to the climate change effect and scale up the effect for each scenario. Extreme temperature was used to predict the future risk of rail heat stress (buckle); extreme rainfall was used as a proxy for determining the increased risk of known flood events, and low-lying areas (elevation <5 m above sea level) provided the basis for highlighting sections of the road and rail network potentially vulnerable to inundation from sea level rise (lack of a national higher resolution coastal topography dataset prevented refinement of risk below this datum).
- **Adaptation:** A number of steps to prepare and adapt national land transport systems are described based on available literature and adaptation options identified in Stage One. Adaptation options were prioritised using MCA. MCA was considered a useful tool to assess climate change adaptation options because of:
  - the inherent lack of certainty about the scale and extent of predicted change in climate conditions, and the effects on the land transport network; and
  - the limited scope of this research to undertake economic analysis of the cost of effects (as these have not been fully identified), and therefore the cost-effectiveness of adaptation responses and benefits (dollars) such as flow-on benefits in social, environmental and wider economic terms.

Adaptation responses to reduce the vulnerability of land transport from climate change (see Appendix A) have been assessed based on the following considerations (adapted from Parry et al. 2007):

- the magnitude and rate of climate change: adaptation is more feasible when climate change is moderate and gradual than when change is abrupt;
- clear identification or establishment of where responsibility for adaptation options may lie, plus any influence on these options;
- where existing risk management responses can accommodate climate change considerations; and
- where adaptation actions can be effective in achieving specific (and other) goals, acknowledging that adaptation responses can have unintended consequences e.g. increased flood risk downstream or reducing resources available to address vulnerabilities elsewhere.

1.5 Assumptions and limitations

The following assumptions and limitations apply to the work conducted under Stage Two:

- The study has focused on how predicted weather patterns associated with climate change might affect three high-risk scenarios affecting the national land transport system. The predicted patterns of key climate variables considered in this research are drawn from the output of multiple global climate models for a single mid-range greenhouse gases (GHG) emission scenario (A1B). Global climate models are physics-based models and take account of natural climate variability patterns such as the El Niño/La Niña cycle and the Interdecadal Pacific Oscillation with varying degrees of accuracy depending upon the model. The twelve global climate models chosen for this study have been shown to represent historic climate in the New Zealand region realistically. Global climate model outputs have been statistically downscaled to correlate with weather and climate patterns in New Zealand.
- In Stage One of this research, climate scenarios under optimistic and pessimistic GHG scenarios were highlighted as a potential area for focus in Stage Two of this research. Comparing climate patterns under multiple GHG scenarios was decided against because:
  - the national scale of this research sought to identify the location and timeframe of high-risk climate conditions, which would have been complicated by multiple GHG emissions scenarios; and
  - the lack of high-level description of effects for the national land transport network outside of this research required us to provide a starting point from which future research can investigate other GHG scenarios in more detail.
- Stage Two of this research has been based on one GHG emissions scenario, A1B, which describes a mid-range estimate, consistent with the methodology used in Stage One. Site-specific climate adaptation studies may be a more appropriate scale for exploring the effects of multiple GHG scenarios, if infrastructure operators are seeking certainty that value for money investment is justified.
- Limitations in the availability, quality or completeness of national datasets available for this study, particularly in respect of the vulnerability of transport networks to current weather extremes, was a common theme as the study progressed. This issue shaped development of the national/regional profiling methodology and the extent to which it could be applied to the transport networks to predict effects of climate change. Where data issues were found, recommendations have been made to remedy the gaps in order to provide transport providers with a firmer basis for strategically managing the risk of climate extremes that affect their networks.

1.6 Report structure

The report is set out as follows:

The introduction (Chapter 1) provides the context for this report, including the background to Stage One, and the purpose, scope and methodology adopted for Stage Two. Chapter 2 sets the scene for the three national risk profiling studies by providing an overview of vulnerability, evaluating climate change effects on and adaptation relevant to the land transport sector. Chapters 3, 4 and 5 describe, respectively, the rail buckle, coastal inundation and inland flood studies. The main conclusions from each study and recommendations for future consideration are summarised in Chapter 6.

A number of appendices are included to provide supporting technical information. Appendix A is an MCA summary of adaptation options for the three studies. Appendix B is a table of selected flood events in New Zealand that have affected land transport networks, while Appendix C is a summary of flood events recorded by ONTRACK over the last four years that have affected the national rail network. Appendix D contains a glossary of technical terms and abbreviations used in this report.

2 Context: vulnerability, adaptation and measuring climate change effects

2.1 Introduction

Critical assets of transport infrastructure such as bridges and wharf decks have lives of up to 100 years or more. Therefore, existing and new assets will probably face additional physical stresses in response to the effects of extreme weather induced by climate change.

Responses to a stakeholder questionnaire conducted in Stage One of this research found that infrastructure providers and funders seek guidance about appropriate responses to predicted climate change effects. However, deciding whether a response to predicted effects of climate change is prudent involves knowing the asset's current vulnerability to weather effects, determining the risk of such adverse effects arising within the asset's lifetime (based on an assessment using local scale climate modelling), and weighing up the benefit of additional investment costs against possible costs if future weather patterns are predicted to cause disruption, increased maintenance and reduced life.

This process is termed 'adaptation assessment', and is the practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency and feasibility.

On the whole, climate change adaptation literature considers society to be capable of efficiently and effectively adapting to changing climate conditions. On one hand, industry and society are considered capable of adaptation, depending on the competence and capacity of individuals, communities, enterprises and local governments, along with access to financial and other resources (Parry et al. 2007). On the other hand, Easterling et al. (2004) see society *eventually* being able to make modifications to accommodate changing conditions. Adaptation requires a flexible approach because of the inherent uncertainties, long timeframes and substantial costs involved.

This chapter provides an overview of:

- approaches to vulnerability,
- how to evaluate the effects of changing climate patterns, and
- adaptation responses relevant for the land transport sector.

Its purpose is to give a context to findings from the national risk profiling studies described later in the report.

2.2 Vulnerability of transport infrastructure to climate change effects

The research conducted in Stage Two seeks to identify specific areas within the land transport system that may be vulnerable to the effects of climate change on temperature, rainfall and sea level rise/storm surge, and the indicative timeframe when these effects may start to become significant.

Parry et al. (2007) define *vulnerability* as follows:

> *Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.*

In the context of the definition above, two other terms need defining (Parry et al. 2007):

> *Sensitivity:*
> *Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise.*
>
> *Adaptive capacity (in relation to climate change impacts):*
> *The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.*

In the context of this study, 'vulnerability' is therefore the degree to which the land transport system is likely to be disrupted or damaged by weather effects exacerbated by climate change conditions.

The approach adopted in this study was, first of all, to consider the vulnerability of the present-day land transport networks to severe weather conditions by examining asset management records showing events where disruption or damage has occurred. By assessing the effect of projected climate change-induced weather patterns on these networks, the study has then sought to identify where and when changes in event patterns are most likely to occur, and therefore allowing researchers to give priority to areas where detailed studies may identify effective and efficient adaptation responses.

Parry et al. (2007) outline vulnerability assessment criteria to climate change effects based on magnitude of impact, timing, persistence and reversibility, likelihood and confidence, potential for planned adaptation, geographical distribution and importance of the vulnerable system. These factors are considered below in relation to New Zealand's land transport system using findings from the risk assessment completed in Stage One of this research:

- **Magnitude of impact:** Extreme rainfall events, heat effects on rail and coastal inundation were assessed as posing potentially high magnitude impacts on land transport systems in New Zealand.
- **Timing:** The land transport system is already vulnerable to flooding, which causes costly disruption to road and rail networks. Predicted increases in extreme rainfall associated with higher temperatures are likely to result in increased frequency and magnitude of flooding, requiring a relatively rapid pace of adaptation. The incremental increase in temperature and sea level are considered effects to which the transport system can be made resilient e.g. by accommodating such changes through modifications to maintenance standards, asset elevations and technical standards.
- **Persistence and reversibility:** Flooding already affects parts of the land transport networks but the effects are generally temporary and reversible. The predicted increase in frequency and magnitude of flood events under climate change implies greater persistence in the absence of adaptation measures. Similarly, the effects of sea level rise are predicted to be persistent and irreversible. Generally speaking, the effects of extreme climatic events on transport operations and assets are considered reversible to the extent that repairs and renewal permit full recovery.
- **Likelihood and confidence:** NIWA provides estimates of confidence in the direction and magnitude of climate change projections for New Zealand that vary widely with effect (MfE 2008a). Thus high confidence is placed on the projected temperature extremes and sea level rise, moderate confidence in extreme rainfall and storm surge prediction, but only low confidence in strong winds and storminess.
- **Potential for planned adaptation:** Technical and operational solutions to changing climatic patterns are feasible for land transport networks, as demonstrated in New Zealand by, for example, historical changes to design standards for acceptable flood levels according to flood risk and value of assets at risk. Other countries successfully operate transport systems at present in the more extreme heat conditions predicted in future for New Zealand.
- **Geographical distribution:** Flooding effects occur across numerous catchments throughout New Zealand and therefore are considered a widespread risk. Transport networks are designed to avoid areas with natural hazards (e.g. flood plains) or are otherwise protected from them, but are more vulnerable in extreme weather events. Some climate change effects are, by nature, restricted geographically (e.g. sea level rise affects coastal areas but not inland areas) and the vulnerability of the transport infrastructure will depend on local variables such as relative elevation and the resilience of seawall defences.

Overall, New Zealand's land transport system could be considered to have moderate vulnerability to the effects of climate change for aspects considered in this research (i.e. extreme rainfall, increasing temperature and rising sea levels) given the length of the coastline and lack of options for alternate routes. Actual vulnerability will vary widely, and will depend on regional and local characteristics.

A risk assessment of New Zealand surface transport network was completed in Stage One. This assessment prioritised the climate change effect categories in relation to risks for each mode (road, rail and ports). This table is reproduced overleaf as Table 2.1.

2.3 Evaluating adaptive response to changing climatic conditions

The extent of climate variability is a key factor underlying any adaptive responses. Extreme events such as floods and coastal inundation pose challenges to adaptive studies, given the varying frequency, intensity and persistence of predicted climate change. Responding to extreme events is likely to be more difficult and costly compared to managing marginal changes to average climate conditions (Easterling et al. 2004).

Adaptive responses in the land transport sector once climatic events have occurred are suggested to be more costly than proactive responses, particularly given the high capital investment and long design life of transport assets and infrastructure.

Having a degree of confidence in the potential extent of climate change effects is a vital component of enabling the effectiveness and affordability of adaptation responses to be assessed, as illustrated in Figure 2.1.

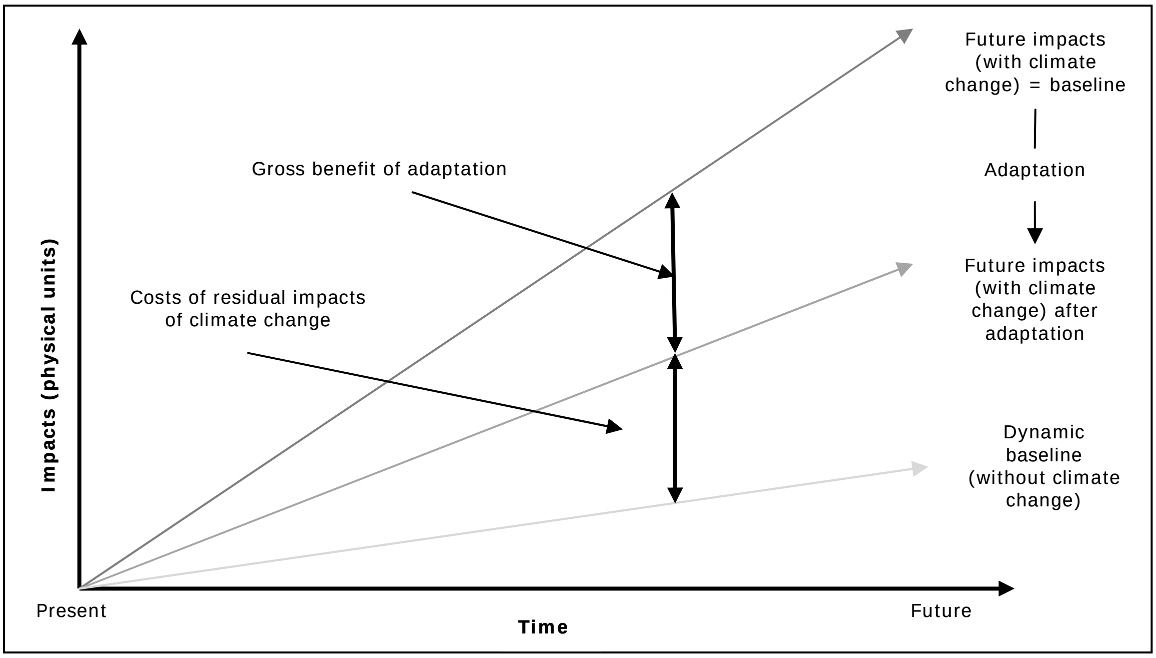

Figure 2.1 Climate change impacts over time and relationship to costs and benefits (adapted from Marsden Jacob Associates 2004).

Table 2.1 Prioritisation of climate change effect categories in relation to high risks to land transport networks.

Climate change effect category	Risk	Possible 'true' risk (raw risk)	Additional factors	Priority
Coastal flooding (sea level rise and storm surge)	High risk to all three modes	Rail risk may reduce to moderate	• Top five risk to coastal shipping. • Only some coastal locations affected. • Significant costs likely for response options. • Particularly important for assets with a long design life.	✓✓✓✓
Flooding	High risk to all three modes	–	• Top five risk to road. • Significant costs likely for reinstatement or rebuilding. • Particularly important for assets with a long design life.	✓✓✓✓
Rainfall	High risk to road and rail	–	• Top five risk to road and rail. • Significant costs likely for reinstatement or rebuilding. • Particularly important for assets with a long design life.	✓✓✓✓
Inland erosion and instability	High risk to road and rail	–	• Top five risk to road. • Significant costs likely for reinstatement or rebuilding.	✓✓✓✓
High temperature	High risk to rail	–	• Top five risk to rail. • Rail has a long design life. • Forward planning is required to allow staged replacement of at-risk rail, and to ensure new designs are adequate.	✓✓✓✓
Storminess	High risk to all three modes	–	• Aggregate effects (extreme rainfall and high winds) are top risks for all modes and recommended priorities to progress. • Potentially widespread distribution of effects.	✓✓✓
Coastal erosion	High risk to road and coastal shipping	–	• Not a top five risk. • Only some coastal locations affected. • Significant costs likely for response options. • Particularly important for assets with a long design life.	✓✓✓
High winds	High risk to road and coastal shipping	–	• Top five risk to coastal shipping. • Most high risks can be mitigated at short notice; however, protecting ports may be difficult.	✓✓✓
Wildfire	High risk to rail	Rail risk may reduce to moderate	• Not a top five risk. • Wildfire is related to drought risk, which is expected to worsen significantly. Further consideration is warranted even though the 'true' risk may be moderate.	✓✓
Fog and humidity	High risk to all three modes	Risk may reduce to moderate	• Not a top five risk. • Risk can be mitigated within short time frame with little infrastructure investment required. • Little information for climate change projections is available.	✓
Snow and ice	High risk to road and rail	Risks may reduce to moderate	• Not a top five risk. • Vegetation control to mitigate rail risk (trees falling on lines) can be done at short notice and therefore forward planning is not required. • Actions in relation to large snow and ice events (blizzards) will generally be limited to maintenance (snow clearing, etc.). • More storminess is possible but little information for climate change projections is available.	✓
Lightning	High risk to rail	Risks may reduce to low	• Not a top five risk. • More storminess is possible but little information for climate change projections is available. • Electrical storms are uncommon so a large increase would be required before it would become a significant problem.	✓
Drought	No high risks identified	–	–	×
Low temperature	No high risks identified	–	–	×

✓✓✓✓ Highest priority
✓✓✓ High priority
✓✓ Moderate priority
✓ Low priority
× Not a priority

Adaptation studies rely on quantitative interpretations of how climate changes may affect weather-related events such as storm surge or flooding. Such calculations are fraught with large errors, statistical uncertainty and long timeframes of observation that are required to verify their development (New Zealand Climate Change Office 2001):

> *More than 50 years of observations would be required to test whether a '1-in-100 year' flood has in fact become more frequent and now occurs, for example, every 25 years. If the flood did become more frequent, substantial damage would occur while waiting 50 years for proof.*

Design philosophies will need to adapt to the changing databases and associated statistical analyses will need to take into account the projected incremental changes in the base datasets (Kouvelis 2008).

Uncertainty about the distribution and timing of climate change impacts at the local level makes judgments about the scale and timing of adaptation actions very difficult, particularly when seeking to weigh up the costs of climate change effects against the potential benefits of adaptation. Where climate change adaptation and other economic or social objectives share benefits, early action can get support. In other cases, limits on predictability tend to delay adaptation until scenarios and implications can be estimated better (Parry et al. 2007).

To evaluate the economic effectiveness of proposed adaptation options, decision makers need access to figures that represent the net costs of climate change. For example, Kinsella & McGuire (2005) in New Zealand assessed the potential cost implications of increased flood flows for state highway bridges and were therefore able to determine the cost-effectiveness of proposed adaptation options.

However, Parry et al. (2007) suggest that it is difficult to determine the levels of climate change effects or their costs with a specified number of degrees of mean global warming or with a particular time horizon (such as 2050 or 2080) when so many of the factors that influence these effects and costs are not directly climate related. Parry et al. also suggest adaptation studies to date lack adequate consideration of the complex flow of costs and benefits of adaptation measures throughout wider social and economic networks.

A study into the economic impacts of climate change effects on floods (Walton et.al. 2004) highlighted the importance of calculating and distinguishing economic (wider flow-on effects on society) from financial (direct asset damage) costs. Disruption to a lifeline utility such as the transport system was used as an example to demonstrate how an impact in one sector can have potentially significant consequences for the remainder of the economy through loss of productivity and diversion of public funds for disaster management and infrastructure repairs.

In this study, the limited information on monetary costs and benefits highlights the usefulness of MCA for prioritising adaptation options.

2.4 Adaptation

The IPCC has identified adaptability and adaptation as:

> *... the degree to which adjustments are possible in practices, processes or structures of systems to projected or actual changes of climate. Adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of changes in conditions*

Research has sought to distinguish the capability of the land transport system to be *reactive* and resilient to climate change conditions, and the extent to which *proactive* preparations for projected climate conditions are warranted. Adaptation will invariably occur in response to climatic events, but it needs to be demonstrated whether a reactive or proactive approach will provide value for money.

Reactive and proactive responses to flooding help to distinguish between the two types of adaptive responses. Flooding can cause significant disruption and damage to land transport networks. As climate change conditions are projected to result in higher mean temperatures, increases in mean rainfall in some locations, and potentially more frequent and/or intense rainfall events, transport managers have an opportunity to consider whether proactive adaptation to climate change effects is possible, cost-effective and consistent with stakeholder expectations.

Reactive responses to flooding, such as diverting traffic, engaging emergency works and repairs, seek to restore the affected network sections and enable the system to return to pre-event service capacity, albeit after necessary delays.

Proactive responses to flooding risk could include:

- preventing flooding by improving the rainfall capture and storage capacity of a catchment (e.g. by enhancing or mimicking the water storage capacity of the soil);
- increasing conveyance capacity to disperse floodwaters;
- creating policies to maintain existing levels of service which incorporate climate change factors at the time of repairs or upgrades;
- establishing physical protection measures, e.g. building stop-banks;
- managing the effects of flooding by removing at-risk land use such as infrastructure and the built environment in floodplains; and
- managing the expectations of communities in flood-prone areas to expect and cope with flood events.

Easterling et al. (2004) suggest proactive adaptation strategies are most effective when flexibility is built into adaptation so that it is effective under a wide variety of potential climate conditions.

The gaps in knowledge and capacity to understand potential effects of climate change that are identified in Chapter 10 of Volume One can act as barriers to implementing effective adaptation, for example:

- uncertainty in regional climate change projections, expected effects when climatic factors combine, and a lack of readily available high-resolution models of relevant effects;
- a lack of strategic direction from legislation and policy to drive adaptation; and
- a lack of sector-specific information sources and methodologies to assess how effective adaptation responses could be.

The IPCC note the range of technological, financial, cognitive and behavioural, and social and cultural constraints impeding flows of information and knowledge to decision makers (Parry et al. 2007).

Central government can play a role in adaptation by encouraging proactive adaptation mechanisms such as:

- knowledge and learning,
- risk and disaster management and response,
- infrastructure planning and development,
- institutional design and reform,
- increased flexibility of sensitive managed and unmanaged systems,
- avoidance of maladaptation, and
- technological innovation.

As stated in Parry et al. (2007), the central issue when adapting industry, settlements and societies for the effects of climate change is whether climate change impacts are likely to require responses that go beyond ‘normal’ adaptations to varying conditions. Analysis in Stage One of this research ranked climate risks to surface transport modes and examined barriers that might prevent adaptation from occurring.

In one example, industry capability was considered adequate to deal with the impacts of climate change on extreme high temperature and effects on road surface treatments. The reasonably short life of pavements, the resiliency of current pavement specifications to cope with increases of mean temperature of 1°C and 2°C over 50 to 100 years, respectively, and locally adaptable and regularly reviewed bitumen specifications were considered adequate by industry experts in a risk prioritisation exercise (see Chapter 6 of Volume One).

Development of adaptation strategies are motivated both by strategic planning, as demonstrated by Kinsella & McGuire (2005), but can also be triggered by relatively extreme weather events. In South Canterbury, flood levels for consideration in planning decisions were changed from 1 in 50 year flood levels to 1 in 500 year flood events following property damage and loss of life in a significant flood event in 1986.

Effective adaptation relies on cost-effective responses to accommodate predicted climate change effects. It is difficult to weigh up various performance and cost implications of transport infrastructure design and maintenance decisions, particularly in the face of an uncertain climate future and funding frameworks that focus on short timeframes and least-capital cost solutions. In a questionnaire undertaken for Stage One of this research, stakeholders were asked to describe perceived barriers to addressing the adverse impacts of climate change. Funding criteria was cited by all stakeholder groups as a barrier to climate change adaptation (see Appendix C of Volume One).

Local councils can face community resistance to higher capital costs of future-proofing transport infrastructure against predicted climate conditions (T. Moore, Christchurch City Council; S. Lamb, Environment Bay of Plenty: pers. comms.). Higher disturbance, maintenance and repair costs as a result of changing climatic conditions are also likely to be received less favourably by communities in future.

Proactive practices to adapt to climate variability have advanced significantly in recent decades with the development of operational capability to forecast the onset of El Niño and La Niña events related to El Niño Southern Oscillation several months in advance (Cane et al. 1986), as well as improvements in climate monitoring and remote sensing to provide better early warnings on complex climate-related hazards (Dilley 2000). Since the mid-1990s, a number of mechanisms have also been established to facilitate proactive adaptation to seasonal to inter-annual climate variability. These include institutions that generate and disseminate regular seasonal climate forecasts (National Oceanic and Atmospheric Administration 1999), and the regular regional and national forums and implementation projects worldwide to engage with local and national decision makers to design and implement anticipatory adaptation measures in infrastructure (NIWA produce three-month climate outlooks for all of New Zealand every month. The outlooks are available from http://www.niwa.co.nz/ncc/seasonal_climate_outlook).

An evaluation of the responses to the 1997–98 El Niño across sixteen developing countries in Asia, Asia-Pacific, Africa and Latin America highlighted a number of barriers to effective adaptation. These included: spatial and temporal uncertainties associated with forecasts of regional climate, low level of awareness among decision makers of the local and regional impacts of El Niño, limited national capacities in climate monitoring and forecasting, and lack of co-ordination in the formulation of responses (Glantz 2001).

Making regional climate change scenarios available to all regions around the country is an important step in addressing knowledge gaps. A national study of climate change assessments at a regional level (as conducted in this study) may identify areas of New Zealand that have not considered climate change implications for their region, including regional transport infrastructure.

3 Climate change effects and heat stress on rail

3.1 Study background

Track buckling during hot weather is a universal issue for rail operators, with high air temperatures being a significant contributing factor to such events. Figure 3.1 illustrates the severity of track buckling during a heat wave (Volpe National Transportation Systems Center 2008).

Figure 3.1 Track buckle illustrations (Source: Volpe National Transportation Systems Center 2008).

Volume One of this research contains a combined risk register that was compiled to identify the significant risks to the land transport network associated with projected climate change conditions. This vulnerability assessment identified that higher temperatures (mean temperatures and extreme highs caused by climate change) posed a high risk for the national rail network because of:

- sensitivity to the effects of heat such as heat buckling, speed restrictions and potential derailments; and
- exposure to greater maintenance pressures in order to adapt the network to an intensifying heat environment.

A study was therefore conducted to determine what impact climate change may have on the incidence of heat buckling on the rail network in response to the expected greater magnitude and frequency of extreme temperatures and related heat wave events. The focus was to identity any regional impacts where increased heat stress may occur and the likely timeframe over which they may emerge, and to propose adaptation measures appropriate for the affected regions.

3.2 Rail buckling and temperature extremes

Extreme variations in rail temperature are responsible for a number of stress-related defects. Tracks are pre-stressed following installation to withstand a specified temperature range. Should the range be exceeded, the track may buckle in hot weather, requiring additional maintenance and possible speed restrictions. At high ambient air temperatures, expansion of rails can contribute to rail buckling in the presence of at least one other factor, such as a lack of ballast, low strength sleepers and fastenings, or a rail stress-free temperature (SFT)[2] that is too low to cope with ambient air temperatures (Chapman et al. 2005).

One issue is that once track has been laid, the SFT does not remain constant. The stress resistance of continuous welded rail (CWR) track deteriorates over time as a result of maintenance, the natural deterioration of the track components and the variable quality control of CWR-related activities. The track therefore becomes overstressed (reduced SFT) and prone to buckling at a lower temperature. For this reason, rail operators may periodically de-stress sections of CWR track to regain the loss in SFT before the onset of seasonally high temperatures.

Over the last decade, New Zealand's rail track operators have made concerted efforts to identify and stabilise sections of track susceptible to buckling (so-called 'at-risk' sites). Untreated at-risk CWR track lengths are subject to 40 km/hr speed restrictions whenever risk temperature thresholds are exceeded during the summer months. (Conversely, some of the same sites are subject to disruptions from weld failures, joint pull-apart and rail breaks through the winter months when the rail contracts).

Heat stress on rail is managed by rail operators in New Zealand and internationally via a range of mechanisms such as:

- specifying asset materials and maintenance standards to withstand heat and track load conditions, including the ability to vary rail de-stressing conditions in the summer season as temperatures rise;
- heat gauges to monitor rail temperatures;
- monitoring and inspection; and
- speed restrictions.

[2] Stress-free temperature (SFT) is the temperature where no thermal forces are acting on the rail. It is also referred to as the rail neutral temperature.

3.3 Approach and methodology

3.3.1 Background

Stage One recommended conducting this study for the rail network in the northern part of the North Island, as this area was expected to be at greatest risk of heat buckling, based on a projection of where the highest temperatures would be most felt under climate change. However, the study was later widened to consider the whole rail network after the current distribution of heat buckling events was found to be scattered across the country.

The initial approach planned to identify and plot all heat-related buckling events that have affected the rail network and to analyse the temperature parameters for each event retrospectively in order to establish a relationship that could be use to predict the occurrence in future years under different climate change scenarios. While the plot of current heat buckling events was completed, this approach proved to have too many variables and was not pursued.

An alternative and simpler approach was adopted, following a literature review, which broadly comprised the following steps:

- determining the relationship between air temperature and rail temperature (literature review),
- establishing a critical rail temperature for heat buckling under New Zealand conditions,
- estimating the equivalent threshold air temperature for risk of onset of heat buckling,
- predicting the distribution of the threshold temperature under defined climate change scenarios, and
- identifying which parts of the rail network may exceed the threshold temperature in future years.

Details of the data inputs and methodology used are described below.

3.3.2 Collation of existing rail heat buckle events

Previous data relating to heat buckling events and ambient air temperatures were sought from ONTRACK to identify temperature conditions that have caused heat-related events. Track defect records, including incidence of heat buckling, are stored within ONTRACK's IRIS (Incident Reporting Information System) database.

The database was searched for the period from 1 July 2004 to 30 September 2008 to obtain a list of all heat buckling events that had occurred on the national rail network, including date and location. The data were sorted by year and geo-referenced using a grid of 'kilometrage' datum pegs, and the affected track sections were plotted on a GIS map of the national mainline rail network.

3.3.3 Development of climate data set for rail temperature analysis

A climate dataset was developed by intersecting the national rail network mapped with air temperature data (measured at 1.2 metres above ground surface) from NIWA's Virtual Climate Station Network. This segments the track into five-kilometre thermal zones which serve as the geographic basis for analysis. The dataset contains daily maximum and minimum temperatures for the three time scenarios, and uses a mid-range GHG scenario (referred to as A1B) to project temperature patterns in the 2040s and 2090s (refer to Section 3.1 and Appendix B of Volume One for details about climate model considerations and methodology).

3.3.4 A risk model for heat buckling

A literature review identified a rail track temperature and heat buckling risk model that has been developed under United Kingdom (UK) conditions (Chapman et al. 2008). The UK model was developed to determine the role of maintenance standards in exposing rail to a risk of heat conditions that may necessitate temporary speed restrictions.

The model uses the concept of a Critical Rail Temperature (CRT) to define a rail temperature above which buckling problems may arise. The CRT is defined in terms of the rail SFT, which represents the temperature at which the rail experiences zero longitudinal force. An example of CRT standards used in the UK for track in good and poor states of repair is given in Table 3.1 (Chapman et al. 2008).

Table 3.1 UK CRTs for track in good and poor states of repair.

Track condition	On standby [a]	Preventative measures	
		Impose 30/60 mph speed restrictions	Impose 20 mph speed restrictions
Good condition	SFT + 32°C	SFT + 37°C	SFT + 42°C
Poor condition [b]	SFT + 10°C	SFT + 13°C	SFT + 15°C

Notes to Table 3.1:
a) SFT is normally 27°C in the UK.
b) e.g. inadequate ballast

The UK model involves estimating rail track temperature from air temperature using a multiplier of 1.5 and then determining the probability of requiring a temporary speed reduction in the event of high temperatures that are conducive to risk of buckling. The probability is determined on the basis of whether the CRT will be exceeded.

The UK model was applied to the New Zealand rail network using two maintenance thresholds:

- CRT = SFT+13°C representing track in poor repair ('low condition'), and
- CRT = SFT+37°C (representing track in good order ('high condition').

These parameters were derived for the United Kingdom rail network. While it is unlikely that they will have direct applicability outside this environment, the model was applied in this research study in the absence of a local equivalent model. The results of this analysis for the New Zealand rail network, using the UK rail track temperature and heat buckling risk model, are summarised in Section 3.5.1.

3.3.5 Determination of air temperature threshold for heat buckling in New Zealand

Given the limitations of the UK-based parameters used in this analysis, an attempt was made to establish an air temperature threshold for onset of rail heat buckling under New Zealand conditions. Determining this threshold was essential in order to model the effect of increasing air temperatures, and therefore the risk of heat buckling risk, under climate change conditions.

The basis for this threshold was the relationship between ambient air temperatures and CRTs in New Zealand. Assuming a rail neutral temperature of 32°C in New Zealand, the CRT was determined as follows:

$$CRT = SFT + 13°C = 45°C \qquad \text{Equation 1}$$

(The 13°C buffer was based on the initiation of speed restrictions under 'low condition' as per UK CRT standards for initiation of speed restrictions – refer to Table 3.1 above). The threshold air temperature ($T_{threshold}$) beyond which the CRT is assumed to be at risk of exceedance was then calculated from:

$$T_{threshold} = CRT/1.5 = 30°C \text{ (expressed as a maximum daily temperature)} \qquad \text{Equation 2}$$

3.3.6 Seasonal effects of temperature change

To assess the potential impact of climate change on the seasonal spread of temperatures conducive to heat stress, seasonal occurrences of air temperatures exceeding 30°C were calculated. These were expressed as the number of days projected to exceed 30°C across each month for the base period (1970–2000), and the 2040s and 2090s, based on the A1B GHG scenario.

3.3.7 Sensitivity analysis

Given the uncertainty in the relationship between air temperature, CRT and heat buckling events, a sensitivity analysis was undertaken. This examined the change in days from the 1970–2000 base (national average), given different design thresholds (15–35°C) and magnitudes of mean temperature increase (0–3°C).

3.3.8 Data limitations

ONTRACK's IRIS database was a useful source of information about the location and timing of heat buckling events. However, representatives of ONTRACK advised that events recorded in IRIS were only partially representative of heat buckling risks, as preventative maintenance practices responded to approximately three times as many heat risk sites around the network as are measured in IRIS. Records of these 'near miss' events were not accessible during this research programme.

Similarly, records of heat gauge or rail thermometer readings were not accessible during this study; therefore a rail and ambient air temperature relationship was not able to be developed using real-time data records.

3.4 Current incidence of heat buckling on the rail network

The distribution of heat buckling incidents recorded by ONTRACK in their IRIS database over the last four years is shown in Figure 3.2.

Approximately 78 discrete events have been recorded, although some of these are located in close proximity and hence are not distinguished in the national plot. In most cases, a short length of track was affected but the defect may also occur in other heat-vulnerable sections such as points (switches). Based on the available records from July 2004 to September 2008 in ONTRACK's IRIS database, it is estimated that approximately 680 kilometres of track were affected by heat buckling defects in this period.

From a seasonal perspective, most events occurred in summer (December–February, inclusive), with the highest number recorded in the summer of 2004/05 (21 records) and the summer of 2007/08 (19 records). For years where full records are available, the IRIS records indicated a reducing trend in heat buckling: 32 incidents in 2005, 11 in 2006 and 6 in 2007. However, 24 events were noted in 2008 (up to September, the date of the report, and therefore excluding the higher risk months of October, November and December), indicating that the issue is exacerbated by years with extreme hot weather.

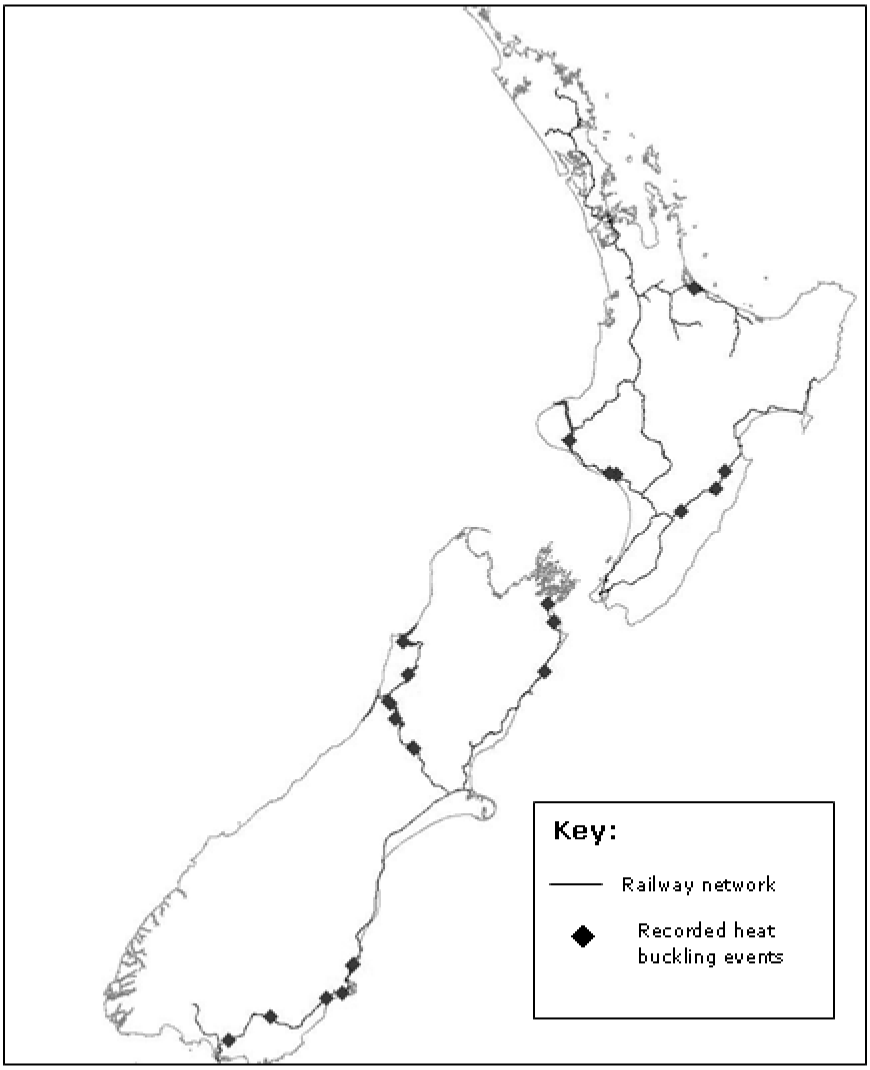

Figure 3.2 Distribution of rail track heat buckling events from July 2004 to September 2008 (Source: ONTRACK's IRIS database).

A significant aspect of this plot is that heat-induced buckling of tracks is widely distributed around New Zealand. From a regional perspective, the plot shows roughly five areas or lines where buckling has been most frequently identified:

- Invercargill to Dunedin (Main South Railway),
- Westport via Arthur's Pass (Midland Line),
- Kaikoura to Blenheim (Main North Railway),
- Masterton to Hawkes Bay (Palmerston North–Gisborne Line (PNGL)), and
- Wanganui to New Plymouth (Marton–New Plymouth Line (MNPL)).

Typically, heat buckling incidents are investigated by a ganger called out to make an inspection after the defect is reported (e.g. by a train driver or track maintenance team). The location of these events is found both within and outside designated heat restriction areas (where temporary speed restrictions (TSRs) are in force on the line).

In some cases, the buckling results in a train stoppage and delay while the track is cleared. Heat alarms have been placed alongside the track in known heat-sensitive areas in order to give warning or to allow pre-emptive maintenance, and thus avoid the track defect. Records show that this is not always infallible as in some cases, the heat alarm is not activated.

For safety reasons, heat restricted sections extend well beyond the actual length of track affected. In the UK, Chapman et al. (2008) note the practice of applying widespread TSRs when only a small section of track may contain conditions at risk of buckling in hot conditions. ONTRACK estimates that approximately 1000 of the 4160 kilometres comprising the national mainline network are subject to heat-risk related speed restrictions.

Figure 3.3 demonstrates the current effect of TSRs on freight movements in New Zealand using an index of lost time from TSRs, weighted by net tonnage of freight affected. Whether the index fluctuations are a result of greater freight volumes or increased heat-sensitive sections of the network is unclear. However, these statistics indicate that the heat buckling phenomenon is potentially a significant business risk to the rail network in New Zealand.

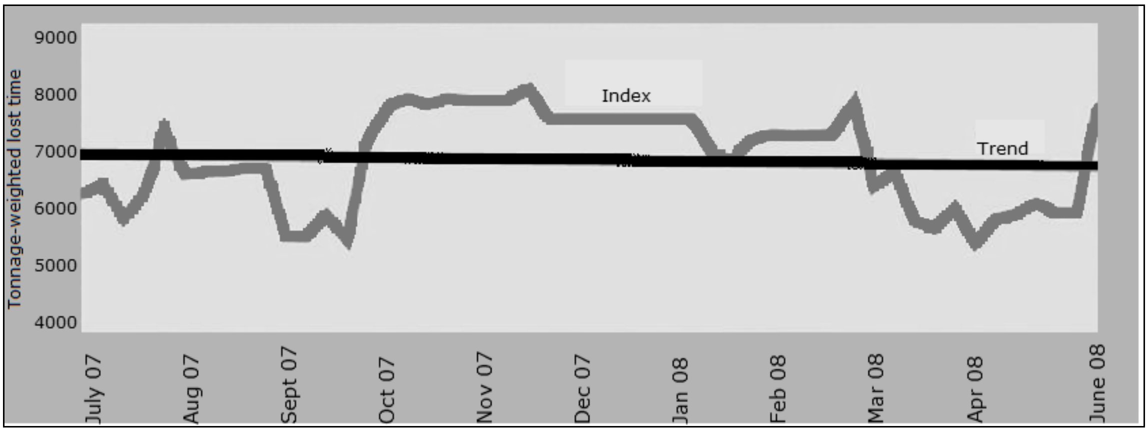

Figure 3.3 Index of temporary speed restrictions (TSR) lost time, weighted by net tonnage of freight affected (Adapted from ONTRACK's annual report (ONTRACK 2008a)).

3.5 Risk of heat buckling from climate change

3.5.1 Results from applying the UK rail risk model

The results of analysing the New Zealand rail network using the UK rail track temperature and heat buckling risk model are summarised in Table 3.2.

Table 3.2 Days per year (national total) triggering a speed restriction on New Zealand rail travel[a] for predicted temperatures.

Scenario	Base[b]			2040			2090		
	5th	Mean	95th	5th	Mean	95th	5th	Mean	95th
National mean track temperature (°C)	25.5	21.6	28.9	22.8	26.9	30.5	24.1	28.6	32.9
High condition	0	0	0	0	0	0	0	0	0
Low condition	1	6	20	7	13	29	4	23	49

Notes to Table 3.2:
a) Based on UK CRTs – see Table 3.1.
b) Table shows the 5th percentile, mean and 95th percentile of the twelve-model climate change scenario ensemble.

Under the thresholds used for high (good) track condition, the risk of a speed restriction being placed is negligible. Even under the most extreme climate change scenario used in this study – a 33°C national average track temperature (the 95th percentile in 2090; Table 3.2) – no speed restriction days were predicted. Under the low condition (poor track) threshold, speed restriction days ranged from a low of seven days for the least extreme scenario in 2040 through to 49 days for the most extreme climate scenario in 2090.

Although the analysis is based on parameters developed for the UK, the results in Table 3.2 highlight the key influence of track condition and maintenance in determining the risk of rail heat stress rather than effects of increasing temperature. They also show that it should be possible to mitigate the physical risks of rail heat buckling in New Zealand, even under the worst climate change scenario.

3.5.2 Predicting rail buckling risk using air temperature threshold

Maps showing the regional distribution of the number of days exceeding a maximum daily air temperature of 30°C (representing the assumed air temperature threshold for onset of heat buckling in the New Zealand rail network) are presented in Figures 3.4–3.6.

The probability of maximum daily air temperatures exceeding 30°C was used as a basis for future risk projections of heat buckling. This was expressed as the frequency and distribution of days/year >30°C, and was modelled across three time scenarios:

- 2010 base case (generated from historical data covering the period 1970–2000),
- 2040 projection (20-year period centred on 2030–2049), and
- 2090 projection (20-year period centred on 2080–2099).

The results are presented as maps in Figures 3.4–3.6.

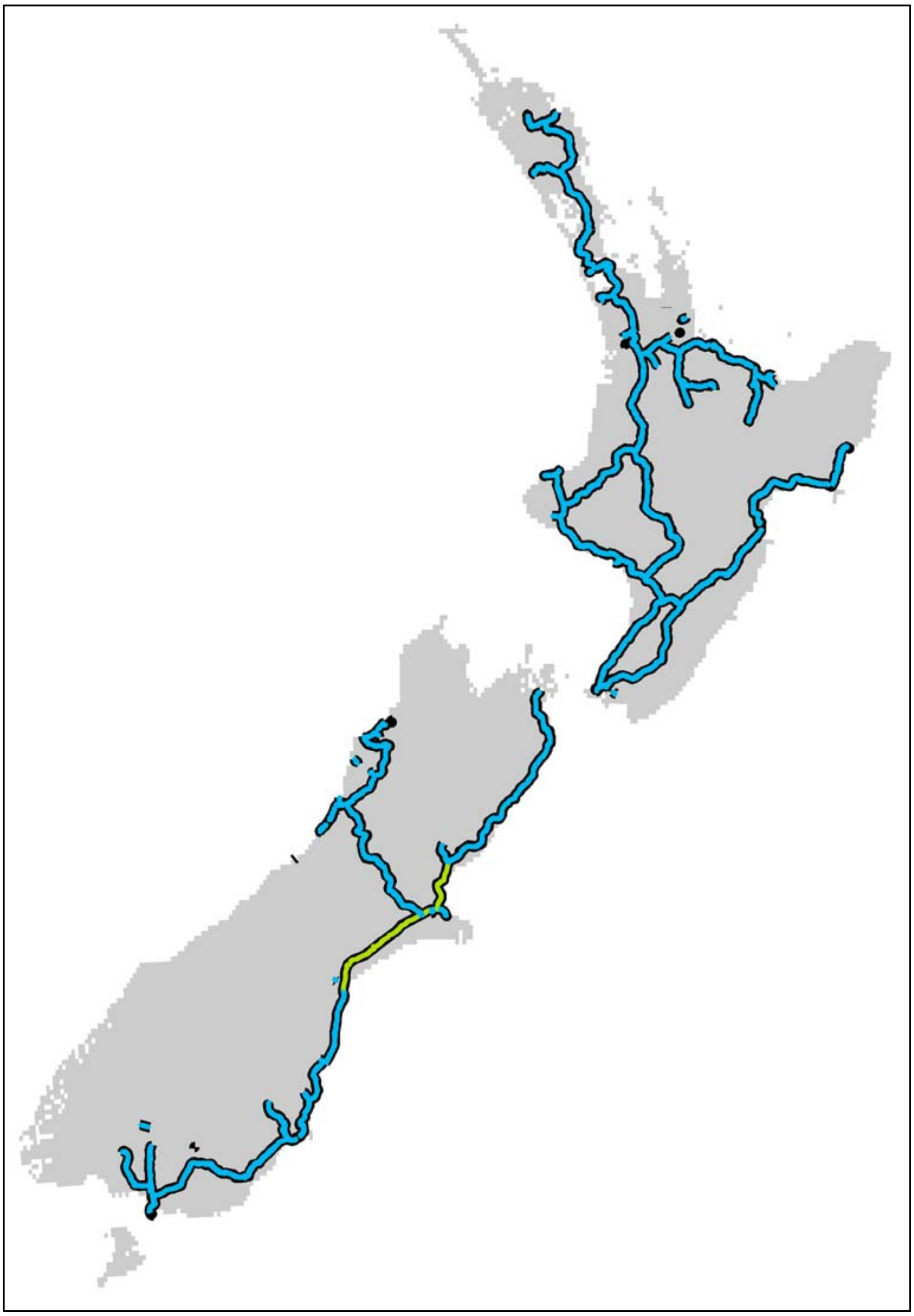

Figure 3.4 Predicted number of day with air temperatures exceeding 30°C throughout the national rail network for 1970–2000, based on meteorological records.

Key:

blue = 0–5 days per year,

green = 5–10 days per year,

orange = 10–20 days per year,

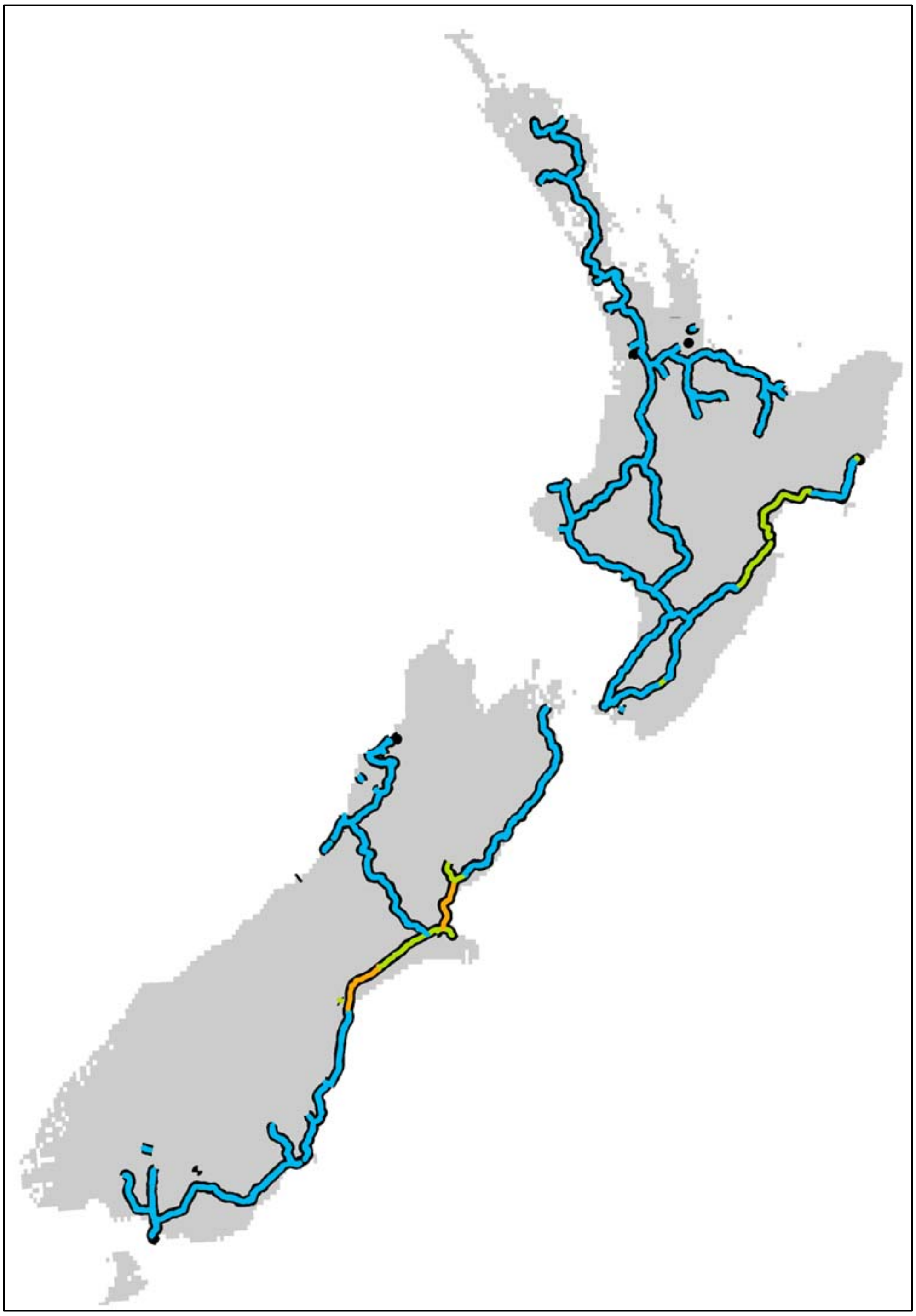

Figure 3.5 Predicted number of day with air temperatures exceeding 30°C throughout the national rail network for 2040, based on an average over twelve climate change models for an A1B emission scenario.

Key:
blue = 0–5 days per year,
green = 5–10 days per year,
orange = 10–20 days per year,

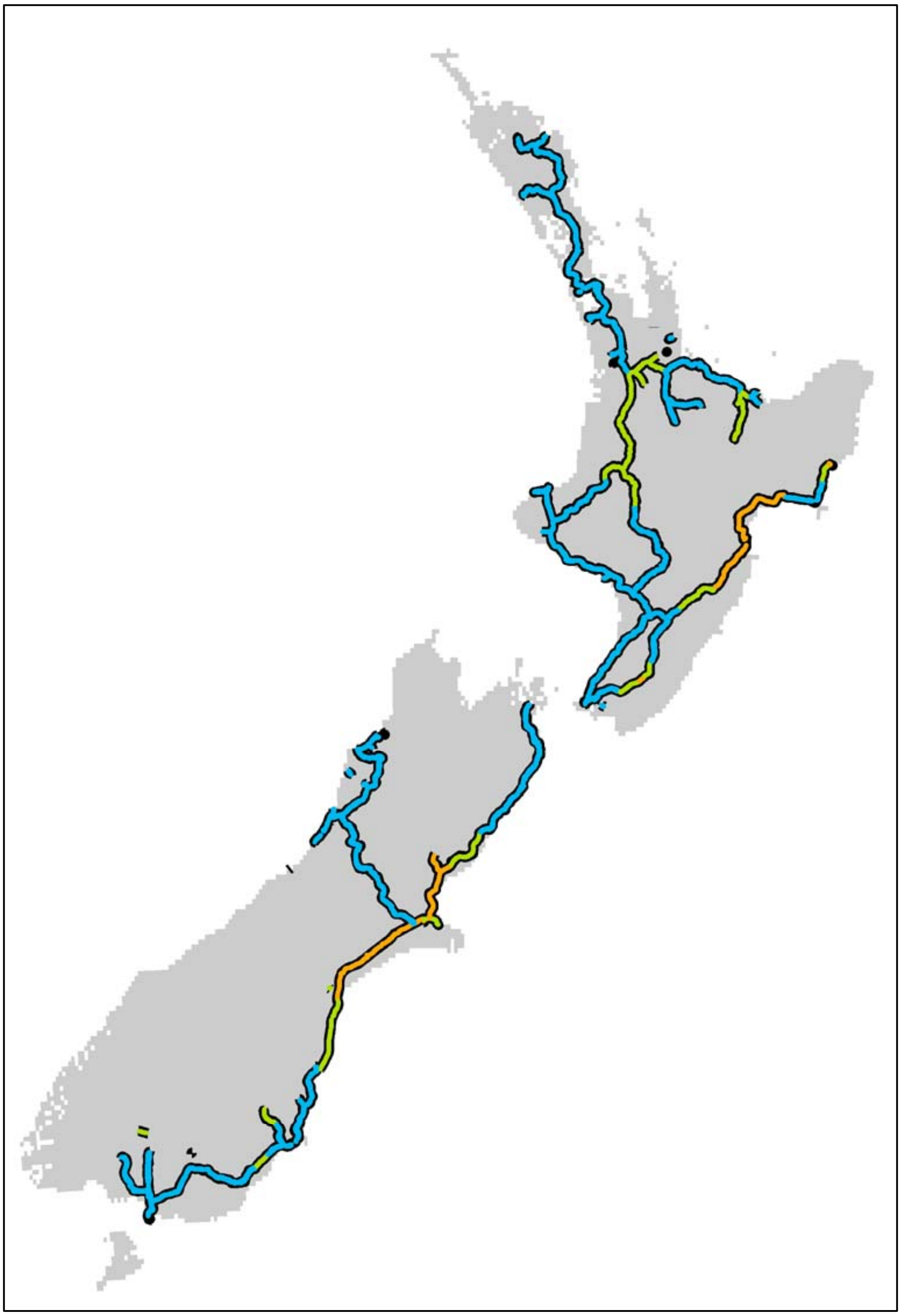

Figure 3.6 Predicted number of day with air temperatures exceeding 30°C throughout the national rail network for 2090, based on an average over twelve climate change models for an A1B emission scenario.

Key:
blue = 0–5 days per year,
green = 5–10 days per year,
orange = 10–20 days per year,

The base year map (Figure 3.4) shows 0–5 days per year exceeding 30°C for most of the rail network, rising to 5–10 days for tracks in the coastal Christchurch region. No areas experience more than ten days per year at these temperatures. By 2040 (Figure 3.5), an increase in mean temperature should shift the distribution, with Hawkes Bay now experiencing 5–10 days over 30°C and the coastal areas around Christchurch experiencing 10–20 days >30°C per year. By 2090 (Figure 3.6), the track sections with the highest exposure to extreme air temperature (and therefore risk of heat buckle) appear to be coastal Canterbury in the South Island and Hawkes Bay in the North Island (both 10–20 days per year), with a higher number of days above 30°C appearing for Waikato and Wairarapa.

The air temperature threshold is a broad assumption for the track design threshold for the New Zealand rail network. However, the use of a 30°C ambient air temperature as an indicative threshold for rail heat stress will not be valid for all sections of the national track, as actual design temperatures are known to vary depending upon standards, materials and build practices at the time of construction, as well as ongoing maintenance schedules (ONTRACK pers. comm.; Chapman et al. 2008).

This appears to be reflected in the study findings where the regions experiencing high air temperature projections in Figure 3.4 (above which a risk of heat buckling is possible) do not align with the distribution of known rail buckling incidents reported by ONTRACK (Figure 3.2). Numerous incidents have been reported outside of the Canterbury, Hawkes Bay, Waikato and Wairarapa sections. This finding reinforces the premise that track design and maintenance criteria are likely to be larger influences on rail buckling risk than climate variability.

The trigger for heat buckling depends on a range of variables (including air temperature), which means that predictions based solely on changes in air temperature as a result of climate change (as discussed above) will not be a robust indicator of the actual risk. However, the predictions documented in this study may indicate where such effects are more likely to materialise on a regional basis, and therefore where more vigilance in track maintenance and monitoring may be warranted.

3.5.3 Seasonal effects of temperature change

The seasonal distribution of days exceeding 30°C is shown Table 3.3.

Table 3.3 Seasonal distribution of days exceeding 30°C.

Year	Month											
	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Base	0	0	0	0	1	3	3	1	0	0	0	0
2040	0	0	0	1	2	5	5	2	1	0	0	0
2090	0	0	1	2	3	7	8	2	3	0	0	0

Stratifying the number of days exceeding 30°C by month reveals an increase in the length of the summer season, where for the 2040 and 2090 climate change scenarios, a number of days exceed 30°C during October, November and April. Days exceeding the 30°C threshold in these months were not observed during the base period. The implication is that New Zealand could experience a broadening (i.e. earlier start and later finish) to the summer season (when the risk of rail buckling typically occurs) as the effects of climate change take hold later this century.

3.5.4 Sensitivity analysis

The response surface in Figure 3.7 provides a means to explore the interaction between track design temperature (air temperature threshold) and the risk of heat buckle from climate change.

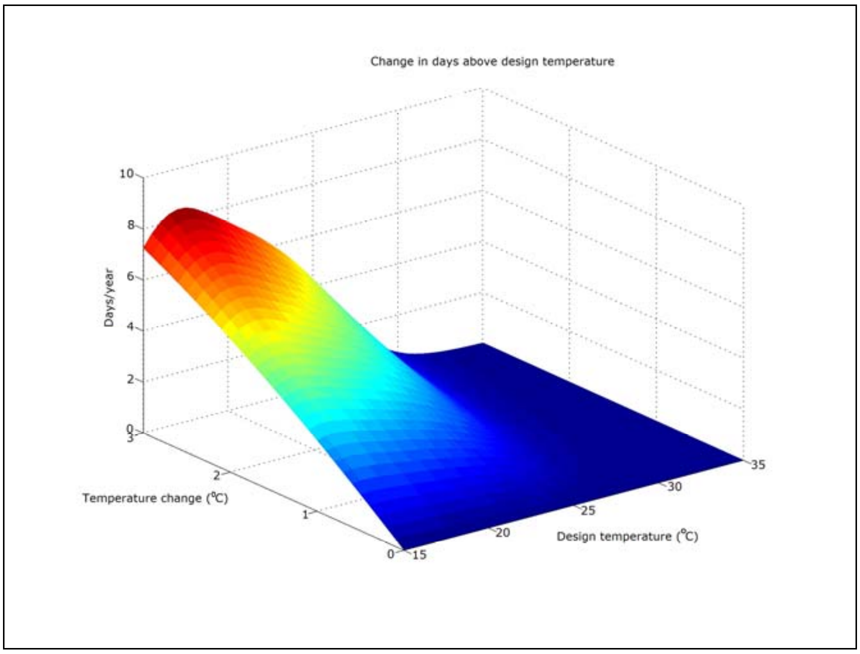

Figure 3.7 Interaction between rail track design temperature, temperature change and days per year above the design temperature.

The relationship shows that for design temperatures above 30°C, almost no increase occurs in days exceeding this threshold, even for a change in mean temperature of 3°C (an extreme climate change for New Zealand). In other words, in meeting a design temperature of 30°C, climate change will play a minimal role in influencing the risk of heat buckling, even in areas subject to the highest temperatures.

However, if design temperatures are around 20°C, buckling risk would increase greatly under the same magnitude of climate change. The response surface starts to decrease as design temperatures near 15°C. This is because at these low design temperatures, the risk in the base period is similar to the risk in the climate change period.

3.6 Heat stress adaptation strategies for the rail network

3.6.1 Strategic context of rail

The government's investment in the passenger and freight rail networks through ONTRACK was emphasised following the repurchase of rail operations on 30 June 2008. A major investment programme in passenger and freight rolling stock (such as locomotives and carriages) is being implemented through KiwiRail.

ONTRACK's Statement of Intent (2008b) notes the $200 million of government funding committed to improve New Zealand's rail infrastructure following a substantial period of under-investment. Greater funding will allow for more maintenance. In the interim, more maintenance may result in more instability in the track network until repairs 'settle in', thus necessitating more speed restrictions to manage vulnerabilities to heat. Limiting maintenance to avoid the heat season may put more pressure on resources to complete more maintenance during the optimal season.

The New Zealand Transport Strategy (NZTS) (MoT 2002) proposes increasing the mode share of rail and coastal shipping for moving freight due to their greater energy efficiency compared with road or air transport (and the fact that they emit less carbon dioxide per tonne-km). A shift to rail and sea modes would also reduce the level of demand for the use of roads. Targets in the NZTS (MoT 2002) expect an increase in rail's share of freight movements from 18% (currently) to at least 25% by 2040. This will result in triple the current level of freight being carried via rail by 2040.

Rail corridors will be considered along with other modes in determining critical routes with the aim of achieving no overall deterioration in travel times and reliability on critical routes by 2015. The Government Policy Statement on Land Transport Funding (New Zealand Government 2008) allows approximately $5m over three years (2009/10–2011/12) for short-term operational subsidies to support the switch of freight movement from road to rail or coastal shipping.

Under these conditions, using TSRs to manage track buckling risk may be inconsistent with other strategic drivers. In this context, it is noteworthy that ONTRACK's 2008 annual report (ONTRACK 2008a) highlighted work to identify the cause of TSRs on key routes and to develop an action plan to eliminate them.

3.6.2 Priority adaptation responses

Although higher temperature extremes are predicted to occur in New Zealand because of an incremental increase in mean temperature (a rise of 1°C by 2040s; 2°C by 2090 (MfE 2008a), the analysis of heat stress risk based on modelling rail threshold temperatures suggests that as long as design temperatures exceed 30°C, the risk of increased heat buckling from climate change will be minimal, even in areas subject to higher temperatures, as long as the track ballast is in good condition. This is a key finding of the rail heat stress study and will dictate the need for, and the nature and timing of climate change responses.

The objective of future adaptation responses for the rail network to heat stress should be to ensure robust track formation standards and maintenance systems are directed at priority rail routes. Insufficient data prevent an analysis of trends in heat buckle frequency over recent years. However, the national distribution of current heat buckle events (Figure 3.2) suggests that progress has been made in achieving this goal. Nevertheless, the index for lost time from TSRs (Figure 3.3) suggests efficiencies can be gained by making the rail network more resilient to heat stress in summer months.

Based on published studies, track and ballast maintenance standards are the key determinants for ensuring the rail network is resilient to increasing temperatures. Managing the risk of heat buckling conditions from an anticipated greater frequency of extreme temperatures under climate change may therefore be achieved by adjustment of the existing maintenance regime. This would include, for example, adjusting the existing track maintenance and de-stressing regime to achieve the optimum SFT in affected regions of the network.

This accommodating maintenance regime is the approach ONTRACK is taking in their short- to medium-term asset management strategy, drawing, where necessary, on experience from colleagues in rail companies operating in hot climates such as across the Tasman (Rushbrook, pers. comm.).

Resourcing and efficiently managing the necessary track de-stressing and maintenance regimes is also likely to be a key challenge for the rail network in adapting to future heat stress conditions. This will require prioritisation of areas at greatest risk in order to achieve optimum results from limited resources. This approach is in accordance with ONTRACK's strategic rail asset management programme (Rushbrook & Wilson 2007).

An MCA of adaptation options for heat effects on rail (see Appendix A) lists a number of adaptation responses (HE1 to HE6) and provides inter-linkages between each action and their relative priorities. Operational initiatives dominate the potential adaptation responses available to minimise the risk of heat effects on the national rail network.

Some research initiatives may also be beneficial in targeting where maintenance should be directed. These could include, for example:

- GIS mapping of existing CWR and jointed tracks, heat sensors and heat-restricted sections to assist optimisation of track maintenance schedules;
- modelling of rail temperatures to optimise the configuration of the existing heat gauge monitoring network; and
- development of a daily rail temperature forecasting tool for managing extreme temperature events (see Section 3.8).

3.7 Conclusions

This study has attempted to determine the likely regional impact of heat buckling on the national rail network caused by an increasing risk of extreme temperatures associated with climate change. The following conclusions are drawn:

- Rail heat stress and resultant track buckling is mainly a summer phenomenon on New Zealand's mainline network that can cause speed restrictions and service delays. ONTRACK estimates that about one-quarter of the 4160 km of track is subject to heat-induced TSRs.
- A plot of recorded heat buckling events over the last four years shows that while the effect may occur across New Zealand's rail network, the regions most affected are track sections between Invercargill to Dunedin, Westport via Arthur's Pass, Kaikoura to Blenheim, Masterton to Hawkes Bay, and Wanganui to New Plymouth.
- A UK heat buckling risk model applied to the New Zealand rail network found that for track in 'good condition', no speed restriction days were predicted, while under 'poor track conditions', the range was from a low of seven days (the least extreme scenario in 2040) to 49 days (the most extreme in 2090). The results indicate the key influence of track maintenance in determining the risk of rail heat stress rather than effects of increasing temperature, even under the worst climate change scenario.
- Regional climate change predictions based on the number of days >30°C (the assumed threshold for heat buckling risk) show temperature 'hot spots' in Canterbury (from 2010), Hawkes Bay (from 2020), Waikato and Wairarapa (by 2090). The highest exceedances (in 2090) relative to the base year for networks on the east coast correspond to an increase of between 10–15 days per year. Caution is needed in assuming tracks in these regions experience a greater risk of heat buckling under climate change, as actual design temperatures vary depending upon maintenance standards.
- The sensitivity analysis shows that for track design temperatures above 30°C, almost no increase occurs in days exceeding this threshold, even for a change in mean temperature of 3°C (an extreme climate change for New Zealand), as long as the track ballast remains in good condition. A key finding of the study is therefore that by optimising the design temperature and achieving a high standard of maintenance, climate change will play a minimal role in influencing the risk of heat buckling, even in areas subject to the highest temperatures.
- Conversely, under low (poor) track conditions (which are likely to occur for parts of the network), the mean number of speed restriction days is predicted to double

from a base year of 6 per year to 13 days per year in 2040, and increase to 23 days per year by 2090.

- Seasonal considerations of the number of days exceeding 30°C in future scenarios suggest that the summer season, when the risk of rail buckling typically occurs, could start earlier and finish later as the effects of climate change take hold later this century.
- Track maintenance criteria are likely to have a larger influence on rail buckling risk than climate variability. Managing any emerging risk of heat buckle from more extreme temperatures under climate change may therefore be met by adjustment of the existing track maintenance and de-stressing regime to achieve the optimum rail neutral temperature in affected regions of the network.

3.8 Future considerations

In an assessment of measurement, modelling and mapping options to predict rail temperature in the UK, Chapman et al. (2008) expect that developing and applying a rail weather information system to monitor and forecast weather conditions for the rail network would enable the accurate prediction of rail temperatures. This would provide decision makers with a valuable tool to manage temperature-related track problems, delays and costs.

Potential benefits of this system include:

- deploying rail staff at appropriate times to the appropriate locations to monitor rail temperatures; and
- targeting speed restrictions where needed as opposed to applying widespread restrictions.

ONTRACK indicated during this study that they intend to integrate a weather forecasting tool into their track condition monitoring system. Such a tool could be developed, for example, from NIWA's EcoConnect environmental forecasting system.

In another forward-looking development, Lemmen (2004) suggests information about atmospheric and other physical conditions may be integrated with Intelligent Transport Systems such as automated traffic control and traveller advisory systems.

Other countries' responses to hot conditions may provide opportunities for ONTRACK to identify appropriate modifications to rail network systems to manage heat stress. A recent press release from the Chief Executive Officer and Managing Director of Australian Rail Track Corporation Limited (Marchant 2008) described an objective to install concrete sleepers within 90% of the north-south line between Melbourne and Brisbane to reduce the impact of heat-related restrictions on the line. Replacement of aged wooden sleepers with concrete units under a capital works programme for priority sections most at risk from heat stress may be a viable option in New Zealand.

4 Climate change effects and coastal land transport infrastructure

4.1 Study background

With 18 000 kilometres of coast, and significant urban development and land uses in coastal areas throughout New Zealand, transport infrastructure in the coastal zone is an important connector to communities and industries, and a vital lifeline to the country as a whole.

Coastal transport networks in some parts of New Zealand are currently at risk from coastal flooding related to storm surge. Rising sea levels, coupled with higher and potentially more frequent storm surges associated with climate change, are set to increase this risk, with potential for associated infrastructure damage and service interruptions.

Volume One contains a combined risk register which was compiled to identify the most significant risks associated with climate change conditions. The potential effects of climate change and coastal inundation on state highways, the railway network and ports were identified as a high risk to the national land transport network from predicted climate change conditions.

The outcome of a vulnerability assessment and risk analysis conducted in Stage One identified coastal flooding impacts as potentially posing a high risk to all three modes. Climate change effects on coastal land transport infrastructure were identified as a priority for Stage Two of this research for the following reasons:

- Important transport assets with long design lifetimes are located in the coastal zone.
- Only some coastal transport sections are likely to be potentially at risk from inundation because of varying topography and landforms; identifying these areas would provide a regional perspective of this risk and allow prioritisation of regional risk assessments for subsequent study.
- Several of New Zealand’s critical multi-modal (road and rail) coastal networks traverse narrow corridors where steep inland topography pre-empts alternative inland routes other than tunnelling (e.g. the section from Kaikoura to Christchurch); these transport corridors require an in situ adaptation response and their identification is seen as a priority.
- Inundation caused by storm surge was listed in the top five risks for ports and coastal shipping.
- Significant costs could result from adaptation options and thus it is important to ensure that adaptation responses are only provided to locations most at risk.

The purpose of this study was to conduct a high-level regional profile of New Zealand’s coastal road and rail networks and ports to identify which regions are potentially most at risk from inundation caused by sea level rise and storm surge, based on their elevation with respect to mean sea level. The focus was on identifying regional impacts where increased inundation risk may occur and the likely timeframe over which this may emerge, and to propose adaptation measures appropriate for these affected regions.

4.2 Approach and methodology

4.2.1 Background

An initial review in Stage One established that available national elevation datasets are unlikely to be available to support precise analysis of coastal sea level rise or inundation from flooding for a national profiling exercise across New Zealand. Lack of high-resolution topographic data with full national coverage was confirmed at the start of Stage Two and an alternative approach therefore had to be developed based on the data that were available.

The adopted approach identifies those coastal sections of the national state highway, local roads and rail networks that currently are situated in low-lying areas (elevation <5 m with respect to mean sea level), and are therefore potentially at risk of inundation from sea level rise associated with climate change. A broad estimate of risk is determined as the total length of network within this elevation. Finer resolution within the 0–5 m band was not possible owing to a lack of high-resolution topographic data, and hence the method is not able to map risk contours corresponding to different sea level rise/storm surge scenarios.

Sections of road or rail that are situated within the 5 m elevation contour are, of course, not necessarily prone to inundation. Only a proportion of the network within the 5 m zone is expected to be situated at the lower end of this range where the combined effects of sea level rise and storm surge are likely to be experienced (assumed to be no more than 2–3 m above mean sea level for a 100-year scenario). Furthermore, the network within the 5 m zone may be protected by sea wall defences or may be elevated with respect to the surrounding land e.g. situated on an embankment or bridge. On the other hand, risks to coastal transport routes may accrue well before inundation occurs. For example, potential increases in storm surge may increase coastal erosion, leading to a weakening of embankment structures or local cliff subsidence.

The topographic risk profiling described in this section is therefore intended to provide a high-level ‘first cut’ of potentially vulnerable coastal road and rail sections, and to point to where further site-specific risk analysis could be considered.

The following sections include a review of available data sources for the inundation risk study, the methodology adopted and an example showing how the method is applied at the regional level, along with a brief discussion on the adequacy of the satellite topography data used to derive national metrics for the inundation risk profile of the surface transport networks.

4.2.2 Basis for determining inundation risk

For the purposes of this high-level study, determination of the risk of inundation of the coastal road or rail networks involved comparing the elevation of each part of the network infrastructure to a critical elevation below which adverse effects are expected. All parts of the network situated below the critical datum are then assumed to be potentially at risk, irrespective of whether any protection measures (e.g. sea wall defences) are in place.

Depending on data availability, two approaches may be followed:

- comparing the absolute elevation of the road pavement or rail track to the critical elevation (direct method), or
- comparing the coastal topography through which the road or rail traverses with the critical elevation (indirect method).

The direct method provides a more definitive assessment of assets at risk but requires accurate, high-resolution network elevation data. In the absence of such data, the indirect method may be used to determine whether a section of the transport network falls below the critical datum. In both cases, an adequate and increasing level of resolution and accuracy are required to provide meaningful results depending on whether effects are assessed at the national, regional or local scale. Limited data availability meant that an indirect approach was chosen, as described below.

The critical elevation in relation to coastal inundation is determined by a range of local factors that are difficult to extrapolate to a national risk profile. When the effects of rising sea levels, swells, tides and winds combine during coastal hazard events, the reach of coastal inundation events can be significant. Guidance from MfE (2008b) suggests baseline assessments of climate change effects on sea level rise should account for a 0.5–0.8 increase in mean sea levels. In a worst case scenario including storm surge, effects could be felt up to 2 m above mean sea level.

Unfortunately, the lack of high-resolution national coastal topographic data precluded mapping risk contours corresponding to different sea level rise/storm surge scenarios. In practice, therefore, a relatively coarse elevation of 5 m above sea level was adopted as the critical datum.

4.2.3 Data inputs and availability

4.2.3.1 Network elevation datasets

Datasets were sought to identify the elevation of land transport networks and to prioritise sections of the land transport network vulnerable to the effects of climate change on coastal inundation. As NIWA's predictions of climate change influences on coastal inundation project sea level rises of between 0.5 and 0.8 m by 2100, this study sought datasets that locate transport infrastructure elevations within 1–2 m accuracy.

Elevation data for the state highway network were not available on a national scale to this fine resolution. The annual skid resistance survey of the state highway network uses the Sideways-Force Coefficient Routine Investigation Machine. At 10 m intervals, this machine records horizontal and vertical survey measures using satellite triangulation. The height reference system varies and therefore elevation data are accurate to within 5 to 10 metres, falling within a range of error too coarse for this study.

Datasets identifying the elevation of the national rail system were also not available. ONTRACK is developing a high-resolution topographical dataset for the national rail network using aerial photos; however, this database was incomplete and therefore not available for use in this study.

4.2.3.2 Coastal topographic datasets

With the direct method ruled out, a search was made for available high-resolution coastal topographic data with a national coverage in order to develop the indirect approach.

Elevations in the New Zealand topographical dataset provided by Land Information New Zealand (LINZ) are provided every 20 m and are accurate to within +/-10 m. However, the available resolution and range of error were considered to be too coarse for this study.

LiDAR datasets report vertical elevations to 1 m with an accuracy from 0.05–1 m and could therefore provide the required level of precision and accuracy for the national inundation risk profile. LiDAR is extensively used by councils for local and regional assessments of flood inundation in New Zealand. For this reason, the central and local government initiative GLiDAR has been set up to share knowledge and experience gained from acquiring and using LiDAR data.

Regional analysis of coastal hazards have been undertaken by many regional councils, with a focus on coastal dwellings and the adequacy of coastal protection structures. For example, regional modelling of coastal hazards for the Otago region estimated inundation depths of up to 2.5 m during storm surge events (NIWA 2008). However, while many councils around New Zealand hold LiDAR datasets for their region, a national dataset is not available. LiDAR technology was therefore not used for this national profiling study.

4.2.3.3 Satellite data

As a way forward, this study used a national high-resolution digital elevation model dataset reprocessed from images collected by NASA's Shuttle Radar Topography Mission in 2000. This is the only available topographic data set that covers the whole of New Zealand with a resolution and accuracy (stated to be within 5–8 m) suitable for this study.

A plot of this satellite data was published as Figure 3.1 in the Ministry for the Environment's *Coastal Hazards and Climate Change Guidance Manual for Local Government in New Zealand* (MfE 2008b). The plot was used in the manual to identify the areas requiring risk analysis to establish their likely vulnerability to coastal inundation as a result of sea level rise.

The data were used in this study to identify coastal areas of New Zealand within 5 and 10 metres elevation above year 2000 sea levels.

4.2.4 Adopted methodology for coastal transport networks

The reprocessed satellite dataset provided by NIWA was subsequently converted from ArcGIS into MapInfo format, assembled into a national GIS layer, and superimposed on the road and rail network layer generated during Stage One of this research. Areas of <5 m elevation and between 5–10 m elevation were contoured for subsequent risk analysis. The resultant plot for New Zealand showing coastal areas <5 m elevation (coloured red and referred to as 'low-lying' in this study) is shown as Figure 4.1.

were processed to provide a map showing where the networks traversed the low-lying areas – these road and rail sections are denoted 'at risk' in this report. The extent of the network sections at risk was estimated from the length of the road (or rail) situated within the low-lying zone. This metric was determined across the whole network.

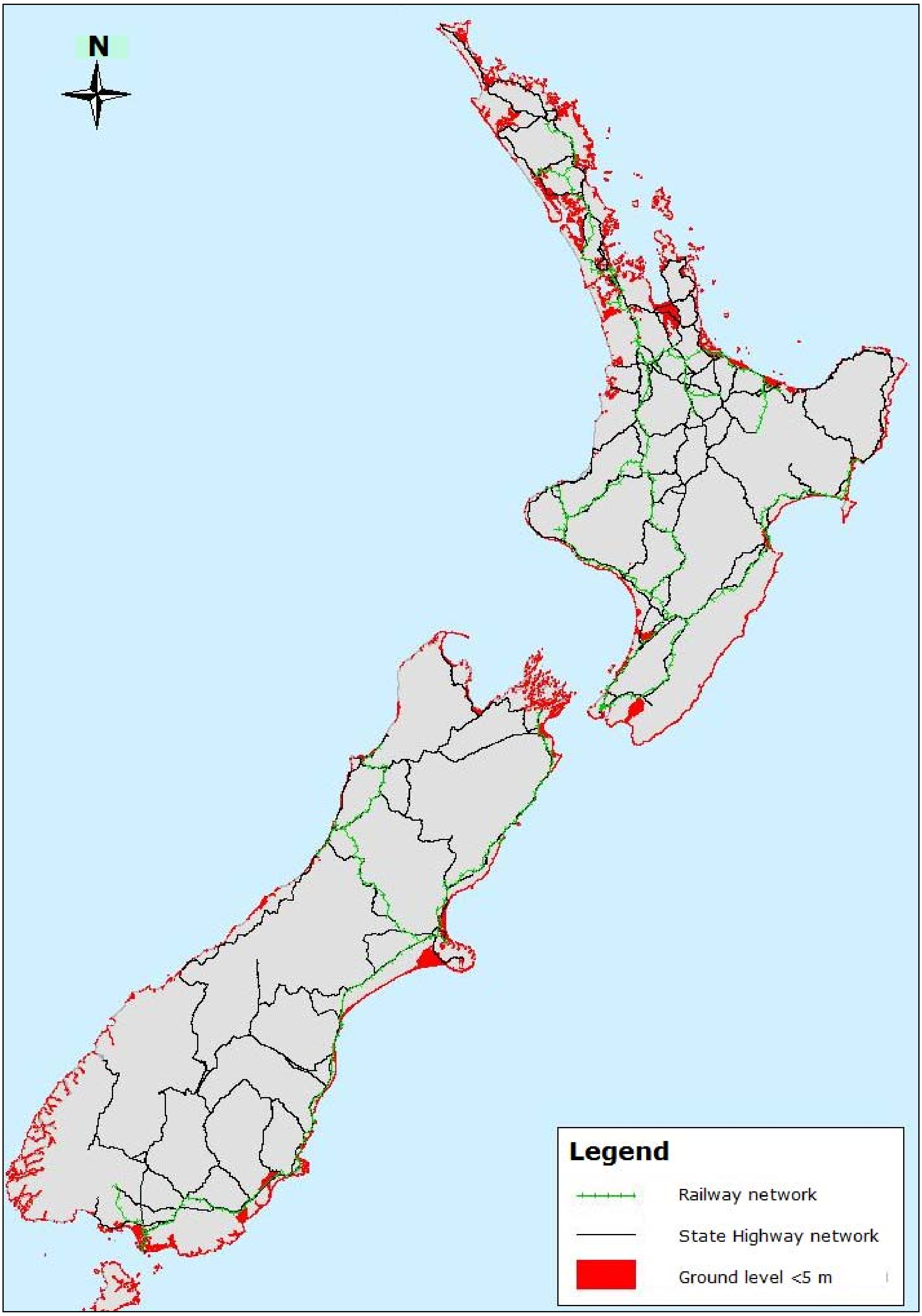

Figure 4.1 Relationship of land transport infrastructure to low-lying coastal areas.

The sections of the state highway, road and rail networks traversing these low-lying areas In the case of rail, the length of low-lying track was determined for each regional main line and rolled up to provide the national figure. A similar process was followed for individual state highways. In the case of local roads, the spatial value was the length of low-lying roads summed for each region. (A national calculation based on Territorial Local Authority (TLA) boundaries would be more appropriate but was not attempted because of the lengthy processing time required).

A sample regional map for the Hawkes Bay coastal region is given as Figure 4.2. Low-lying areas (<5 m elevation) are coloured red while those 5–10m are coloured orange. The railway is shown as a stippled green line and the state highway is indicated in black. The map shows the at-risk sections of the state highway and rail networks situated in low-lying areas in the coastal belt. The lengths of these sections have been measured and added to sections in other regional ‘low spots’ across New Zealand to generate the national coastal inundation metric for each network.

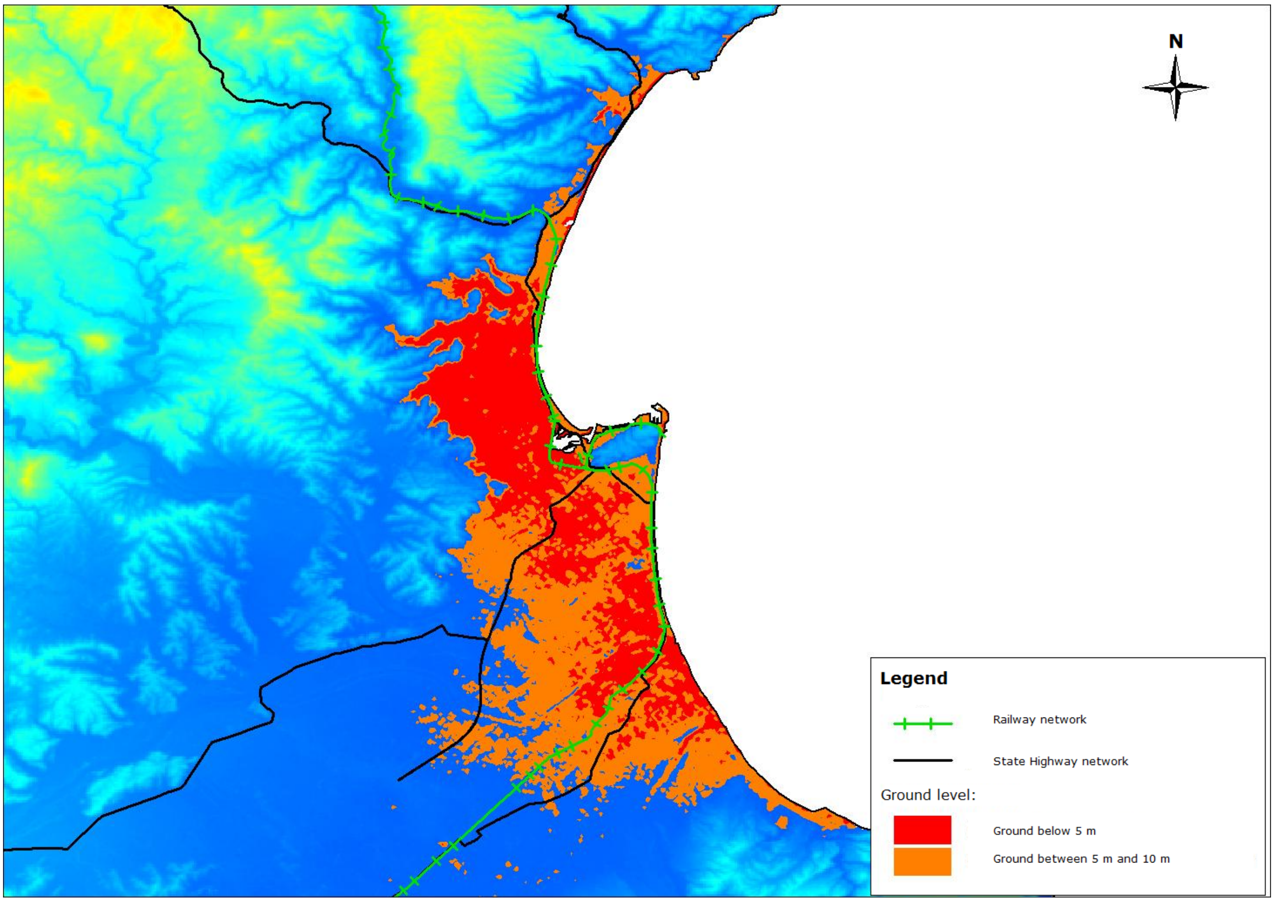

Figure 4.2 Coastal map for Hawkes Bay showing road and rail sections within the low-lying (<5 m elevation) zone potentially at risk from inundation.

4.2.5 Calibration of satellite data

A check was made of the satellite-derived topographic data to provide assurance that it provided adequate accuracy for generating metrics for use in the national coastal inundation risk profile. A comparison was made with 1 m resolution LiDAR topographic data obtained from Wellington City Council. The basis for calibration was comparing how well the 5 m and 10 m elevation contours of the satellite data matched those in the respective LiDAR dataset. A plot of the calibration test area (centred on Wellington airport) showing the two sets of topographic data is given in Figure 4.3.

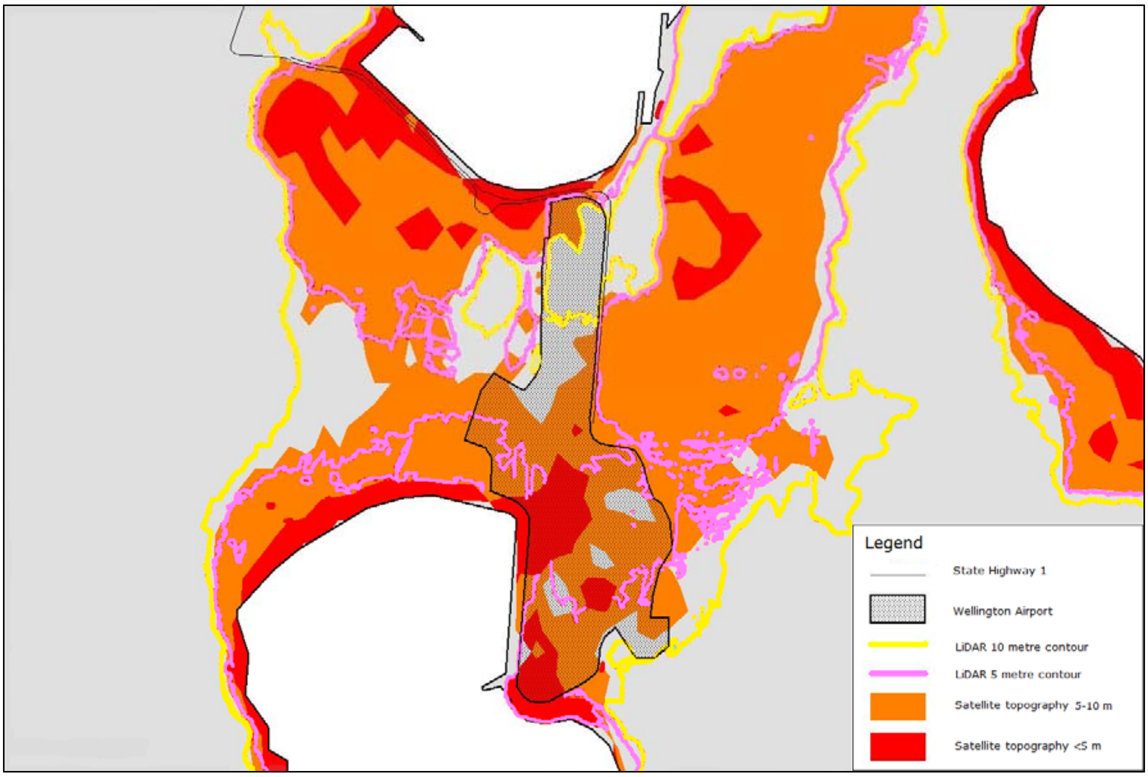

Figure 4.3 Comparison of satellite topography data (red area = <5 m; orange area = 5–10 m) with 1 m LiDAR contours (pink =5 m; yellow = 10 m) for the area around Wellington Airport.

For the 5–10 m elevation range, satellite data (10 m elevation contour situated at the boundary of the orange area) and the LiDAR 10 m contour (yellow line) generally agree well. For the <5 m elevation range, the satellite data (5 m elevation contour situated at the boundary of the red area) underestimated the true area shown by the LiDAR 5 m contour (pink).

The calibration test indicated that metrics derived for the at-risk (<5 m elevation) sections of the transport network using the satellite data will underestimate the true value. Consequently, the satellite data are not suitable for local analysis (such studies are normally conducted using 1 m LiDAR data which are generally available at the local scale). However, for the purposes of this high-level national profile of transport networks, the satellite dataset is considered to provide an acceptable first approximation of potential risk from inundation.

4.2.6 Methodology for port inundation risk

As part of the coastal inundation study, a national survey of port authorities was conducted to determine their views on the vulnerability of ports to sea level rise. The focus was on determining the current freeboard (based on wharf deck height and design flood level), and therefore a measure of the relative vulnerability at each port to the effects of sea level rise/storm surge under various scenarios.

To identify port vulnerabilities to sea level rise, each port was approached individually with a request to provide answers to the following questions:

- What are your critical (lowest) wharf deck elevations in relation to the chart datum?
- What design water level (tide and storm surge – in the chart datum) and associated ARI (e.g. 100-year) do you currently use to determine wharf elevations?
- What freeboard is currently set over the design water level for your wharf decks?
- What is the minimum acceptable freeboard for safe/efficient operation of your wharf decks?
- Do you expect that sea level rise (predicted by 2100 to add between 0.5–0.8 m to mean sea level and therefore storm tide levels) may affect your port operations e.g. inundation of critical infrastructure, wharf/docking operations, dredging or coastal protection?

The information request (including the background to the project) was made by email to each of the fifteen port authority CEOs and followed up with telephone calls where appropriate.

4.3 Potential extent of coastal inundation effects on land transport networks

4.3.1 Overview

This section describes the proportion and regional distribution of existing land transport infrastructure situated in low-lying areas. The derived metric (expressed as the absolute length and percent of the network below the 5 m elevation contour) provides a high-level indicator of potential risk to coastal inundation and therefore identifies priority areas for further risk assessment in the context of climate change.

The national rail and state highway networks are considered individually, followed by an analysis of multi-modal at-risk sections in the country where rail and highways share a common coastal corridor. Finally, local coastal roads are examined, both at the national and regional level (using the Wellington region as an example).

4.3.2 National rail network vulnerable to coastal inundation

Sections of the national rail network situated in low-lying coastal areas of the country are shown by the red areas in Figure 4.4 (note that the relevant sections of track have been magnified for ease of illustration). Table 4.1 gives the length of at-risk track for the North and South Islands, and the whole network. Data include both the at-risk metric (<5 m elevation) and the length situated 5–10m above sea level.

Table 4.1 Distribution of length of low-lying rail at risk from coastal inundation.

Region		Total length	Track length above mean sea level*	
			<5 m	5–10 m
North Island	km	2873	68	301
	%	100	2.4	10.5
South Island	km	1610	93	196
	%	100	5.8	12.2
National rail	km	4483	160	497
	%	100	3.6	11.1

* Year 2000 data

The analysis indicates that 160 kilometres (approximately 3.6% of New Zealand's rail network) are low-lying and potentially at risk from inundation. Of these 160 km, 68 km are situated in the North Island and 93 km in the South Island.

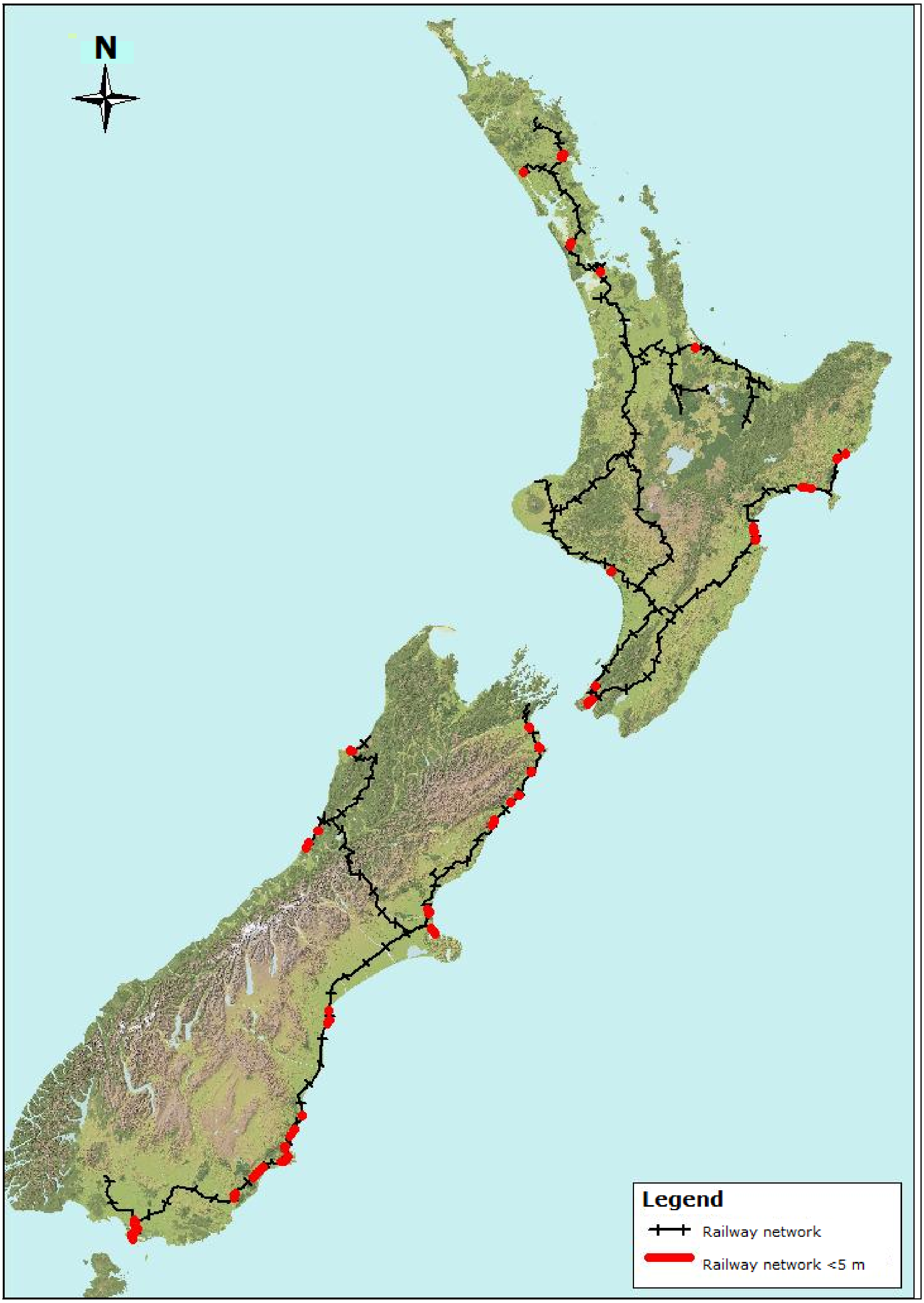

Figure 4.4 Sections of railway corridors in low-lying coastal areas.

The regional distribution of the at-risk sections in each island has been analysed for each main line. The histogram in Figure 4.5 for the North Island shows that 60 km or about 88% of the total 68 km of track at risk are found on four main lines:

- North Island Main Trunk (NIMT) Line (Auckland, Paremata);
- Palmerston North–Gisborne Line (PNGL)(Napier, Wairoa, Gisborne);
- Wairarapa Line (section from Wellington to Petone); and
- North Auckland Line (Whangarei).

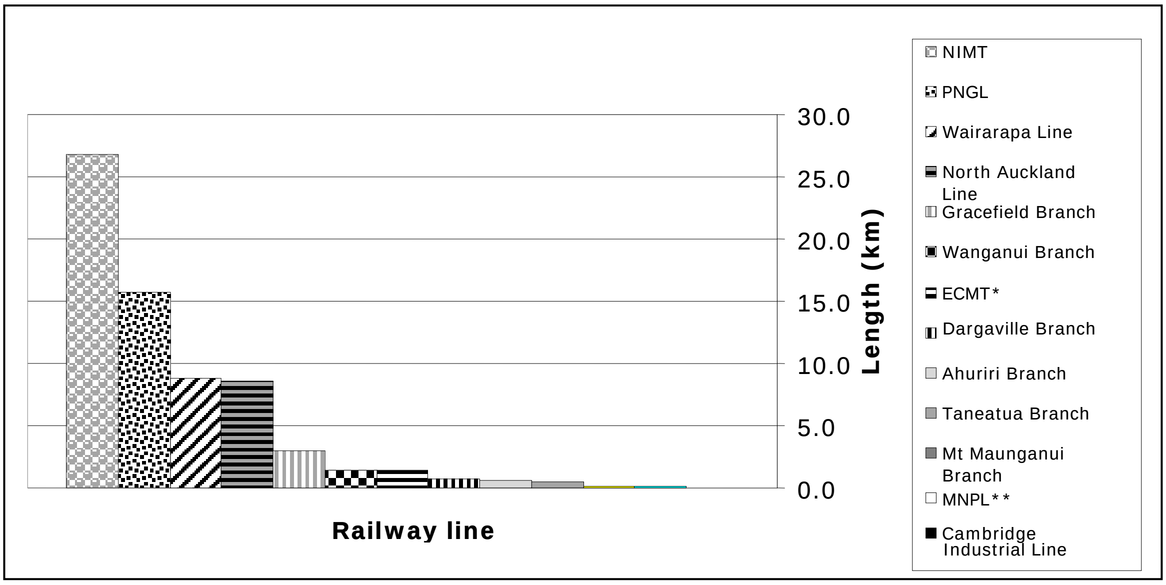

Figure 4.5 Lengths of the North Island rail network <5 m above sea level.

* ECMT = East Coast Main Trunk Line
** MNPL = Marton–New Plymouth Line

ONTRACK's IRIS database over the last four years (Appendix C) shows that the coastal rail section of the Wairarapa Line between Wellington and Petone is already susceptible to extreme weather and has experienced one major event requiring temporary line closure almost every year (i.e. August 2004, September 2005, April 2006 and June 2008). In these cases, heavy seas and strong southerly winds (sometimes combined with a high tide) resulted in overtopping of the sea wall defences with resultant washing of ballast onto the tracks. Such effects are expected to be magnified and occur more frequently in the future following an incremental increase in the mean level of the sea caused by global warming.

In the South Island (Figure 4.6), 84 km or around 90% of the 93 km of at-risk rail are located on three main lines:

- Main North Railway (Marlborough region, Kaikoura coast);
- Main South Railway (Christchurch, Timaru, Oamaru and notably around Dunedin); and
- Bluff Industrial Line (Invercargill).

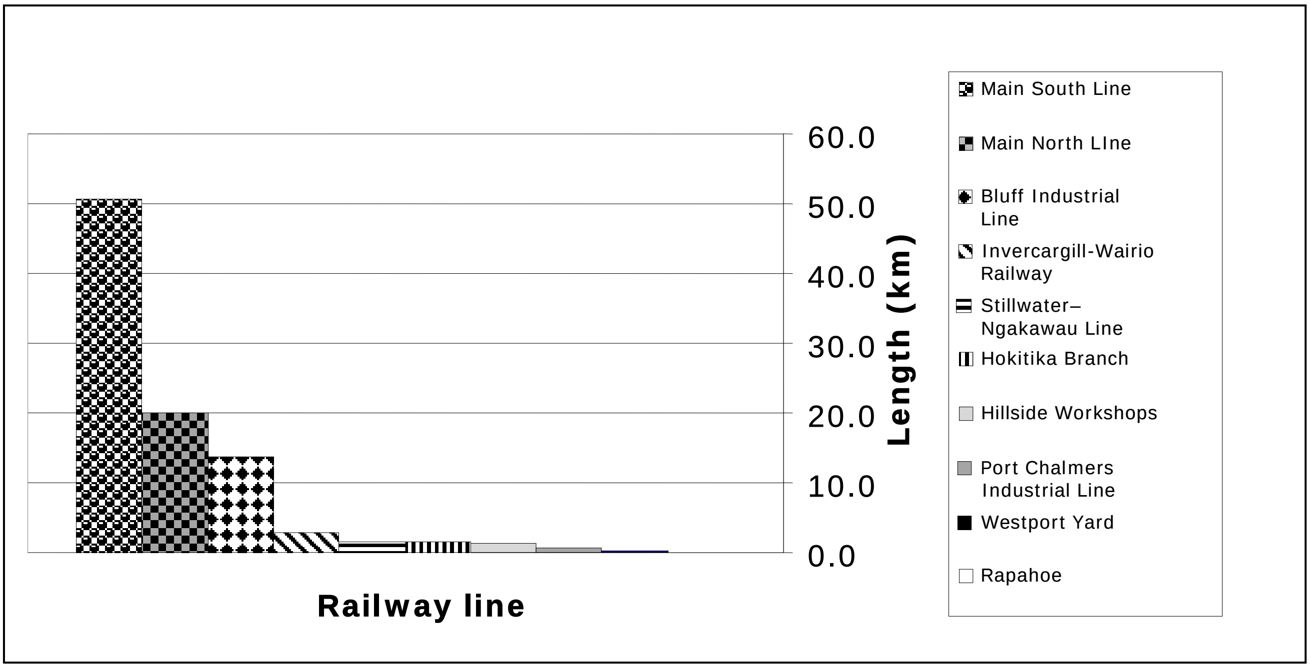

Figure 4.6 Lengths of the South Island rail network <5 m above sea level.

It is understood from ONTRACK that sea walls are planned to be installed along sections of the Kaikoura line where the track runs very close to the sea.

In a worst case scenario, if all low-lying (<5 m elevation) sections of the national railway network were to experience coastal inundation requiring ballast and formation replacement, ONTRACK's rough-order figure for ballast and formation replacement of $500,000/km suggests coastal inundation could pose a future asset replacement bill of up to $80 million in today's terms.

Notwithstanding an underestimate from use of satellite data (Section 4.2.4), the actual length of line at risk (and resultant damage estimates) from future inundation is expected to be smaller than these coarse national screening figures would suggest, for a number of reasons:

- The coastal sections of track are generally elevated (e.g. on an embankment) with respect to the surrounding ground level (although, as mentioned earlier, incipient risks may accrue from increased risk of erosion of these embankments or the nearby coastline as a result of enhanced storm surges).
- In places where the line passes very close to the same elevation as the wave run-up, an existing measure of protection from existing sea defences may already be in place.
- The risk to assets from future episodic inundation (e.g. from an increase in storm tide conditions caused by sea level rise and/or storm surge) would probably be felt up to around 2 m elevation in the lower half of the 5 m elevation range used in the screening profile.

Data from ONTRACK's flood database over the last four years (Appendix C) confirms that under current climate conditions, a recorded flood event of the national track has seldom been caused by sea incursion (a notable exception on the Wellington–Petone line is discussed above).

The regional analysis of potential inundation 'hot spots' provides the basis for identifying where more detailed risk assessment studies should be prioritised on the national rail network. These will allow refinement of the actual assets at risk, taking account of local site characteristics, including the vulnerability of existing sea defences to climate change. Such quantitative studies would require high-resolution topographic and/or asset elevation data in combination with local sea level rise/storm surge/wave modelling for a range of climate change scenarios.

By identifying the exact elevation and location of priority sections in relation to existing and potential coastal hazards, and by assessing the adequacy of coastal protection structures to prevent overtopping under predicted climate change conditions, a better sense of potential implications of climate change can be determined for the rail network.

An example of an overseas study on modelling the impact of sea level rise and wave overtopping of sea defences for coastal rail infrastructure is described briefly in Section 4.5.3. Further information on risk assessment of coastal hazards (including erosion) is provided as guidance for local government in New Zealand in the *Coastal Hazards and Climate Change Manual* (MfE 2008b).

4.3.3 National state highway network vulnerable to coastal inundation

Sections of the national state highway network situated in low-lying coastal areas of the country are shown by the red areas in Figure 4.7 (note that the relevant sections of highway have been magnified for ease of illustration).

Table 4.2 gives the length of affected highway for the North and South Islands, and the whole network. Data include both the at-risk metric (<5 m elevation) and the length situated 5–10 m above sea level.

Table 4.2 Distribution of length of low-lying state highway at risk from coastal inundation.

Region		Total length	Road length above mean sea level*	
			<5 m	**5–10 m**
North Island	km	6244	100	427
	%	100	1.6	6.8
South Island	km	9952	122	224
	%	100	1.2	2.3
National state highway	km	16 196	222	651
	%	100	1.4	4.0

* Year 2000 data

Figure 4.7 Sections of state highways situated in low-lying coastal areas (categorised according to the National State Highway Strategy (Transit 2007)).

The analysis indicates that about 222 km or approximately 1.4% of New Zealand's state highway network is low-lying (within 5 m elevation of sea level) and potentially at risk from inundation. The regional analysis indicates that approximately 100 km (or 1.6%) of the North Island and 122 km (or 2.5%) of the South Island state highway networks are located on low-lying coastal land. Future planning in these areas will need to take account of these potential risks.

Of the 100 km of low-lying sections in the North Island, approximately 60 km occur on state highways identified for proposed or possible increases in passing and overtaking opportunities in a 30-year timeframe in Transit's[3] National State Highway Strategy (Transit 2007). Of these, 22 km occur on state highways prioritised for 'national' standards in areas such as Whangarei district (Marsden Point), Auckland, Taranaki district and Napier.

Of the low-lying sections of the network in the South Island, approximately 88 km occur on state highways identified for proposed or possible increases in passing and overtaking opportunities in a 30-year timeframe in Transit's National State Highway Strategy. Of these, 82 km are situated on state highways prioritised for 'national' standards in areas such as Kaikoura, Christchurch, Timaru and Dunedin.

For illustrative purposes, a rough order of magnitude calculation of potential costs to respond to the effects of climate change on coastal inundation of low-lying sections of state highways has been derived from these figures. The assumption is made that estimated costs to raise and rebuild a 10 m wide section of state highway carriageway is in the order of $400,000/km in today's terms. In a worst case scenario, if raising and rebuilding all sections of state highway in low-lying areas was identified as an appropriate climate change adaptation response, the cost may be in the order of $88 million. This broad cost analysis does not take account of any damage to other assets (e.g. bridges) or the disruption cost associated with transport delays.

Similarly to the rail network, and notwithstanding an underestimate from use of satellite data (Section 4.2.4), the extent of the state highway network that is vulnerable to coastal inundation is likely to be less than estimated above, given the presence of existing sea defences and the coarse nature of the 5 m elevation risk zone used in this screening study.

Further analysis of low-lying sections of the state highway network identified in this study is recommended to refine the estimated extent of the network actually vulnerable to coastal inundation effects, and to provide the basis for a detailed adaptation response for priority areas. The analysis should focus on the following aspects at a local/regional scale:

- providing accurate highway asset elevation and high-resolution LiDAR datasets;
- modelling the current and future risk of coastal inundation for a range of climate change scenarios;

[3] In August 2008, Transit and Land Transport New Zealand merged to become the NZ Transport Agency (NZTA). The NZTA is now responsible for implementing this strategy.

- investigating the nature of coastal inundation (and erosion) effects on the network, including operational and maintenance requirements; and
- calculating the remaining life of coastal state highway sections and the relative merits of accounting for predicted climate conditions in any scheduled repairs or improvements.

4.3.4 Multi-modal corridors (state highway and rail) vulnerable to coastal inundation

4.3.4.1 Vulnerable land transport corridors

Data from the previous sections describing the vulnerable coastal sections of the individual rail and state highway networks have been combined in Figure 4.8. This shows at least ten low-lying coastal transport corridors (coastal sections common to rail and highway) that are at risk from inundation, as follows:

- North Island:
  - North Auckland Line and SH16 near Helensville along the southern end of the Kaipara Harbour;
  - East Coast Main Trunk Line and SH2 around Tauranga;
  - PNGL, and SH2 and SH35 near Gisborne;
  - PNGL, and SH2 and SH50 in the Hawkes Bay, near Napier;
  - NIMT and SH1 in Porirua Harbour; and
  - Wairarapa Line and SH2 between Wellington City and Petone.
- South Island:
  - Main North Railway and SH1 between Blenheim and Kaikoura;
  - Main North Railway and SH1 immediately north of Christchurch;
  - Main South Railway and SH1 north and south of Dunedin; and
  - Bluff Industrial Line and SH1 between Invercargill and Bluff.

Metrics were not estimated for these corridors but their relative length and location can be seen in Figure 4.8.

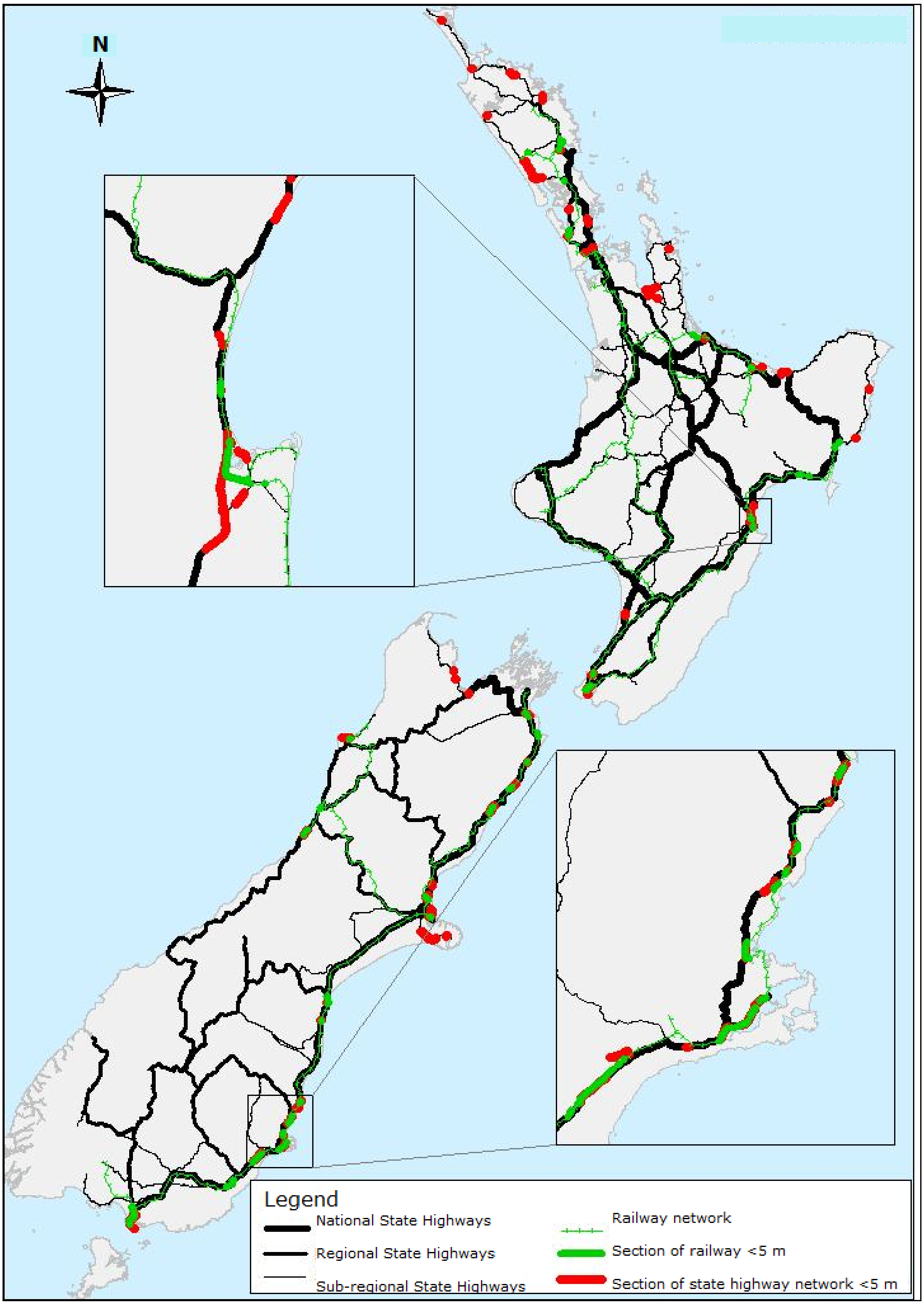

Figure 4.8 Low-lying coastal road and rail transport corridors vulnerable to inundation.

Several of these corridors represent high priority transport routes that contain a number of low-lying sections representing 'weak links'. Two are cited as examples in the following subsections.

4.3.4.2 The coastal section from Blenheim to Kaikoura

This strategic route has five individual at-risk sections on a corridor containing a major trunk line (parts of which are in tunnels) and a national (category) state highway. The closure of any one of these sections would cause major transport disruption because deviations inland from this corridor are difficult given the proximity of the Inner Kaikoura and Richmond ranges. The risk (probability x consequence) of disruption is magnified by the number of contiguous at-risk sections.

It is notable that both SH1 and the Main North railway line in the Kaikoura region were seriously affected simultaneously by multiple closures in August 2008 resulting from flooding and major slips following heavy rainfall. A major slip south of Kaikoura buried both the railway line and SH1. The highway was closed all the way from Ward (north of Kaikoura) to Cheviot, with some parts of the road seriously damaged. While sea inundation played no part in this 2008 event, it is likely that future storms could further weaken the transport infrastructure in these vulnerable sections. This example serves to highlight the need to take account of multiple risks from climate change (i.e. flooding, slips and coastal erosion) in such vulnerable areas.

4.3.4.3 The coastal section north and south of Dunedin

This inter-regional corridor containing a major trunk line and national state highway links Dunedin with Christchurch to the north and with Invercargill to the south. The route north and south of Dunedin has about six individual at-risk sections (see lower inset in Figure 4.8) where closure could cause serious transport disruption; road deviations inland from this corridor are circuitous and would need to follow a regional or sub-regional state highway.

Detailed risk assessments are recommended to understand the actual risk to strategic coastal transport corridors under realistic climate change scenarios. The modelling should address multiple climate change risks using joint probability models.

4.3.5 Local road networks vulnerable to coastal inundation

Sections of the national (local) road network situated in low-lying coastal areas of the country are shown by the red areas in Figure 4.9 (note that the relevant sections of road have been magnified for ease of illustration). Table 4.3 shows the distribution of the length of these roads by region for the whole of New Zealand (Note: these estimates are based on the LINZ database and include roads existing only on paper as well as actual built roads).

Table 4.3 Local roads in New Zealand (by region) located in low-lying coastal areas.

Region	Local road length (km)	Length below 5 m (km)	Percent below 5 m
Canterbury	19 352	463	2.4
Otago	13 859	357	2.6
Northland	7855	216	2.7
Southland	10 083	205	2.0
Waikato	17 243	201	1.2
Hawkes Bay	7254	148	2.0
Wellington*	4917	107[a]	2.2
Blenheim	2673	88	3.3
Auckland	9799	77	0.8
West Coast	3886	76	2.0
Bay of Plenty	6905	61	0.9
Manawatu-Wanganui	10 466	58	0.6
Tasman	4101	33	0.8
Gisborne	3187	18	0.6
Nelson	447	4	0.9
Taranaki	3873	1	0.03
Total	**125 898**	**2112**	**Average: 1.6%**

* Table 4.3 has a breakdown of this figure by TLA.

Approximately 2100 km, or an average of 1.6% of local roads nationally, are located on low-lying coastal land within 5 m elevation of sea level. These at-risk roads are roughly equally split between the North and South Islands. Canterbury, with 463 km, carries the highest risk of low-lying roads being affected by coastal inundation while Taranaki has the lowest risk (essentially no sections of road with less than 5 m elevation).

In the North Island, the regions with most at-risk roads are Northland (216 km), Waikato (201 km), Hawkes Bay (148 km) and Wellington (107 km), representing between 1.2% and 2.7% of their local road networks. In the South Island, local roads in low-lying coastal areas in Canterbury (463 km), Otago (356 km) and Southland (205 km) account for more than half of the potentially affected areas.

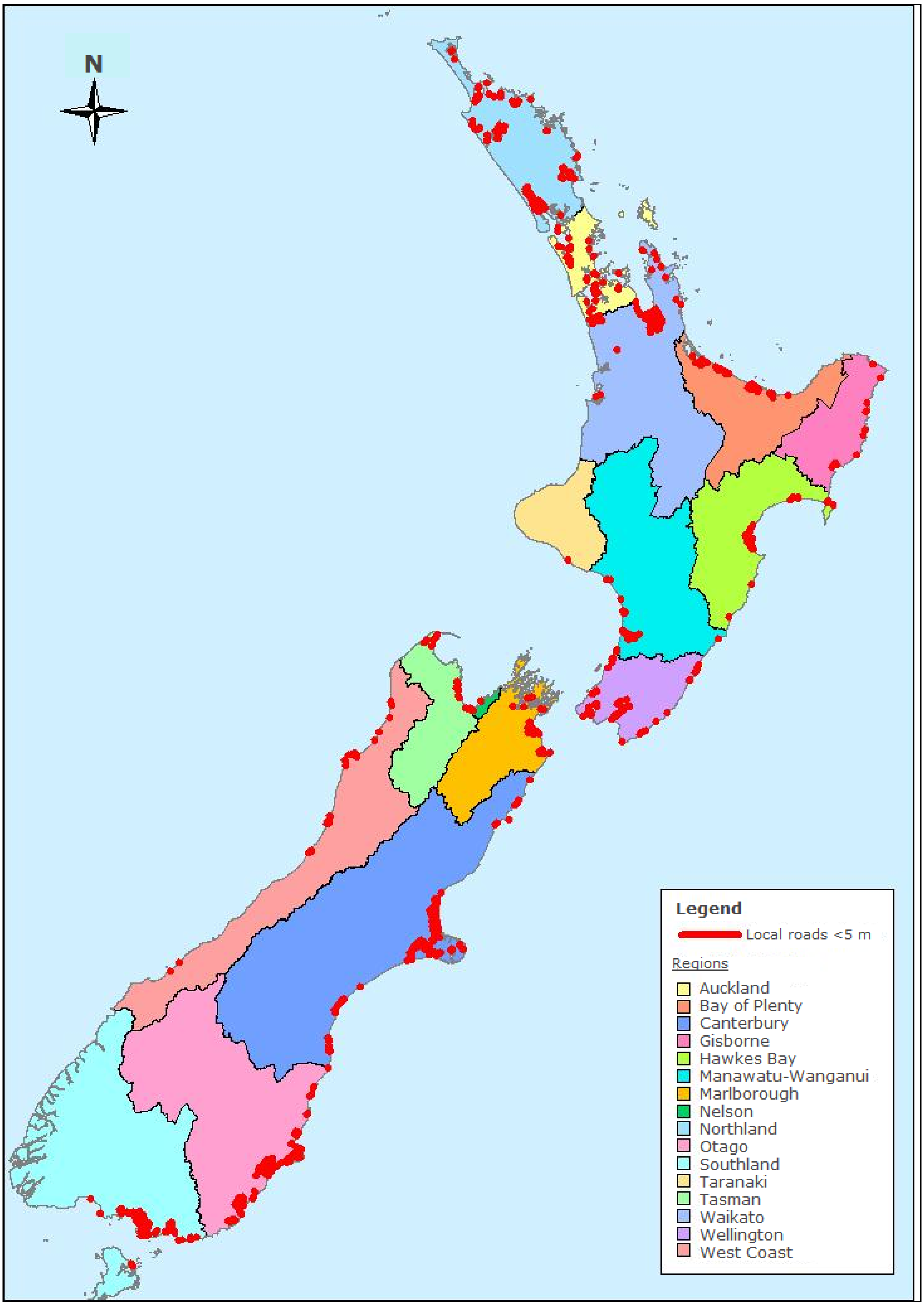

Figure 4.9 Local roads in New Zealand located in low-lying coastal areas.

An analysis of low-lying local roads has been made for the Wellington region (Figure 4.10) to provide more detail that is not apparent in the national map (Figure 4.9). The affected areas are shown in relation to the TLA boundaries (the local authorities responsible for maintaining the local road network). The low-lying area of roads centred on Levin (top centre of map) has been included, although this falls under Horowhenua District Council, which that sits outside the Wellington regional council boundary.

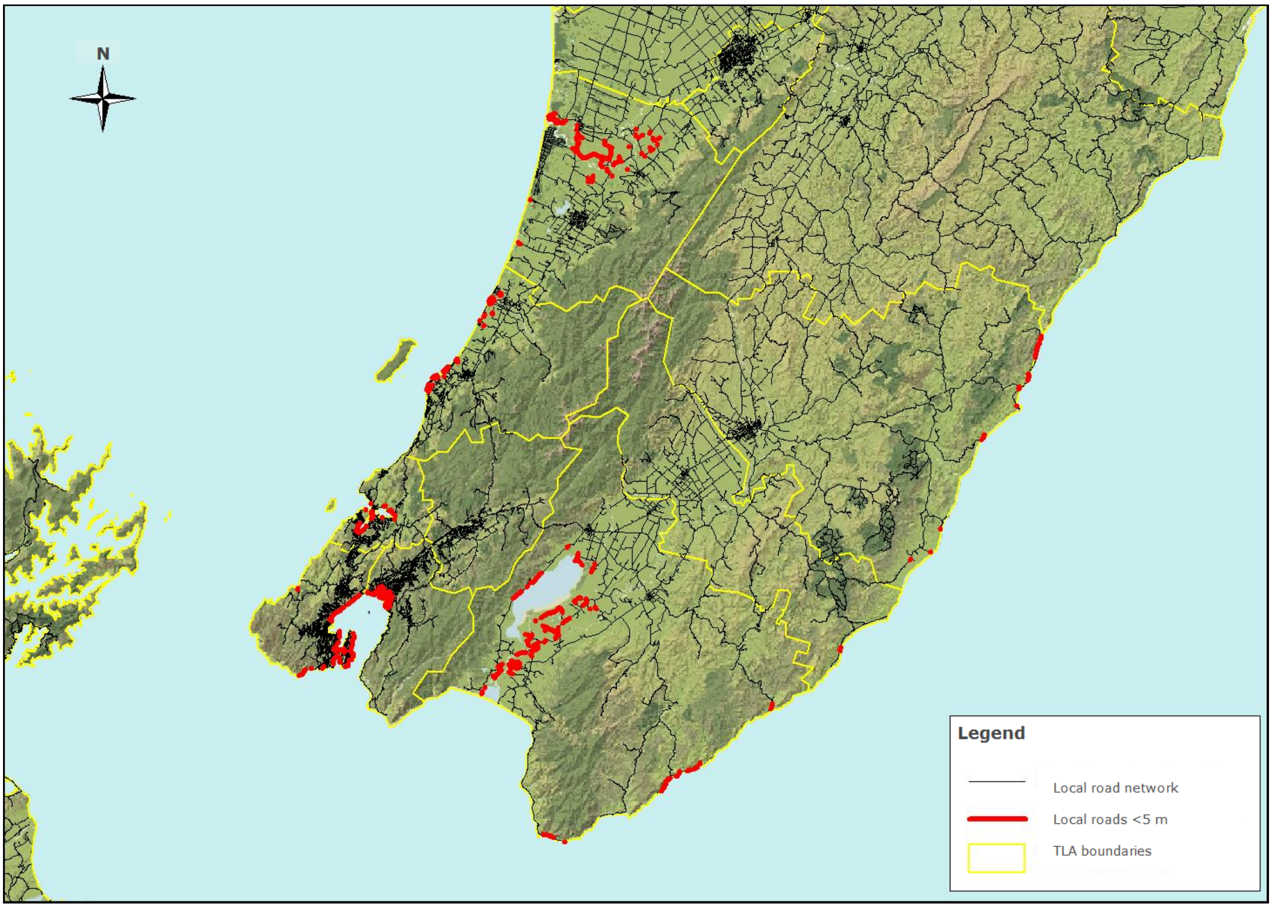

Figure 4.10 Local road networks in low-lying coastal areas of Wellington region.

Table 4.4 gives the corresponding analysis of length of at-risk local roads for the Wellington region.

Table 4.4 Low-lying coastal roads in Wellington region located in low-lying coastal areas, classified by TLA.

TLA	Local road length (km)	Length below 5 m (km)	Length below 5 m (%)
Carterton District	560	0.5	0.1
Masterton District	1033	8	0.8
Kapiti Coast District	494	8	1.7
Porirua City	307	8	2.5
Lower Hutt City	563	19	3.4
South Wairarapa District	852	46	5.4
Wellington City	756	17	2.3
Total	**4565**	**107**	**Average: 2.3%**

The comparatively large figure for South Wairarapa District Council (46 km, representing 43% of the regional total of 107 km) is a result of the network of low-lying roads in the vicinity of Lake Wairarapa. These roads are situated mostly inland but as the lake is connected to the sea, they would continue to be at risk from the effects of rising sea levels and storm tides.

Lower Hutt City has 19 km (18% of the regional total) of low-lying roads, mostly situated around the Petone foreshore. This area is also potentially at risk from flooding by overtopping of the adjacent Hutt River (currently protected by a system of stop-banks). Assessing the effects of climate change on inundation risk in this area will need to take account of the exacerbating effects of flood discharge to the sea.

For illustrative purposes, a rough order of magnitude calculation of potential costs to respond to the effects of climate change on coastal inundation of low-lying sections of local roads has been derived from the national figures, using the same assumption as for state highways to estimate the cost to raise and rebuild a 10 m wide section of local road carriageway (i.e. $400,000/km).

Under a worst case scenario, if raising and rebuilding all sections of local roads in low-lying areas in New Zealand was identified as an appropriate climate change adaptation response, the cost of doing so may be in the order of $840 million, ten times more than the equivalent figure for the national state highway network. This broad cost analysis does not take account of any damage to other assets (e.g. bridges) or services carried in the road corridor, or the disruption cost associated with transport delays.

Similar to the rail and state highway networks, the extent of the local road network adversely affected by coastal inundation is likely to be less than estimated, given the presence of existing sea defences and the coarse nature of the 5 m elevation risk zone used in this screening study.

Further analysis of low-lying sections of road identified in this study is recommended to refine the estimated extent of the road network actually vulnerable to coastal inundation effects and to provide the basis for a detailed adaptation response for priority areas. As for state highways, this should focus on the following aspects at a local/regional scale:

- providing accurate asset elevation and high-resolution LiDAR datsets,
- modelling the current/future risk of inundation (and erosion) for a range of climate change scenarios,
- investigating the nature of coastal inundation effects on local roads (operational effects and repair requirements), and
- calculating the remaining life of sections of local roads and the relative merits of accounting for predicted climate conditions in any scheduled repairs or improvements.

4.4 Port vulnerability to coastal inundation

4.4.1 Overview

This section looks at the vulnerability of ports to sea level rise from two related aspects:

- a review of port authorities' response to a survey on their perception of risk, and
- vulnerability of key coastal transport networks servicing the ports.

4.4.2 Port authority response to survey on sea level rise vulnerability

The purpose of the national port survey was to provide feedback from port authorities on their perceived risks from sea level rise and to determine a 'first cut' risk profile of individual port vulnerability to inundation, based on the expected reduction in current freeboard of critical wharf infrastructure relative to future sea levels.

Analysis of survey responses

Five of the fifteen port authorities contacted provided a response to the survey. A summary of their replies to the five survey questions is given in Table 4.5. Individual ports have not been identified for reasons of commercial sensitivity.

The survey provided an initial appraisal of how the threat of climate change is viewed by senior port management. The relatively low response (33%) probably reflects the feeling that, for many ports, sea level rise is not an issue requiring immediate attention (rather than being an issue that is well understood and being actively managed).

Table 4.5 Port authority response to survey of vulnerability to sea level rise.

Port	Response to questions*				
	Q1 (deck heights)	**Q2 (design water level)**	**Q3 (current freeboard)**	**Q4 (minimum acceptable freeboard)**	**Q5 (Perceived risk to port from future sea level rise)**
A	6.2 m, 4.9 m, 4.3 m and 4.1 m (above CD)	Not applicable – has not been considered as construction of new wharves not planned in the short to medium term.	3.2 m, 1.9 m, 1.3 m and 1.1 m	Has not been assessed.	No
B	5.5 m above CD	Max of 5 m	0.5 m	0.5 m	Yes - corrosion of wharf decking components, stormwater backflow through sumps, reclamation, and coastal protection.
C	Vary between +3.28 m to +4.5 m above CD, with new construction providing for greater heights.	+1.981 m above CD – Wellington Harbour Board design height.	Varies between 1.30 m and 2.51 m	+1.00 m	No, this rise would not detrimentally affect us at our main working berths. At our older berths, the freeboard would be very low, but less critical – a rise, in fact, would lessen our dredging need! By 2100, who knows what the footprint of the port may look like?
D	Lowest wharf deck is 4.45m above CD	Current design water levels (relative to CD) are: • MHWS 1.839 m, • MHW 1.739 m, • MSL 1.048 m, • MLW 0.295 m, • MLWS 0.166 m.	2.711 m above MHW	Minimum acceptable freeboard in past has been driven by construction techniques.	The reduction in freeboard is more likely to cause minor accelerated corrosion of below-deck services and increase overspray rather than impact on port operations.
E	All wharf deck heights are 5.0m above CD (LAT).	Would have to ask port designers	5.0 m less height of tide (2.1 m) = 2.9 m	Not sure this has been reviewed.	Can foresee no issues should such a rise occur.

a) Questions are given in Section 4.2.6
Abbreviations:
CD: Chart Datum
MHWS: Mean High Water Springs
LAT: Lowest Astronomical Tide
MHW: Mean High Water
MSL: Mean Sea Level
MLW: Mean Low Water
MLWS: Mean Low Water Springs

The limited response and variable nature of data provided preclude an analysis of the risk profile of individual ports or commenting on how this aspect is viewed by the industry as a whole. However, some observations on the responses to each question in Table 4.5 are given below:

Deck heights (Q1)

Detailed elevations were obtained from all respondents. New wharf decks tend to be higher than older ones, thereby potentially offsetting the increased risk of overtopping from sea level rise.

Design water level (Q2)

This question sought to determine the water level at which the wharf height was designed to take account of local high tides in combination with storm surge. Ports B, C and D provided design levels while Port A stated that this was not applicable, as no new wharves are planned. Interestingly, no ports provided the ARI for their design storm event. Information on current design water levels is necessary as a starting point in order to estimate loss of freeboard (and therefore increased risk of wharf overtopping) caused by future sea level rise/storm surge scenarios under climate change.

Current freeboard (Q3)

This query sought to determine the available freeboard (i.e. safety margin) of the wharf decks in relation to the design water level. Ports D and E provided responses in relation to local tide levels rather than a design level. For the lowest wharfs, current freeboard ranged from a low of 0.5 m (Port B) to a high of 2.9 m (Port E).

Minimum acceptable freeboard (Q4)

Only two ports provided actual values (0.5 m for Port B and 1 m for Port C), with other respondents stating they either did not know or that this aspect had not been assessed. These latter responses indicate that this is generally not an issue of concern, particularly for those ports which are operating with a comparatively large freeboard (i.e. large safety factor). Setting a minimum threshold at the wharf planning stage would be beneficial in deciding at what point an adaptation response to sea level rise should be considered. This aspect is likely to receive more attention from those ports currently operating at their minimum threshold (e.g. Port B).

Any perceived adverse effects from sea level rise on port operations (Q5)

The responses generally indicated that no significant effects would arise that would affect port operations. Ports A, C and E gave an unequivocal ‘no’ to this question, while Port D acknowledged the likelihood of comparatively minor effects from increased corrosion and overspray. Only Port B provided a ‘yes’ response citing additional concerns from increased corrosion and stormwater backflow, but mentioned nothing that would hinder port operations. It is noteworthy that Port B is operating with the lowest freeboard (0.5 m) of the five respondents.

4.4.3 Discussion of findings

Overall, the survey provided informed feedback from a sample of port authorities on their perception of the threat from sea level rise. Volume One's questionnaire responses showed that while many port authorities acknowledged the adverse effects of sea level rise, the severity and likelihood of these effects and their timing are, for the most part, not well understood. For this reason, and because the practical implications of climate change appear to be a long way off, no concerted attempt has been made to conduct detailed port risk assessments and develop adaptation plans. This is despite the fact that wharves have a design life of up to 100 years, and within this timeframe, the risks of damage and disruption to ports from climate change is potentially significant in the absence of adaptation measures.

Of course, exceptions can be found. Discussion with regional councils and port representatives during this study indicated that some ports have completed their own investigations into the risks presented by climate change. For example, the Port of Napier has determined new wharf designs that are resilient to both sea level rise and seismic risks. Other ports may be taking a closer look at the climate change risks but, based on the survey response in this study, these are more likely to be the exception rather than the rule.

The analysis in this study of port vulnerability has a narrow focus on wharf elevations and the risk of inundation. However, many other adverse effects can be associated with sea level rise (see Chapter 8 of Volume One). Much of the infrastructure of a port will be affected by a change in sea level, as will associated marine terminals and offshore structures. Compared with current conditions, decking and wharves will be exposed more frequently to larger uplift forces, ships will ride higher at the wharf, and cargo handling facilities will have less access to all parts of a ship. Loading and unloading may have to be scheduled for low tide periods to allow greater access into the ship, or else mooring and cargo handling facilities will need to be elevated (California Coastal Commission 2001).

Jetties or breakwaters protecting the port will be less efficient as peak tides rise, and may need raising and strengthening. The alternative is for the port to accept an increased risk of overtopping during storm surge and therefore a higher risk of damage. An increasing sea level will also result in a larger tidal prism[4] (volume of tidal water entering/leaving the harbour) resulting in increased scour of foundations of marine structures. On the positive side, a rise in sea level will provide opportunities for ports to accommodate deeper draught vessels and undertake less dredging to maintain required channel depths (a positive aspect cited by Port B).

The analysis points to the need to address the expected deteriorating level of service from climate change in future planning and upgrades. The strategic importance of ports to the economy (discussed in Section 4.5.2) should ensure that these risk factors be given further consideration by port authorities, if they are not already planned or underway.

[4] The difference in the volume of water in a water body between high and low tides.

4.4.4 Vulnerability of key surface transport networks servicing the ports

The previous section discusses the vulnerability of a selection of New Zealand's ports to sea level rise. However, even if the facility's infrastructure and operations are not unduly affected by climate change (e.g. because the port authority is taking steps to adapt to such changes), the commercial wellbeing of a port is critically dependent on secure transport links to other parts of the country.

Ports may be adversely affected by interruptions in passenger and freight traffic caused by transport delay following damage to road and rail infrastructure. Thus, aside from the port itself, the vulnerability of its key road and rail links also need to be considered in the context of climate change.

The location of New Zealand's coastal ports and their relationship to the inter-regional state highway and rail transport networks that service them are shown in Figure 4.11. Low-lying sections of the coastal networks that are potentially vulnerable to inundation (as discussed in Section 4.3.4) are also highlighted.

Figure 4.11 was used to categorise New Zealand ports according to their risk of losing connections with coastal transport links if these links are closed by flooding caused by sea level rise and storm surge. The qualitative categorisation is based on the following risk factors in respect of these transport links:

- single or multi-modal links (a single mode has a higher risk),
- serviced by single or multiple transport corridors (a single corridor has a higher risk),
- vulnerability of modal links (networks with one or more low-lying sections have a higher risk), and
- the relative importance of modal corridors (e.g. a vulnerable section of national state highway carries a higher risk than a regional or local highway; no differentiation was made for main lines).

The links refer to inter-regional connections, not local road and rail connections within the port precinct – the latter are assumed to be all low-lying and therefore do not provide a basis for differentiation.

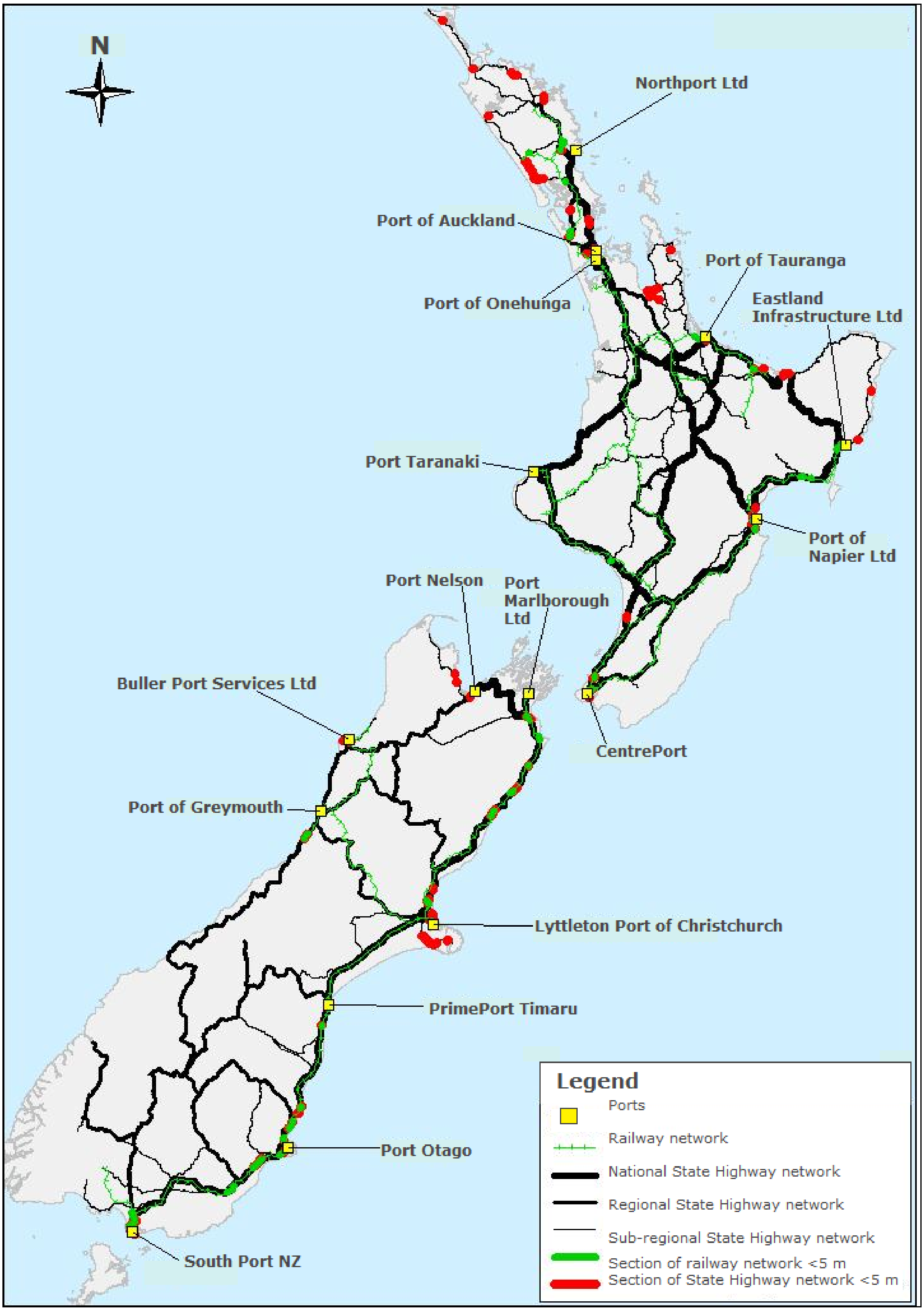

Figure 4.11 Relationship of ports to adjacent state highway and rail transport feeder routes that are vulnerable to inundation.

The results of this broad-brush risk assessment are given in Table 4.6. Table 4.6 attempts to place a broad risk category for each of the ports based on these considerations. The intention is to illustrate the range in risk to ports based on the vulnerability of their coastal surface transport links. However, it is important to stress that inundation is only one risk to transport networks resulting from climate change. A more comprehensive perspective on loss of transport connectivity to and from the ports would need to consider all other adverse effects of climate change such as increased magnitude and frequency of inland flooding, slips and strong winds.

Port Taranaki has the lowest transport link risk profile, as both state highway and rail links are above the nominal 5 m elevation risk threshold. Ports with a low risk profile based on their transport link vulnerability to sea level rise include Port Nelson and Port Northport. In the case of Port Nelson (a single mode connection), all freight arrives by road, so any disruption to road transport provides a significant consequence. However, the likelihood of this is low, as the main route east to Marlborough is elevated above the coastline and has no vulnerable sections, so the overall risk is low.

The moderate risk ports are characterised by multi-modal connections or multiple transport corridors where only one mode is vulnerable, or where at least one coastal access corridor is not vulnerable. In this case, movement of goods is less at risk if one mode or corridor fails (e.g. Lyttleton, Port of Tauranga).

At the higher risk end of the scale are ports serviced by multi-modal connections with one or more transport corridors which all contain low-lying sections that are susceptible to inundation from future sea level rise (e.g. Port Otago, South Port NZ).

Table 4.6 Indicative risk categorisation of New Zealand ports based on loss of connectivity of coastal transport links caused by vulnerability to sea level rise*.

Risk category**	Port/location	Comment on risk factors
A (low)	Taranaki	Taranaki has no at-risk (low-lying) state highway or rail connections.
B	Nelson, Northport Buller, PrimePort Timaru	Nelson has a single mode connection (road) but the main (eastern) state highway corridor is not vulnerable. Northport has a single mode (road) but the main (southern) state highway corridor is not vulnerable; Buller has multi-modal links, with only rail being vulnerable. Timaru has multi-modal links, with only the south corridor being at risk.
C	Marlborough (Picton), Greymouth, Lyttleton, Tauranga, Eastland (Gisborne)	Multi-modal ports with only one mode vulnerable and having at least one coastal access corridor that is not vulnerable.
D	Otago, Napier, Wellington, South Port NZ(Bluff), Auckland/Onehunga	Multi-modal ports with all modes and coastal access corridors vulnerable.

* Vulnerability is assessed in terms of transport links being low-lying (<5 m elevation) and therefore potentially at risk from inundation caused by sea level rise/storm surge.
** The indicative risk is for comparative purposes and does not imply that risk will eventuate.

4.5 Coastal inundation adaptation strategies for roads, rail and ports

4.5.1 Coastal vulnerability

The report of the IPCC (Parry et al. 2007) identified a number of climate change impacts and vulnerability for New Zealand. In terms of coastal impacts, the report noted that:

> *Sea-level rise is virtually certain to cause greater coastal inundation, erosion, loss of wetlands, and salt-water intrusion into freshwater sources, with impacts on infrastructure, coastal resources and existing coastal management programs. The likely rise in sea-level, together with changes to weather patterns, ocean currents, ocean temperature and storm surges are very likely to create differences in regional exposure. In New Zealand, there is likely to be more vigorous and regular swells on the west coast.*

Priorities for adaptation responses for coastal transport networks and ports to the risk of inundation are discussed in the context of their increasingly strategic importance.

4.5.2 Strategic context

New Zealand's coastal transport networks have been clearly emphasised and prioritised for further development and use into the future in government policy. The drivers are rising fuel costs and the need to raise the current share of domestic freight carried at sea in order to reduce GHG emissions that lead to climate change. Thus the country's strategic transport objectives outlined in policy documents such as New Zealand's domestic sea freight strategy, *Sea Change* (MoT 2008), and the NZTS (MoT 2002) all emphasise the role for coastal shipping in contributing to freight movements and the importance of making best use of existing networks and infrastructure.

Road and rail access to ports is a critical link to keep coastal shipping activities connected to suppliers and consumers. While a key motive for greater use of rail and coastal shipping is the reduction in GHG from use of more efficient transport modes, climate change mitigation aspirations may not be achieved if parts of the coastal land transport network are not adequately prepared for the effects of climate change. The investment in port infrastructure and associated freight handling facilities, as envisaged in *Sea Change* (MoT 2008), will therefore need to take full account of the future risks posed by sea level rise and storm surge over the lifetime of these assets.

The New Zealand Coastal Policy Statement (NZCPS) enacted under the Resource Management Act 1991 (RMA) (New Zealand Government 1991) requires coastal priorities to be given regard to in all transactions governed by the RMA, such as plan making and resource consent decisions. In proposed changes to the NZCPS (Department of Conservation 2008), a new policy (Policy 51) would require policy statements and plans to include assessments of high priority sites at risk from coastal hazards including the effects of climate change. Hazard risks would be assessed over at least a 100-year timeframe.

The proposed Policy 52 would seek to avoid new developments or redevelopment on land at risk from coastal hazards, or in a way that would increase the risk from coastal hazards. Redevelopment or changes in land use to reduce the risk from coastal hazards would be encouraged. In considering the use of hard coastal protection structures to protect against coastal hazards, the proposed Policy 54 would encourage local authorities to consider the expected effects of climate change, over a timeframe of at least 100 years.

Under the RMA, climate change effects are currently matters that applicants and regulators must have particular regard for. If proposed changes to the NZCPS proceed, climate change risks and timeframes will be required components of decision making in a more explicit manner than presently required.

If land transport network operators are looking to align adaptation responses with strategic policy and legislation, protecting the resiliency of existing transport infrastructure and securing the passage of energy-efficient freight transport is supported by New Zealand's transport strategies. Considering the effects of climate change also aligns with RMA requirements.

In summary, considering the effects of climate change and protecting the resiliency of existing and future transport infrastructure is consistent with New Zealand's transport strategies, and should be an integral part of the adaptation responses developed by land transport network operators to ensure these align with strategic policy and legislation.

4.5.3 Priority adaptation responses

The national profile of coastal transport at risk from inundation described in this report is a first step in identifying where future studies in network vulnerability should be focused. It is essentially a screening study that provides network operators with the knowledge to proceed with more detailed assessments at the local level.

A key finding of this study is the relatively small proportion of the national networks that are potentially at risk from inundation based on the metric used in this study (i.e. length of network <5 m elevation):

- rail: 3.6% (160 km);
- state highways: 1.4% (222 km);
- local roads: 1.6% (2112 km).

While these order of magnitude estimates are relatively small in relation to the size of their respective national networks, it is important to place the regional risk into perspective. Thus it is emphasised that the figures also represent a comparatively large number of individual at-risk sections, any one of which may be considered a 'weak link'. When one or more at-risk sections occur together along a priority route, this may present a more significant climate change risk to the transport network.

Nevertheless, a review of the findings supported by field inspections is likely to show that many of the sections flagged as potentially 'at risk' are, in fact, not so because of local mitigating site characteristics (e.g. sea defences). On the other hand, where assets are confirmed to be at risk, a detailed appraisal will be needed (supported by local modelling) to define the likely effect(s) on the network. This will, in turn, enable cost/benefit analysis of the impacts and the development of the most appropriate adaptation options.

An MCA of adaptation options for coastal inundation of road, rail and ports (see Appendix A) lists a number of adaptation responses (C1 to C8), and provides inter-linkages between each action and their relative priority.

Research initiatives are a major component of the adaptation options given the uncertainty attached to which coastal transport assets are at risk, when these risks may arise, and what transport or port infrastructure may need protection. The general direction of adaptation options required in the short term may be summarised as follows:

- **Research:** The combined effects of climate change on inundation, coastal erosion and storm patterns need to be modelled and applied to fine-scale topographical maps of at-risk coastal areas identified in this study. To do this effectively, a more detailed understanding of at-risk coastal areas is required, including field inspection and knowledge of the location, extent and effects of local coastal areas that are known to be susceptible to inundation or erosion.
- **Planning:** Coastal land use planning schemes should be assessed for potential risk if land transport networks are vulnerable to coastal inundation.
- **Design:** The design of new transport assets in low-lying coastal zones is recommended to take account of predicted changes in coastal conditions caused by climate change.
- **Operation:** The protection of at-risk assets in priority locations (relocation is another alternative, where possible) should be based on cost/benefit considerations. Consideration of changing coastal climatic conditions is recommended when asset renewal or improvement is proposed.

Because of the uncertainty associated with future projections of sea level rise and the fact that sea level rise is one of many factors that will affect transport infrastructure on the coast in future, adaptation responses should either be flexible and allow for climate change conditions to be clarified, or seek to reduce uncertainty by identifying future climate conditions in more detail (as discussed above). Where climate change adaptation responses align with other objectives, such as routine maintenance, asset renewal or redevelopment, benefits are likely to outweigh costs.

Having screened the coastal transport networks to the risk of inundation, the focus of future adaptation responses should turn to site-specific studies of priority areas identified in this study. This is the most appropriate geographical scale to conduct climate change risk assessment of infrastructure. Site-specific studies could include, where appropriate:

- accurate site topography data;
- detailed bathymetry and tide gauge data;
- site exposure to prevailing winds, plus predicted changes in wind speeds;

- a detailed definition of assets at risk and reviews of level of service;
- peak storm analysis, including the duration of the peak, wave run-up considerations and extreme wave levels (including tide, storm surge and sea level rise) across a range of ARI events such as 100, 2000 and 10 000 years;
- delineation of the 1% Annual Exceedance Probability sea inundation level;
- vulnerability of any sea defences; and
- potential for flooding from surface water discharges.

An example of a site-specific approach to evaluation of sea defences is provided by the UK Rail Safety and Standards Board investigation (Rail Safety and Standards Board 2008). This study investigated the impact of climate change on coastal rail infrastructure in the Dawlish area of Devon and used this study as a basis for development of the methodology and application to other coastal and estuarine defences around the network. National and regional level assessments need to be made up of such local assessments to take account of site-specific factors such as coastal land form and the adequacy of existing coastal protection structures.

The Road Safety and Standards Board study found coastal defences to be vulnerable to predicted increases in the frequency and extent of wave heights over time as a result of sea level rise if current defences are not renewed to more robust standards. It was predicted that the return period of the 2006 1 in 100 year design wave height would reduce to 1 in 40 years in the 2020s, 1 in 25 years in the 2050s and 1 in 14 years in the 2080s. Detailed surveys of coastal frontages identified the most exposed sites on a particular part of the rail network, in consultation with incident records, network engineers, coastal protection asset databases and flood risk mapping.

4.5.4 Related studies

A number of related parallel studies have been recently completed or are underway (or planned) to determine risk from inundation and other coastal effects that may arise from climate change. These are relevant to the transport sector and are briefly summarised below.

These developments should provide input for a more comprehensive assessment of climate change risks to transport and other infrastructure in the coastal environment. Future considerations are discussed in Section 4.7.

NIWA Coastal Explorer

Work is underway by NIWA as part of the Coastal Explorer programme to provide a national perspective of the risk and vulnerability of coastal communities and associated infrastructure to natural hazards. The Coastal Explorer is part of the NZCoast initiative, an information portal for information that is relevant to the New Zealand coastal environment and its associated hazards, developed as part of the 'Reducing the impact of weather related hazards' programme and funded by the Foundation for Research, Science and Technology (FRST).

The primary aim of NZCoast is to provide maps, data and images that describe coastal environments, and their functions and associated hazards. The Coastal Explorer is a GIS-based web-accessed member-only database containing a coastal classification and beach type classification for the New Zealand coast. A beach hazards assessment directory is in development, and will be a useful risk exposure prioritisation tool for future climate change studies.

Wave and Storm Surge Projections (WASP)

This three-year (2008–2011) FRST research programme aims to develop and produce regional projections of waves, swell and storm surge to support local government and engineering or planning consultants in making decisions about adapting to climate change in coastal areas. The research involves:

- generating a hindcast (30–40 years), and two sets of future projections (one for waves/swell; one for storm surge) around New Zealand at a consistent national scale which use the same weather inputs (winds and mean-sea level pressures) but different models (i.e. a wave model and a storm surge model);
- developing the delivery system (WASP) to download information on waves/swell and storm surge, and the likely climate change impacts at the regional or sub-regional scale. This information would apply offshore from the wave breaking zone (i.e. the 50 m depth contour), where spatial changes along the coast are much less marked than local variations at the shoreline; and
- undertaking a pilot demonstration in Waitemata Harbour on how the offshore information from WASP can be incorporated into a more detailed assessment of the wave/swell and storm surge hazard at the shoreline (both now and in the future).

Regional modelling of the future New Zealand climate

Part of this three-year (2008–2011) FRST research programme aims to identify regional ocean deviations in sea level rise from the global average, and undertake a more rigorous assessment of available long-term New Zealand sea level records. This will involve:

- assessing sea level rise scenarios and their associated uncertainty bounds of regional oceanic departures of sea level rise in the Southwest Pacific Ocean from the global mean eustatic (absolute) rise derived from global ocean/climate models;
- new estimations of relative sea level rise rates for several regions based on medium- or long-term New Zealand sea level gauges in the NIWA and Standard Port networks; and
- defining average vertical rates of coastal land movement in different regions of New Zealand, from which the relative sea level rise can be evaluated.

Tools to derive extreme coastal design conditions

Research is underway to improve tools to derive probabilistic estimates of hydrodynamic conditions (e.g. waves and water levels) and how such extreme conditions are correlated (e.g. joint probabilities of occurrence). Much of NIWA's current work in this area has focused on the Auckland and Wellington coastal regions, including the derivation of coastal hydrodynamic conditions incorporating climate change allowance for new road design in Auckland. The improved tools will allow more robust estimates of hydrodynamic design conditions to be derived.

4.6 Conclusions

4.6.1 Review of methodology

The purpose of this study was to conduct a national/regional risk profile of New Zealand's ports and coastal road and rail networks in relation to inundation resulting from sea level rise and storm surge. The study identified those coastal sections of the surface transport networks that are currently situated in low-lying areas and therefore potentially at risk of inundation.

Sections of state highway, local road and rail situated <5 m elevation above mean sea level (denoted 'at-risk') were identified and a broad estimate of risk was determined from the total length of network within this risk zone. The lack of high-resolution national coastal topographic data precluded mapping risk contours for sea level rise/storm surge scenarios.

Satellite topography data overlaid with the national transport networks were used to derive the national metrics for the inundation risk profile. Comparison with 1 m LiDAR indicated that metrics derived from the satellite data underestimate the true value. For purposes of this high-level national profile, the satellite dataset is considered to provide an acceptable first approximation indicator of potential risk from inundation.

4.6.2 General conclusions

- While the national profiles show that a relatively small fraction (<4%) of the land transport networks are at risk from coastal effects of climate change, the regional impacts may be much higher, depending on the distribution of at-risk sections and the priority of the affected transport routes.
- The actual proportion of transport network at risk is expected to be smaller than this figure as the inundation/storm surge risk lies in the lower half of the 0–5 m elevation risk zone, and the screening profile takes no account of elevated coastal assets (e.g. those on embankments) or those protected by sea defences.
- The topographic 'risk profiling' provides a high-level 'first cut' of coastal road and rail sections potentially vulnerable to inundation, and a pointer to where more detailed risk assessment studies should be prioritised on the national transport networks. These will allow refinement of the actual assets at risk, taking account of local site characteristics, including the vulnerability of existing sea defences to climate change.

4.6.3 Land transport vulnerability

The following conclusions are drawn regarding risks to New Zealand's land transport networks:

National rail network:

- Approximately 3.6% of New Zealand's rail network (160 km) is low-lying and potentially at risk from inundation. Of this, 68 km are situated in the North Island and 93 km in the South Island.
- In terms of regional distribution, 88% of the track at risk in the North Island occurs on four main lines (NIMT, PNGL, Wairarapa Line and North Auckland Line). For the South Island, 90% of the track at risk occurs on three main lines (Main North Railway, Main South Railway and the Bluff Industrial Line).

National state highway network:

- Approximately 1.4% of New Zealand's state highway network (222 km) is low-lying and potentially at risk from inundation. Of this, 100 km are situated in the North Island and 122 km in the South Island.
- For the North Island, approximately 60 km of the 100 km of at-risk sections occur on state highways identified for proposed or possible increases in passing and overtaking opportunities in a 30-year timeframe in the National State Highway Strategy (Transit 2007). For the South Island, approximately 88 km of the 122 km of at-risk sections meet this criterion.
- In terms of distribution of at-risk sections on state highways prioritised for 'national' standards, 22 km of these occur in the North Island (e.g. in Whangarei district, Auckland, Taranaki and Napier) and 82 km are situated in the South Island (e.g in Kaikoura, Christchurch, Timaru and Dunedin).

Multi-modal corridors:

- Nationally, at least ten low-lying coastal transport corridors (i.e. coastal sections common to rail and state highway) are at risk from inundation (metrics not estimated). Several of these corridors represent high priority transport routes and include the coastal sections from Blenhiem to Kaikoura, and the coastal transport corridors north and south of Dunedin.

Local road network:

- Approximately 1.6% (or around 2100 km) of New Zealand's local roads on the LINZ database are low-lying and potentially at risk from inundation, split roughly equally between the North and South Islands. Canterbury, with 463 km, carries the highest risk while Taranaki has the lowest risk (essentially no roads are at less than 5 m elevation).
- From a regional perspective, in the North Island, the most at-risk roads are found in Northland (216 km), Waikato (201 km), Hawkes Bay (148 km) and Wellington (107 km), representing between 1.2% and 2.7% of their local road networks. In

the South Island, low-lying coastal roads occur most commonly in Canterbury (463 km), Otago (356 km) and Southland (205 km), representing collectively more than half of potentially affected areas.

4.6.4 Port vulnerability

As part of the coastal study, the vulnerability of ports to sea level rise was assessed from two related aspects: a review of responses from port authorities to a survey on their perception of risk (responses were received from five of the 15 authorities contacted), and vulnerability of coastal state highway and rail networks servicing the ports. The main findings are as follows:

- New wharf deck elevations were reported to be generally higher than older structures, indicating that a margin of safety is being incorporated, thereby offsetting the increased risk of overtopping from sea level rise to some extent. However, gaps in responses on the design water level and minimum acceptable freeboard indicate that consideration of climate change may not yet be 'on the radar' for some authorities. This is despite the fact that wharves have a design life of up to 100 years.
- No perceived threat from climate change was identified by the majority of respondents. Thus four of the five port authorities' responses considered that a sea level rise of 0.5–0.8 m by 2100 would not have a major impact on port operations, although one respondent (with the lowest freeboard) noted that operational impacts could emerge from effects such as increased corrosion and stormwater backflow. It is not known whether these responses are based on perceptions or formal risk assessments.
- Notwithstanding the small sample size, it is concluded that while many port authorities acknowledge the adverse effects of sea level rise, the severity and likelihood of these effects and their timing are, for the most part, not well understood, a point that emerged from the Stage One questionnaire. For some authorities, the practical implications of climate change appear to be a long way off and it appears that the industry has not made a concerted effort to conduct climate change risk assessments or, by implication, to develop an adaptation response.
- Aside from the ports themselves, the vulnerability of their key road and rail links also need to be considered in the context of climate change. New Zealand ports were categorised according to their risk of losing connections with coastal transport links owing to inundation from sea level rise/storm surge. This categorisation shows a wide range in risk. At the higher end are ports serviced by multi-modal connections where the coastal transport corridors all contain multiple low-lying sections that are susceptible to inundation (e.g. Port Otago, South Port NZ).

4.7 Future considerations

The objective of short-term studies should be to refine the coastal risk profile analysis completed in this research. This should identify which sections of the 160 km of railway corridor, 222 km of state highway and approximately 2100 km of local roads situated in low-lying coastal areas are actually at risk from inundation caused by climate change, and to provide the basis for a detailed adaptation response for priority areas.

The analysis should focus on the following aspects at a local/regional scale:

- providing accurate transport asset elevation using high-resolution LiDAR datasets;
- modelling the current and future risk of coastal inundation for a range of climate change scenarios;
- investigating the nature of coastal inundation (and erosion) effects on the network, including operational and maintenance requirements; and
- calculating the remaining life of coastal state highway sections and the relative merits of accounting for predicted climate conditions in any scheduled maintenance or improvement works.

A complementary aspect would be to determine the current resilience of these at-risk sections to extreme weather events. These studies should include other risks from climate change such as coastal erosion and slips, which were not considered in this study.

Future consideration of risks from climate change to coastal transport networks should include the following in order to allow adaptation responses to be prioritised to areas of greatest need:

- categorisation of the potential risks to national road/rail network based on the coastal classification and vulnerability profile (the NZCoast project) to help national transport agencies identify where potential hot spots are and where further more detailed assessment are required;
- quantification, where identified (and required) from the above assessment, of the key coastal hazard pathways and resulting coastal hazard risk to road/rail/port networks, and how this risk may change with climate change (taking account of changes in sea level rise, storm surge and waves).
- collation of the location, characteristics and condition of coastal structures protecting coastal transport infrastructure (in the form of a GIS-based asset management database), and assessment of their current serviceable performance and how this performance may change under climate change effects such as sea level rise and enhanced erosion (a review of catchment management plans and lifelines emergency vulnerability studies may assist in identifying these at-risk coastal protection structures);
- development of a performance-based design process for future coastal structure design (e.g. overtopping and structure damage) using probabilistic coastal hydrodynamic conditions and incorporating climate change;
- investigation of the effects of climate change on port infrastructure and operations including: potential for increased wave disturbance in harbours, increased water

depths, increased risk of inundation, changes in sedimentation in harbour and shipping channels, and resulting dredging requirements; and

- a comprehensive assessment on loss of transport connectivity to and from New Zealand's ports caused by climate change related factors, given the strategic importance of ports and coastal shipping as set out in the Government's *Sea Change* strategy (MoT 2008)and proposed changes to the NZCPS (Department of Conservation 2008).

5 Climate change and inland flooding effects on road and rail networks

5.1 Study background

Flooding is the cause of significant damages in New Zealand, and is dubbed New Zealand's most frequent and costly natural hazard (Officials' Committee for Domestic and External Security Co-ordination 2007).

New Zealand's transport lifelines are vulnerable to the effects of flooding. The impact of floods and other natural disasters on the national state highway network were highlighted in Transit's 2005/2006 annual report (Transit 2006):

> *April storms flooded roads in the Bay of Plenty, river water submerged the SH2 Gorge Road for seven hours, a flood of over two metres submerged SH56 near Palmerston North in July, the July storms resulted in the collapse of the Ngaturi Bridge over the Mangamahu River, SH4.*

Storms are associated with regular exceedances of highway operations' emergency management budgets. Over a six-year period, Transit reported an average of 20% spending over budget to restore state highway operations after floods and slips caused by storms (Figure 5.1).

Figure 5.1 Surface flooding of the state highway network at Mapara and Honikiwi, Waikato.

New Zealand's rail network is also vulnerable to the effects of floods, particularly if parts of the network's approximately 12 900 culverts and associated longitudinal drains fail to convey flood flows, causing overtopping or washout (Figure 5.2).

Figure 5.2 Washout caused by flooding affects the national rail network (location unknown).

As noted by Rushbrook & Wilson (2007), in the last two decades, failures of the culvert and drainage system resulting from flooding on the New Zealand rail network have been the single biggest cause of infrastructure-related line closures, derailments, geotechnical instability, decline in track formation condition and deaths/injuries.

In an effort to quantify the cost of floods on the national rail network, a hydraulic flood risk and cost model was applied to a 14 km sample section of the NIMT railway track to determine culvert performance during rainfall events. The research found that 97% of anticipated costs could be attributed to the failure of 10% of culverts in the study area, primarily as a result of frequent small flood events rather than less frequent extreme weather events (MacIver 2006).

In Stage One of this research, increased risk of flooding as a result of climate change where raised average temperatures increased the frequency of extreme rainfall events was identified as a major concern across the rail, road and port networks. Flooding effects on existing road and rail networks were considered to be a high risk, whereas flooding on existing port areas was assessed as a moderate risk. The risk rankings indicated further assessment was needed of climate change effects on flood risk, with a particular focus on the future effects of floods on the national road and rail networks.

For this reason, Stage Two included a national profile of flood risks. The purpose of this study was to identify areas of the land transport network (road and rail) currently at risk of (or prone to) inland flooding as a basis for estimating parts of the networks that are likely to be affected by climate change.

5.2 Approach and methodology

5.2.1 Approach

Infrastructure providers are advised that climate change will not create new hazards (with the possible exception of hazards resulting from sea level rise), but will rather exacerbate the frequency and severity of existing weather events (Reisinger et al. 2005). Consistent with this advice, the approach used in this study to understand potential changes in flood risk for the national road and rail networks is based firstly on determining where these networks are currently being affected by flooding, and then making predictions on the change in ARI in future years caused by an increased frequency of extreme rainfall.

The advantage of this approach is that it is relative simple to apply and provides an estimate of the increased flood risk at known locations of the network, thus enabling the network operator to build in necessary changes to the design or maintenance regime. The disadvantage is that it does not identify which parts of the networks are likely to flood in the future but which are currently not immediately at risk (i.e. the present day 'near misses'). This may only be achieved by hydrological modelling of flood risk at the catchment level.

Modelling flood risk (and the increased risk under climate change) is a complex issue. For planning and decision making purposes (e.g. in regard to impacts on infrastructure from current 'near misses'), this requires hydraulic analysis of the individual catchment. This approach defines future scenarios in terms of increased mean temperature, determines the increase in extreme rainfall, models the resultant increase in river flow in the catchment, and determines the change in river elevation and hence the risk of overtopping and inundation (see Gray et al. 2005 for a description of this methodology developed for New Zealand).

For this study, the simple screening assessment (described in MfE 2008a) was used as a basis for the national profile of flood risk for surface transport networks. This method defines future scenarios in terms of increased mean temperature and determines the increase in extreme rainfall using a simple scaling factor (approximately an 8% increase in atmospheric moisture for every 1°C rise in mean temperature). The method assumes that the future change in flood risk at a given location is proportional to the increase in extreme rainfall at that location. This is based on the premise that a given percentage increase in heavy rainfall translates into a similar percentage increase in peak river flow. These assumptions are acceptable for the purposes of the national profile developed in this study.

The extent to which this screening approach could be applied to each network was dependent on the availability of current flood event data. Details of the data sources, their availability and the adopted methodology for each network are described below.

5.2.2 Data sources on flood events affecting surface transport

5.2.2.1 National flood events in New Zealand

Data on the incidence of flooding across New Zealand since 2006 were obtained from the annual publication *Natural Hazards*, prepared by GNS and NIWA (2007). This report includes a review of the major floods of the previous year using flood hazard data sourced from the National Climate Centre. National maps show the locations of moderate (<10 years ARI magnitude), severe (10 to 50 years ARI) and extreme (>50 years ARI) floods. Flood data were collated from the 2006 and 2007 annual reports, and overlaid with the national state highway and rail networks to provide a base GIS map for identifying a first approximation as to where flooding is likely to have affected different regions of the transport networks.

5.2.2.2 NIWA flood database with recorded transport impacts

The national flood data referred to above provide an indicative location for flooding but do not provide direct information on whether the flood events affected the national state highway or rail networks. Therefore, other sources of flood risk were sought to identify this information. From their historical database of flood events, NIWA sourced details of incidents with noted effects on land transport networks. Data were sourced from a combination of event-based reports, newspaper articles and rain gauge/flow gauge records. Twenty-three events recorded from January 2005 to August 2008 were identified. The incidents are summarised in Appendix B and include a narrative description of places and transport assets affected, and in some cases, an estimation of value of damage incurred.

5.2.2.3 National database on flood-prone land

Information sourced from the *National Hazardscape Report* (Officials' Committee for Domestic and External Security Co-ordination 2007) was also reviewed to determine whether this could provide an indication of flood-prone land based on land areas with gentle slopes of less than 1°. A range of factors other than slope profile can influence the flood risk to road and rail networks, such as land cover, land use, natural and engineered drainage, conveyance capacity and condition, and elevation of track and pavement in relation to flood levels. Consequently, the dataset was not considered suitable to provide a useful indicator of road and rail assets at risk of flooding.

It should be noted that some councils have created flood hazard maps for specific catchments based on detailed model assessments. In at least one instance, and as part of a proposed district plan change, one district council has updated their flood risk maps following public consultation (Thames-Coromandel District Council 2008).

5.2.2.4 Railway floods

Track defect records, including incidence of flooding, are contained within ONTRACK's IRIS. The database was searched for the period from 1 July 2004 to 30 September 2008 to obtain a list of all floods (extracted as Code CN Sub-Code FLD) that had occurred on the national rail network, including date and location. The IRIS database contained records of approximately 70 flood events affecting the national rail network during this four-year period. Events are described in terms of the date, line and location of events. Appendix C presents the data extracted from the database in tabular form.

5.2.2.5 State highway flood data

Floods affecting the national state highway system, including lane closures and expected recovery times, are recorded in NZTA's Traffic Road Event Information System (TREIS). At the time of this study, TREIS was encountering technical difficulties which prevented data prior to July 2008 from being accessed.

As an alternative approach to identifying flood risk areas on the national state highway network, information about flood history was sought from each of NZTA's 24 network operations regions by reviewing flood-prone site details listed in 'recurring hazards' sheets prepared as a requirement of NZTA's *State Highway Maintenance Contract Proforma Manual (SM/032)* (2009).

5.2.3 Methodology adopted for flood risk

The methodology adopted for the national profile of flood risk was based on data held by the rail and state highway management agencies about floods that affected their networks.

The adopted approach comprised the following steps:

- identifying which parts of the networks currently experience flooding,
- establishing the current ARI for each flood event using HIRDS, and
- predicting the future ARI (2040 and 2090) for each location based on the historical flood-producing rainfall totals.

The process followed was dependent on the quality and completeness of data, and was different for each network, as outlined below.

For the national flood database analysis, NIWA selected the main events from 2005–2008 where records showed that surface transport had been affected, extracted the rainfall data from the hardest hit areas and calculated the ARI of the rainfall based on HIRDS. The current ARI values were used for the 2010 scenario. The ARIs were then re-calculated based on a 1°C increase in mean temperature (the 2040 scenario) and on a 2°C increase in mean temperature (the 2090 scenario). The changes to the ARIs were calculated according to the latest MfE climate change guidance notes (MfE 2008a).

For the railway flood events, MWH converted the current flood line and location details into latitude and longitude co-ordinates using a geo-referenced grid of 'kilometrage' datum pegs, and plotted the affected track sections on a GIS map of the national mainline rail network.

NIWA analysed the ONTRACK floods by identifying the nearest rain gauge to the site of the event, then extracting the 1-day, 2-day or 3-day rainfall total, depending on the duration of the event. ARIs were calculated for rainfalls for the respective location using HIRDS. Finally, ARIs for the same rainfalls in 2040 and 2090 were calculated using predictions of 8% (associated with a 1°C mean temperature increase) and 16% (associated with a 2°C mean temperature increase) increases in rainfall over these periods, respectively. Projections for the ten-year period from 2010 were assumed to be the same as present conditions.

For the state highway network, responses to requests for details about recurring hazard sites on the state highway network were received from 16 of the 24 state highway network operation regions. However, the format and level of detail in responses received varied considerably and the authors of this report are not confident that the data from the different regions are comparable. In particular, the dates of the flood events were generally not recorded, with the result that no analysis of rainfall and ARI change could be undertaken. For state highways, therefore, a close relationship between flood events and the network was not able to be determined to a level of detail suitable for presenting a national perspective of flood events.

5.3 National flood events in relation to surface transport

5.3.1 National flood events in 2006 and 2007

Flood event data from the *Natural Hazards* publications (NIWA & GNS 2007, 2008) are given for 2006 (Figure 5.3) and for 2007 (Figure 5.4). Floods are classified as moderate, severe or extreme, depending on their ARI.

The number of floods varies widely between the two years, with 2006 having over twice the total number than the following year, indicating the variability in heavy rainfalls in these years. The North Island appears to have experienced a higher incidence of severe of extreme floods compared with the South Island in each year.

The national flood plots also show the location of the national state highway and rail networks, and generally indicate the regions of the state highway and rail networks which may have been affected by these flooding events. However, caution is needed, as the point referencing each flood is the location of the flood gauge in the catchment that indicated an abnormal flow, and the flood itself may only have materialised some way downstream of the catchment. Hence it is not possible to determine which parts of the road or rail networks may have actually been affected by such events.

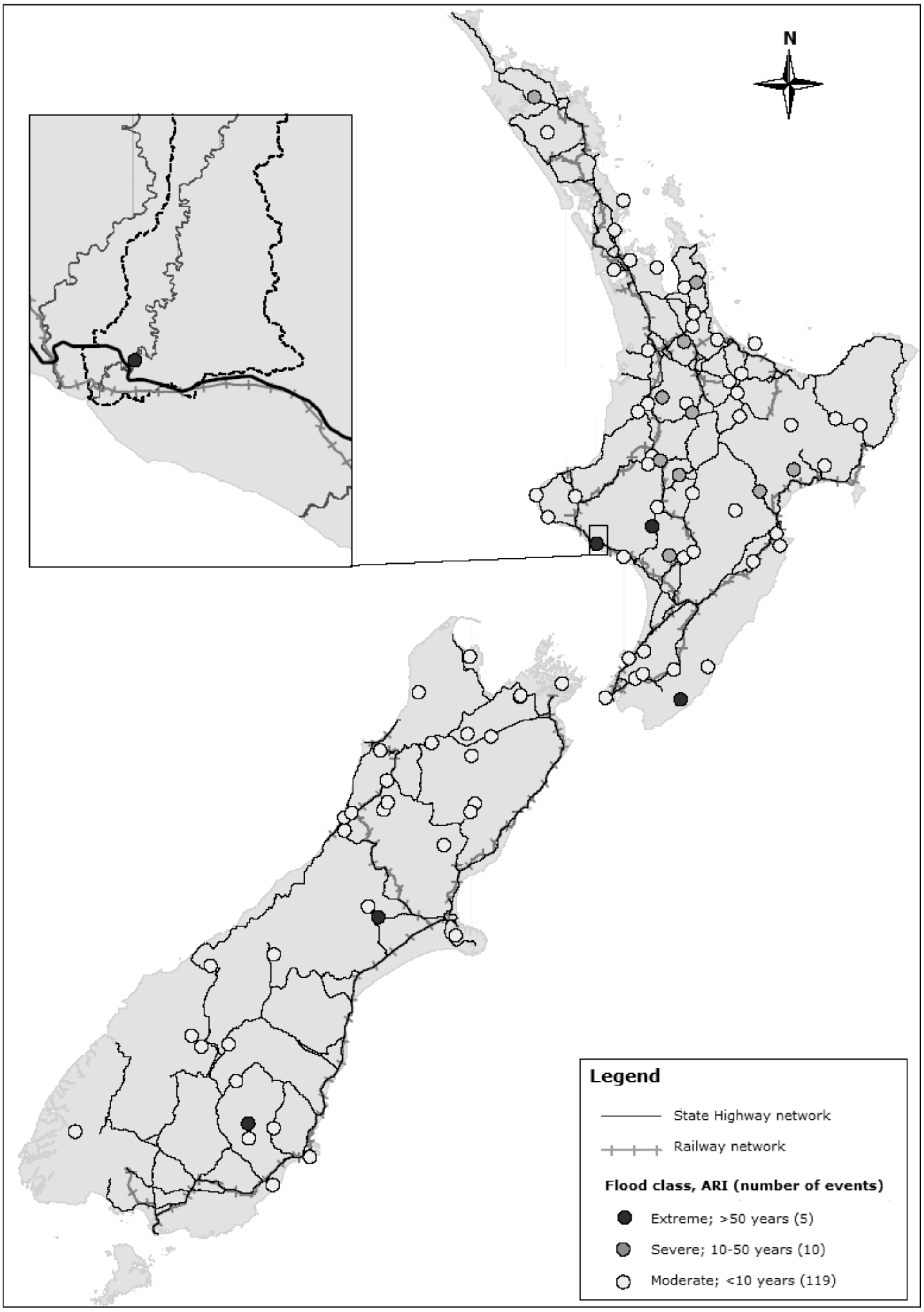

Figure 5.3 Floods in 2006 recorded at flow gauges in relation to national rail and state highway networks (adapted from NIWA & GNS (2007)).

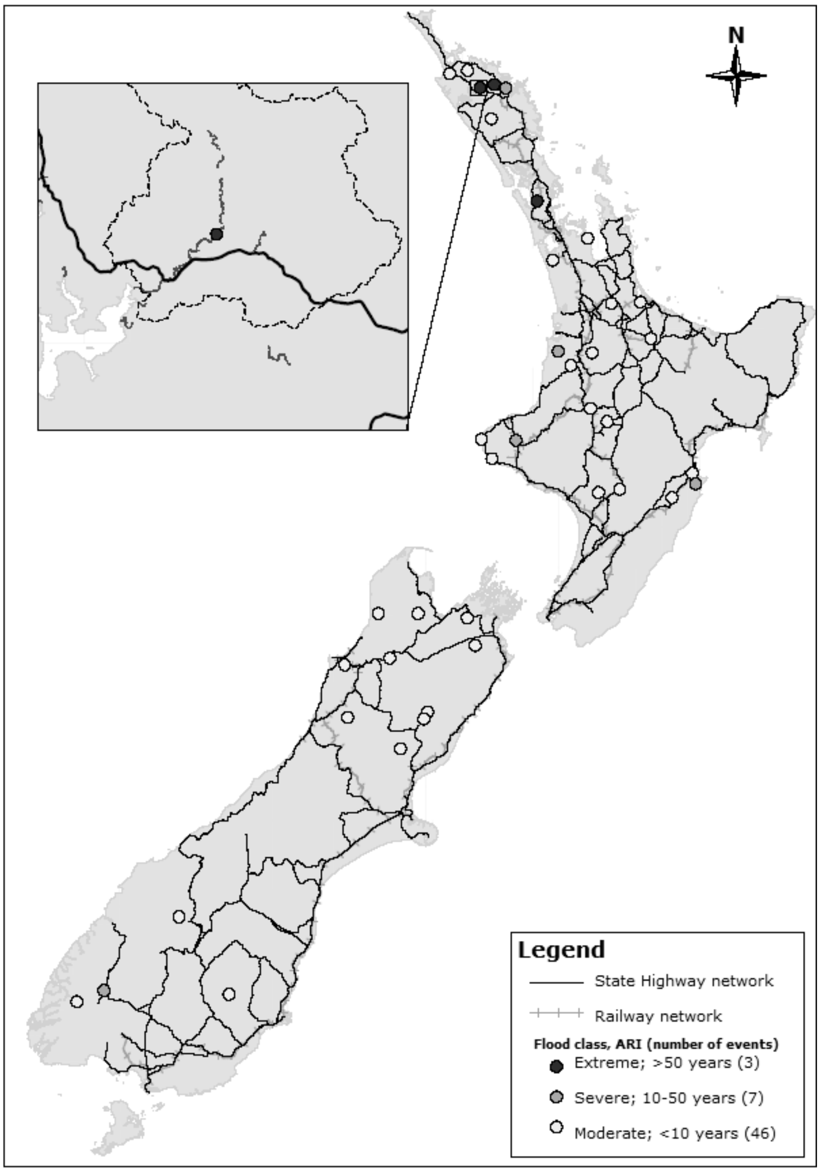

Figure 5.4 Floods in 2007 recorded at flow gauges in relation to national rail and state highway networks (adapted from NIWA & GNS (2008)).

The task of assigning these national flood events to catchments and determining their effects with regional network operators around the country was more onerous than time permitted; the value of this dataset was therefore limited to a general indication of the regional distribution of recent floods. Recorded flood data provided by the network operators were found to be the only unequivocal method of determining the relationship between floods and mode vulnerability, as discussed below.

5.3.2 National flood events in relation to land transport networks

Appendix B details the main floods from 2005–2008 recorded in NIWA's historical database where transport networks were affected, as reported in event-based reports and newspaper articles throughout New Zealand.

According to this dataset, flooding has been widespread throughout New Zealand during this 3.5 year period, with effects appearing to be predominately on the state highway network, compared with the local road or rail network. Floods of moderate severity (10–50 years ARI) occurred and were reported more frequently, predominantly in the North Island.

The comments recorded on which parts of the networks were affected by the floods are generally non-specific and, in many cases, cover a wide area e.g. 'Gisborne and East Cape'. As the particular locations of these events on the national transport networks were unable to be defined, no spatial analysis was applied to these data.

5.4 Climate change effects on flooding and the national rail network

5.4.1 Current rail network flood profile

Appendix C lists 68 floods recorded in ONTRACKs IRIS from July 2004 to October 2008. All events were recorded as having the same level of severity on the database. The four additional columns reflect the flood analysis of these events with reference to the nearest rain gauge location, rainfall (in mm), period (hours), and the estimated ARI for 2010, 2040 and 2090 (see Section 5.5.2 for methodology and the Section 5.4.2 for a discussion on climate change effects).

These floods have been plotted in Figure 5.5 to show their regional distribution. The map shows that recent floods have affected parts of the rail network across New Zealand, although some regions appear to have a higher prevalence e.g. the coastal section near Hauone (western Bay of Plenty), Palmerston North, Arthur's Pass and the Amberley/Rangiora area in Canterbury.

A distinction has been drawn in Figure 5.5 between events with ARI <2 years and those with ARI >2 years. While some floods are strongly related to local rainfall (as for Hauone discussed in Section 5.4.2), the nearest rain gauge data associated with approximately two-thirds of the IRIS flood incidents show rainfall events of ARI <2 years at the time the flood damage was reported. In other words, the majority of the IRIS flood events are not associated with a significant local rainfall event (as measured at the nearest rain gauge). Rather than being localised flooding, the events with ARI <2 years may represent disruption potentially caused by heavy rainfall and resulting flooding of a stream or river further down the catchment. Such non-localised flood events require catchment-based hydrological modelling to understand the nature of flood flows.

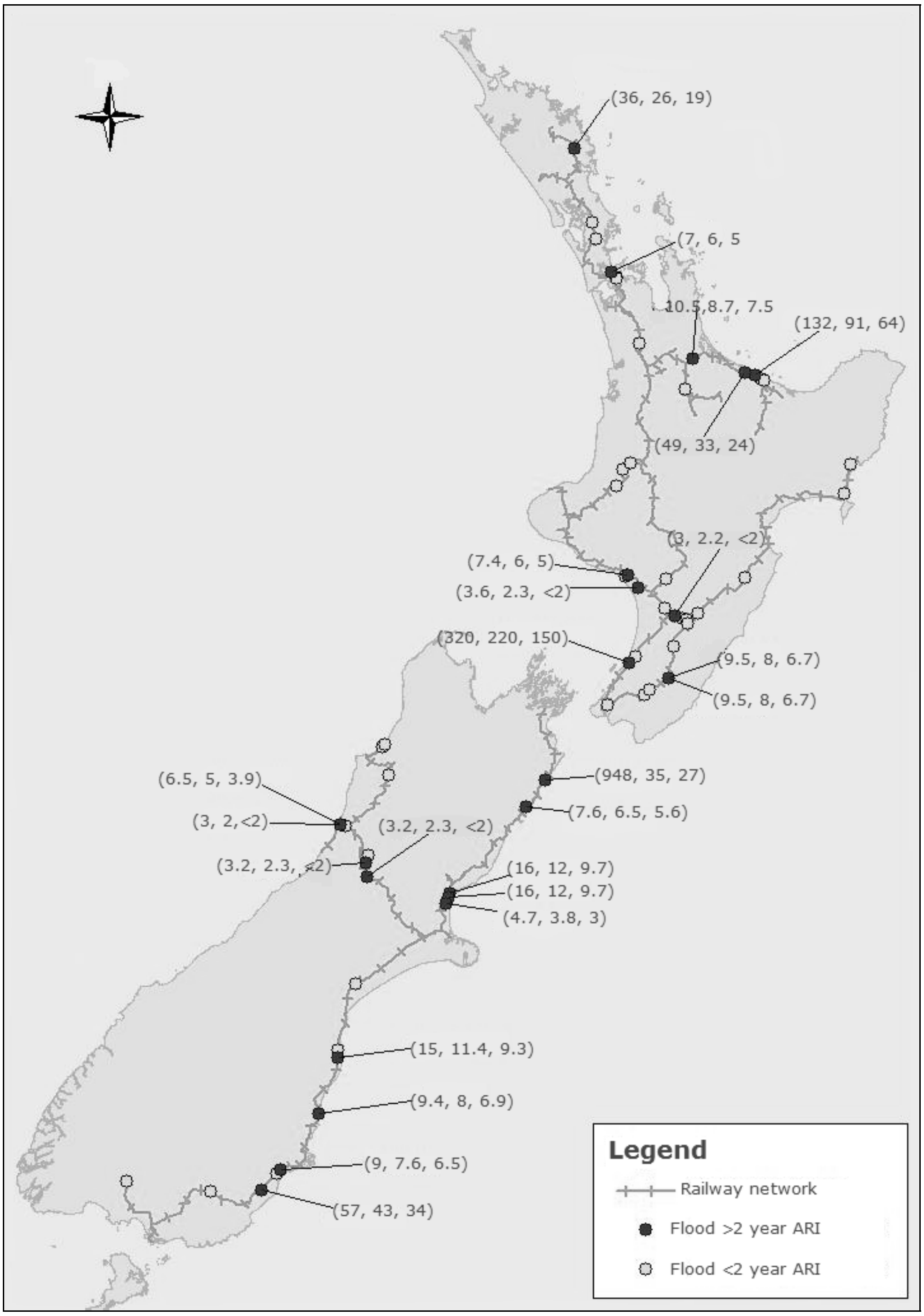

Figure 5.5 Recorded flood events on the national rail network and predicted effects of climate change on ARIs at these sites (2010, 2040 and 2090) (Source: current flood data from ONTRACK's IRIS database over July 2004–September 2008).

The national floods have been analysed for their regional distribution in terms of main lines affected. The distribution of floods and their magnitude (ARI) by main railway line are shown in Figure 5.6 (for the North Island) and Figure 5.7 (for the South Island).

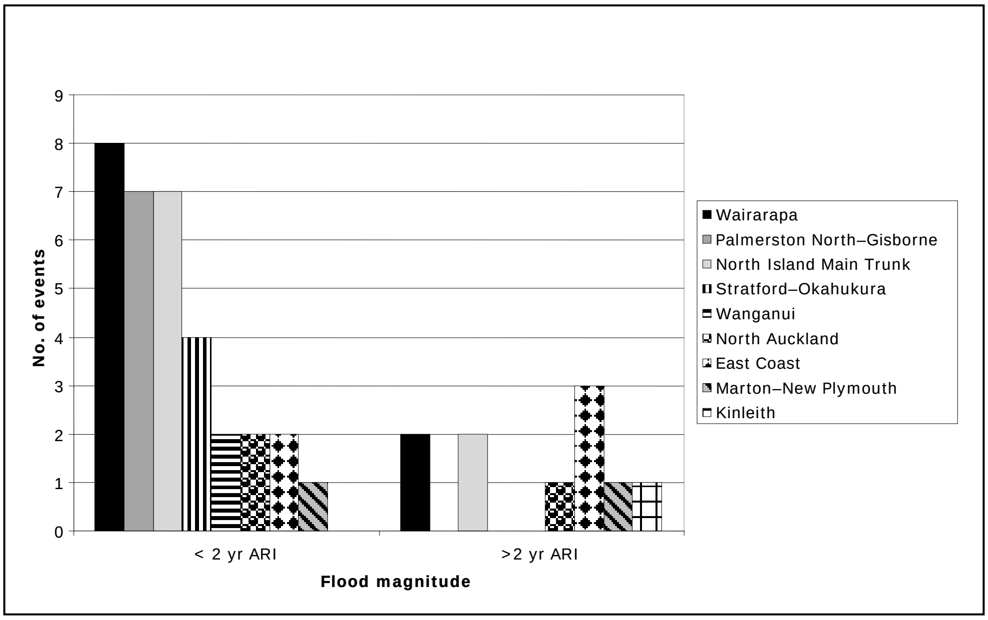

Figure 5.6 Distribution of flood incidents July 2004–August 2008 by line and magnitude on the North Island rail network.

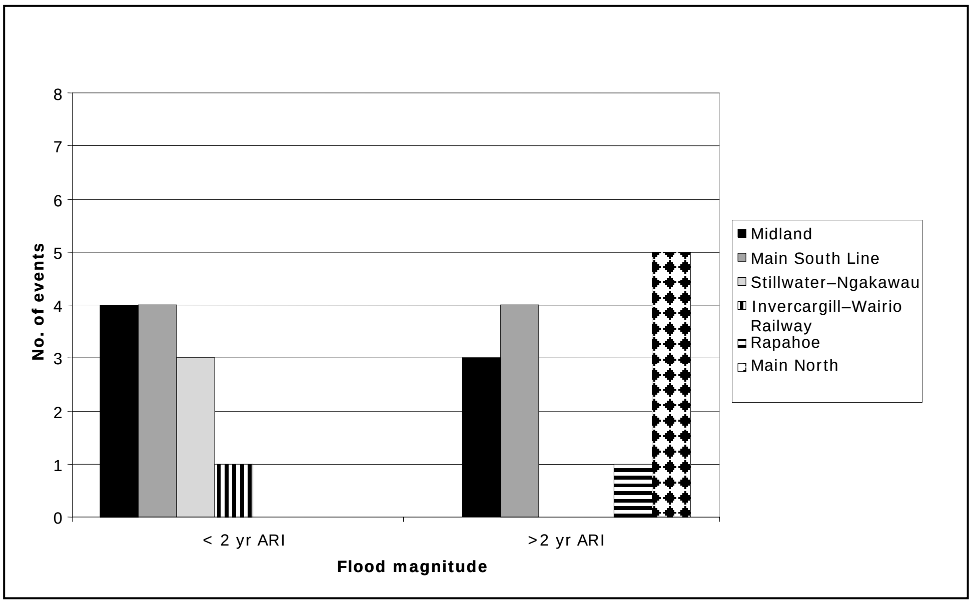

Figure 5.7 Distribution of flood incidents July 2004–August 2008 by line and magnitude on the South Island rail network.

5.4.2 Impact of climate change on rail flood profile

Data for high magnitude floods (ARI >2 years) recorded in the past four years (extracted from Appendix C) were used to predict how a climate change scenario could affect the recurrence interval or likelihood that a similar scale rain event could occur if an 8% or 16% increase in rainfall associated with the flood was experienced in 2040 and 2090, respectively. The results (Table 5.1) indicate that those events considered to be high magnitude in today's terms will occur more frequently as a result of climate change.

Table 5.1 Estimated current and future ARIs for recorded floods affecting the rail network*.

Line	Rainfall (mm)	Period (hours)	Predicted ARI		
			2010	2040	2090
NIMT	224.2	48	320	220	150
ECMT	228.8	24	132	91	64
Main South Line	104	24	57	43	34
ECMT	188.2	24	49	33	24
Main North Line	210	48	48	35	27
NAL	282.6	48	38	26	19
Main North Line	112.2	48	16	12	9.7
Main North Line	112.2	48	16	12	9.7
Main South Line	84	48	15	11.4	9.3
ECMT	275.3	72	10.5	8.7	7.5
Wairarapa	91.1	24	9.5	8	6.7
Wairarapa	91.1	24	9.5	8	6.7
Main South Line	82.8	48	9.4	8	6.9
Main South Line	80.7	48	9	7.6	6.5
Main North Line	178.3	72	7.6	6.5	5.6
MNPL	81.2	48	7.4	6	5
NIMT	113.8	48	7	6	5
Rapahoe	128.8	24	6.5	5	3.9
Main North Line	82.3	48	4.7	3.8	3
MNPL	58.9	24	3.6	2.6	<2
Midland	304	48	3.2	2.3	<2
Midland	304	48	3.2	2.3	<2
PNGL	84.4	72	3	2.2	<3
Midland	114	24	3	2	<2

* ARI >2 years

As an example, for the East Coast Main Trunk (ECMT) line flood of 10 February 2006 (which occurred approximately 1 km west of the coastal settlement of Hauone, western Bay of Plenty), the nearest rain gauge (Pikowai) gave a 24-hour rainfall total of 228.8 mm for this date (the gauge provides a good indication of the likely 24-hour rainfall at the event location, as the separation distance is less than 2 km). The current ARI for this 24-hour rainfall figure is 132 years. IRIS notes the following entry for this event:

> *Flooding reported Pongakawa-Kawerau, Signals staff called out for block fault reported high river levels; Police advise rail under water and debris across rail at approx. 160.00km. AC arrange track inspections as soon as possible.*

Scaling up for the same 24-hour rainfall from the HIRDS projection reduces the ARI to 91 years in 2040; 64 years, in 2090. In broad terms, the risk of this flooding event in 2090 is twice as high as present based on the same 24-hour rainfall. This type of analysis indicates where design changes may be needed on the network to adapt to the increased future flood risk.

5.5 Climate change effects on flooding and the national state highway network

5.5.1 Current state highway flood profile

From the range of flood data sources reviewed as part of this research, flooding is clearly widespread throughout the national state highway network. The floods recorded in NIWA's historical flood database (Appendix B), and shown in the 2006 and 2007 *National Hazards* publications (NIWA & GNS 2007, 2008) show potential effects on the state highway network in most regions(see Figures 5.3 and 5.4).

Recurring hazard sheets in state highway maintenance contracts are used for recording a range of hazards, including floods, that affect the state highway network. Details include the site where a recurring hazard has occurred and the recommended inspection frequency to monitor the effects of a given hazard at that site.

A summary of the flood-related recurrent hazard sites (state highway and number of events recorded) as advised by sixteen of NZTA's 24 state highway regions is given in Tables 5.2 and 5.3. Recurring flood hazard details from these sixteen network operations indicate all except one region (Marlborough South) have recorded floods affecting the state highway in the past.

Table 5.2 Flood-related recurrent hazard sites as advised by state highway regions in the North Island.

Northland		Auckland		East Wanganui		Waikato		West Waikato		Rotorua		Coromandel		East Bay of Plenty		Wellington	
SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites
1N	4	1	3	1	3	3	1	1	6	5	2	2	2	2	4	1	6
10	7	16	8	2	2	30	1	3	1	36	3	25	5	30	1	2	7
11	1	22	1	3	1	31	1	23	5							53	1
				56	1												

Table 5.3 Flood-related recurrent hazard sites as advised by state highway regions in the South Island.

Marlborough South		Marlborough North		West Coast		North Canterbury		South Canterbury		Central Otago		Coastal Otago		Southland	
SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites	SH	Event sites
no flood related events		1	1	6	3	1	9	80	2	8	2	1	4	6	16
		6	5	7	1	7	1	82	1			8	3	1	24
				67	1							85	1	93	4
												87	1	94	29
												90	2	95	3
														96	10
														97	2
														99	9

As a regional example, and to demonstrate the extent of flood risk mapping that existing data sources allow, the recurring hazard flood data for the Wellington region are shown in Table 5.4 and plotted in Figure 5.8 along with the major catchment boundaries (note that two data points in the hazard sheet could not be plotted because of a mismatch between the highway centreline and the flood location).

Table 5.4 Recurring hazard flood data for Wellington state highway region.

SH	RS[a]	RP[b]	Side	Location	Hazard description
1	995	4	B	Waitohu	Flooding
1	995	10.68	B	Mangaone	Flooding
1	1023	11	B	Paekakariki BP culvert	Flooding, debris build up
1	1035	14.2	B	Mana Esplanade	Flooding
1	1060	5.2	B	Johnsonville tunnel*	Flooding
1	1060	5.6	B	Ngauranga	Surface flooding
2	962	All	B	Owens Street	Flooding*
2	946	0.9	B		Flooding
2	946	2.2	B		Flooding
2	946	13.8	B		Flooding
2	962	7.55	B		Melling, flooding
2	962	11	B	Korokoro/Petone	Flooding
2	962	14.2	D	BP culverts	Flooding
53	0	14.2	B	Jenkins Dip & Waihenga Bridge	Flooding, monitoring and clean up

Notes to Table 5.4:
a) RS = Reference Station, i.e. a 'benchmark' along the state highway.
b) RP = Route Position
* Data not plotted in Figure 5.8 because of an alignment mismatch; date of events not known.

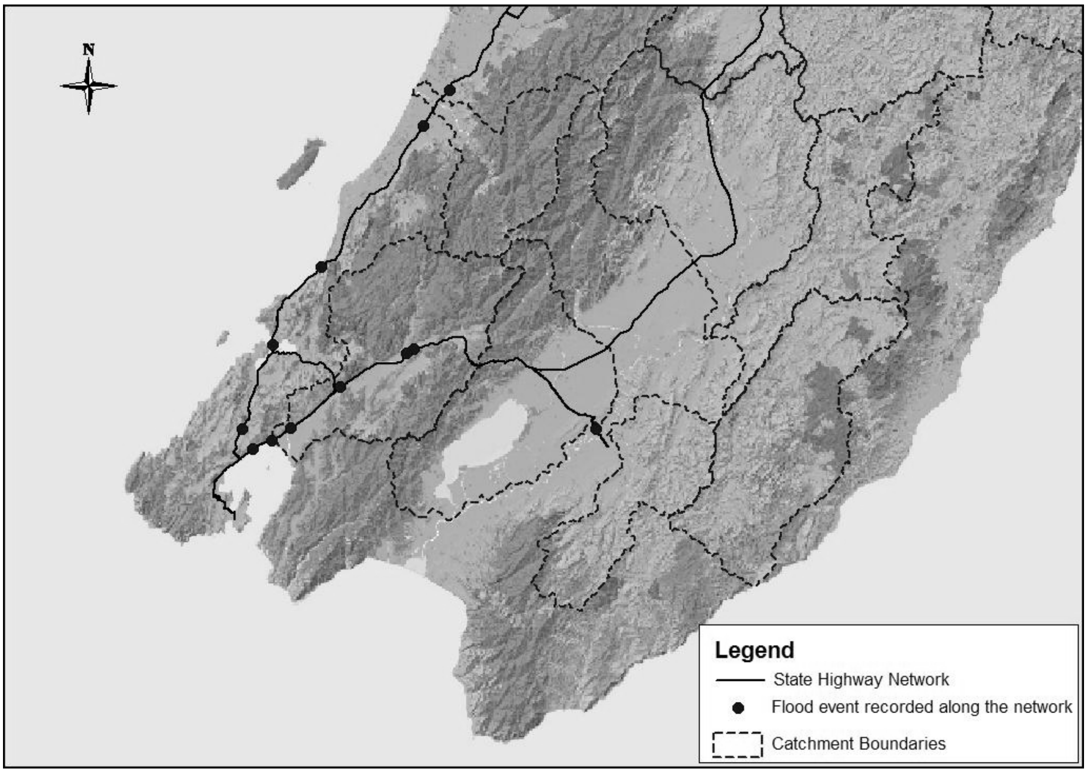

Figure 5.8 Recurring flood hazard sites for the Wellington state highway network.

The variance in details in recurring hazard sheets between state highway network regions indicated a lack of consistency in the interpretation of a 'recurring flood hazard'. Thus for Southland, all flood events have been included, not just recurring ones.

The lack of detail about when floods occurred and the uncertainty in the frequency of recurrence, along with a shortfall in data for approximately 30% of the network regions prevented compilation of a national flood profile as well as any detailed analysis of flood magnitude (based on rainfall and ARI) or prioritisation of regions for further investigation.

5.5.2 Impact of climate change on regional state highway flood profile

Because insufficient data describe the extent of existing flooding of the state highway network (see above), it was not possible in this study to build a national profile of flood events or to analyse these in terms of likely change in flood risk based on predictions of ARIs under future climate change scenarios.

5.6 Adaptation strategies: climate change related flood effects on surface transport

5.6.1 Vulnerability

The report of the IPCC (Parry et al. 2007) identified a number of climate change impacts and vulnerability for New Zealand. In terms of flooding and impacts on infrastructure, the report noted that:

> *Heatwaves and fires are virtually certain to increase in intensity and frequency (high confidence). Floods, landslides, droughts and storm surges are very likely to become more frequent and intense… (high confidence). Large areas of mainland Australia and eastern New Zealand are likely to have less soil moisture, although western New Zealand is likely to receive more rain (medium confidence). Risks to major infrastructure are likely to increase. By 2030, design criteria for extreme events are very likely to be exceeded more frequently. Risks include failure of floodplain protection and urban drainage/sewerage, increased storm and fire damage, and more heatwaves, causing more deaths and more blackouts (high confidence).*

The strategic context of the rail and state highway networks and priorities for adaptation responses for transport networks to the increased risk of flooding are discussed below.

5.6.2 Strategic context

5.6.2.1 Rail

The government's investment in the passenger and freight rail networks through ONTRACK was emphasised following the repurchase of rail operations on 30 June 2008. ONTRACK's Statement of Intent (2008–2011) (ONTRACK 2008b) notes the $200 million of government funding committed to improve New Zealand's rail infrastructure following a substantial period of under-investment.

ONTRACK acknowledge the vulnerability of the network over the past two decades to weather extremes, particularly in respect of inadequacies in the culvert and drainage system (Rushbrook & Wilson 2007). A culvert risk analysis model and sample study of rail culverts and drainage (MacIver 2006) has been useful in prioritising maintenance and inspection work to target improvements to the national culvert and drainage system. Greater funding and strategic initiatives to understand the condition of the rail culvert and drainage system better has enabled ONTRACK to take a strategic review of the vulnerability of its assets and apply a range of measures to improve its performance including:

- extending culvert risk analysis to other mainlines in the network,
- applying highly engineered solutions to eliminate the risk of flooding,
- special patrols to ensure track safety for passage during adverse weather events,
- applying train speed restrictions or ceasing train service, and
- having infrastructure staff able to respond to and repair damage.

5.6.2.2 State highways

Improving the reliability of journey times is a target of the NZTS (MoT 2002), with a particular focus on routes identified as 'critical'. The definition of these routes is a priority task for local and central government. Once defined, the critical routes' classifications will help transport operators prioritise future investigations into existing and potential future flood risk as a result of climate change in order to ensure that critical routes continue to be resilient to natural hazards.

From a strategic perspective, Kinsella & McGuire (2005) analysed the direct impacts of climate change on a range of state highway assets. Using a two-stage screening process to identify adaptation actions, Transit New Zealand (now NZTA) concluded that current asset management practice (through incrementally adjusting design standards) is generally sufficient to manage climate change effects for most of the network in the short to medium term (up to 25 years). However, current policy and practice may not be sufficient to protect assets with a long design life adequately, specifically culverts with a design life of more than 25 years and bridges. Table 5.5 summarises the likely impacts on bridges and culverts by 2080 and changes required to current practice.

The work by Kinsella & McGuire resulted in an amendment to Transit's *Bridge Manual* (2003) to include consideration of relevant climate change factors in the design of major new bridges and culverts. Their paper also recognised that climate change is an evolving science and that the practice current at that time needed to be reviewed, with specific mention made of planning and route selection, catchment management and screening bridges for scour risk and treatment.

Table 5.5 Assessment of climate change impacts on state highway bridges and culverts (adapted from Kinsella & McGuire 2005).

Asset type	Climate parameter affecting the state highway network by 2080	Level of certainty	Design life (estimated years)	Current practice
Bridges	Increased mean annual rainfall in western New Zealand.	Medium	100	**Minor changes to current practice required.** Bridges are designed for a 5% probability that the design criteria will be exceeded (e.g. by flooding) in any given year. A reduction in flood ARIs constitutes an increased risk to bridge stock.
	Increased intensity and/or frequency of heavy rainfall throughout New Zealand, leading to flooding and soil saturation and slips.	Low		
	Sea level rise (for coastal bridges)	High		
Culverts in waterways	Increased mean annual rainfall in western New Zealand	Medium	20–100	**Minor changes to current practice required.** See ‘Bridges’ for longer life culverts (30+ years). See ‘Drainage’ for shorter life culverts (<30 years)
	Increased intensity and/or frequency of heavy rainfall throughout New Zealand, leading to flooding and soil saturation and slips.	Low		
	Sea level rise (for coastal culverts)	High		
Drainage (surface)	Increased intensity and/or frequency of heavy rainfall throughout New Zealand, leading to flooding	Low	20	**Current practice sufficient.** Drainage systems are designed for local conditions. Improvement works to cope with changes in climate can be undertaken as part of periodic reconstruction when the impact occurs.

5.6.3 Priority adaptation responses

As heavier and/or more frequent extreme rainfalls are expected under climate change with moderate confidence (MfE 2008a), it is important that land transport network operators assess the implications in terms of which assets are at greatest risk from flooding and when such risks may arise in relation to the asset’s lifetime.

A fundamental starting point in determining climate change risk is an assessment of how vulnerable the transport networks are under current climate conditions, and using this as a basis for identifying those parts of the network where future risks may prompt the need for an adaptation response (e.g. planning, design, operation or maintenance).

Rail

This study has shown that certain regional areas of the network are vulnerable to flooding, and that climate change is set to increase the flood risk in these locations (e.g. by up to a factor of 2 in 2090). The objective of future adaptation responses should be to ensure rail assets with longer (50- to 100-year) lifespans will be resilient to future flood conditions.

To achieve this objective, ONTRACK should investigate long-life assets in existing flood-prone areas highlighted in this report to identify their risk profile and need for potential adaptation responses. In terms of new assets, design standards should consider site-specific flood flows under climate change scenarios as part of culvert and drainage design calculations.

It is noted that ONTRACK already undertakes full hydrological studies when undertaking bridge replacements (e.g. Grey River) and uses guidance from the relevant regional council to build in climate change factors into the design. A bridge freeboard of 1.2 m is allowed wherever feasible.

State highway network

While certain parts of the network are vulnerable to flooding, and climate change is set to increase the flood risk, this study was not able to present a national profile of this current risk (based on recorded flood events) or provide estimates of future risk (based on changes in flood ARI). The main barrier is the absence of a central database of asset vulnerability to extreme weather events. The present method of recording such information does not lend itself to network-wide assessment. While such events are managed on a regional basis and data records are held at the regional level (as ‘recurring hazard sites’), this information is not collated in a systematic and uniform way across each region, and is not in a form that can be rolled up to the network level.

Information gathering is key at this time for the state highway network, as the more comprehensive flood recording conducted now will enable more robust analysis to be undertaken in future. Adaptation response in the short term should therefore focus on the systematic collation of data on extreme weather events that cause disruption/damage to the state highway network. Establishing a national database of asset vulnerability will assist asset managers and other decision makers to:

- model the effects of climate change scenarios on flood risk across the network,
- identify long-term assets requiring priority for adaptation studies (e.g. existing bridges), and
- investigate examples of drainage infrastructure that successfully manage flood conditions.

Multi-criteria analysis

An MCA of adaptation options for inland flooding for the state highway and rail networks (see Appendix A) lists a number of adaptation responses (F1 to F8), and provides inter-linkages between each action and their relative priority. National flood details, site-specific flood modelling and cost/benefit analysis dominate the responses available to adapt to the risk of climate change related flood effects. The general direction of adaptation options required in the short term may be summarised as follows:

- **Research:** Use institutionalised (i.e. event records) or network knowledge (i.e. local personnel) to:
  - discover which parts of the network that are currently prone to flooding (as identified in this study) as the focus of more detailed flood risk studies,
  - consider catchment-based flood modelling in high-risk areas to refine risk assessments for critical assets (e.g. bridges and major culverts), and
  - to identify 'near miss' sites (areas not currently affected but which could be under future scenarios).
- **Operation:** Include the systematic data collation of floods (where, when, extent of disruption or damage, and costs) in all asset hazard records to assist future adaptation studies (damage estimation is needed to enable determination of current and potential future costs of flooding, and therefore the cost-effectiveness of adaptation initiatives). Flood monitoring may assist real-time network management to limit risks to assets, freight and passengers.

Regarding flood monitoring, the UK Highways Agency, in conjunction with the (UK) Meteorological Office, has identified the value of early warning systems for extreme weather. Forecasts a few hours in advance and longer-range forecasts (weekly, monthly and seasonal) could also be very useful for short- and medium-term planning. On this point, representatives from ONTRACK indicated a weather forecasting system (heavy rain, high temperature etc.) will be used in the near future to minimise travel disruption on the national rail network.

5.6.4 Related studies

A number of related parallel studies in New Zealand have been recently completed or are underway (or planned) to determine the risk from flooding that may arise from climate change. These are relevant to the transport sector and are briefly summarised below.

MfE Climate change flood guidance (NIWA)

This MfE-funded project is developing a technical guidance note (shortly due for release) to assist local government in assessing the effect of climate change on the risk of river flooding, and is complementary to a related guidance note on planning aspects of the same issue. The technical note summarises what is known about flood-related impacts from climate change in New Zealand based on the most recent projections in the IPCC FAR. It includes a range of prediction tools that allow the user to estimate the impact of climate change on rainfall, to convert changes in rainfall to runoff (flood flows) and then to assess the risk of inundation. The guidance has both screening level and advanced techniques and is illustrated with five case studies.

Regional climate modelling project (NIWA)

This FRST-funded research (July 2008–September 2011) will produce detailed projections and datasets of future climate change from regional model runs, supplemented by statistical downscaling of information from the multi-model ensembles developed for the IPCC FAR. This allows projections to be expressed in a probabilistic framework and will allow better quantification of uncertainty for end-user risk management. Climate model outputs will be used to drive a number of other environmental models, including hydrological models to assess changes in stream flow and flood risk under climate change.

Regional Riskscape project (NIWA & GNS)

In the FRST-funded Regional RiskScape Project (October 2008–September 2016), NIWA and GNS are jointly developing a decision-support tool for land-use and emergency management planners. The model incorporates data on a range of natural hazards – both meteorological and geological – so that planners can compare the risk posed by each hazard in a consistent way, using outputs such as physical damage, direct and indirect losses (in dollars), civil disruption and casualties. This analysis can then inform decisions on topics including investment in infrastructure, land development and emergency preparedness.

Impacts of climate change on soil conditions, river flow and floods (NIWA)

This research programme (January–December 2009), funded by the Sustainable Land Management Mitigation and Adaptation to Climate Change programme of the Ministry of Agriculture and Forestry via FRST, will assist communities to adapt to changing climate-related hazards. This will be achieved by providing robust assessments of flood risk for strategically selected catchments around New Zealand. These flood risk assessments will be produced by linking both current rainfall records and regional climate model predictions to a stochastic rainfall model, which in turn drives a hydrological model. This will enable the presentation of specific and targeted information outputs, such as percent increase in events causing over-bank flow, which are required by land managers to plan for risks such as damage to fences, bridges and culverts.

Climate change impacts on urban infrastructure and built environment (NIWA, MWH, GNS and BRANZ)

This FRST-funded research programme (October 2008–September 2011) will help central and local government to identify opportunities and reduce the impacts of climate change on urban and built environment/infrastructure. The programme plans to develop a science-based risk assessment process and to identify adaptation options. By collaborating with councils spanning a range of environments and demographies, the project will:

- identify present and expected future spending on various aspects of urban and built environment and infrastructure;
- develop a process to identify and quantify key risks and opportunities for aspects sensitive to climate change;
- determine the current level of adaptation to these opportunities and risks, and additional options and their costs and benefits; and
- develop processes for councils to integrate these methods for managing climate change risks and opportunities into their activities and plans, and to identify and reduce barriers to their implementation.

The project output will be a generic framework for climate change risk and opportunity management for use by central and local government.

These developments should provide a more comprehensive tool kit for assessing flood and other risks to transport and related infrastructure from climate change.

5.7 Conclusions

The purpose of this study was to conduct a national profile of New Zealand's road and rail networks to identify which areas are potentially most at risk from inland flooding caused by climate change. The basis for the study was the regional distribution of existing floods and projected future flood ARIs based on increased frequency of extreme rainfall.

The method assumes that the future change in flood risk at a given location is proportional to the increase in extreme rainfall at that location. This is based on the premise that a given percentage increase in heavy rainfall translates into a similar percentage increase in peak river flow. These assumptions are acceptable for the purposes of this national profile. The following conclusions are made:

National rail network:

- In terms of current vulnerability to flooding, the rail network has experienced approximately 68 floods during the period available for this study (July 2004 to September 2008). While floods occur across New Zealand, regions with a higher flood prevalence include the coastal section near Hauone (central Bay of Plenty), Palmerston North, Arthur's Pass and the Amberley/Rangiora area in Canterbury.
- On a regional basis, the IRIS database flood data for this four-year period indicate more events affecting main lines in the North Island (32) than in the South Island (20), with two events in particular (both in the North Island) exceeding a 100-year return period.
- The majority of the IRIS flood events have a flood ARI <2 years and are interpreted as representing flooding further down the catchment. Such non-localised flood events require catchment-based hydrological modelling to understand the nature of flood flows and to provide predictions of future recurrence under climate change.
- ONTRACK acknowledges the vulnerability of the network over the past two decades to weather extremes. Their research has shown that 97% of anticipated costs could be attributed to the failure of 10% of culverts, primarily as a result of frequent small flood events rather than less frequent extreme weather events.
- In terms of climate change, this study shows that by 2090, the flood risk is set to increase in identified flood-prone parts of the rail network by up to double current levels. These predictions indicate where design changes may be needed on the network to adapt to the increased future flood risk.
- The approach used in this study considers the future effect of known floods, but does not identify which parts of the networks are likely to be flooded in the future but which are currently not at risk (i.e. the present day 'near misses'). These may only be identified by hydrological modelling of flood risk at the catchment level.
- The objective of future adaptation responses should be to ensure rail assets with longer (50- to 100-year) life spans will be resilient to future flood conditions. This will entail site-specific flood modelling and cost/benefit analysis for bridges and culverts most at risk.

National state highway network:

- At the time of this study, the TREIS database was encountering technical difficulties which prevented data prior to July 2008 from being accessed; therefore recourse was made to data held at the regional level.
- Responses to requests recurring hazard sites on the state highway network were received from 16 of the 24 state highway network operations regions. The data indicate that all but one region (Marlborough South) have recorded floods affecting the state highway in the past. However, the lack of dates for when the floods occurred and the uncertainty in the frequency of recurrence, along with a shortfall in data for approximately 30% of the network regions, prevented a regional comparison.
- While certain parts of the state highway network are vulnerable to flooding, and climate change is set to increase the flood risk, this study was not able to present a national profile of this current risk (based on recorded flood events) or provide estimates of future risk (based on changes in flood ARI). The main barrier is the absence of a central database of asset vulnerability to extreme weather events.
- For all transport networks, the current design standards and design philosophies require review and standardisation in order to respond adequately to climate change (Kouvelis 2008).

5.8 Future considerations

For the state highway network, adaptation response in the short term should focus on the systematic collation of data on extreme weather events that cause disruption/damage to the network, and more detailed flood risk studies for those parts of the network that are currently prone to flooding, as identified in this study. Catchment-based flood modelling should be considered in high-risk areas to refine risk assessments for critical assets (e.g. bridges and major culverts), and to identify ‘near miss’ sites (areas not currently affected but which could be in future).

For the national rail network, further studies should investigate long-life assets in existing flood-prone areas highlighted in this report to identify their risk profile and their need for potential adaptation responses. In terms of new assets, design standards should consider site-specific flood flows under climate change scenarios as part of culvert and drainage design calculations.

Other future considerations in terms of assessing how the flood risk from climate change affects surface transport networks could include the following:

- **A systemised, centralised database of floods and their impacts** to provide the backdrop for sound flood management policy making. Ericksen (quoted in Walton et al. 2004) noted that no agency in New Zealand maintains a consistent and comprehensive database of flood events and their impacts, a situation that remains unchanged.
- **Documenting details of current flood events and flood mitigation projects**, recording responses to predicted climate change conditions (including quantification of costs and benefits) to best target adaptation funds. Walton et al. (2004) note

that sensible analysis of how the costs of flooding may change as a result of future climate change scenarios can only be undertaken if planners have some understanding of past and current flood losses.

- **Estimation of the increase in area to be included in the 100-year floodplain** would give a good national overview of the impacts of increasing rainfall on flooding. Suarez (2005) reports that flooding impact estimates in the US are based on work by the National Flood Insurance Programme. The flood insurance studies developed under this programme involved the detailed modelling of coastal and riverine flooding to produce Flood Insurance Rate Maps. These maps show the 100-year and 500-year floodplains: areas that, on any given year under current conditions, have a probability of being flooded equal to 1% and 0.2%, respectively.

6 Key messages from Stage Two and future directions

The three climate change studies completed in Stage Two of this project should be viewed as an initial high-level appraisal of the regional implications of climate change effects for the land transport sector. They also provide an initial assessment of adaptation options for consideration under the existing transport asset management programme, as well as aspects needing further consideration.

The Stage Two findings provide a pointer to those parts of the land transport networks where more detailed studies could be prioritised under an ongoing research programme to confirm the actual risk of climate change, quantify the likely damage and cost implications, and provide the basis for a robust, cost-effective adaptation response, where needed. Detailed conclusions from these individual studies and recommendations for further work are documented in earlier sections of this report.

The key messages from Stage Two which deal with broader aspects of climate change are set out below. Many of them are interlinked and some aspects have already been discussed in Stage One but are repeated here as their importance has been further underscored during completion of the national profile of transport networks in the current stage.

The following key aspects are highlighted from the Stage Two study:

- **Lack of national datasets:** A recurring theme of the study was the limited availability, quality or completeness of national datasets required to evaluate strategic implications of climate change risks to national transport networks (e.g. high-resolution topographic coastal data for New Zealand for inundation risk profiling).
- **Gaps in transport data:** Existing asset management systems held by transport providers are generally not set up to provide the information required to predict effects on the networks from climate change. High-resolution elevation datasets of transport assets are generally not available, particularly with national coverage. Transport providers need to map their national assets to a high resolution so as to enable risks from climate change (e.g. flood, coastal inundation and slips) to be assessed at the local/regional level. Such datasets are essential to determine current network resilience and to provide the basis for climate change projections.
- **Vulnerability of transport networks to extreme weather:** A corollary of the above is that the current vulnerability of surface transport networks to climate extremes is not well documented and the quality and retrievability of nationally-consistent data on weather events varies widely (e.g. the rail network has a relatively robust system). More robust systems are needed to assist evaluation of the significance of extreme weather events and weather variability in the design, cost, mobility and safety of existing networks. Analysis of current weather events that affect transport systems will assist future forecasting of effects under climate change. Data required to conduct such analysis could include:

  - the nature of the weather event and climatic conditions;
  - the physical extent of affected infrastructure including location and elevation details; and
  - the nature of adverse effects, such as the period of disruption to normal operations, extent of damage, and the cost and nature of repairs.

- **Greater use of weather forecasting systems:** Related to the previous aspect, while providing an excellent basis on which to make operational decisions, such systems may also be used to collect information on the weather events that cause disruption to transport networks, supplemented by incident reports including quantifiable observations about the extent of damage or disruption to network assets, users and adjacent properties.
- **Linkage of climate change to asset management:** Better integration of climate change considerations into transport providers' current asset management programmes (covering planning, design, operation and maintenance) is needed, as well as linkage to wider sustainable transport initiatives (such as priority transport corridors and lifelines perspectives).
- **Regional/local impact analysis:** The effects that a changing climate might have on transportation infrastructure and services are very dependent on regional climate and local site characteristics. These require local-scale modelling of such effects in order to provide the basis for cost-effective adaptation responses. Higher resolution climate models for regional and sub-regional studies would support the integration of region-specific data with transportation infrastructure information.
- **Risk analysis tools:** In addition to more regionally-specific climate data, transportation planners also need new tools to address the uncertainties that are inherent in projections of climate change. Such methods are likely to be quantitative and based on a probabilistic framework with greater clarity on uncertainty for end-user risk management. Given the long-term timeframe of climate change (e.g. +50, +100 years), other factors such as demography, future land use and technological advances also need to be taken into account in the risk analysis model.
- **Integrated transport planning approach:** This study provided an initial analysis of where climate change (e.g. risks from flood and coastal inundation) could affect parts of individual transport networks. Future studies need to consider the risk to transport systems as a whole. For example, the risks to ports from climate change do not depend simply on the vulnerability of the port infrastructure but rely critically on the transport networks servicing the ports. Climate change therefore needs to be considered in the context of an integrated transport network. This could take the form of an issues/options study on an integrated adaptation framework for climate change impacts on the surface transport network.
- **Economic evaluation:** A wider assessment of the economic cost of climate change on surface transport is necessary, seeing that calculating the true economic impact of climate change is fraught with 'hidden' costs. Besides the replacement value of infrastructure, for example, other real costs include re-routing traffic, lost workdays and productivity, provision of temporary shelter and supplies, and potential

relocation and retraining costs (Ruth et al. 2007). Systematic collection of data relating to such impacts should be investigated in future.

On a final note, the analysis of how a changing climate might affect transportation in New Zealand is at an early stage. The research themes listed above are needed to enable engineers, scientists, planners, network operators and policy makers to understand the risks from climate change more fully, and to improve the resilience of transport systems in response to these threats.

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Appendix A MCA of climate change effects on the land transport system

A1 Rail heat stress study

Regarding the persistence and reversibility of this climate-change related effect, heat buckling risk factors may persist until maintenance conditions are reinstated. This is not reversible (permanent track damage requires track replacement). The timing of these effects is uncertain: a gradual rise in mean temperature leads to increasing frequency of hot days and this effect is seasonally dependent.

The rail network will experience more days >30°C as follows:

- From 2010: Canterbury region;
- From 2040: Hawkes Bay;
- From 2090: Waikato, Gisborne and Bay of Plenty.

The type of adaptation proposed in the MCA shown in Table A1 relate to operation of the rail network. Ownership of these adaptations should be taken by ONTRACK.

Table A1 MCA of the effects of rail heat stress.

Aspect of the effect	Adaptation reference					
	H1	H2	H3	H4	H5	H6
Adaptation	Restrict track laying and maintenance activities in heat-prone areas during the hot season.	Assess the effectiveness and, if necessary, improve the current track inspection and repair regime (linked to ONTRACK's TSR investigation).	Raise standards for CWR installation, monitoring and maintenance in heat-prone areas.	Assess the effectiveness and, if necessary, improve standards to warn and update dispatch centres, crews and stations about heat risk.	Assess the effectiveness and, if necessary, improve the current heat gauge network, particularly in heat-prone regions.	Impose 'Heat 40' TSRs as per track inspections and dependent on H4.
Recommended timeframe[b]	• Short: Canterbury; • Medium: Canterbury, Hawkes Bay and Gisborne; • Long: Canterbury, Wairarapa, Hawkes Bay, Waikato and Bay of Plenty.	Short	Medium – if heat buckling events continue despite H1 maintenance restrictions.	Short	Short	As required
Cost/VFM	Low cost	Medium cost	VFM assessment required	Low cost	Low–medium cost: could involve some capital investment.	Medium cost: service delays.
Scale[c]	Heat-prone region focus	National	Heat-prone region focus	Heat-prone region focus	Heat-prone region focus	Site-specific
Co-benefits/ unintended consequences[d]	Limiting non-urgent track and ballast maintenance in these areas during the hot season could put pressure on maintenance staff availability.	Economic: maintenance savings.	Economic: potential maintenance and time delays cost savings.	Economic: could identify more cost-effective maintenance responses.	Economic: could identify more cost-effective use of existing heat gauge facilities.	–
Priority	Low regrets	Low regrets	Low regrets	No regrets	No regrets	–
Comments	As per existing practice.	ONTRACK (2008a) highlighted work to identify the cause of TSRs on key routes and to develop an action plan to remove TSRs had begun and was ongoing.	See H2	See H2	See H2	As per existing practice.

Notes to Table A1:

a) Short = to 2010; medium = by 2040s; long = by 2090s; as required = responsive
b) VFM = value for money
c) e.g. low cost and high return = priority
d) e.g. social, economic or environmental consequences; alignment with policies.

A2 Inland flooding study

The MCA of the effects of inland flooding on the national state highway and rail networks is shown in Table A2.

This effect is reversible, as flooding subsides. This type of event always occurs following the onset of extreme rainfall events.

This report identifies 68 floods affecting the national rail network between July 2004 and September 2008 based on weather event reporting. Comparable data for the state highway network are not available. This report identified regions that have experienced floods in the past four years based on weather event reporting. No detailed national report about the extent of flood risk to network structures, particularly bridges, exists at present.

Table A2 MCA of the effects of inland flooding on the national state highway and rail networks.

Aspect of the effect	Adaptation reference				
	F1	**F2**	**F3**	**F4**	**F5**
Adaptation	Use known flood sites and a survey of potential (near miss) flood sites to identify specific areas and assets (e.g. via bridge and culvert inspections) at risk of future damage.	Model flood flows under predicted climate change conditions. Dependent on F1.	Calculate the potential future costs of flooding. Dependent on F1 and F2.	In situ protection in areas at risk of future flooding, e.g. flood protection, improved drainage, raising carriageway/ rail levels or installing debris traps. Dependent on F1, F2 and F3.	Record the flood details and the extent of flood damage to assets and adjacent properties.
Type	Research	Research	Research	• Design (new) • Operating (existing)	Operation
Ownership	Road and rail network operators; CRIs[a].	Road and rail network operators; Researchers.	Road and rail network operators; CRIs.	Road and rail network operators; Designers and maintenance crews.	Road and rail network operators.
Recommended timeframe[b]	Short	Short	Short	Short; Short–medium	Short
Cost/VFM	Good VFM – required to inform future prioritisation and funding decisions.	Good VFM – required to ensure adaptation meets future conditions.	Good VFM – required to inform future funding decisions.	VFM assessment required in each case. Dependent on F2.	Low cost – extension of current hazard register systems.
Scale[c]	National, but conducted on a local/district scale.	Site-specific studies	National, but conducted on a local/district scale.	Local	National
Co-benefits/ unintended consequences[d]	Aligns with FRST research strategy.	–	–	Environmental: resource efficiency	Valuable information for future flood studies.
Priority	No regrets	No regrets	No regrets if supported by VFM assessment.	–	–
Comments	–	Riskscape methodology exists.	–	May also need a programme to manage expectations in areas identified in F1 as being vulnerable.	–

Table A2 (cont.) MCA of the effects of inland flooding on the national state highway and rail networks.

Aspect of the effect	Adaptation reference			
	F6	F7	F8	F9
Adaptation	Use flood warning systems	Transport network diversions/change in speed conditions.	Relocate transport network at risk. Dependent on F1 F2 and F4.	Replace damaged structures with capacity to withstand predicted climate change conditions; Reinstate networks
Type	Capacity	Operation	• Design (new); • Operation (existing).	Emergency response
Ownership	Road and rail network operators.	Road and rail network operators (maintenance).	• Road and rail network operators (design and maintenance crews); • Consent authorities.	–
Recommended timeframe[b]	Short	As required	Short; Short–medium	As required
Cost/VFM	Good VFM if protection works are not viable. Dependent on F3.	VFM assessment required in each case. Dependent on F3.	VFM assessment required in each case. Dependent on F2.	VFM assessment required in each case.
Scale[c]	National programme conducted at regional scale.	Local, although national procedures could be developed.	Local	As per existing flood risk and additional areas, depending on catchment-specific flood modelling.
Co-benefits/ unintended consequences[d]	Social: community preparedness.	Social: risk exposure prevention.	Social: risk exposure prevention.	Not consistent with resiliency objectives of NZTS (MoT 2002).
Priority	Medium risk of sustaining damage to the network and avoidable disruptions if F3 sites are addressed.	Low regrets if supported by VFM assessment.	High risk	No regrets
Comments	–	–	–	Coastal protection structure studies should determine: • location and description of structures, e.g. rip-rap wall, culvert or pipe; • description of coastal hazard and effect on each structure, e.g. flooding, tides, storm tide; and • degree of effect, e.g. 40% inundated during 1 in 100 year flood.

Notes to Table A2:

a) CRI = Crown Research Institute
b) Short = to 2010; medium = by 2040s; long = by 2090s; as required = responsive
c) e.g. low cost and high return = priority
d) e.g. social, economic or environmental consequences; alignment with policies.

A3 Coastal inundation study

This climate change effect will impinge upon ports, and road and rail networks. The effect is predicted to be persistent and irreversible. The timing of the effect will be dependent on gradual sea level rise combined with sudden-onset storms.

The networks will be affected to the following spatial extent:

- State highway network:
  - North Island: 100 km may be affected, 60 km of which are identified for expansion in the next 30 years, including 22 'national' category state highways in Whangarei district (Marsden Point), Auckland, Taranaki district and Napier.
  - South Island: 122 km may be affected, 88 km of which are identified for expansion in the next 30 years, including 82 km in 'national' category state highways in Kaikoura, Christchurch, Timaru and Dunedin.
- National rail network:
  - North Island: 60 of the 68 km of rail on land within 5 m elevation of year 2000 sea levels are located on the NIMT (Auckland, Paremata), the PNGL (Napier, Wairoa, Gisborne), the Wairarapa Line (near SH 2 north of Wellington) and the North Auckland Line.
  - South Island: 84 of the 93 km of rail on land within 5 m elevation of year 2000 sea levels are located on the Main North Railway (Marlborough region, Kaikoura coast), the Main South Railway (Christchurch, Timaru, Oamaru, Dunedin), the Invercargill-Wairio Railway and the Bluff Industrial Line.
- National ports network:
  - Risks to individual ports have not been identified.

An MCA relating to the coastal inundation study is shown in Table A3.

Table A3 MCA of the effects of coastal inundation on ports, and the national state highway and rail networks.

Aspect of the effect	Adaptation reference			
	C1	C2	C3	C4
Adaptation	Review the findings of this study on vulnerable section of the network and coastal inundation records, and assess the adequacy of land transport asset/ coastal protection structures under existing conditions.	Map infrastructure assets and coastal margins at 1 m scale or better, with at least 0.2 m precision in elevation across tidal reach from MLWS to at least 3 m above MHWS.	Model combined effects of inundation risk (sea level rise plus storm surge plus wave run up) at priority areas identified to be vulnerable. Dependent on C1 and C2.	Monitor coastal hazard risk. Consult coastal hazard zones included on district planning maps. Monitor magnitude of site-specific coastal hazards (e.g. sea levels and waves (MfE 2008a).
Type	Research	Research	Research	Research
Ownership	NZTA, ONTRACK and ports.	CRIs, land transport operators, and local and regional authorities.	CRIs, land transport operators, and local and regional authorities.	Regional councils and coastal property owners.
Recommended timeframe[a]	Short	Short	Short	Short and ongoing
Cost/VFM	Good VFM	Good VFM	Good VFM	Good VFM
Scale[b]	Localised in low-lying areas.	Prioritise those areas where land transport asset/ coastal protection structures are at risk under existing conditions.	Prioritise those areas where land transport asset/ coastal protection structures are at risk under existing conditions.	National
Co-benefits/ unintended consequences[c]	Economic: will prioritise which assets are inadequate for current conditions.	Economic: will enable climate change modelling to reflect localised topography.	–	Will improve the accuracy of information available for decision makers.
Priority	No regrets	No regrets	No regrets	No regrets
Comments	–	Identified by NIWA as an area of data with low confidence.	An analysis of the increase in the predicted 1 in 100 year wave heights and wave energy at the toe of coastal defence structures would give a good indication of the impact of sea level rise on the structural integrity of the existing defences and the design requirements for future replacement defences (Mouchel Parkman 2008).	–

Table A3 (cont.) MCA of the effects of coastal inundation on ports, and the national state highway and rail networks.

Aspect of the effect	Adaptation reference			
	C5	C6	C7	C8
Adaptation	Redesign/retrofit facilities and structures with appropriate protection, or relocate. Dependent on C1, C2, C3 and C4.	Take account of existing and predicted changes in coastal conditions in new transport asset design. Dependent on C3 and C4.	Take account of predicted changes in coastal conditions on existing transport assets where they require rehabilitation or improvement. Dependent on C3 and C4.	Take account of predicted changes in new and existing transport assets when population growth is facilitated through land use changes in costal areas.
Type	Operation	Design	Operation	Planning
Ownership	NZTA, ONTRACK and ports	NZTA, ONTRACK and ports	NZTA, ONTRACK and ports	NZTA, ONTRACK, and local and regional authorities
Recommended timeframe[a]	Medium to long	Short and ongoing	Short and ongoing	Short and ongoing
Cost/VFM	Good VFM	Good VFM	Good VFM	Good VFM
Scale[b]	Localised in low-lying areas.	Localised in low-lying areas.	Localised in low-lying areas	Particularly in low-lying areas.
Co-benefits/ unintended consequences[c]	Economic: will prioritise which assets are inadequate for current conditions.	Minimises risk of over-engineering.	Minimises risk of over-engineering.	Social: minimising the risk of disruption to communities.
Priority	Low regrets	Low regrets	Low regrets: preventative action.	Low regrets
Comments	See main text below table.	–	–	–

Notes to Table A3:
a) Short = to 2010; medium = by 2040s; long = by 2090s; as required = responsive
b) e.g. low cost and high return = priority
c) e.g. social, economic or environmental consequences; alignment with policies.

The MCA noted comments regarding measure C5 which were too lengthy to present in the table. These comments noted that operators can raise roads and rails if required, and reduce 'cope' levels to minimise the likelihood of water flowing across docks, and they can construct flood defence mechanisms. Potential engineering solutions include designing a suitably strong structure to withstand the wave and/or hydrostatic forces, supported by soft engineering where appropriate (such as beach nourishment or vegetated buffers). Other solutions may include:

- using water-resistant materials,
- elevating critical operating components, or
- installing suitable drainage (including pumps) at low levels.

Set back distances or protective land uses on the seaward side may reduce the exposure of transport infrastructure from coastal inundation under climate change scenarios. Abandonment may be an option if the costs of maintaining the network are higher than associated benefits. Waitaki District Council, for example, have abandoned a 1 km section of Beach Road because of coastal erosion.

Appendix B Floods with noted effects on land transport networks

The data presented in Table B1 were sourced from NIWA's historical database.

Table B1 Floods that have affected land transport networks, 2005–2008 inclusive.

Date	Location	Rainfall total (mm)	ARI			Comments
			Current (2010)	Predicted (2040)	Predicted (2090)	
5/01/05	Kapiti, Horowhenua, Manawatu, the Hutt Valley and Golden Bay	100 mm (max for area)	2	<2	<2	The Waitohu Valley Road Bridge, west of the Tararua Range, was washed out during the high rainfall/flooding event. Flash floods on the Kapiti coast resulted in metre high (waist deep) water at Otaihanga, and 23 houses near the Waikanae River (which breached its banks) were evacuated. Roads out of Wellington, including SH 1 at Paekakariki were closed for a time.
13–14/2/05	Temuka	100 mm (approx.)	40	30	25	Surface flooding and a temporary closure of SH 1 south of Timaru.
3–4/5/05	Tauranga, especially in Otumoetai, Arataki and Omanu	144 mm at Tauranga Airport	10	8.5	8	Localised surface flooding.
17–18/5/05	Tauranga to Matata	369.6 mm at Tauranga Airport in 48 hours	>150	>150	>150	A state of emergency was declared on 18 May in Tauranga and Matata. Railway lines were buckled and about 20 motorists were trapped. Parts of roads and two bridges near Matata on SH 2 were washed away.

Table B1 (cont.) Floods that have affected land transport networks, 2005–2008 inclusive.

Date	Location	Rainfall total (mm)	ARI			Comments
			Current (2010)	Predicted (2040)	Predicted (2090)	
20–21/10/05	Gisborne and East Cape	148 mm at Gisborne Airport	10	9.2	8.6	Damage to roads on the Tolaga and Poverty Bay plains.
10–11/2/06	Whakatane and Rotorua	182 mm at Whakatane Airport in 48 hours	23	17	16	SH 2 at Matata was closed because of slips and surface flooding.
25–26/4/06	North and East Otago	123 mm at Dunedin Airport	85	65	50	Much of the Taieri Plains including Mosgiel were flooded. The towns of Oamaru and Waitati were also flooded.
27–28/4/06	Hauraki/ Coromandel	116 mm at Paeroa	5.7	5.3	5	Floodwaters resulted in the closure of the Karangahake Gorge Road between Paeroa and Waihi, and SH 26 between Pareoa and Te Aroha.
4–6/7/06	Wairarapa, Manawatu, Wanganui, and Taranaki	Three-day rainfall accumulations exceeded 200 mm.	100	70	50	In Wairarapa, more than 50 roads were closed because of flooding or landslips. In Taranaki, SH 45 was closed by surface flooding. Martinborough was isolated by the floodwaters, and surface flooding also affected Masterton, Greytown and Carterton. The settlement of Mangamahu (northeast of Wanganui) was completely isolated by the collapse of the Mangawhero river bridge (damages estimated at $10 million).
21–24/10/06	Wellington and Manawatu	200 mm at Wainuiomata; 109 mm at Northern Tararuas; 89 mm at Manawatu.	70	50	35	Manawatu Gorge closed by slips. Slips and debris closed the Wainuiomata Road. Heavy seas pounded coastline and disrupted ferry crossings.
5–7/2/07	Northland	Up to 180 mm near Kaitaia and Kaikohe	85	57	40	Major disruption caused by flooding in parts of Northland and western Waikato. Flooding damaged bridge on SH 1 near Te Kao, cutting off people for several days.
17/03/07	Westport	26 mm at Westport in 1 hour	2	<2	<2	Landslips blocked roads. Flooding caused several road closures.
28–29/3/07	Northland	244 mm at Whangarei Airport; 139.4 mm at Kaikohe	90	62	45	Slips and fallen trees in Northland. Floods blocking roads north of Whangarei. About 200 vehicles stranded on SH 10. SH 1 flooded and closed near Portland (Whangarei).

Table B1 (cont.) Floods that have affected land transport networks, 2005–2008 inclusive.

Date	Location	Rainfall total (mm)	ARI			Comments
			Current (2010)	Predicted (2040)	Predicted (2090)	
22–23/5/07	Nelson and Taranaki	98 mm at Nelson	7.2	5.9	4.8	Flash floods hit Nelson and New Plymouth. Mainly surface flooding, some of it knee deep. Insurance claims totalled over $1 million.
9–10/7/07	Northland	273 mm at Kaeo in 24 hours; 148 mm at Ohaeawai; 194 mm at Whangarei Airport in 48 hours.	150	103	73	Hundreds of roads were closed or affected by flooding, fallen trees and powerlines in the far North, Whangarei, Auckland and north of Thames. Kirikopuni Bridge was washed out.
17–18/7/07	Hawkes Bay	140 mm in worst affected areas.	35	27	20	Flooding and a 500 m slip covered Kereru Rd leading to Maraekakaho. Two submereged bridges closed SH 50 near Tikokino. A section of SH 56 near Opiki was closed after two days of steady rain.
30/07/07	Otago	81 mm at Dunedin Airport in 24 hours; 104 mm at Taieri Plain in 48 hours	20	14	10	Major floods along South Canterbury–Otago coast. Three Mile Hill Rd, a major route into Mosgiel, was closed by flooding.
8/01/08	Kapiti	320 mm at Oriwa; 140 mm at Waikanae; 120 mm at Levin in 30 hours.	11.5	9	7.6	Heavy rain resulted in major flooding in the Kapiti area.
22–24/2/08	Northland	204 mm at Kaeo in 48 hours	17	12	9.4	SH 10 closed north of Kaeo at least twice. Rangiahua Bridge flooded and impassable.
15/04/08	Waikato/ Bay of Plenty	126 mm at Matamata	21	8.5	7.5	In South Waikato, heavy rain caused severe surface flooding on roads. Manaia Bridge on SH 25 was closed with no alternative routes.

Table B1 (cont.) Floods that have affected land transport networks, 2005–2008 inclusive.

Date	Location	Rainfall total (mm)	ARI			Comments
			Current (2010)	Predicted (2040)	Predicted (2090)	
29/07/08	Coromandel (plus other areas)	300 mm at Golden Cross (Coromandel)	25	18.5	15	SH 25 between Coromandel and Whangapoua was closed by a large slip. SH 2 in the Karangahake Gorge between Paeroa and Waihi was flooded.
30/07/08	Marlborough (plus other areas)	144 mm at Kaikoura	17	13	10	Marlborough roads faced months of repairs after damage from the floods. Transit's Marlborough Roads division said the flood impact on roads was the worst for 10 to 15 years.
25–26/08/08	North Canterbury	135 mm at Hanmer	30	23	18	SH 7 from the Hanmer Springs turnoff to Hanmer Springs closed. Several slips blocked the inland road from Waiau to Kaikoura. Mason River, a tributary of the Waiau River, burst its banks.

Appendix C Floods affecting the national rail network, July 2004–September 2008

ONTRACK's IRIS database floods were extracted as Code CN Sub-Code FLD. The rain gauge location, rainfall, period and ARI columns in Tables C1–C13 were added as part of this flood study.

Table C1 Details of floods that have affected the Main North Line July 2004–September 2008.

Location_km*	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
247	25/08/08	Kekerengu, Valhalla	210	48	48	35	27
38.5	25/08/08	Rangiora	82.3	48	4.7	3.8	3
51.7	25/08/08	Amberley, Railway Tce	112.2	48	16	12	9.7
47.65	25/08/08	Amberley, Railway Tce	112.2	48	16	12	9.7
206.15	19/07/09	Hapuku–Grange Hill	178.3	72	7.6	6.5	5.6

* This column refers to the 'kilometrage' location listed in the IRIS database, and is the distance in kilometres from the reference point – usually the start of the railway line – to the recorded event.

Table C2 Details of floods that have affected the Main South Line July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
218	31/07/08	Waimate	84	48	15	11.4	9.3
408	01/08/08	Dunedin Aero AWS*	39.6	24	<2	<2	<2
294.55	30/07/07	Trotter's Creek	82.8	48	9.4	8	6.9
401.8	31/07/07	Balmoral, Outram	80.7	48	9	7.6	6.5
514	24/06/07	Nithdale	32.8	24	<2	<2	<2
435.1	26/04/06	Lovells Flat	104	24	57	43	34
210.1	14/02/05	Waimate	37.7	48	<2	<2	<2
129.5	30/12/04	Orari Estate	6	24	<2	<2	<2

AWS = Automatic Weather Station

Table C3 Details of floods that have affected the PNGL July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
121.71	03/07/08	Ohutu	74.3	48	<2	<2	<2
343.1	12/02/08	Mahia AWS	74.2	24	<2	<2	<2
27.18	06/06/06	Waipuna Woodville	34.5	24	<2	<2	<2
10	24/10/06	Palmerston North AWS	84.4	72	3	2.2	<2
379.86	28/11/05	Gisborne AWS	102.2	72	<2	<2	<2
43	05/10/05	Kiritaki	52.7	24	<2	<2	<2
23	03/09/04	Pahiatua	21.5	48	<2	<2	<2

Table C4 Details of floods that have affected the NIMT Line July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
76.5	03/07/08	Manakau	26.2	48	<2	<2	<2
573.87	05/08/08	Te Akatea Station	16	48	<2	<2	<2
64.73	08/01/08	Te Horo, Longcroft	224.2	48	320	220	150
668.7	01/03/08	Mangere EWS*	29.2	48	<2	<2	<2
151.29	18/03/07	Feilding Sewage PT	17.1	24	<2	<2	<2
681.15	29/03/07	Khyber Pass, Auckland	113.8	48	7	6	5
669.93	03/05/06	Khyber Pass, Auckland	21.2	24	<2	<2	<2
273.87	18/07/05	Te Akatea, Paerangi	77.4	72	<2	<2	<2
205.33	23/12/04	Ngahere Iti	14.6	24	<2	<2	<2

*EWS = Electronic Weather Station

Table C5 Details of floods that have affected the ECMT Line July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
162	30/07/08	Omeheu	90	48	<2	<2	<2
62.6	30/03/07	Te Ariki Falls, Matamata	275.3	72	10.5	8.7	7.5
137	10/02/06	Maniatutu	188.2	24	49	33	24
150.65	10/02/06	Pikowai*	228.8	24	132	91	64
158.2	12/07/05	Pikowai	75	24	<2	<2	<2

* discussed in Section 5.4.2

Table C6 Details of floods that have affected the North Auckland Line July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
90.6	15/04/08	Warkworth EWS	53.3	24	<2	<2	<2
114	17/08/07	Warkworth EWS	75	24	<2	<2	<2
231.2	29/03/07	Whangarei Aero AWS	282.6	48	38	26	19

Table C7 Details of floods that have affected the Midland Line July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
210	29/06/07	Greymouth Aero EWS	114	24	3	2	<2
141.6	17/10/07	Rotomanu 2	81.5	24	<2	<2	<2
203.8	12/07/06	Dobson	26.6	24	<2	<2	<2
129.7	14/11/06	Arthur's Pass	304	48	3.2	2.3	<2
112.8	14/11/06	Arthur's Pass	304	48	3.2	2.3	<2
141.6	02/01/06	Rotomanu 2	93.5	24	<2	<2	<2
112.8	17/11/06	Arthur's Pass	241.5	48	<2	<2	<2

Table C8 Details of floods that have affected the Stratford–Okahukura Line July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
86.2	02/07/07	Ohura Rd	67.5	72	<2	<2	<2
112.78	07/07/06	Taumaranui	50.9	72	<2	<2	<2
112.78	18/11/06	Taumaranui	23.6	24	<2	<2	<2
125.5	30/11/06	Taumaranui	72.1	48	<2	<2	<2
112.78	18/11/06	Taumaranui	23.6	24	<2	<2	<2

Table C9 Details of floods that have affected the Wanganui Freight Branch Line July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
2.45	02/04/07	Wanganui, Spriggens Park	16.8	24	<2	<2	<2
0.01	18/04/06	Wanganui, Spriggens Park	11	24	<2	<2	<2

Table C10 Details of floods that have affected the Wairarapa Line July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
164.02	08/03/07	Waipuna, Woodville	8	24	<2	<2	<2
91.5	05/07/06	Masterton, Te Ore Ore	91.1	24	9.5	8	6.7
90.96	20060705	Masterton, Te Ore Ore	91.1	24	9.5	8	6.7
65.98	19/01/06	Woodside 2	11.6	24	<2	<2	<2
57.15	05/07/06	Featherston	68.9	24	<2	<2	<2
170.38	06/07/06	Waipuna, Woodville	34.5	24	<2	<2	<2
65.98	12/07/06	Woodside 2	43.4	24	<2	<2	<2
129.82	11/08/06	Eastry Station	0	24	<2	<2	<2
8.3	20/09/05	Maungaraki No. 2	21.7	24	<2	<2	<2
7.5	17/08/04	Johnsonville, Ceres Crescent	33.3	24	<2	<2	<2

Table C11 Details of floods that have affected the Stillwater–Ngakawau Line July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
160.29	29/01/07	Westport Aero AWS	50.6	24	<2	<2	<2
81.2	14/11/06	Inangahua 2	66.5	24	<2	<2	<2
155.87	16/11/06	Westport Aero AWS	24	24	<2	<2	<2

Table C12 Details of floods that have affected the MNPL July 2004–September 2008.

Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
					Current	2040	2090
41.32	06/07/06	Wanganui, Spriggens Park	81.2	48	7.4	6	5
17.61	07/07/06	Okoia, Mangaone	58.9	24	3.6	2.6	<2

Table C13 Details of floods that have affected other New Zealand railway lines July 2004–September 2008.

Line	Location_km	Date (dd/mm/yy)	Rain gauge location	Rainfall (mm)	Period (hours)	ARI		
						Current	2040	2090
Invercargill-Wairio Railway	71.3	28/12/06	Nightcaps	21.3	24	<2	<2	<2
Kinleith	30.49	30/07/06	Tirau, Circle K	36.3	24	<2	<2	<2
Rapahoe	0.1	17/02/05	Greymouth Aero EWS	128.8	24	6.5	5	3.9

Appendix D Glossary and abbreviations

D1 Definition of key terms

Adaptation benefits: The avoided damage costs or the accrued benefits after adopting and implementing adaptation measures.

Adaptation assessment: The practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency and feasibility.

Adaptation costs: Costs of planning, preparing for, facilitating and implementing adaptation measures, including transition costs.

LiDAR: A method of detecting objects and determining their position, velocity or other characteristics by analysis of pulsed laser light reflected from their surfaces.

Resilience: The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change. In the context of infrastructure, resilience is the ability of a system or component to withstand stressors.

Risk: The chance of something happening that will have an impact on objectives. (AS/NZS 4360:2004).

Sea level rise: An increase in the mean level of the ocean. Eustatic sea level rise is a change in global average sea level brought about by an increase in the volume of the world's oceans. Relative sea level rise occurs where the level of the ocean increases locally relative to the land, which might be caused by ocean rise and/or land level subsidence. In areas subject to rapid land level uplift, relative sea level can fall.

Stress-free temperature: Stress-free temperature is the temperature where no thermal forces are acting on the rail. It is also referred to as the rail neutral temperature.

Tidal prism: The difference in the volume of a water body between high and low tides.

Vulnerability: The susceptibility to failure or inability to meet expected performance. A system or component is said to be vulnerable if it has a low tolerance to failure (in some regards, it is the opposite of resilience).

D2 Abbreviations

ARI:	Average Recurrence Interval
CRI:	Crown Research Institute
CRT:	Critical Rail Temperatures
CWR:	Continuous Welded Rail
ECMT:	East Coast Main Trunk (railway line)
FAR:	Fourth Assessment Report
FRST:	Foundation for Research, Science and Technology
GHG:	Greenhouse Gas(es)
GIS:	Geographical Information System
GNS:	Institute of Geological and Nuclear Sciences
HIRDS:	High Intensity Rainfall Design System
IPCC:	Intergovernmental Panel on Climate Change
IRIS:	Incident Reporting Information System
LiDAR:	Light Deflection and Ranging
LINZ:	Land Information New Zealand
MCA:	Multi-Criteria Analysis
MfE:	Ministry for the Environment
MHW:	Mean High Water
MHWS:	Mean High Water Springs
MLW:	Mean Low Water
MLWS:	Mean Low Water Springs
MNPL:	Marton–New Plymouth (railway) Line
MoT:	Ministry of Transport
MSL:	Mean Sea Level
NIMT:	North Island Main Trunk (railway line)
NIWA:	National Institute of Water and Atmospheric Research
NZTA:	NZ Transport Agency
NZTS:	New Zealand Transport Strategy
PNGL:	Palmerston North–Gisborne (railway) Line
RMA:	Resource Management Act 1991
SFT:	Stress-Free Temperature
SH:	State Highway
TLA:	Territorial Local Authority
TREIS:	Traffic Road Event Information System
TSR:	Temporary Speed Restriction
UK:	United Kingdom
VFM:	Value for Money
WASP:	Wave And Storm Surge Protection