TTAC Limited
For More Effective
Management of Risk
and Uncertainty

Ruapehu Lahar Residual Risk Assessment

a report produced for the
Ministry of Civil Defence & Emergency Management,
New Zealand

by Tony Taig, TTAC Limited

October 2002

DISCLAIMER

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Executive Summary

This is the report of an assessment of the residual risks associated with the anticipated lahar which will occur when the tephra barrier deposited on the rim of the crater of Mt Ruapehu in the 1995/96 eruptions collapses under the weight of the water in the crater lake. It has been carried out by TTAC Limited in cooperation with numerous other parties for the Ministry of Civil Defence and Emergency Management, to assist in development of appropriate response arrangements for this event.

The assessment considers:

- the nature and scale of the anticipated lahar
- how the lahar flow will develop as it travels down the mountain
- the risk to key assets and infrastructure in the path of the lahar
- the risk to people if those assets are damaged
- the effectiveness and reliability of warning and response systems.

Conclusions are drawn as to the likely residual risk, a) with arrangements as they currently stand, and b) with what should realistically be achievable, given all the planned and proposed improvements to asset protection, readiness, warning and response arrangements discussed in the report. The residual risk is estimated in terms of the likelihood that the lahar will lead to one or more fatalities (ie directly answering the key question "*How likely is it that someone will die as a result of this lahar?*").

An important issue throughout the assessment has been the high levels of uncertainty surrounding this lahar, and the potential for different interpretations and perceptions to develop in the face of that uncertainty. Care has been taken to expose uncertainty, to understand what matters most in the face of uncertainty wherever possible, and to draw conclusions which are robust, notwithstanding the uncertainties. Risk estimates presented in this Executive Summary are upper values, given all the associated uncertainties. That is, when we say a risk would be "*No more than 10%*", we mean "*There can be a high degree of confidence this risk would be no more than 10%*". The risk may actually be a lot lower, but we cannot definitively say so with confidence in the face of all the uncertainties.

The principal conclusions are:

1 There is a wide range of possible sizes of the anticipated lahar, but experts believe that the range of possibilities can be bracketed by considering a range of 2x2x2x3 (= 24) scenarios corresponding to different:
   - levels of the crater rim below the tephra dam[1]
   - heights of the crater lake up the dam at the time of failure
   - rates of failure of the dam once it does fail, and
   - bulking factor as the lahar flows down the upper mountain.

2 There is high uncertainty as to when the tephra dam will fail and the lahar will happen, but general agreement among experts that:
   (a) it will fail quickly when it does fail, and
   (b) the lake is likely to reach a level high up the dam before failure.

3 The anticipated flows down the mountain span a wide range of possible sizes of lahar. Most scenarios involve flows above, and travel times below, those experienced in the 1953 lahar which led to the Tangiwai rail disaster. Some scenarios involve lower, less damaging flows.

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[1] Note – the term tephra dam is used loosely throughout this report to describe the tephra barrier, although the barrier will not technically become a "dam" until the crater lake rises part way up it, which is many months away at present.

4 The bund constructed at the bottom of the Whangaehu Gorge to prevent flow crossing over to the Waikato Stream is considered highly effective in preventing such crossover.

5 The Tangiwai Memorial area and Strachan's Bridge are virtually certain to be severely damaged by the lahar; the rail and road bridges at Tangiwai, and the Tirorangi Marae Bridge, are at high risk (30 to 80% chance of severe damage). There is a high level of uncertainty as to the risk to SH1 in the vicinity of the Wahianoa Aqueduct, while the level of risk to SH1 at the Waikato Stream crossings is significantly lower because of the effectiveness of the bund.

6 With arrangements in their present state (with ERLAWS part commissioned, Transit automated barriers on SH49 not yet in place, and rudimentary local response plans) the residual risk of somebody being killed as a result of the lahar could be as high as 30 or 40% or as low as a few per cent. This uncertainty is unlikely to be reduced much by further analysis.

7 With measures already in progress or planned, and other measures identified in this assessment put in place, we can be confident of reducing this residual risk to a less than 10% chance of somebody being killed as a result of the lahar. The risk is uncertain and may be much lower, but we cannot say with confidence that it would be much less than 10%.

8 The main contributors to the risk of there being a fatal accident are road accidents associated with the lahar, and events at the Tangiwai Memorial. The likelihood of a passenger train accident is significantly lower (less than 0.1% with current arrangements, realistically reducible to less than 0.01%).

9 The measures required to progress from the "*could be 40%*" to the "*less than 10%*" state are described in detail in Section 10.2 of the report. The associated challenges and costs should not be underestimated. In summary, the measures involve:

(a) removing risk on SH1 by further measures to protect the road from lahars

(b) closing the high risk Tangiwai Memorial site, car park and toilets

(c) enhancing warning and response arrangements at Tangiwai itself

(d) enhancing readiness, warning and response arrangements downstream of Tangiwai, and

(e) reducing possible risk to people in the Tongariro River associated with Genesis Power's response actions to lahars.

10 Priorities for emergency response after the lahar event should focus on 9 (c) and (d), and not on attempting to send personnel high up on Mt Ruapehu to warn and evacuate people. Risk management on the mountain should focus on managing access to at-risk areas.

11 Risk reduction to provide high assurance of residual risk levels down to about 1% chance of a fatal accident could be achieved, but at a much higher price. Further reduction would require additional warning systems over and above ERLAWS, and sophisticated response arrangements and systems well beyond any currently envisaged.

12 If risk reduction to a less than 1% chance of a fatal accident is required, or the costs of achieving the "*less than 10%*" or "*around 1%*" levels are considered excessive, then the decision to allow the lahar to happen when nature dictates it would have to be revisited.

13 Some significant factors relevant to the decision to allow the lahar to happen have been revealed in the course of this assessment. In particular:

(a) different people had interpreted previous qualitative risk assessments very differently

(b) there does not appear to have been a shared appreciation of what is involved, and what it costs, to provide high reliability warning and response arrangements to protect life, and

(c) false perceptions that "*we will know then this lahar is going to happen*" may have led some people to overestimate the likely effectiveness and reliability of response arrangements.

1 Introduction

The 1995 and 1996 eruptions of Mt Ruapehu deposited a wall of tephra (loose ash and debris) over the outlet of the crater lake. It is expected that the lake will fill up, and the tephra dam will likely collapse, some time in 2003 or later, leading to a large lahar down the Whangaehu Valley. This is the report of an assessment of the residual risks associated with that lahar.

The assessment was commissioned by the Ministry of Civil Defence & Emergency Management (MCDEM) to assist in the evaluation and development of warning and response plans for the anticipated lahar. Tony Taig of TTAC Limited was contracted by MCDEM to lead the assessment. The work described here was carried out during May and June 2002.

The aims of the assessment are:

1 to assist utilities, local authorities, emergency services and MCDEM in preparation of their response plans for the lahar, and

2 to provide an overview for government and other stakeholders of the residual risks associated with the lahar, to inform consideration of whether further measures might be appropriate, and if so which such measures would provide the most effective risk reduction.

The report covers:

- The background to the lahar and government's strategy for dealing with it (Section 2)
- The approach adopted to the assessment of residual risks (Section 3)
- Scenarios at the crater that could give rise to different size lahars (Section 4)
- Lahar flows down the mountain (Section 5)
- Risk to assets potentially in the path of the lahar (Section 6)
- Risk to people potentially affected by the lahar (Section 7)
- Warning and response issues (Section 8), and
- Risk to people on the upper parts of Mt Ruapehu, from this and other lahars (Section 9).

The findings of the assessment are brought together in Section 10, and discussed in Section 11.

This report collates the expertise and knowledge of many parties, including: the Director and staff of MCDEM, the utility organisations involved (Genesis, Transit, Transpower and Tranz Rail), and staff of Ruapehu District Council (RDC), Ohakune Police and others involved in response planning. Particular contributions have been made by Harry Keys* (DoC), Grant Webby* (Opus International Consultants Ltd), Graham Hancox* and his colleagues (GNS) and Adam Milligan* (Optimx), some under contract to MCDEM and others (DoC and GNS) giving freely of their time and expertise[2]. I am most grateful personally to all who have contributed to this assessment.

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[2] Various key judgments on asset damage and people risk were made in an "*expert review*" meeting at MCDEM on 20 June 2002. Those present (in addition to the author) are marked * above. Other staff of MCDEM, DoC and GNS also participated in a broader review of the risk assessment which set the agenda for the experts' meeting.

2 Background

The last major lahar associated with sudden collapse of crater lake containment (rather than eruptions and other volcanic phenomena) was the 1953 event which caused the railway disaster at Tangiwai in which 151 people died. Recognition that the tephra dam deposited by the 1995/96 eruptions might well cause another such large lahar has therefore brought with it a strong focus on the potential for accidents and harm to people of such a lahar.

The Department of Conservation (DoC) has for several years been monitoring the development of this potential lahar, and completed a landmark environmental risk assessment in 1999. That work assessed the scale and likelihood of various lahar scenarios arising and discussed the possible outcomes. This provided enabling information for others to assess (for example) the likelihood that specific utilities' assets would be damaged, and, if so, what scale of harm might arise and with what probability. Various parties have since been involved in developing asset protection, lahar warning, and emergency response plans.

DoC has been particularly active in developing risk reduction measures on the mountain. In recognition of the particular risks to State Highway 1 and the Tongariro River of lahar flows spilling over from the Whangaehu Valley into the Waikato Stream, DoC has constructed a bund just below the Whangaehu Gorge to prevent such flows. The other major DoC initiative has been to establish the East Ruapehu Lahar Alarm & Warning System (ERLAWS), which uses diverse monitoring instruments on the crater and at various points down the lahar flow path to provide an alarm which will be paged automatically to RDC, the police and key utilities.

The utilities with assets at risk in the path of the lahar have also been actively reviewing the risk to their assets and any consequential risk to people, and putting in place appropriate protective measures. The principal parties and assets involved are:

- Genesis Power, with generation assets in the Tongariro River (a lahar in 1995/96 caused some $10m of damage to the Rangipo Power Station)
- Tranz Rail, with responsibility for the rail bridge at Tangiwai and train services over it, where a dedicated lahar protection system independent of ERLAWS has been installed since the 1953 accident
- Transit, with responsibility for State Highways 1 and 49, and
- Transpower, whose transmission lines run north-south near SH1, at places not far above the Whangaehu Valley.

Territorial authorities, regional councils and emergency services in the area have also been active in developing emergency plans. RDC is playing the lead role in developing response plans (note – risk in the Tongariro catchment is the responsibility of Taupo District Council). RDC and the Ohakune Police are the parties currently being wired in to the ERLAWS pager system in order to enable them to initiate and lead emergency response plans, and have prepared a first draft local response plan which has been submitted to RDC for approval. Transit is also being wired in to ERLAWS to facilitate rapid road closures. Genesis Power host the ERLAWS computers and pager system at their Tokaanu Power Station, and complete the set of people who would, as things currently stand, receive automated warnings via ERLAWS that the lahar was on its way.

MCDEM has been involved since October 2001 in three capacities:

1 facilitating the preparation of response plans by local authorities and emergency services

2 providing an overview for Government of the response plans of the key utilities, and of the key residual national scale risks (eg of a rail accident at Tangiwai, or of interruption of Auckland's power supply) associated with damage to utility assets, and

3 advising Government on the overall risk issues, in particular with respect to loss of life.

A government policy statement in December 2001, informed by MCDEM's initial review of the assessment work to date, established a number of important policy points, including:

- placing the emphasis of government (DoC's) strategy on providing high reliability warning of the impending lahar in time to permit effective response action, and
- placing the responsibility clearly on utilities, local authorities and emergency services to carry out their own risk assessments and put in place appropriate asset protection and response arrangements (facilitated and coordinated by MCDEM)

An expert scientific advisory committee has been convened to advise government on an ongoing basis as to the likely nature and management of the lahar. The committee draws in the best available international expertise on volcanic hazards and lahars to support its work.

In taking forward its responsibility to facilitate and coordinate response planning, MCDEM has commissioned this assessment of the residual risks of adverse outcomes of the impending lahar. The assessment is based on the latest scientific knowledge, but also incorporates an assessment of the efficacy and reliability of arrangements to protect assets and people, and of the warning and response measures currently in place or planned. The focus is on risks to people, rather than economic risks. The expertise brought to bear in preparing this assessment relates to the assessment of risks and to supporting difficult decisions in the face of large uncertainties, rather than to volcanic hazards, lahars and their effects per se.

MCDEM hope to use the results of this assessment:

1. to assist in the development and coordination of response and asset protection plans, and, in consultation with the parties involved
2. to identify any areas which require further assessment, and
3. to identify any areas which require further protection, and the most promising avenues to be explored in developing that protection (if any).

3 Approach

The general approach taken in the assessment is illustrated in Figure 1 below.

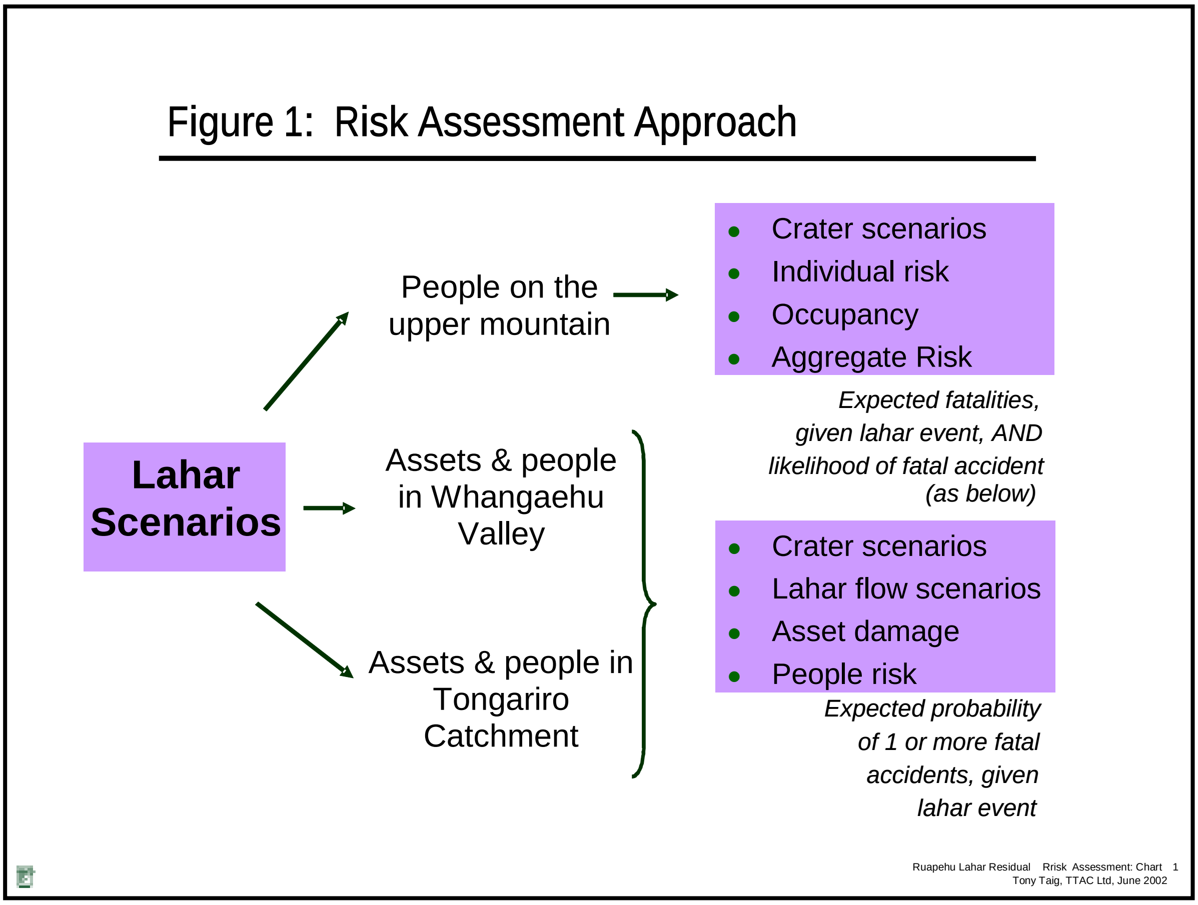


Figure 1: Risk Assessment Approach

Lahar Scenarios

People on the upper mountain

- Crater scenarios
- Individual risk
- Occupancy
- Aggregate Risk

Expected fatalities, given lahar event, AND likelihood of fatal accident (as below)

Assets & people in Whangaehu Valley

Assets & people in Tongariro Catchment

- Crater scenarios
- Lahar flow scenarios
- Asset damage
- People risk

Expected probability of 1 or more fatal accidents, given lahar event

Ruapehu Lahar Residual Risk Assessment: Chart 1
Tony Taig, TTAC Ltd, June 2002

The first step is to characterize the various possible lahar scenarios that might arise through failure of the tephra dam, and how they compare with other lahars experienced on Mt Ruapehu in the past. This is tackled here in two stages:

- first, understanding the issues surrounding the crater lake and the tephra dam which will determine how much water pours out of the crater and how quickly, and
- second, understanding how these flows will develop as the lahar flows down the mountain, and the likely scale of flows and travel times to various locations where people or important assets might be present.

The first people at risk from any lahar would be those high on the mountain (skiers, climbers, trampers or others) who find themselves directly in its path. The anticipated lahar associated with the tephra dam collapse is likely to be much less severe in this respect than lahars which occur regularly (every 5-10 years or so) in association with volcanic eruptions. This is because its course is constrained to the Whangaehu Valley where relatively few people tend to be present (in comparison with major ski areas such as Whakapapa for example, where thousands of people can potentially be present, and from which dozens of people may visit the crater rim on a busy day).

An assessment of likely occupancy levels on the upper parts of the mountain for various groups of people, and of the risk to them under tephra dam collapse and eruption lahar scenarios, is presented in Section 9 of this report. This provides both:

- an assessment of the contribution of risks on the upper mountain to the overall risks of a fatal accident arising from a tephra dam collapse lahar, and
- an interesting point of comparison between the overall effects of a dam collapse lahar, and the estimated overall effects of regularly occurring eruption lahars (the hazard of which to people tends to be more confined to the upper parts of the mountain).

The larger part of this assessment is concerned with hazards lower down the mountain, where people would not normally be at risk from regularly occurring eruption lahars. This assessment considers the flow of lahars down the mountain in two stages:

1 the pour from the crater into the head of the Whangaehu Valley, and the relatively rapid flow down the steep upper part of the mountain and through the Whangaehu gorge, and

2 the flow from the gorge onwards, beyond which the gradient rapidly tapers off and the Whangaehu River fans out, then turns south to flow roughly parallel to SH1 (the Desert Road) before turning westward towards Tangiwai.

There is considerable uncertainty as to the size and duration of the lahar likely to be associated with the tephra dam collapse, so a range of lahar scenarios has been considered corresponding to a range of different possible key characteristics of the pour from the crater and the behaviour of the lahar on the upper mountain. Crater pours and lahar flows have been modelled in support of this assessment by Grant Webby of Opus International Consultants Limited, to provide estimates of peak flow rates, lahar depths and travel times to various points of interest down the Whangaehu Valley. Grant and other members of the Government's Scientific Advisory Panel (Harry Keys of DoC and Graham Hancox of the Institute of Geological and Nuclear Sciences, GNS) have been closely involved in developing the set of lahar scenarios to be modelled.

Having considered flow down the mountain in Sections 4 and 5 of this report, we then consider the impact of lahar flows at various locations, in particular (in "*going down the mountain*" order, with sites where people could be at risk marked with an asterisk):

- At the site of the DoC bund, where failure or overtopping of the bund could enable lahar material to cross over to the Waikato Stream, with potential implications for State Highway 1, and for power generation assets, people* and wildlife in the Tongariro River (into which the Waikato Stream flows).
- In the fan area where the Whangaehu changes direction to flow parallel to SH1. Risk to the state highway* and the power transmission pylons in the area has been considered.
- In the vicinity of the Wahianoa Aqueduct, which carries water collected from streams to the south side of Ruapehu across the Whangaehu River and SH1 to Lake Moawhango. Risk to the aqueduct itself, to SH1*, and to other power transmission pylons in this area was considered.
- At Tangiwai, where risks to the railway*, the Tangiwai Memorial* and parking area, and the road bridge* over the Whangaehu on SH49 are all considered, and
- Further downstream the Whangaehu River, where various local road bridges* and the Fields Track* which runs along the path of the river are particularly at risk.

It is important to note that, so far as we are aware, nobody lives or works directly in the anticipated path of this lahar, or spends significant portions of their time in the river or immediately surrounding valley where the lahar might directly reach them. The risk to people is thus associated with damage to the assets marked with an asterisk above (which is what happened, for instance, in the Tangiwai disaster in 1953), and not with people being directly caught in the path of a lahar as would be the case for people at risk on the upper parts of the mountain.

The risk to these assets is considered in Section 6 of this report, with the primary emphasis on assets where people's safety is at risk, and some comments along the way on important utility assets potentially at risk.

The risk to people, IF the assets are damaged, is estimated in terms of the likelihood of there being a fatal accident, GIVEN the lahar has happened and that the asset involved has been seriously damaged. This is addressed in Section 7. The approach taken is:

1. Estimate the risk given asset failure and no effective mitigative action
2. Reduce this estimated risk by taking into account the estimated effectiveness and reliability of any utility or other countermeasures which are independent of the ERLAWS warning system (the risk estimate so obtained is presented as the "*Before ERLAWS*" risk), and
3. Factor in the estimated effectiveness and reliability of lahar warning and response systems, all of which currently hinge on provision of an alarm by ERLAWS.

Risk assessment results are presented "*Without ERLAWS (and responses triggered by it)*" and "*With ERLAWS (and responses triggered by it)*", in Section 7 of the report.

The reliability and effectiveness of ERLAWS and associated responses is then considered in Section 8 of the report, which presents estimates of a) the likely reliability as things currently stand, and b) as, in my judgment, they might reasonably stand if all the issues people are currently intending to address, are addressed.

The results of the three main parts of the assessment:

1. Likelihood of asset damage, given the lahar
2. Likelihood of a fatal accident, given asset damage but without ERLAWS and response
3. Effectiveness and reliability of ERLAWS and response

are then brought together in Section 10 to provide an overview of safety risks. Section 11 discusses options for further risk reduction, and which appear most promising in the light of the assessment results.

3.1 Dealing with Uncertainty

A key issue from the outset of this assessment has been that we are dealing with a situation of great uncertainty. The risk assessment has taken this into account in four main ways:

1. The most fundamental uncertainty, as to what will happen to the tephra dam as the lake fills up, has been addressed by considering not one lahar scenario, but a wide range of scenarios corresponding to different ways in which the key uncertain issues might turn out. A set of 24 lahar scenarios in total has been propagated right through the analysis – effectively carrying out 24 "*what if*" risk assessments, not just one.

2. Wherever possible, the uncertainty associated with the parameters presented in the assessment has been openly stated and incorporated into any numerical estimates. Numbers are generally presented as a range of values, which the experts involved believe is likely to contain the actual value for the lahar.

3. Wherever expert judgment has been used as the basis for estimating likelihood or probability, this is clearly stated as such, and a clear distinction is drawn between probabilities which express the degree of belief of experts, and probabilities which derive from clear evidence as to the proportion of situations which will lead to one outcome rather than another.

4. Where uncertainties are large, the assessment tries to help understand what matters most or is most critical in determining outcomes relevant for safety.

3.2 Definition of "Risk"

Different people understand different things by the term "*Risk*", so it is extremely important to define at the outset what we mean by the term. Key attributes of risk that are important to pin down are:

- the risk of WHAT?
- to WHOM?, and
- HOW is it measured?

A very simple definition of safety outcomes and risk has been used throughout the report (except in parts of the Upper Mountain model, where it was easier to deal with numbers of people at risk and work back towards the type of definition used elsewhere). The safety outcome of concern is:

"*The likelihood of anyone affected by the lahar being killed, when the lahar happens.*"

This has removed explicit modelling of numbers of people involved (indication of the numbers of people at risk in different circumstances are provided alongside results for specific assets and locations). This measure of risk was chosen partly because of its simplicity, and partly because the single concern people have voiced to me most strongly about the lahar is: "*Will anyone die?*" This measure of risk provides the simplest possible answer to that question. It has the added advantage that all other risk factors are also estimated in terms of conditional probabilities, so that propagation of numbers through the assessment is very transparent and straightforward.

4 Lahars – Crater Scenarios

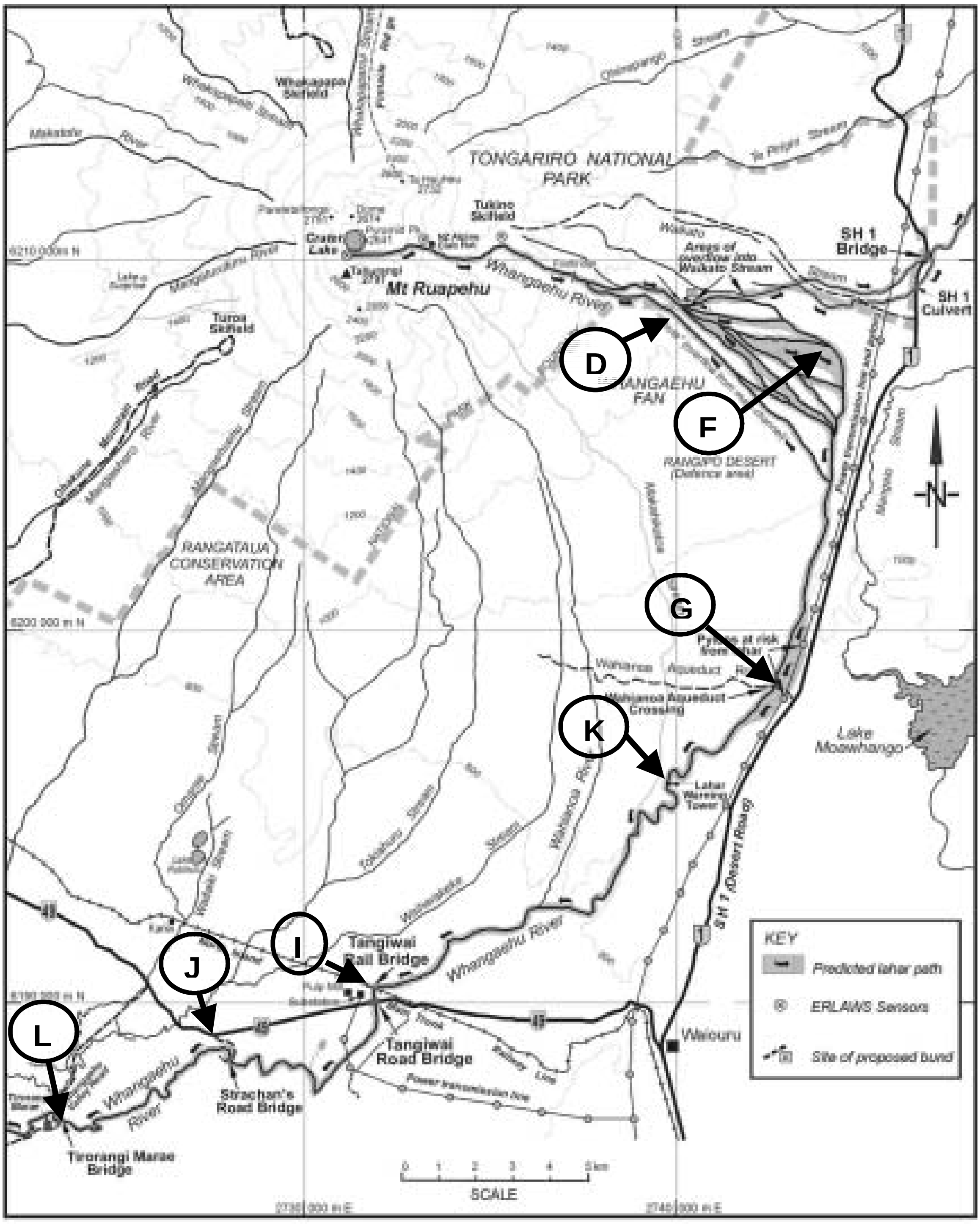
The situation at the crater outlet, the upper part of the Whangaehu Valley, and the anticipated flow paths of lahars down the valley, are illustrated in the photos and map brought together in Figures 2(a), 2(b) and 2(c) below.

Figure 2(a): Crater Lake, Outlet and Dam (DoC web site)

Figure 2(b): Upper Whangaehu Valley (DoC Web Site)

Figure 2(c): Map Showing Path of Anticipated Lahars

(Courtesy of Graham Hancox, GNS)



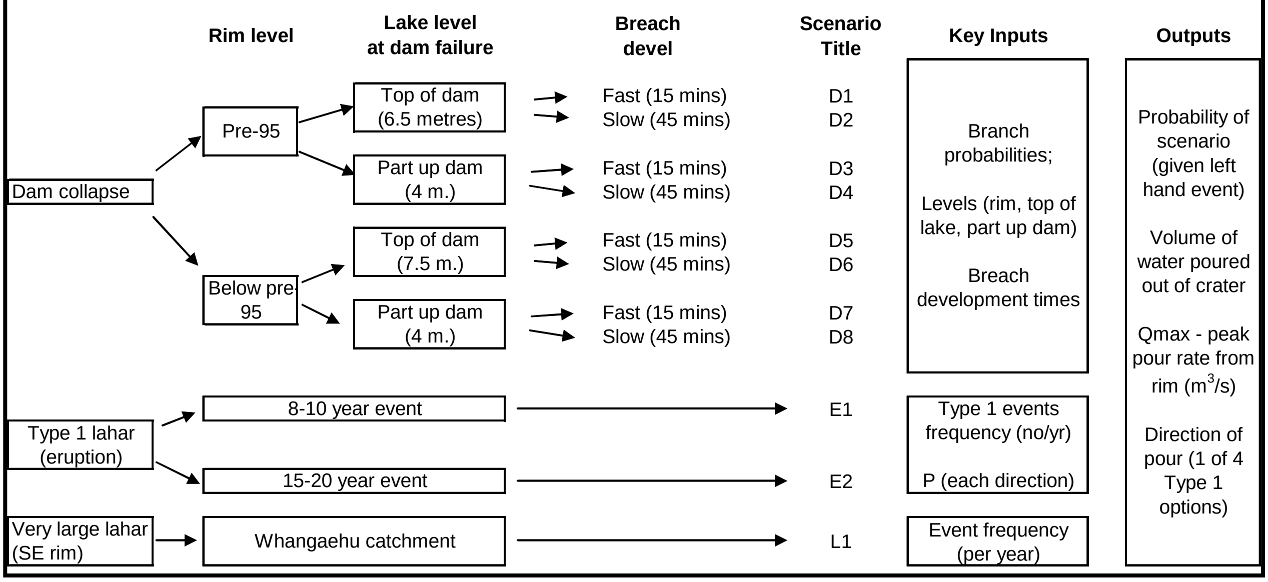
Map of the Mt Ruapehu area showing the predicted flow path of a potential lahar formed by collapse of the 1995-96 tephra barrier at the Crater Lake outlet. Key sites and infrastructure likely to be affected, and proposed hazard mitigation options are also shown.

There are many uncertainties surrounding what will happen as the crater lake fills up, which have been considered in detail by the Government's Scientific Advisory Panel. I have paraphrased the issues into a series of key questions, whose answers in simplistic terms, as I understand them, are summarized below:

Question	Current State of Knowledge
Why are we so worried about this tephra dam?	Because the nature and size of the material forming the barrier are such that the barrier is likely to fail as the Crater Lake rises towards the top of it.
How much water could be held behind the dam?	Up to about 1.4 million cubic metres, depending on the level of the lake above the level of the lava lip on which the barrier is founded.
When will the dam fail?	Probably within months or years of the lake filling up; it is very hard to predict – but it could be earlier, when the lake is part full
What will cause the dam to fail?	Gradual erosion over a long time of finer particles from the core of the barrier by seepage of lake water ultimately results in the development of a small "*pipe*" or series of pipes from the downstream base of the barrier to the upstream face. Establishment of a full pipe would accelerate pipe growth, resulting in eventual collapse of the crest and an overtopping breach of the barrier. But it is also possible that some sudden surge of water (caused, for example, by venting of a volcanic gas "*burp*" or an ice or rock fall into the lake) could lead to overtopping of the tephra dam, which could then cut a channel down into the tephra, with similar rapid collapse effects.
Has this happened before?	Yes, though no one was there to see exactly what happened. The 1953 lahar which caused the Tangiwai accident was the nearest such event in recent times, but the pour out of the crater in that case was restricted by having to flow through an ice tunnel.
How quickly will the dam fail?	Evidence from earth dam collapses has been reviewed by the Scientific Advisory Panel. This material would be towards the end of a spectrum of properties that make collapse and failure, once it starts, more rapid rather than less. The time taken for a channel the full depth and width of the dam to develop is expected to be between 15 and 45 minutes (and almost certainly to be a good deal quicker than the estimated 2-3 hours it took the 1953 lahar to develop and pour out of the lake).

In discussion with the experts from the Scientific Advisory Panel who have been involved in this assessment, it was agreed that the uncertainty associated with the pour of water out of the crater and into the Whangaehu Valley could be captured by considering the plausible range of values for three key uncertain factors: the level of the rock rim below the dam, the level of water up the dam at the time of failure, and the rate at which the dam breach would develop, once failure occurred. An event tree showing the possibilities raised by the different combinations of these parameters is shown as Figure 3:

Figure 3: Crater & Lake Scenarios



The lake levels shown at dam failure correspond to the height of the top of the lake above the lowest part of the rock rim underneath the dam. Thus for scenarios in which the lake rises to the top of the dam before failure the effective "*slice*" of the water from the top of the dam which would pour out of the crater is 6.5 metres above the position of the level of the crater rim before the 1995/96 eruption (scenarios D1 and D2).

The first branch on the figure considers the possibility that the rock rim could be a metre or so lower than the pre-95/96 level (DoC is attempting to measure the depth of the dam along its length using hand-held probes, but this is difficult to do). If the lake rises to the top of the dam, this would mean the top 7.5 metres of the lake would then pour out of the crater (D5 and D6).

The second branch on the figure considers the possibility that the dam fails while the water is still part way up (taken as 4 metres above the lowest point of the rim). Clearly, the associated volumes of water are now lower, and the peak flows out of the crater will be correspondingly lower. For scenarios D7 and D8 (with the lower rim level) it is assumed that the width of the lowered portion of the rim would be less than the whole width of the dam, which would provide some constraint on flow in comparison with scenarios D3 and D4. Because the cross-section of the lake is roughly conical, scenarios D7 and D8 would also involve a slightly smaller total volume of water pour overall than would scenarios D3 and D4.

The third branch on the figure considers the rate of development of failure of the dam, which is an important factor in determining the peak flow rate out of the crater, which in turn is a primary determinant of the lahar peak flows and heights downstream. Note that this is a different parameter from the time taken for the crater to empty down to the level of the rim, which would typically be rather longer.

Considering each possible combination of these three key uncertainties, which the experts agree should broadly encompass the range of possible lahar scenarios associated purely with dam failure, we thus have eight scenarios corresponding to different pours of water out of the crater. These pours, and their subsequent flow down the Whangaehu Valley, have been modelled as described in Section 5.

Figure 3 also shows three other types of lahar scenarios at the bottom of the figure, which have been considered alongside the dam failure lahars which are the primary focus of this assessment. The first two scenarios (E1 and E2) correspond to the relatively frequent eruption lahars which are experienced on Mt Ruapehu. Such events do not generally lead to very large lahars posing serious risks to people far down the valleys surrounding the mountain, but are potentially very hazardous for people on the mountain, particularly in the crater area.

Historic information on eruption lahars from 1945 to 1995/96 has been considered in Section 9, and used to provide a basis for estimating risks to people at various locations on the upper parts of the mountain. The risk for "*typical*" eruption lahar scenarios E1 and E2 (derived by consideration of averaged features of the 1945-1996 events) has been estimated using a simple model of occupancy of the mountain today, in combination with estimates of the hazard at various locations derived from consideration of past eruptions and the extent and nature of their effects. These calculations of eruption lahar risk are presented in the summary section (Section 10) to provide a point of comparison between the anticipated dam breach lahar, and other lahar risks which are known and broadly tolerated on the mountain already.

The same occupancy model, along with simple estimates of risk for people at the crater outlet area and in the upper Whangaehu Valley (where the DoC footbridge is a particular location of high risk), has been used to estimate casualties in dam breach lahars.

Finally, at the bottom of Figure 3, the possibility is also illustrated of a potentially much larger lahar associated with more dramatic collapse of the crater rim. This is not considered at all an issue associated with the tephra dam collapse. But there is clearly the possibility, in so geologically active an area, of seismic or volcanic activity leading to more major realignment of the crater geometry and, potentially, to lahars involving most of the lake contents, not just the top few metres. The maximum possible lahar volume with the current crater configuration would be of order 10 million cubic metres (ie about seven times the size of the dam failure lahars considered here).

We have not considered here in any detail how likely such a scenario is, or what its consequences would be, but it would clearly be a very large event in comparison with any considered here. Such events have definitely occurred from Mt Ruapehu over the past few thousand years; Turangi is thought to be built on material deposited from a very large lahar which occurred in the 16th century. The experts involved in this study had different views as to the stability or otherwise of the rock rim around the crater. All agreed that it was thick and solid today, but there were different views on its vulnerability to various hazards. The general consensus was that the likely annual probability of such an event, given today's crater configuration, is somewhere in the range 1 in 50 to 1 in 500 years.

The eruption and very large event lahars thus provide something of a "*bracket*" around the dam failure lahar scenarios which are the main subject of the report. When we come to interpret the results of the assessment, it will be useful to bear in mind the fairly regular occurrence of the smaller eruption type events, and the more remote (but by no means vanishingly small) likelihood of very much larger events, in relation to which few of the countermeasures discussed in this report would be of great effect.

Having characterised the range of possible pours out of the crater, we now move on to consider their flow down the Whangaehu Valley.

5 Lahars – Flow Down the Mountain

The Whangaehu Valley can conveniently be divided into two sections for consideration of lahar flows:

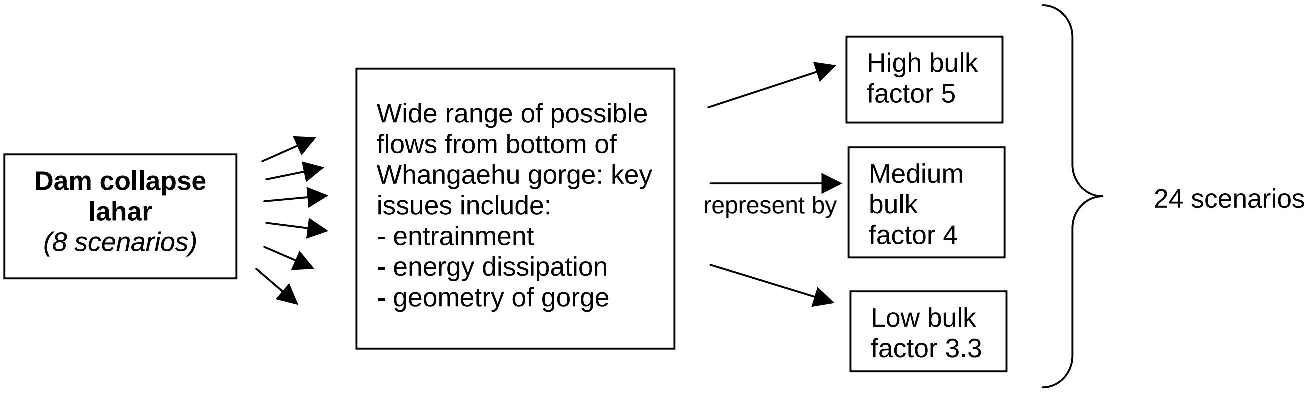
1. The steep upper part of the valley, from the crater outlet down to where the river emerges from the gorge, just above the location of the DoC bund (shown in Figure 2b). During this part of its flow, the lahar will be fast moving and turbulent, entraining considerable volumes of solids to produce a mixture often compared to a wet concrete slurry.

2. From the bund onwards, the river quickly fans out as can be seen in the map (Figure 2c). From here on the lahar would be expected to be depositing material (overall) rather than entraining it, though local areas of the river valley may be subject to severe scour and erosion.

5.1 Flow Down to the Bund

The first set of issues considered here are those surrounding the flow of the lahar down the upper valley, until it emerges from the gorge. There are many uncertainties surrounding this flow, which are discussed in more detail in Annex 1 of Appendix 1. They have all been wrapped up and represented in this assessment by the key parameter of Bulking Factor, as illustrated in Figure 4.

Figure 4: Whangaehu Valley Flow Scenarios



The bulking factor is the assumed multiple by which the volume of water poured from the crater will be increased by the time the flow reaches the bottom of the gorge. A bulking factor of 4 thus implies a lahar of which 75% of the total mixture (sediment plus water) volume is entrained solids; a bulking factor of 3.3 corresponds to 70% (etc etc).

Bulking factors for this lahar of 3.3 and 4 have been considered in earlier assessments. This assessment also considered the possibility of a higher bulking factor (5), based on the advice received by the Scientific Advisory Panel. This was based on the opinion of a US expert that, if sufficient material were available for entrainment in the upper Whangaehu Valley, the geometry of the valley could lead to bulking factors similar to those observed previously at Mt St Helens. Subsequent work at GNS by Graham Hancox et al (private communication) has confirmed the availability of plenty of material for entrainment.

Combining the eight crater pour scenarios with the three bulking factors considered likely to span the range of lahar flow increase through the upper Whangaehu Valley, thus leads to a total of 24 possible lahar scenarios. A summary of the flows involved from the crater and out of the gorge is provided in Table 1, based on the calculations carried out for this study by Grant Webby of Opus International Consultants. Grant's calculational approach has previously been described elsewhere; a summary of key points relevant to these calculations is provided as Appendix 1.

These 24 lahar scenarios are propagated through the next part of the report to inform our judgment as to the likely flows at various points in the Whangaehu Valley, and the likelihood of asset damage.

5.2 Flow down the Whangaehu Valley

The 24 lahar scenarios shown in Table 1 were used as sources to a model of flow down the Whangaehu Valley, and of flow spread and height at various key points in the valley, developed and applied by Grant Webby (as described in Appendix 1).

Table 1: Lahar Scenarios -
Flows/Times at Bund (below Whangaehu Gorge)

Crater Scenario	**Bulking factor**		**Peak flow Q_{max} (m^3/s)**	**Lahar travel time T (min)**
	Scale	**Value**		
D1	Hi	5	3290	19
	Mid	4	2690	21
	Low	3.33	2320	22
D2	Hi	5	2130	27
	Mid	4	1770	29
	Low	3.33	1510	30
D3	Hi	5	1970	28
	Mid	4	1670	29
	Low	3.33	1420	31
D4	Hi	5	1230	32
	Mid	4	990	35
	Low	3.33	820	36
D5	Hi	5	3450	19
	Mid	4	2820	21
	Low	3.33	2420	22
D6	Hi	5	2280	23
	Mid	4	1950	28
	Low	3.33	1720	29
D7	Hi	5	1660	29
	Mid	4	1350	31
	Low	3.33	1130	33
D8	Hi	5	1130	33
	Mid	4	910	35
	Low	3.33	760	37

The calculated flows down the Whangaehu for the range of lahar scenarios, from the biggest (D5 – Hi) to the smallest (D8 – Lo) are illustrated in Figure 5. The sites marked on the figure are as shown (indexed by letter) on the map in Figure 2c, and correspond to the nomenclature of Whangaehu Valley sites used in previous assessments of lahar impacts by GNS and Opus.[3] Figure 6 shows corresponding graphs for travel times of lahars down the valley.

Figure 5 shows the approximate flow rates estimated for the 1953 and 1975 lahars at Tangiwai. (*Note – the term "discharge rate" used in these figures refers to the volumetric flow rate at the site in question, NOT to the rate of discharge of water from the crater lake.*) As the figure clearly shows, only the bottom end of the flows predicted for the anticipated dam failure lahar overlap with the 1953 levels. For most of the dam failure scenarios modelled, flows at Tangiwai are considerably higher than that for the 1953 event.

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[3] References to the earlier flow calculations and methods are provided in **Appendix 1**.

Figure 6 shows that travel times are less sensitive in absolute terms to the lahar characteristics than are peak flow rates. But for many of the scenarios modelled here, travel times to Tangiwai are significantly less than the 150 minutes or so which many people have in their minds by association with the 1953 event. The largest flow scenarios considered here involve travel times to Tangiwai of just over 90 minutes.

Given the wide range of possibilities, it is important to try and understand which of the uncertain lahar characteristics are most important in determining the flows and travel times which are vital for assessing asset damage and the time available for emergency response. Figure 7 shows the peak flow at Tangiwai plotted for each crater pour scenario (D1 to D8), showing a bar for each scenario corresponding to the range of bulking factor assumptions used. Figure 8 shows the corresponding charts for travel times to Tangiwai.

Figures 7 and 8 help understand which of the uncertainties as to the lahar characteristics have most effect. Observations which can be drawn by comparing the effects of different scenarios and bulking factors are presented underneath the figures themselves.

The range of flows associated with the range of lahars involved is considerable. But the uncertainty is greater than that shown in these figures, which present only a point estimate calculated flow or travel time value. Grant Webby was also asked to provide estimates of the +/- percentage uncertainty in the flow values for each site modelled. He did so, as described in Appendix 1, providing both a) uncertainty in peak flow rate (Q_{max}) given a specific lahar, and b) uncertainty in lahar height, given a firm value of Q_{max}.

Consideration of asset failure, in the face of these uncertainties, is the topic of Section 6.

Figure 5: Peak Lahar Flows in the Whangaehu Valley

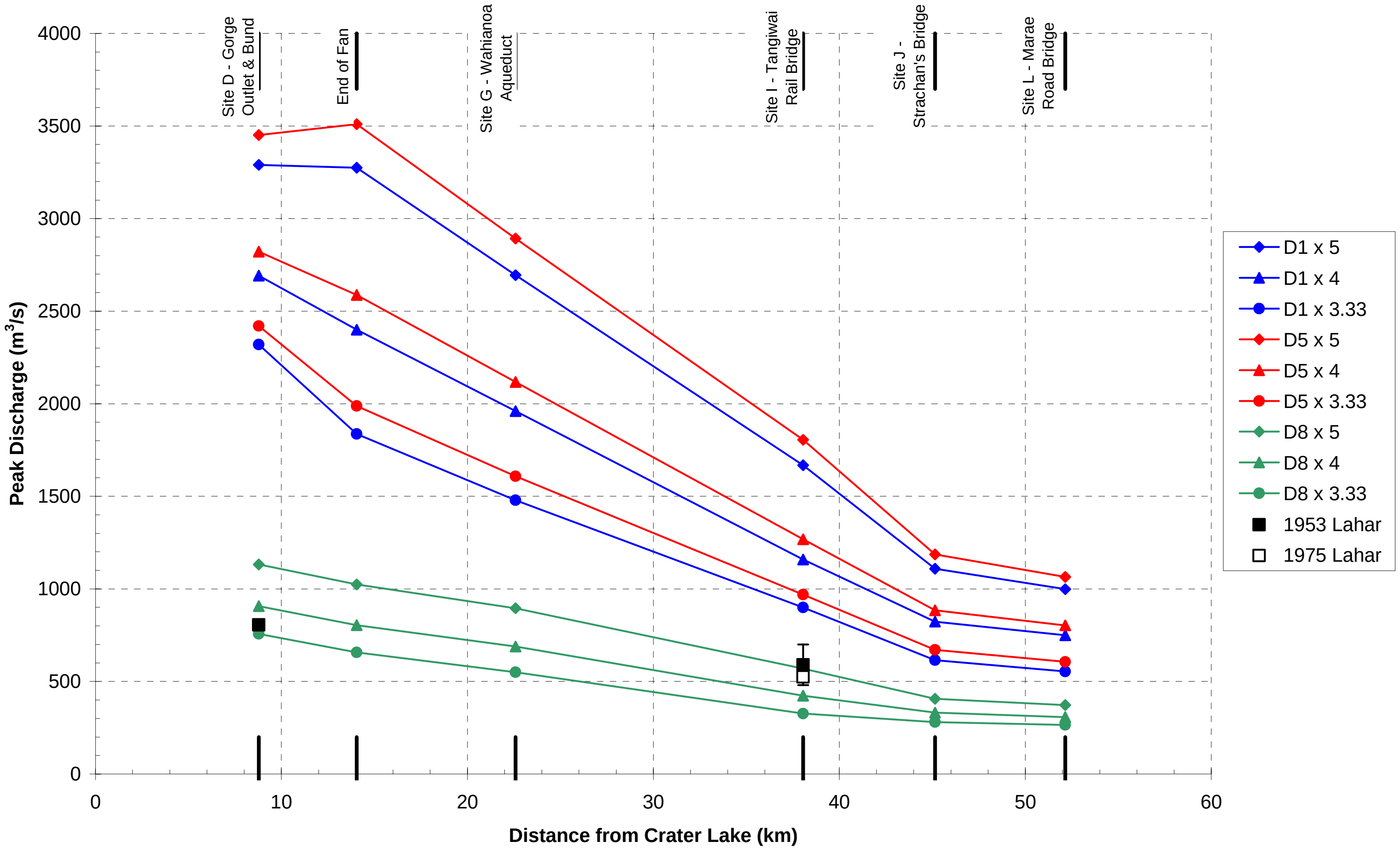
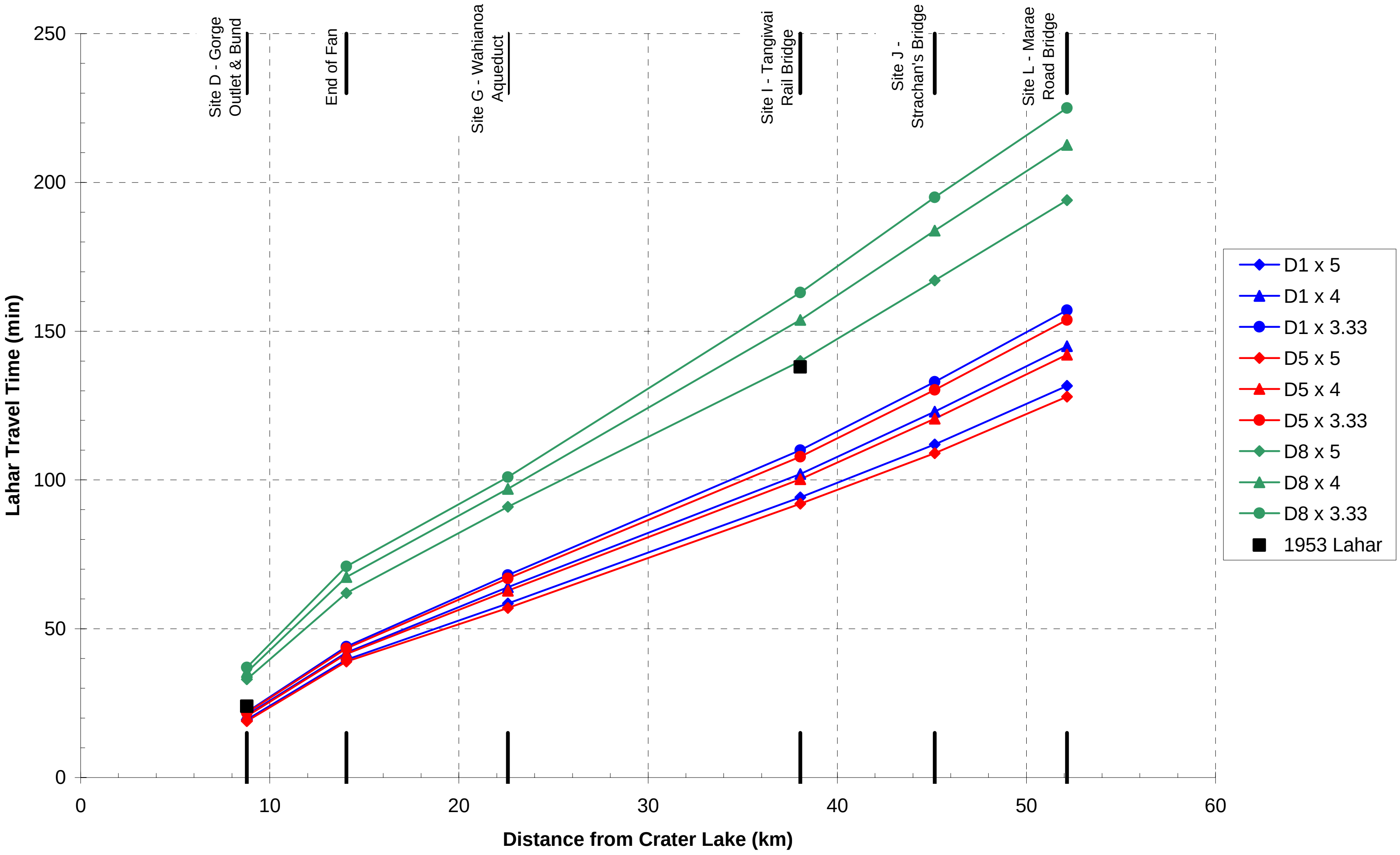
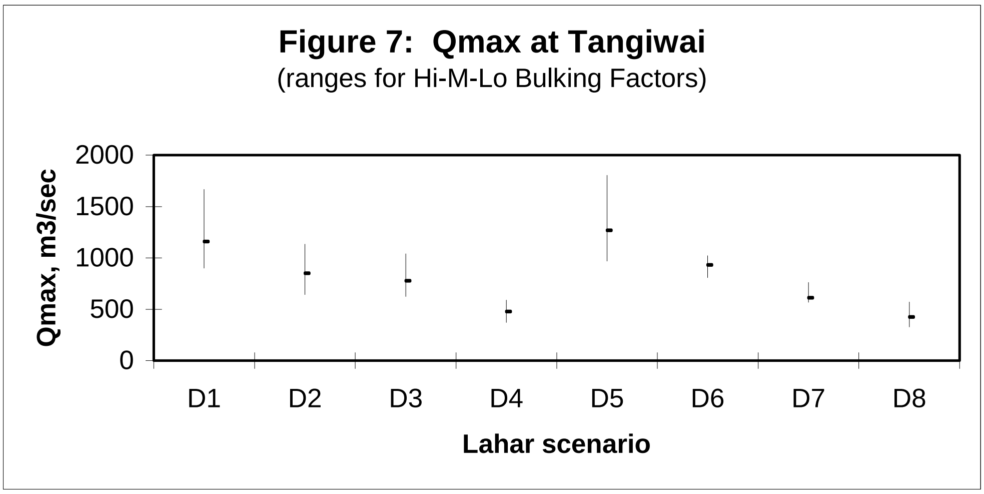
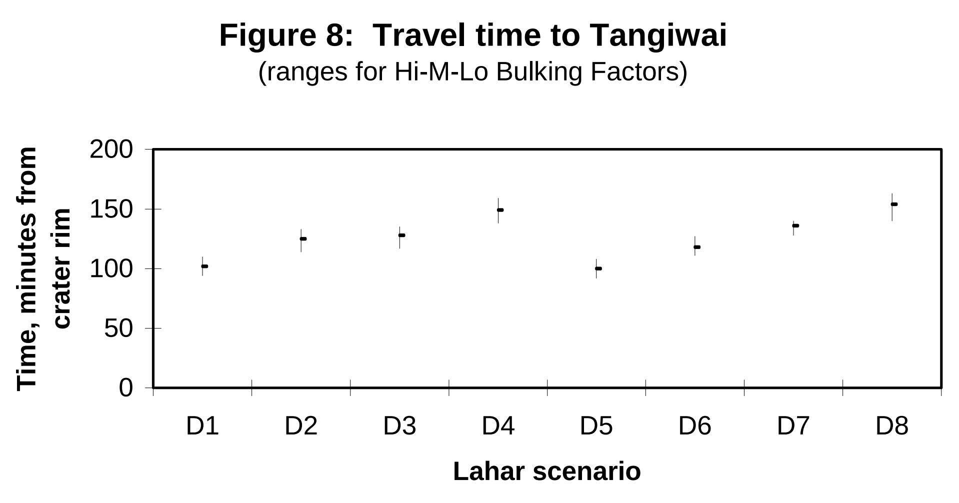


Figure 6: Travel Times for Lahars in the Whangaehu Valley







Observations that can be made from these figures include:

1 Travel time is less sensitive in absolute terms to uncertainties in lahar parameters than is lahar flow. Overall times to reach Tangiwai vary from about 90 to about 160 minutes, whereas peak flows at Tangiwai vary between about 400 and about 1800 cumecs (cubic metres per second).

2 As regards peak flow rate (discharge), the order of importance of the factors considered (for the ranges considered) is:

  (a) bulking factor (makes about x2 difference in most scenarios)

  (b) height of lake up dam at time of failure (D1 vs D3, etc, approx x1.5 difference)

  (c) rate of failure of dam (D1 vs D2 etc, makes about x1.5 difference), and

  (d) level of rock rim beneath dam (D1 vs D5 etc, makes about x1.05 difference).

3 The same order of importance is associated with effects on travel times, with bulking factor making the biggest difference, lake height and dam failure rate about the same, and rim level the least difference to calculated travel times.

6 Risk to Key Assets

6.1 Assets at Risk

The assets potentially at risk are as follows: those where people might be at risk are marked with an asterisk thus*. Letter references are to the sites marked on figure 2(c) above.

Upper Mountain

- DoC Footbridge* (see figure 2b)

Bund/Waikato Stream

- DoC Bund (see figure 2b)
- Genesis Waikato Stream alarm
- State Highway 1 – Waikato Stream N channel (bridge)*
- State Highway 1 – Waikato Stream S channel (culvert)*
- Tongariro River*

Whangaehu Valley

- Pylons (Sites F-G)
- Wahianoa Aqueduct (Site G)
- State Highway 1 – near Aqueduct (Site G)*
- Tangiwai Rail Bridge* (Site I)
- Tangiwai Memorial and Car Park* (Site I)
- Tangiwai SH49 Road Bridge* (Site I)
- Strachan's Bridge* (Site J)
- Tirorangi Marae Bridge* (Site K)
- Field Track and other downstream (road) sites close to Whangaehu River*.

6.2 Asset Damage Models

The issue of interest for these assets is whether the anticipated lahar will reach them and, if so, whether it will damage them sufficiently to prevent them safely carrying out their function. Four kinds of such damage are particularly important for this assessment.

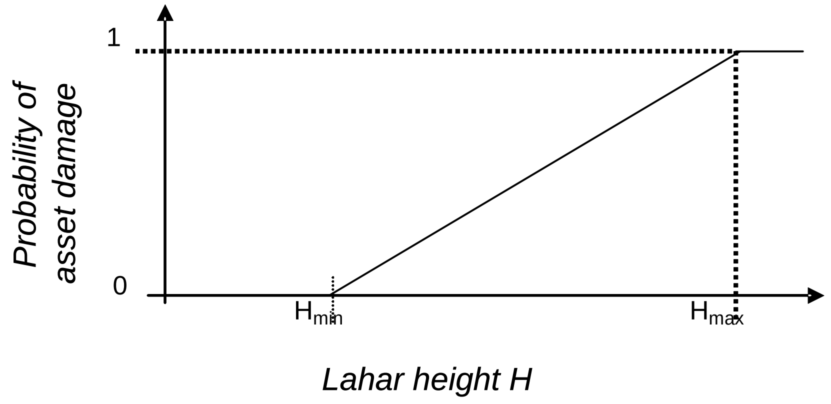
- For bridges, damage sufficient to prevent traffic being able to pass safely
- For roads, lahar material reaching and/or damaging the road surface
- For occupied areas (such as the Tangiwai memorial), lahar material rendering areas unsafe for people to occupy, in cars or on foot
- For the Tongariro River, increases in flow sufficient to put people using the river at risk.

For the first three assets, the key lahar characteristic that will determine whether damage is incurred is the height of the lahar at the site in question. This will determine whether the lahar reaches road, the risk it presents to bridges, and whether potentially occupied areas can be inundated.

For the Tongariro River the critical parameter is the change in flow of the river in the lower reaches, where people use the river extensively for fishing and (to a lesser extent) for rafting. Such changes might be produced either by lahar material reaching the Tongariro River directly, via the Waikato Stream, or by Genesis' responses to protect Rangipo Power Station and Lake Rotoaira from the threat of a lahar, which are discussed in Section 7.4. The key lahar characteristics of relevance to risk in the Tongariro River are thus a) the peak flow of lahar material into the river, and b) whether or not the lahar causes various alarms to be tripped which trigger Genesis emergency actions to comply with environmental regulation by preventing the diversion of contaminated material into Lake Rotoaria and to protect Rangipo Power Station.

The asset damage models used here are generally of the form shown in Figure 9 below.

Figure 9: Typical Asset Damage Model



Up to a certain size of lahar (typically the highest depth for which we can be confident the lahar would not reach the asset in question), the probability of asset damage is zero. It then increases linearly up to unity at the lowest lahar height beyond which damage is virtually certain. The difference between the two heights is small for roads whose elevation is well known, and larger for bridges (typically the height H_{max} is set at the height above the river bed of the soffit[4]). The maximum and minimum lahar sizes assumed to estimate probabilities of asset damage using this model are shown in Table 2.

Note 1: There is no pretence that the probabilities estimated in this way provide some sort of precise, quantitative estimate of risk. They have been used simply to provide a rough indication of degree of concern about key assets. In the spreadsheet model used to perform these calculations, the user can input a threshold probability value above which any combination of asset and lahar scenario exceeding the threshold is coloured red. A glance at a table of lahar scenarios/assets then provides a rapid indication of whether none, a few or many lahar scenarios would put the asset at risk.

Note 2: The values used for key state highway bridges and Tangiwai Rail Bridge have been discussed with Transit and Tranz Rail and have been agreed to be reasonable. The value for SH1 at the aqueduct site is substantially uncertain and MCDEM are checking the topography of this area with Transit. The values for damage to the Wahianoa aqueduct are indicative only and have not been specifically discussed with Genesis, though Genesis have informed me that they regard the risk to the aqueduct from the anticipated lahar as being very high.)

Note 3: Notes of discussions with Tranz Rail, Transit, Genesis Power and Transpower which underpin these assessments and those in Section 7 are attached as appendices 2-5. All these notes have been verified with the utility organisations concerned.

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[4] The lowest cross members of the bridge.

6.3 Predictions from Flow Calculations

The predicted heights of each of the 24 lahar scenarios modelled at sites relevant to asset damage are shown in Table 3 below.

The “*best (central) estimate*” asset damage probabilities corresponding to the lahar heights shown in Table 3 are presented in Table 4. These asset damage and flow models were reviewed at a meeting in MCDEM on 20 June 2002, a note of which is provided as Appendix 6. Reviewers felt uncomfortable about coming to firm decisions about the non-vulnerability of assets in the face of such uncertainty as to lahar flows, so asked that this table be re-drawn, but now using the upper bounds of the uncertainty ranges provided by Grant Webby for each site modelled. The resulting revised version of the asset damage table is shown in Table 5. These tables were originally drawn with rows of equal width, but it was later recognized that this was not a “*presentationally neutral*” form of presentation. The one key uncertainty about the lahar on which experts are agreed is that it is more likely to happen when the lake level is nearer the top of the tephra barrier rather than lower down towards the level of the lava outlet lip. Rows in the table were accordingly resized to reflect the judgments of the 20 June meeting as to the relative likelihood of lahar scenarios, to provide a better visual representation in the tables of the experts’ degree of belief as to the plausibility of each of the 24 lahar scenarios.

The threshold probability of damage above which the cells in these tables are shaded was set at 10%. The interpretation of these tables is discussed in section 6.4.

Table 2: Asset Damage - Assumptions and Values

Site	Watercourse	Asset	Upper threshold for P[damage] = 0	Lower threshold for P[damage] = 1
A	Waikato Stream	SH1 Bridge	5.00 m	5.95 m
D	Whangaehu River	Bund	7.2 m	8.2 m
E	Waikato Stream	SH1 Culvert	0.2 m	0.5 m
F	Whangaehu River	Transpower Pylons	12.0 m	12.1 m
G	Whangaehu River	Wahianoa Aqueduct	1,000 m^3/s	2,000 m^3/s
G	Whangaehu River	SH1	10.0 m	10.5 m
G	Whangaehu River	Transpower Pylons (80m and 180m U/S of Site G)	8.6 m	8.7 m
H	Whangaehu River	SH49 Tangiwai Road Bridge	4.0 m	6.2 m
H	Whangaehu River	Tangiwai Memorial	3.0 m	3.5 m
I	Whangaehu River	Tangiwai Rail Bridge	6.0 m	8.0 m
I	Whangaehu River	Transpower Substation	9.7 m	10.0 m
J	Whangaehu River	Strachans Bridge	5.0 m	5.4 m
L	Whangaehu River	Marae Bridge	5.0 m	7.3 m

Note:

Values in unshaded cells are based on available survey information and records of historical lahar events recorded in the GNS report.

Values in shaded cells are a current "best guess" and require confirmation at a later date.

Site letters in Table 2 refer to the sites marked on Figure 2c above.

Table 3: Peak lahar flow depth (metres, best estimate) at key locations

Crater Scenario	Bulking factor		Site D Gorge Outlet & Bund	Site G Wahianoa Aqueduct	Site H SH49 Tangiwai Road Bridge, Tangiwai	Site I Tangiwai Rail Bridge	Site J Strachan's Bridge	Site L Marae Road Bridge
	Scale	Value						
D1	Hi	5	5.6	9.5	5.3	7.5	7.4	8.0
	Mid	4	5.0	8.7	4.6	6.5	6.5	5.9
	Low	3.33	4.5	7.8	4.1	5.9	5.7	4.8
D2	Hi	5	4.3	8.4	4.5	6.4	6.1	5.1
	Mid	4	3.8	7.2	4.0	5.7	5.6	4.6
	Low	3.33	3.5	6.3	3.6	5.0	5.0	3.9
D3	Hi	5	4.2	8.2	4.4	6.2	5.9	5.0
	Mid	4	3.7	6.9	3.9	5.5	5.4	4.4
	Low	3.33	3.3	6.2	3.5	5.0	5.0	3.9
D4	Hi	5	3.1	6.0	3.5	4.9	4.9	3.8
	Mid	4	2.7	5.4	3.2	4.5	4.7	3.6
	Low	3.33	2.4	4.9	3.0	4.1	4.5	3.3
D5	Hi	5	5.8	9.7	5.5	7.8	7.6	8.6
	Mid	4	5.1	8.8	4.7	6.7	6.7	6.4
	Low	3.33	4.6	8.1	4.2	6.1	5.9	5.1
D6	Hi	5	4.5	7.9	4.2	6.0	5.8	4.9
	Mid	4	4.1	8.1	4.3	6.2	5.9	5.0
	Low	3.33	3.8	7.0	3.9	5.6	5.5	4.5
D7	Hi	5	3.7	6.8	3.8	5.4	5.3	4.3
	Mid	4	3.2	6.1	3.5	4.9	4.9	3.9
	Low	3.33	2.9	5.9	3.4	4.8	4.9	3.8
D8	Hi	5	2.9	5.9	3.4	4.8	4.9	3.8
	Mid	4	2.5	5.2	3.1	4.3	4.6	3.5
	Low	3.33	2.3	4.7	2.9	4.0	4.4	3.2

Table 4: Risk of Asset Damage, Central Flow Estimates (as listed in Table 2)

Crater Scenario	Bulking Factor		Site D Gorge outlet & Bund	Site G Wahianoa Aqueduct	Site G SH 1*	Site H SH49 Tangiwai Road Bridge	Site H Tangiwai Memorial	Site I Tangiwai Rail Bridge	Site J Strachan's Bridge	Site L Marae Bridge
	Scale	**Value**								
D1	Hi	5	0.00	1.00	0.00	0.58	1.00	0.76	1.00	1.00
	Mid	4	0.00	0.96	0.00	0.25	1.00	0.26	1.00	0.40
	Low	3.33	0.00	0.48	0.00	0.06	1.00	0.00	1.00	0.00
D2	Hi	5	0.00	0.78	0.00	0.22	1.00	0.21	1.00	0.06
	Mid	4	0.00	0.29	0.00	0.01	1.00	0.00	1.00	0.00
	Low	3.33	0.00	0.01	0.00	0.00	1.00	0.00	0.00	0.00
D3	Hi	5	0.00	0.36	0.00	0.03	1.00	0.00	1.00	0.00
	Mid	4	0.00	0.19	0.00	0.00	1.00	0.00	0.95	0.00
	Low	3.33	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
D4	Hi	5	0.00	0.00	0.00	0.00	0.93	0.00	0.00	0.00
	Mid	4	0.00	0.00	0.00	0.00	0.45	0.00	0.00	0.00
	Low	3.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D5	Hi	5	0.00	1.00	0.00	0.67	1.00	0.89	1.00	1.00
	Mid	4	0.00	1.00	0.00	0.33	1.00	0.37	1.00	0.60
	Low	3.33	0.00	0.61	0.00	0.11	1.00	0.04	1.00	0.03
D6	Hi	5	0.00	0.47	0.00	0.05	1.00	0.00	1.00	0.00
	Mid	4	0.00	0.35	0.00	0.02	1.00	0.00	1.00	0.00
	Low	3.33	0.00	0.23	0.00	0.00	1.00	0.00	1.00	0.00
D7	Hi	5	0.00	0.17	0.00	0.00	1.00	0.00	0.00	0.00
	Mid	4	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
	Low	3.33	0.00	0.00	0.00	0.00	0.84	0.00	0.00	0.00
D8	Hi	5	0.00	0.00	0.00	0.00	0.85	0.00	0.00	0.00
	Mid	4	0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.00
	Low	3.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 5: Risk of Asset Damage (Extreme Flow calculations)

Crater Scenario	Bulking factor		Site D Gorge Outlet & Bund	Site G Wahianoa Aqueduct	Site G SH1 *	Site H SH49 Tangiwai Road Bridge	Site H Tangiwai Memorial	Site I Tangiwai Rail Bridge	Site J Strachan's Bridge	Site L Marae Bridge
	Scale	Value								
D1	Hi	5	0.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Mid	4	0.00	1.00	0.80	0.67	1.00	0.91	1.00	0.91
	Low	3.33	0.00	0.63	0.00	0.43	1.00	0.54	1.00	0.35
D2	Hi	5	0.00	0.96	0.26	0.63	1.00	0.86	1.00	0.50
	Mid	4	0.00	0.41	0.00	0.37	1.00	0.44	1.00	0.25
	Low	3.33	0.00	0.11	0.00	0.13	1.00	0.03	1.00	0.00
D3	Hi	5	0.00	0.49	0.00	0.39	1.00	0.48	1.00	0.29
	Mid	4	0.00	0.30	0.00	0.29	1.00	0.30	1.00	0.11
	Low	3.33	0.00	0.08	0.00	0.11	1.00	0.00	1.00	0.00
D4	Hi	5	0.00	0.02	0.00	0.07	1.00	0.00	1.00	0.00
	Mid	4	0.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00
	Low	3.33	0.00	0.00	0.00	0.00	1.00	0.00	0.94	0.00
D5	Hi	5	0.34	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Mid	4	0.00	1.00	1.00	0.75	1.00	1.00	1.00	1.00
	Low	3.33	0.00	0.77	0.00	0.49	1.00	0.64	1.00	0.47
D6	Hi	5	0.00	0.61	0.00	0.43	1.00	0.54	1.00	0.34
	Mid	4	0.00	0.48	0.00	0.39	1.00	0.48	1.00	0.28
	Low	3.33	0.00	0.35	0.00	0.32	1.00	0.36	1.00	0.17
D7	Hi	5	0.00	0.28	0.00	0.27	1.00	0.27	1.00	0.08
	Mid	4	0.00	0.06	0.00	0.10	1.00	0.00	1.00	0.00
	Low	3.33	0.00	0.00	0.00	0.05	1.00	0.00	1.00	0.00
D8	Hi	5	0.00	0.00	0.00	0.05	1.00	0.00	1.00	0.00
	Mid	4	0.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00
	Low	3.33	0.00	0.00	0.00	0.00	0.98	0.00	0.67	0.00

OVERALL high and low probabilities of asset damage carried forward to residual risk assessment

P[Asset Failure]$_{HIGH}$ $^{\#}$	**0.01**	**0.80**	**0.30 ***	**0.80**	**1.00**	**0.80**	**1.00**	**0.80**
P[Asset Failure]$_{LOW}$ $^{\#}$	**0.003**	**0.30**	**0.10 ***	**0.30**	**1.00**	**0.30**	**0.50**	**0.30**

** - Likelihood of lahar reaching SH1 here is highly uncertain because of topographic uncertainties.*

6.4 Interpretation and Summary

The 20 June review group at MCDEM considered the flow and asset damage estimates above, and came to a judgment as to the likely range of asset damage probabilities which should be propagated forward into our safety risk assessment. The interpretation of Tables 4 and 5 followed the following logic:

1 A solid column of shading in Table 4 implies that any of the lahar scenarios considered will lead to asset damage. On the assumption that our range of scenarios includes what will turn out to be the actual scale of the anticipated lahar, this means that asset damage is a virtual certainty. Thus **the Memorial Car Park is considered virtually certain to be badly damaged by the anticipated lahar**.

2 A column in Table 4 with a significant shaded area implies that a good portion of the "*parameter space*" within which the lahar is expected to lie would lead to asset damage. In these cases we have assumed the asset to be at very high risk (ie **Strachan's bridge and the Wahianoa Aqueduct are considered to be at very high risk**). Little consideration is subsequently given to the possibility of these assets' survival in our safety risk estimates.

3 A column in Table 4 with few or no patches does not lead us to the conclusion that risk is low, but caused us to look more carefully at the location and asset in question. Our first step was to include the possible effects of upward uncertainties in lahar flow (ie by stepping from Table 4 to Table 5). This significantly increases the shaded areas for **the rail and road bridges at Tangiwai and the Marae Bridge**. Our collective view was that these assets **should also be considered as high risk**; they have a good chance of surviving without major damage ONLY in scenarios in which the lake does not rise to the top of the tephra dam before the lahar occurs. It was felt, though, that the possibility of their survival should be reflected in subsequent safety risk estimates.

4 This leaves only the issue of bund overtopping and flows into the Waikato Stream in the "*not high risk*" category, with just two lahar scenarios, even at the upper range of Grant Webby's flow calculations (ie Table 5), leading to predicted heights sufficient to overtop the bund. This was subject to more detailed consideration as to the extent and consequences of bund overtopping, as described in Appendix 6. The important conclusions were:

   (a) The maximum peak flow over the bund, in an absolute worst case scenario, might be of order 20-30 cumecs so long as the bund retained the bulk of its integrity

   (b) There was a possibility, not considered particularly likely, but meriting serious consideration, that overtopping of the bund would lead to its rapid erosion, which might increase peak flows up to 100-110 cumecs.

   (c) The next important issue was whether the flow would be sufficient, having come over the bund, to travel upwards the 2 metres or so necessary to cross the watershed between the Whangaehu River and the Waikato Stream. This was considered impossible if bund integrity was retained, but if the bund failed it was considered plausible that 30-40 cumecs peak flow might enter the Waikato Stream. *(Note – this conclusion is based on an eyewitness report to the Scientific Panel that the divide between the north branch of the Whangaehu and the Waikato Stream is about 2 metres above the Whangaehu Stream bed. This should be confirmed, eg by a site survey to produce a large scale map of the cross-over area, given the importance of this conclusion)*

   (d) This flow would certainly be sufficient to trigger the Genesis alarm in the Waikato Stream, and the course of subsequent actions to protect power generation assets which is described in Section 7.4 and Appendix 4.

   (e) Some of the entrained solids would deposit out from this lahar before it reached SH1, but 20-30 cumecs of peak flow was considered plausible reaching SH1. This would be expected to split between the north channel (15-20 cumecs) and the south channel (5-10 cumecs).

(f) The SH1 bridge over the north channel of the stream has ample capacity to pass several times these sorts of flows, and is not considered significantly at risk.

(g) The culvert is a modest diameter pipe under the road, and could not pass 5-10 cumecs without blocking and leading to lahar material flowing over the road.

(h) Any lahar material which passed SH1 would flow relatively rapidly and with little depletion down the Waikato Stream and into the Tongariro River. The maximum conceivable flow in the worst case scenario was less than that by which Genesis would in any case increase lower river flows in responding to lahar warnings. Associated risks were thus considered extremely small in relation to the risks associated with Genesis' response to the lahar, and we agreed they did not need to be considered further in this assessment.

Thus far we had not considered making judgments as to the likelihood of one of our 24 lahar scenarios in relation to any of the others. The whole basis of the scenario set was that it constituted a range of eminently plausible scenarios, within which no true expert would try to argue that one part of the range was significantly more or less likely than another.

We felt strongly, though, that the likelihood of significant lahar flows into the Waikato Stream could not be high or very high. We then had to consider what range of probabilities we felt was appropriate to carry forward into our safety risk assessment. We used a simple event tree methodology, assigning cautious probabilities to express our degree of belief at each stage, to arrive at a rough estimate of what we believed to be the likelihood of significant flow over the bund, sufficient to reach the Waikato Stream and SH1. Our estimate of this likelihood was a probability of .003 to 0.01 (0.3 to 1%), made up of:

- the belief that scenarios D1 and D5 were only a few per cent likely to represent the actual lahar (4%, based on 50% chance of low rim level, 80% chance of dam failure with lake filled to the brim, 50% chance of rapid rather than slower breach time, and 20% chance of a bulking factor of 5; subsequently rounded up to 10% as a precaution against over-confidence)
- the belief that the bund was unlikely to be overtopped and sustain damage sufficient to permit the passage of the 50-80 cumecs considered necessary before there was a possibility of flow over into the Waikato Stream (10%).

The result was a range of probabilities for lahar material passing over the bund, triggering the Genesis Waikato alarm, and reaching SH1, from 0.003 to 0.01, which was propagated through to the safety risk assessment. The final output of the 20 June review, in terms of upper and lower asset damage probabilities for assets at greatest risk for use in the safety risk assessment, is shown in the bottom two rows of Table 5. The numerical ranges correspond to a judgement as to the likely range within which the actual probability of damage would lie, based on consideration of the values in Tables 4 and 5 and the arguments above.

7 Risks to People

This section explains the approach and assumptions used in the assessment to estimate fatality risks associated with failures of the tephra dam at the crater lake, at different sites in the Whangaehu Valley, the Waikato Stream valley and the Tongariro River. Risks to people on the upper parts of Mt Ruapehu are considered in Section 9. Important underlying assumptions throughout are:

1 Risk to people is in each case created by damage to one of the assets considered in the assessment. Unless otherwise stated (in particular for risks associated with Genesis' response to lahars), risk is estimated on the assumption that severe asset damage has occurred (ie all risks discussed here are conditional on the asset damage initiating event having occurred).

2 The safety outcome (ie the consequence of a potentially hazardous event) considered in each case is **the likelihood of there being one or more fatal accidents, given that the initiating asset damage has occurred**.

3 In most cases, the number of people at risk is small. Where this might not be the case (in particular for roads and railways) the likelihood of the accidents in question involving different numbers of people is estimated explicitly to provide an indicator of likely accident scale.

4 All the risk estimates here are made on a "*before ERLAWS and emergency response*" basis. That is, they all assume no forewarning by ERLAWS and no action by emergency services to mitigate the risks. (Utilities' own arrangements to protect life, and their likely effectiveness and reliability, without ERLAWS, are considered here).

5 All of the risk estimates here are uncertain. Each risk model estimates a range of outputs, using a range of input values for parameters that are particularly uncertain.

The purpose of these conditional risk estimates is to provide, in combination with the asset risk information developed in the previous section, an overall picture of the scale of safety risks which the lahar warning and response systems are there to mitigate. This "*before ERLAWS*" risk can then be combined with the expected failure probability of warning and response to estimate the overall residual risk associated with the dam failure lahar.

The scope of locations where people are at risk from dam failure lahars and specific models to estimate that risk are provided here is as follows:

1 Rail users crossing the Tangiwai rail bridge

2 Campers at the Tangiwai Memorial

3 Road users (on SH1, SH49, and bridges and roads downstream of Tangiwai), and

4 People in the Tongariro River.

A number of other groups of people are potentially at risk from these lahars, but have not been included in the assessment. Important groups and reasons for their exclusion include:

- ***Residents and people in their normal workplaces***: we are not aware of any homes or workplaces which are directly at risk from lahar flows. People living and working in the vicinity of the Whangaehu Valley are thus included only insofar as they are at risk while using the roads. There are significant populations (for example at the Winstones Saw Mill at Tangiwai) who are not expected to be at risk from lahars, but who might conceivably be put at risk in the event of a panic and/or a badly handled evacuation. I have not considered this possibility here.
- ***People working outdoors in the Whangaehu Valley***: The Army use the area of the Whangaehu valley to the west of SH1 as a training ground, but are not modelled here as it is understood that they will cease doing so when the crater lake reaches the tephra dam. We are not aware of any other groups who regularly use the valley in the course of their work. We understand that the occupancy levels of people present for maintenance of utility assets, or for farming or other

occasional work-related visits, are very low compared with the other groups who are considered and modelled here, and have thus considered them only insofar as they are road users in the area.

- ***Leisure users of the lower Whangaehu Valley***: There are occasional trampers, kayakers and other leisure visitors to the lower valley (visitors to the higher reaches of the mountain are considered in the Upper Mountain section of this report). But there are no established recreational activities in the valley – there is no fishing, for example, as the water is "*polluted*" by the crater lake and cannot support fish. People at leisure are thus considered only insofar as they are road users in the area.

The risks in each of the four types of location considered (Tangiwai Rail Bridge, Tangiwai Memorial, Road Users, Tongariro River) are considered in turn.

7.1 Tangiwai Rail Bridge

Accidents here are the first concern most people have about lahar risks in the Whangaehu Valley, because of the 1953 tragedy. The strengthening of the rail bridge after the 1953 event, and the ability of the bridge to withstand lahars, was considered in the Asset Damage section of this report. This section focuses on what would be expected to happen, in the absence of warning and response systems, if the rail bridge were seriously damaged by a lahar.

The definition of "*serious damage*" corresponds to "*sufficient to derail a train passing over the bridge*". On this basis, in the absence of any warning and preventive action, the expected sequence of events would be:

- lahar damages bridge
- next train to approach bridge drives over it and derails
- fatalities very likely (not certain, but probably a 50/50 chance or higher).

About 80% of the rail traffic using this line consists of freight trains[5], manned by the driver working on his own. About 20% of traffic consists of passenger trains, which typically carry between 50 and 200 people[6]. Thus in 80% of cases a single fatality might be expected, while in 20% of cases there would be a clear possibility of a major passenger train accident involving 10's or even 100+ fatalities.

We now need to consider the railway arrangements which have been put in place since 1953 to protect people in the event of lahar damage to the bridge. There is a possibility that bridge damage will sufficiently damage the track to break the electrical circuits through the track which actuate signals. If this happened it would set signals to danger either side of the bridge, providing a high degree of protection (the reliability of train drivers stopping at red signals has been honed over many years to be one of the most reliable human actions known in response to danger signals, typically with less than a 1 in 10,000 chance of error in most countries and for most signals). But such convenient damage to track circuits cannot be relied upon; it happens in only a minority of derailments. Its effectiveness has therefore been ignored in this assessment.

The key railway system reducing risk to people is the lahar warning and protection system installed and developed by Tranz Rail since 1953. Some important features of the system are illustrated in Figure 10. This assessment is based on discussions with Tranz Rail of which notes are provided as Appendix 2.

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[5] Private Communication, Vern Hoey, Tranz Rail, to Adam Milligan, Optimx, May 2002

[6] Private Communication, Ivan Johnson, Tranz Rail, to Adam Milligan, Optimx, May 2002

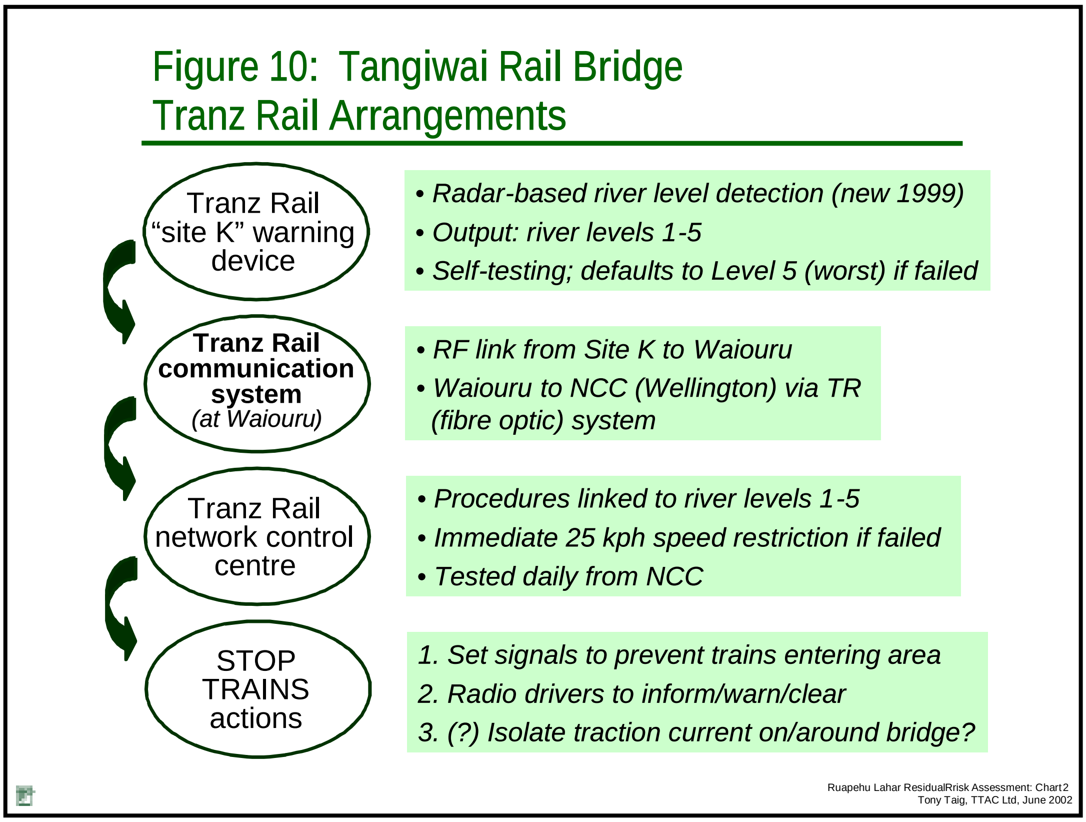


Figure 10: Tangiwai Rail Bridge
Tranz Rail Arrangements

Tranz Rail “site K” warning device

- *Radar-based river level detection (new 1999)*
- *Output: river levels 1-5*
- *Self-testing; defaults to Level 5 (worst) if failed*

Tranz Rail communication system *(at Waiouru)*

- *RF link from Site K to Waiouru*
- *Waiouru to NCC (Wellington) via TR (fibre optic) system*

Tranz Rail network control centre

- *Procedures linked to river levels 1-5*
- *Immediate 25 kph speed restriction if failed*
- *Tested daily from NCC*

STOP TRAINS actions

1. *Set signals to prevent trains entering area*
2. *Radio drivers to inform/warn/clear*
3. *(?) Isolate traction current on/around bridge?*

Ruapehu Lahar ResidualRrisk Assessment: Chart2
Tony Taig, TTAC Ltd, June 2002

The system comprises a radar river level detection device installed in the Whangaehu River just over 12 km upstream of Tangiwai, linked to the Tranz Rail National Control Centre in Wellington by a radio link to Waiouru where it joins Tranz Rail’s own dedicated telecommunication system. Tranz Rail have a well developed procedure triggering actions as the river level rises. Five different river levels are recognised by this system, with an audible alarm in the Control Centre whenever the level increases. For the highest level, all trains over Tangiwai Bridge are stopped by two means, first by the Control Centre staff setting signals to red either side of the bridge, and second by speaking to train crews over the train radio and warning them to move out promptly if they are already in the Tangiwai area, and to stop and stay well clear if they are approaching Tangiwai.

Working as intended, this provides a highly effective system to prevent train access to the bridge and protect people. Its effectiveness is thus limited only by its unreliability. The system will fail if any one of the following fails:

- the detector, or
- the communication link to Wellington, or
- the operators’ response to the alarms.

Of these elements, the detector is a new system designed to address the unreliability problems of the old. It incorporates self-testing, and the system in Wellington reverts to an alarm state (in which all trains are slowed to 25 kph and drivers told to take extreme caution over Tangiwai Bridge) if the detector is unavailable. The likelihood of both the detector being failed, and of the precautionary approach on its failure, failing to work when needed is considered very small.

Similarly, the likelihood of a successful response once the alarm is raised in Wellington is considered to be very high. First, the likelihood of the alarm being ignored is extremely small. The Control Centre is manned 24 hours a day with three highly trained staff normally on duty. All will be highly attuned to the risk of the forthcoming lahar and well versed in what to do. Barring accidents in which the Control Centre becomes unavailable or has to be evacuated (of which there is no prior Tranz Rail experience of which we are aware) the risk of Control Centre staff responding incorrectly should be extremely small. Second, the signal system on its own should provide very high reliability of stopping trains in time, if properly set from Wellington. Signalling systems are designed and built to the highest of integrity standards, such that the chance of signals on the ground failing to do what the Control Centre asks of them is typically far below one in a million per demand. As previously mentioned, driver reliability in stopping at red signals is also high, typically no worse than 1 failure in 10,000 red signals. The use of train radio as a back-up (Tranz Rail trains do not leave the depot if the radio is not working) provides significant additional reliability of stopping trains once the Control Centre is aware of an impending lahar.

The weak link in this chain is almost certainly the communication link between the monitoring site and Wellington, with the RF link from the monitor to Waiouru the particular weak link, and source of most system unavailability incidents to date. If the failure is revealed by the self-testing equipment at Wellington then risk should be considerably reduced by the precautionary speed restriction Tranz Rail introduce in such circumstances. A particular concern is that there might be mechanisms whereby failure would not be revealed, in which case the system would simply fail to provide a warning of an approaching lahar.

In discussion with Tranz Rail it was noted that the warning system is not designed to signalling integrity levels, but has performed well to date, with only a few hours per year unavailability. On this basis, Tranz Rail agreed that the likely reliability of the warning system as a whole (ie probability of it succeeding in its function of enabling trains to be stopped before entering the risk zone at Tangiwai) was probably in the region of 99 to 99.9%. In the absence of detailed assessment of system unreliability and evidence to substantiate reliability over the coming years averaging to the higher end of this range, a range of 99-99.5% reliability (ie 1-0.5% chance of failure when needed) for the Tranz Rail system has been assumed in this assessment.

It is noted that the weak link in the Tranz Rail system is the one part of the system amenable to dramatic performance improvement if an alternative warning of an approaching lahar can be provided (ie via ERLAWS). Providing a rapid feed of ERLAWS alarms through to Tranz Rail would thus be an effective way of significantly improving the reliability of this system, and of further reducing risks to trains and the people on them. *[Note - this would have the additional benefit, if done verbally via a telephone call, of ensuring that a well manned, highly trained group of people in a secure location with high reliability communication links had early awareness of the lahar and were available to assist in emergency response if other systems were to fail.]*

Putting all this together, the assessment of the risk of there being 1or more fatalities in a train accident at Tangiwai, given that the railway bridge has failed, and before taking into consideration any effectiveness of ERLAWS and associated emergency responses, is:

0.5 – 1 (Probability of fatalities without railway lahar protection system)

* 0.01 (Probability of failure of railway lahar protection system)

= 0.005 to 0.01 Overall (0.5 to 1% chance of an accident with 1 or more fatalities)

We note in addition that in about 80% of cases the casualties would be limited to a single fatality, while in about 20% of cases (passenger trains) there could be many tens of, or even 100+, fatalities.

7.2 Visitors to the Tangiwai Memorial

The presence of the toilets and washing facilities at the Memorial has made it a regular, if not a highly frequented, overnight stopping place for tourists in camper vans, and a very regular stopping-off point for visitors to the Memorial itself during the day. The whole of the car parking area around the Memorial is much closer to river level than the rail and road bridges between which it is situated. The risk of severe lahar damage to vehicles and their occupants is correspondingly higher.

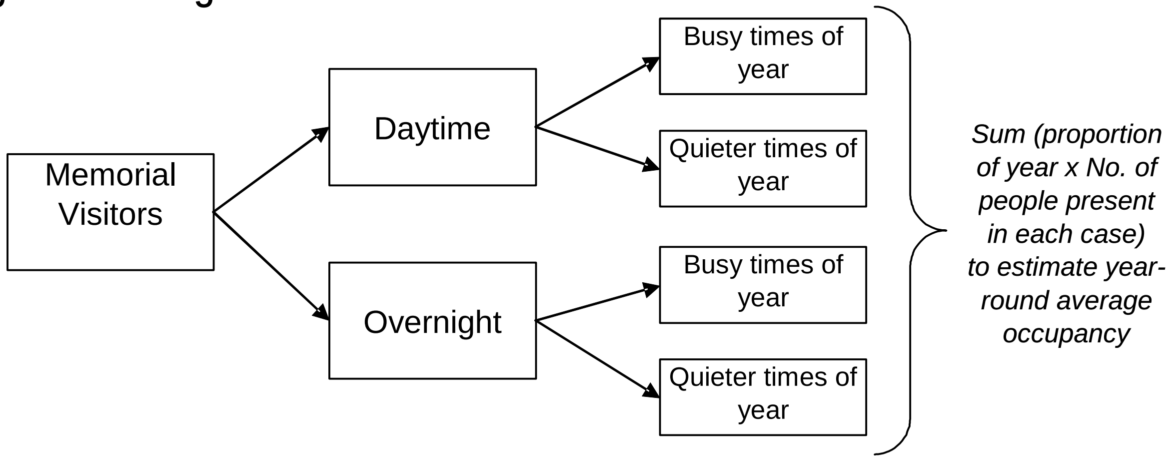
In Section 6 the likelihood that a lahar will rise high enough to move vehicles was considered. The question here is thus "*How likely is a fatal accident, given that a lahar has reached such a level?*" This depends on just two factors:

1 the likelihood that people or occupied vehicles are present, and

2 the likelihood, if so, that somebody will be killed if they or their vehicles are trapped in a lahar large enough to move those vehicles along.

The first factor depends simply on how many people are present at the Memorial. There are two components to the occupancy of the area. First are the daytime visitors, who typically stop for no more than a few tens of minutes. Second are the longer stay visitors who camp overnight in camper vans. The scenarios are illustrated in Figure 11 below.

Figure 11: Tangiwai Memorial



As regards the daytime visitors, we are not aware of any head counts of numbers of visitors, but the author noted in an hour's visit during mid-May outside school holidays that his was one of three well-loaded cars stopping there in the course of an hour. The estimated proportion of the year for which one or more people (in or out of their vehicles) are present for short visits is as follows:

	0.2-0.6	proportion of time someone present at busy times of year in daytime
x	0.3	proportion of year which is busy for tourists (effectively "*summer*")
x	2/3	proportion of hours that are "*daytime*"
=	0.04 to 0.12	(for summer months)
+	.05-0.2	proportion of time someone present at quiet times of year in daytime
x	0.7	proportion of year which is quiet
x	14/24	proportion of hours that are "*daytime*" outside summer
=	0.02 to 0.08	(for other months, approx).

The total proportion of the year for which one or more people are present for a short visit is thus estimated to lie in the range 0.06 to 0.2, or 6% to 20%.

It is important to note that, if ERLAWS provides a timely alarm, Transit's arrangements to close SH49 with automatic barriers that would let people out of the Tangiwai area but not let them in (see Roads section) should provide effective protection against this risk (as discussed in Section 8). Once the barriers are closed, the vast majority of short-stay visitors are likely to be out of the at risk area within a few tens of minutes. Overnight campers are a different story.

Occupancy by overnight campers was discussed with DoC and with RDC and Ohakune Police. Nobody has done a head count of vehicles, but obvious points raised are a) long stays are confined to night time, b) campers are present much more in the summer than the winter months, and c) even in summer, the Memorial site is not occupied by overnight campers for more than a fraction of the time. On this basis, occupancy is estimated as follows:

	3% to 30%	Proportion of nights campers present in non-winter months
x	2/3	Proportion of months that are non-winter
x	1/2	Proportion of 24 hours for which average camper stays
=	1% to 10%	overall.

Turning to the second factor, of how likely people are to be killed if they or their vehicles are caught in a lahar, people outside vehicles would be very vulnerable, but should also have some degree of warning of a large lahar, which would be very noisy (if conditions were such as to drown out the noise of the lahar people would be unlikely to leave their vehicles for long). On the other hand, few tourists are likely to recognise the noise of a lahar, and there is no view at all of the river upstream of the rail bridge from the car park or the space between it and the river where people are most likely to wander. Given a few seconds between detecting the approaching lahar and it arriving, a small proportion of fit people might be able to run out of the way, but the ground is made up entirely of fine gravel and pebbles and, except in the car park itself, is largely unconsolidated – even an athlete would find it difficult to run quickly from, say, the river up to a car (and might well not be safe when they got there). The risk to people outside vehicles is thus considered to be very high for any lahar high enough to reach vehicles in the car park. The risk is non-zero, but probably very small, for smaller lahars which could affect people down by the river but not up at the car park.

The risk to people in their vehicles is probably small unless the lahar is big enough to engulf or to entrain the vehicle and carry it along. It is conceivable that people would survive being carried along at the edges of a lahar, but almost inconceivable that they would survive total engulfment of their vehicles.

Without going into fine detail of what proportion of people spend what proportion of time inside and outside their vehicles, down by the river and up by the memorial, an approximate estimate of the conditional probability of there being one or more fatality, given that people are present at the Memorial site, can be made as follows:

0 For lahars which do not exceed 10 cm depth at the lowest part of the car park, rising to

0.5 For lahars which exceed 10 cm depth at the lowest part of the car park but do not exceed 30 cm depth at the Memorial, rising to

1 For lahars which exceed 1 metre depth at the Memorial.

Daytime visitors and overnight campers are modelled separately in the risk model in view of the very different expected effectiveness of automated access prevention systems actuated by Transit on receipt of an ERLAWS alarm.

Risks to rail users and Memorial Visitors are summarised below in Table 6, next to Table 7 which provides parallel information for road users.

7.3 Road Users

There are three types of hazards for road users, which are considered here in the sequence in which they would arise:

(a) people or their cars are trapped by a lahar as it arrives at their location

(b) people drive into a lahar while it is passing over or along a road, and

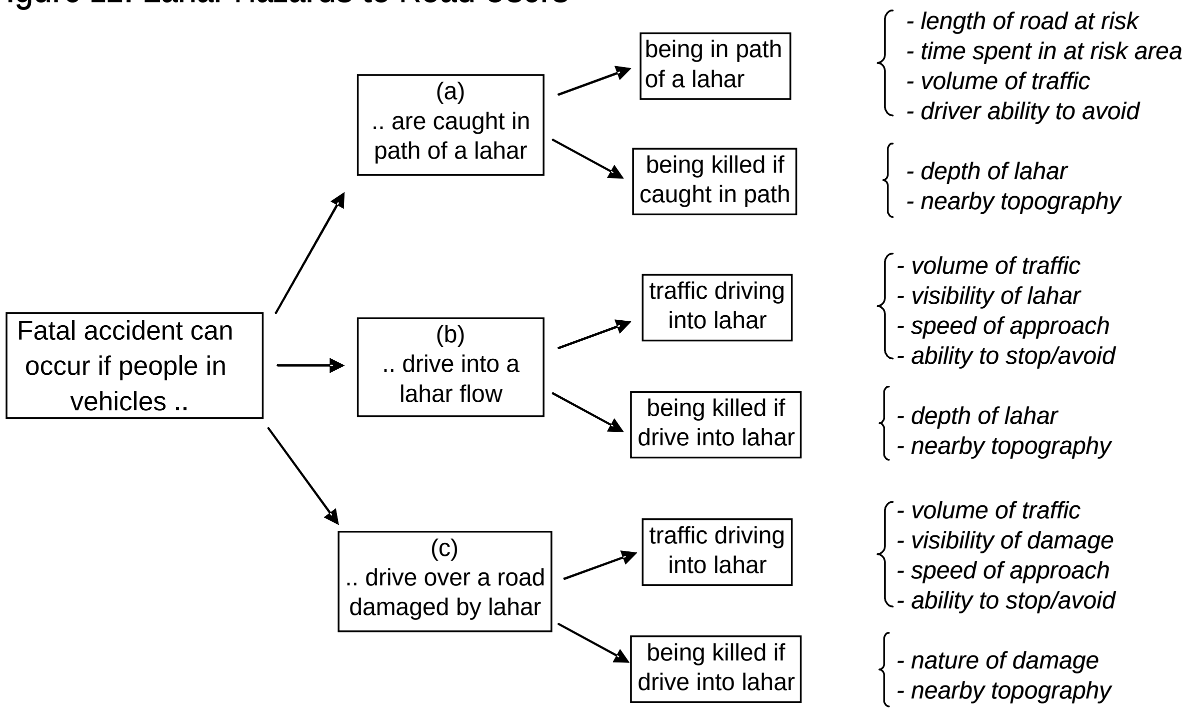
(c) people drive onto a road surface or bridge damaged by a lahar, after the lahar has passed.

These hazards and associated risks are considered for the following locations:

- SH1 – Waikato Stream bridge
- SH1 – Waikato Stream culvert
- SH1 – low point of road near Wahianoa Aqueduct
- SH49 – Tangiwai road bridge
- Strachan’s Bridge
- Marae Bridge
- Other downstream locations (eg Field Track at risk sites)

The factors material to risk associated with these three hazards are illustrated in Figure 12 below.

Figure 12: Lahar Hazards to Road Users



The arrangements for protection of SH1 and SH49 are summarised in Figures 13 and 14 respectively. As can be seen from the Figures, these arrangements depend entirely on the provision of an alarm from ERLAWS. Their effectiveness is thus not considered here, but is incorporated into the assessment of response effectiveness and reliability in section 8.2.

Figure 13: State Highway 1 Closure

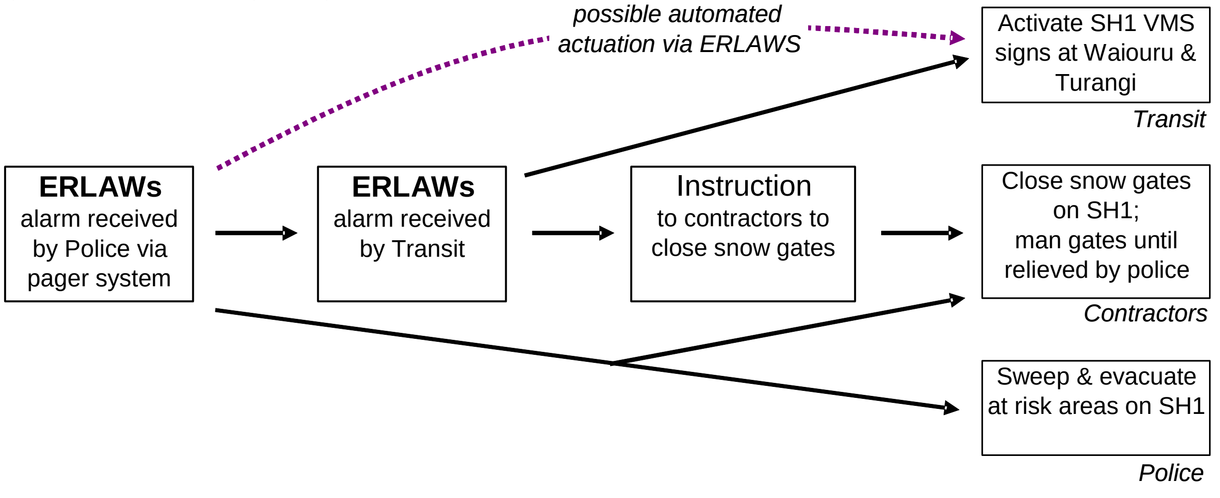
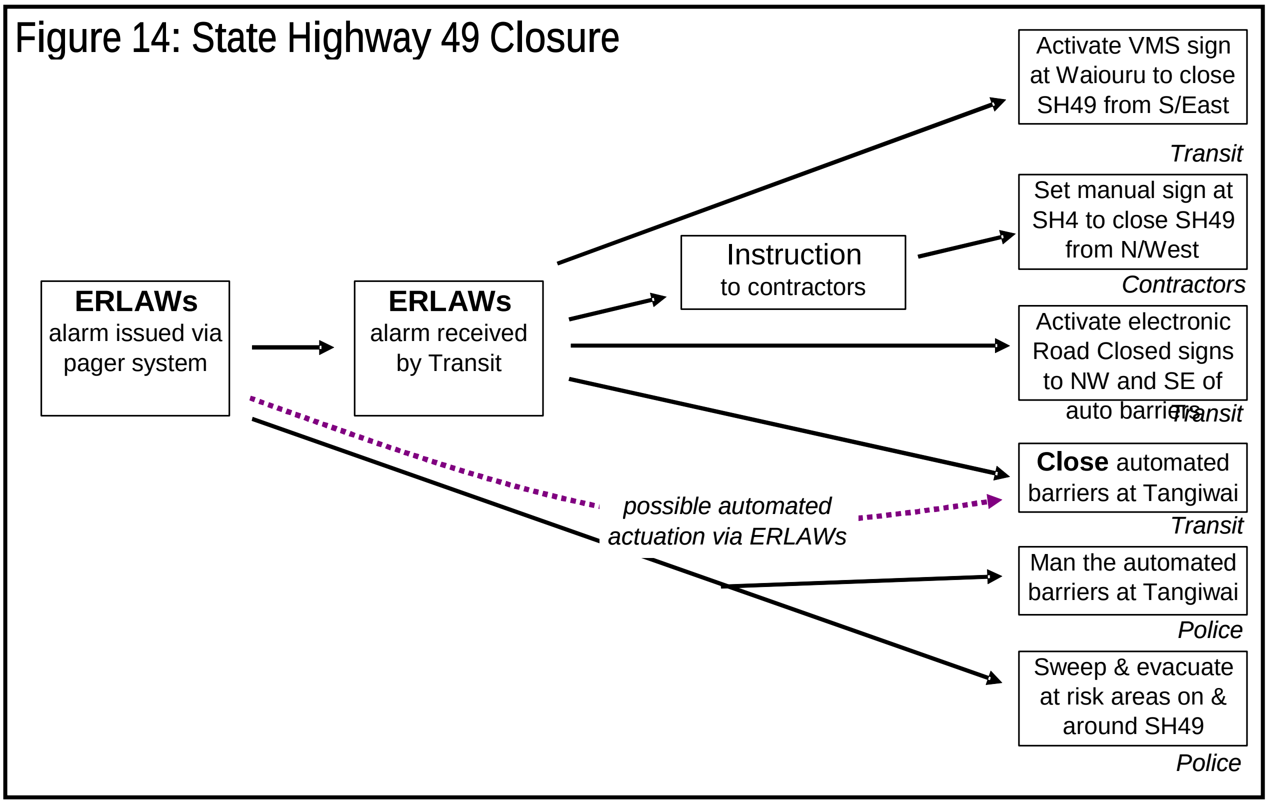


Figure 14: State Highway 49 Closure



For vehicles caught in the path of a lahar, the average number of vehicles trapped is estimated as

N = length of at-risk area (km)
* volume of traffic (vehicles/hour)
/ average speed (kph).

The likelihood of one or more vehicles being trapped is then estimated with reference to the average expected number trapped, with regard to the variability of traffic levels (ie the proportion of the time when there is no traffic present). The probability of there being one or more fatalities given that a vehicle is trapped is estimated as:

0.5-0.9	for vehicles trapped on a bridge, thus facing a significant drop
0.2-0.5	for vehicles trapped at the SH1 Waikato Stream culvert, where there is a small but not insignificant drop at the edge of the road, and
0.1-0.3	for SH1 near the Wahianoa Aqueduct, where there is less of a drop at the road edge.

The resulting estimates of probability of one or more fatalities from this cause at each of the locations considered here are shown in Table 7 below.

As regards hazards associated with people driving into the lahar, or into roads damaged by the lahar, much depends on what happens to the first vehicle or vehicles to reach the affected section of road. If the first vehicle stops, then there is considered to be a very good chance that the road will effectively be closed by one or more stationary vehicles whose drivers are aware of the hazard.

There is considerable experience in New Zealand of drivers encountering badly damaged roads and floods across their path. To gain some feel for the degree of risk associated with such encounters, statistics were reviewed from Transit[7] on the incidence of major road damage events, and from the Land Transport Safety Authority[8] on the incidence of fatal and injury accidents in which road damage or flood was a factor.

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[7] Private communication, John Jones, Transit
[8] Private communication, Lynley Povey, LTSA

Over the period 1997-2001 there were 6 fatal road accidents and 42 other injury accidents in which road edge, landslip or subsidence of the carriageway was a factor. There were 6 more fatal accidents and 58 injury accidents in which flooding was a factor. On average then, the New Zealand experience is of 2-3 fatal accidents per year associated with carriageway damage or flooding. To estimate the likelihood per carriageway damage or road flood event, this can be compared with the annual incidence of major carriageway damage events. Based on Transit records of Transfund committed expenditure for repairs following carriageway damage in the calendar year 2001, there were 35 instances of repairs valued at over $250,000 (roughly the level implying serious damage to more than one carriageway) and 47 instances of repairs valued at over $150,000 (roughly corresponding to serious damage to a single carriageway). 16 of the former and 26 of the latter instances were clearly associated with single damage events (the others were associated, for example, with extreme weather affecting a number of road locations).

On this basis, the figures suggest that 2-3 fatal accidents per year result from perhaps 20-30 instances of very severe carriageway damage – or that the likelihood of a fatal accident per very severe carriageway damage event to a nationally maintained (ie Transit) road is of the order of 1 in 10 or 10%.

In order to extrapolate from this very broad and approximate generalisation to the circumstances that prevail on the roads around Mt Ruapehu, it has been assumed that:

(a) The probability of the first vehicle to approach the lahar, or a road damaged by the lahar, successfully stopping (and thereby avoiding accidents and further risk to other vehicles) is
0.1 to 0.2 in good visibility conditions, or
0.2 to 0.5 in poor visibility conditions (night time or bad weather, assumed 50% of the time)
for a "typical" road.

(b) In situations where road visibility is particularly good in both directions (SH1 at the Waikato Stream culvert or Wahianoa Aqueduct) the "*good visibility*" probability of the first vehicle failing to stop is halved (but the bad visibility probability is unaffected.

(c) In situations where most road users are forewarned of the lahar risk, the probability of the first vehicle failing to stop is halved in both good and bad visibility conditions (Strachan's Bridge, the Marae Bridge, and other roads downstream of Tangiwai).

(d) The probability of there being a fatal accident, given that the vehicle drives into either the lahar (hazard b in figure 12 above) or a road badly damaged by the lahar (hazard c in figure 12 above) is the same as for situations in which vehicles were trapped by the lahar, that is:
0.5 to 0.9 for situations where the lahar or damaged road is on a bridge
0.2 to 0.5 for situations with a smaller drop (SH1 Waikato Stream culvert), and
0.1 to 0.3 for situations with no significant drop at the road edge (SH1, Aqueduct).

The resulting estimates of the likelihood of there being a fatal road accident, GIVEN that the lahar damages the road (ie creates a very hazardous road surface condition) and BEFORE any success is assumed for ERLAWS-led warning and response, are summarised along with the associated key assumptions in Table 7.

Table 6: Risk to People (excl. on roads)

Given Asset Damage (ie lahar has reached asset & rendered condition hazardous)

and BEFORE consideration of ERLAWS and response

Site I - Tangiwai Rail Bridge

	#/Day	% of train type	#/Day	% of total trains	# People per train	% of people killed in collision
Freight	16	1.00	16	0.80	1	1.00
Passenger (typical load)	4	0.70	2.8	0.14	50	0.50
Passenger (heavy load)		0.30	1.2	0.06	200	0.50
Total	20		20			

Reliability of Tranz Rail's warning system at site K and subsequent response	0.99

	Min	Max
Probability of an accident involving one or more fatalities GIVEN damage to Rail Bridge	**0.005**	**0.01**

Site H Tangiwai Memorial

		Day visitors		Overnight campers	
		Busy	Quiet	Not winter	Winter
Proportion of year		0.30	0.70	0.67	0.33
Proportion of time Memorial is occupied	Low	0.20	0.05	0.03	0.00
	High	0.60	0.20	0.30	0.00
Proportion of hours that are daytime		0.67	0.50		
Proportion of day per stop				0.50	0.50
Probability of an accident involving one or more fatalities GIVEN damage to Memorial carpark	**Min**	**0.04**	**0.02**	**0.01**	**0.00**
	Max	**0.12**	**0.07**	**0.10**	**0.00**

Table 7: Risk to Road Users

Given Asset Damage (i.e. lahar has reached road & rendered condition hazardous), but WITHOUT ERLAWS & response

Road Users			Site A - SH1 Waikato Stream Bridge	Site E - SH1 Waikato Stream Culvert	Site G - SH1 Aqueduct	Site H - SH49 Tangiwai Road Bridge	Site J - Strachan's Bridge	Site L - Marae Bridge	Other downstream locations
a) Vehicles trapped by the lahar									
Vehicles/hour (both directions)			200	200	200	100	1	1	1
Length of at-risk area (km)			0.1	0.1	0.5	0.2	0.2	0.2	1
Average vehicle speed (km/h)			60	60	80	80	50	50	50
Average number of vehicles trapped, N_a			0.333	0.333	1.250	0.250	0.004	0.004	0.020
Average number of vehicles trapped, N_a			**0.1-0.5**	**0.1-0.5**	**> 1**	**0.1-0.5**	**< 0.01**	**< 0.01**	**.01-.05**
Probability of 1 or more vehicles involved		Low	0.1	0.1	0.5	0.1	0.0001	0.0001	0.01
		High	0.5	0.5	0.8	0.5	0.01	0.01	0.05
Probability of fatalities if vehicles involved		Low	0.5	0.2	0.1	0.5	0.5	0.5	0.5
		High	0.9	0.5	0.3	0.9	0.9	0.9	0.9
Probability of 1 or more fatalities GIVEN lahar		**Low**	**0.05**	**0.02**	**0.05**	**0.05**	**0.00005**	**0.00005**	**0.005**
		High	**0.45**	**0.25**	**0.24**	**0.45**	**0.009**	**0.009**	**0.045**
b) People driving into lahar (or damaged road)									
Quality of view of road		Direction 1	H	H	H	H	M	M	M
		Direction 2	H	H	H	M	M	M	M
Proportion of time w. good visibility		0.5							
Proportion of time w. bad visibility		0.5							
Probability of first vehicle driving into lahar	Good Visibility	Low	0.1	0.05	0.05	0.1	0.05	0.05	0.05
		High	0.2	0.1	0.1	0.2	0.1	0.1	0.1
	Bad Visibility	Low	0.2	0.2	0.2	0.2	0.1	0.1	0.2
		High	0.5	0.5	0.5	0.5	0.25	0.25	0.5
	Overall	Low	0.15	0.13	0.13	0.15	0.08	0.08	0.13
		High	0.35	0.30	0.30	0.35	0.18	0.18	0.30
Probability of fatalities if vehicles involved (Same as for a)		Low	0.5	0.2	0.1	0.5	0.5	0.5	0.2
		High	0.9	0.5	0.3	0.9	0.9	0.9	0.5
Probability of 1 or more fatalities in first vehicle GIVEN lahar		**Low**	**0.08**	**0.03**	**0.01**	**0.08**	**0.04**	**0.04**	**0.03**
		High	**0.32**	**0.15**	**0.09**	**0.32**	**0.16**	**0.16**	**0.15**
OVERALL Probability of 1 or more fatalities GIVEN asset damage		**Low**	**0.12**	**0.04**	**0.06**	**0.12**	**0.04**	**0.04**	**0.03**
		High	**0.62**	**0.36**	**0.31**	**0.62**	**0.17**	**0.17**	**0.19**

Note: For accidents on SH1 and SH49 there is a further conditional probability, possibly of the order of 1%, that the vehicle involved could be a bus or coach carrying some 10's of people, rather than a car or van with a small number of occupants.

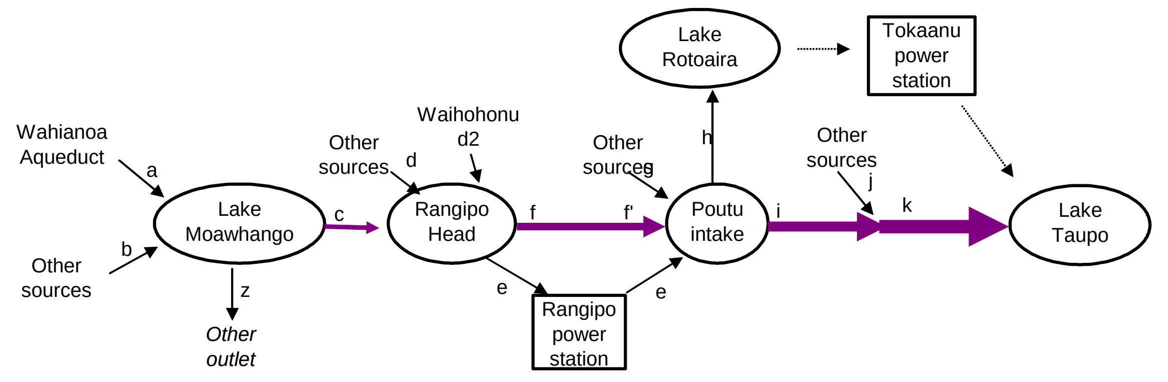
7.4 People in the Tongariro River

The risks associated with lahar flows into the Tongariro River, and Genesis Power's response to the threat of such flows, are discussed in Appendix 4.

Genesis Power Limited operates the Tongariro Power Development (TPD) under a strict set of environmental rules, as required by the Resource Management Act 1991. These rules dictate among other things when water is able to be diverted. Genesis is presently in the process of renewing resource consents to continue to operate the TPD for the next 35 years. These consents include conditions specifically related to the prevention of contaminated material from entering Lake Rotoaira and Lake Moawhango during volcanic events (e.g. eruptions and lahars).

A schematic of the Tongariro River, showing power generation assets and the lower regions where people are potentially at risk from sudden increases in river flows, is shown in Figure 15 (typical flows at the lettered points, and the effects on them of various actions to manage potential lahars, are discussed in Appendix 4). The lower Tongariro River (marked "*k*" in the figure) is extensively used for fishing, and on an average day will contain anything from a handful to several dozen fishermen

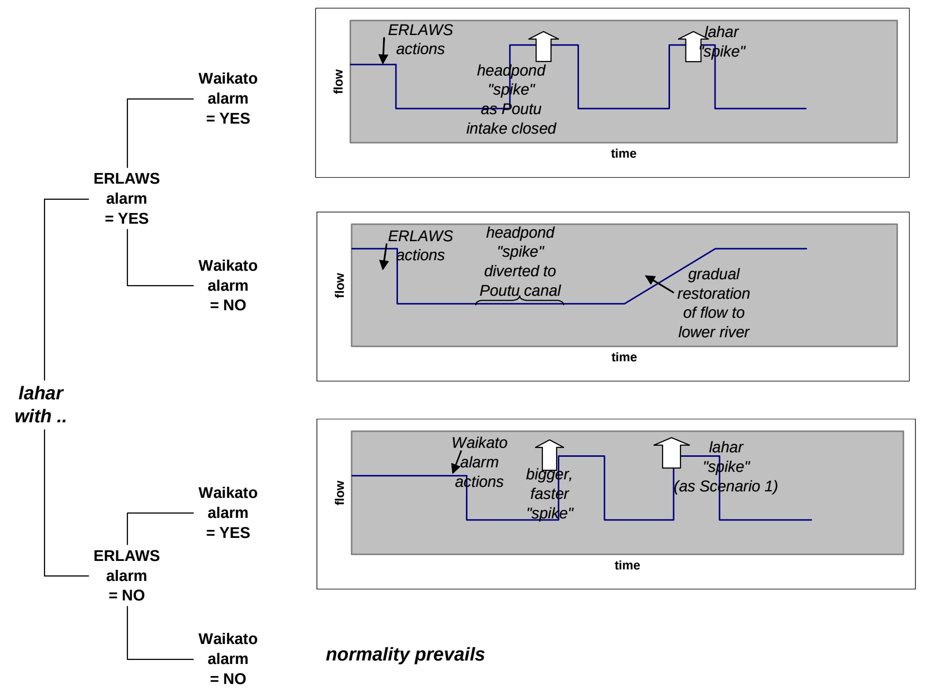
Figure 15: Tongariro Catchment Power Generation - Schematic



immersed to their waists or deeper in the area around Turangi. Less frequent rafting parties use the stretch labelled “*i*” in Figure 15. Rafting parties a) account for much lower occupancy of the river, and b) are much less at risk from sudden flow changes than fishermen, so the focus in this assessment is on the fishermen, who are considered to represent the group most at risk.

The flow scenarios in the lower river associated with Genesis’ response to ERLAWS and to the Waikato Stream alarms, and with a “*spike*” of lahar material entering the river via the Waikato Stream, are illustrated in Figure 16.

Figure 16: Lower River Flow (schematic) under various lahar ingress scenarios (not to scale)



The first and most obvious source of risk associated with lahars is that of sudden increases in flow associated with lahar material entering the river. Based on the discussion of bund performance in Section 4, the assessment reached here is that any such flows associated with a dam collapse lahar would be of order a few cubic metres per second, or maybe a few tens of cubic metres per second at the very most. Such flows are well within the normal spread of sudden flow changes routinely experienced in the river, and are not considered to pose additional hazards to fishermen. An important note to be added here is that this conclusion would NOT apply to some other sorts of lahars, for example such as that which flowed down the Mangatoetoenui Stream in 1975, and which in 1995 led to large deposits of lahar material at the mouth of the Tongariro River in Lake Taupo.

The second potential hazard is associated with Genesis’ response to lahar alarms. The 1995 eruptions led to relatively small lahars and volcanic ash entering the Tongariro River. The volcanic ash acted almost as a grinding paste in Rangipo Power Station, causing some $7million of damage and losing of order $10m value of electricity generation over the months required for repairs. There is thus a very strong commercial incentive to take action to protect the power generation assets, and Rangipo Power Station in particular.

Rangipo Power Station would be seriously affected if either a) lahar material entered the power station, or b) lahar material settled in the headpond above the power station. To prevent (a), Genesis' strategy is to close down the power station immediately ERLAWS detects any lahar on the eastern side of Mt Ruapehu. To prevent (b), Genesis need to drain down the headpond before any lahar material arrives. To avoid doing this suddenly, their policy is to begin draining down at a manageable level (about 40 m^3/second) as soon as an ERLAWS alarm is received. If an alarm is then received from the Waikato Stream (telling them that lahar material will be arriving at the Tongariro River shortly) then the policy is to open the head pond sluices and drain down as rapidly as possible. In tandem, the Poutu Canal, which would be used to manage the steady draining down of the head pond without large flow fluctuations in the lower Tongariro River, would be closed to prevent ingress of lahar material to Lake Rotoaira.
There are thus three potential sources of sudden flow fluctuations in the lower Tongariro River associated with these Genesis responses (all of these apply to "*normal*" river conditions, rather than when the river is already in flood):

(a) Following an ERLAWS alarm; lower river flows will drop when Rangipo Power Station is closed, then at some future point be raised again as normality is restored. This is not considered to represent an abnormal hazard beyond the normal span of river flow fluctuations which Genesis have to manage, and is not considered further here.

(b) Following the Waikato Stream alarm, Poutu Canal gate will be closed thereby allowing the increased flow resulting from the opening of the Rangipo dam sluice gates to pass through Poutu Intake and into the lower Tongariro River, thereby increasing water levels in the lower Tongartiro River by up to 0.4m (~40 m^3/second). The actual risk this represents is uncertain. Some people argue that the sudden surge in flow would be much attenuated by the time the flow reached the lower river, and would in any case be within the span of things most fishermen are used to dealing with. Others argue that a sudden increase of this order would wash away a good proportion of fishermen, and expose all but the stronger swimmers to a very serious fatality risk.

(c) If there is still a significant quantity of water in the head pond at the time the Waikato Stream alarm is raised, then this will be flushed rapidly down the river, causing a corresponding sudden flow increase in the lower river some time later.

The risk of a fatal accident is considered to be effectively zero for lahar ingress and ERLAWS response scenarios associated with the dam collapse lahar. The risk of a fatal accident, GIVEN that the Waikato Stream lahar alarm is triggered by the lahar (Note – as discussed in Section 4 this is considered unlikely in view of the assessed high effectiveness of the bund in preventing lahar material reaching the Waikato Stream), is assessed as:

Proportion of time there is someone in the lower river,

x Probability that post-Waikato alarm flows would cause a fatal accident.

The former parameter is estimated at about 14/24 (ie there is virtually always someone in the river during daylight hours and at dawn/dusk). The latter is estimated as somewhere in the range 0.1 to 0.5. The resulting assessed conditional probability of a fatal accident, GIVEN the Waikato Stream alarm is raised and Genesis' current procedures are followed as written, is in the range of 0.05 to 0.3.

The significant uncertainty (and thus risk) associated with this hazard could be reduced by some mix of:

(a) further work to assess the actual likely flows in the lower river resulting from lahar response actions, and the hazard they represent, and

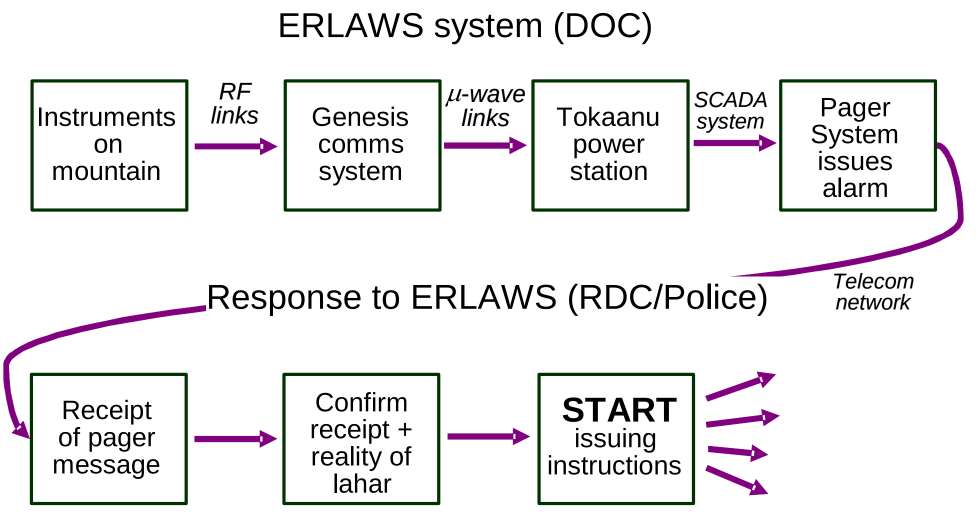
(b) relatively minor modifications to Genesis' procedures to ensure an appropriate balance between risks to, and measure to protect, assets, the environment and lives.

8 Warning and Response Systems

With the exception of Tranz Rail’s independent lahar warning system, warning of the impending lahar is based on the Eastern Ruapehu Lahar Alarm and Warning System (EARLAWS). This provides pager alarms of a lahar at the top of the mountain to RDC, Ohakune Police, Transit, and the DoC duty scientist. The response plan, including a telephone cascade of warnings to local people and organisations, and the summoning of teams of people to various locations to make them safe, would be put into effect by RDC and Ohakune Police.

The overall process by which the response is initiated is illustrated in Figure 17. The important point to be made at the outset is that BOTH the warning AND the response have to work for this process to be effective. Either failing would mean the purpose of the plan was not achieved.

Figure 17: Warning & Response First Stages



Ruapehu Lahar Residual Risk Assessment: Chart 8
Tony Taig, TTAC Ltd, June 2002

Providing the alarm (via ERLAWS), and responding to it are discussed separately in Section 8.1 and 8.2. An assessment of the likely reliability and effectiveness of the response for various locations where people might be at risk is then provided as Section 8.3.

8.1 Providing the Alarm – ERLAWS (top row, Fig 17)

ERLAWS comprises three monitoring sites as shown in Figure 18, linked through a network of RF links to the Genesis telecommunications system at Tukino Hut or Rangipo surge chamber, whence signals are carried to DoC computers housed at Tokaanu Power Station. The system provides an automated pager alarm, currently to one individual each at RDC, Ohakune Police, Transit, and the DoC duty scientist.

ERLAWS is based on a system devised for Mt Saint Helens in the USA, which has operated successfully for several years (though has not been tested in anger). It uses simple and reliable instruments on the mountain, and takes advantage of the high reliability telecommunications infrastructure being installed by Genesis to link monitoring sites part way up the mountain down to Tokaanu. The system has been subjected to extensive design review, which included the involvement of a US expert involved in the Mt St Helens system. It has not been designed or reviewed prior to this assessment by people or organisations routinely involved in safety-critical electronic, communications and computer systems.

The system status communicated by pager would be "*yellow*" (possible lahar) on receipt of any signal from a single sensor threshold being exceeded. A "*red alert*" (lahar probable) is triggered when any two thresholds are exceeded, or when the duty scientist confirms the alarm (eg when a second site had indicated the presence of a lahar). It is assumed here that the "*red*" status would be adopted 10 minutes after the lahar pour began from the crater.

No detailed reliability assessment of ERLAWS has been carried out for this study, but it is possible to make a useful high level assessment on the basis of the key functions ERLAWS must perform in order to provide a timely alarm. These are:

(a) detecting the lahar via instruments up on the mountain

(b) transmitting signals from those instruments

(c) delivering those signals via RF links to the Genesis communications system

(d) delivering the signals via the Genesis system to Tokaanu

(e) interpreting the signals and raising an alarm at Tokaanu

(f) transmitting that alarm from Tokaanu via the pager system, and

(g) delivering the alarm signals to the pagers via normal telephony links.

The performance of the instruments up on the mountain (ie reliability of achieving functions a and b) has not been considered here; they are assumed to be sufficiently straightforward, and there are enough of them in different locations, that the chance of not providing any signal of an impending lahar is relatively small.

Transmission of signals from there on has been discussed with Genesis' telecommunications engineer at Tokaanu (a note of the discussion is provided as Appendix 7). The conclusion formed before that discussion and verified during it was that getting signals from Tukino Hut or Rangipo surge chamber to Tokaanu and thence to the pagers is likely to be relatively reliable (particularly since there is a back-up via the Genesis operator at Tokaanu to getting signals out to the rest of the world, via a telecommunications link independent of the New Zealand Telecom system if necessary).

The weak link in the ERLAWS system in terms of meeting the requirement to raise the alarm (responding to it is discussed later) is almost certainly the RF linkages up on the mountain. The steps involved in getting those signals from the sensors into the Genesis communications system are:

	Site 1 sensors	**Site 2 sensors**	**Site 3 sensors**
	AFM (crater hut)	AFM (NZAC hut)	AFM (Tukino skifield)
	RF link 1	RF link 2	RF link 3
	Dome repeater	Taiping repeater	
	RF link 4	RF link 5	
	Taiping repeater		
	RF link 5		
GENESIS system:	Tukino Hut	Tukino Hut	Rangipo surge chamber

Without considering any other elements of the system, the RF links provide a limit on the availability and reliability achievable by the whole system. A single RF link operating in the harsh environment of Mt Ruapehu ought not to be assumed to be more than 98% reliable (that is, to be working and available for more than 98% of the time – reference Appendix 7). On this basis the limit to the availability that could be assumed for the whole system would be approximately:

94% (Site 1)

96% (Site 2)

98% (Site 3)

These estimates are considered more appropriate for the Ruapehu environment than the "*ERLAWS RF links availability should be between 99.3 and 99.9%*" judgment offered by the US participant in the ERLAWS design review held in October 2001. All the other elements in the system can only add to unavailability, they cannot improve it.

Site 3 is the only site currently operational, and is delivering better than 98% availability at present. There is an important issue here though of the difference between observed availability over a relatively short period of time, and the average availability to be expected over longer periods. Unavailability is the sum for all possible failure modes of the product of:

- how often each failure mode occurs, and
- how long it lasts before the system can be fixed.

Over a short period of time, only a sub-set of the failure modes can be expected to be observed. In most systems, less frequent failure modes with longer times to repair the system make a significant contribution to unavailability. As the period of observation lengthens, the observed unavailability will gradually approach the long-term expected average availability. In the shorter term, the contribution of less frequent failure modes to unavailability can only be revealed by a more comprehensive, first principles approach to the identification of potential failure modes and assessment of the time it would take to repair them (using techniques such as failure modes, effects and criticality analysis).

On the basis of the assessed limits to availability associated with the RF links, and the current good performance of Site 3, the overall assessed ERLAWS system performance parameters in the "*as is today*" state carried forward in this risk assessment are:

? availability of whole system (sites 1 and 2 not yet fully commissioned)

95% assumed long-term availability of site 3
(based on good observed availability and unknown unrevealed
failure modes' contribution to unavailability).

Once the other sites and the Genesis microwave communication system are fully commissioned, and with good reliability management (including both monitoring and response to revealed faults, and first principles assessment to deal with failure modes not yet experienced), it should be realistically achievable to demonstrate performance of the order of:

90%	availability of whole system, and
98%	availability of at least one alarm (Site 3 being the most reliable).

An important factor in determining the reliability of the alarm obtained from ERLAWS will be the policy adopted as to how unavailability of specific items of equipment will be treated. To minimise the chance of missing a real lahar event, unavailability of equipment could be treated as equivalent to an alarm. In practice though, this would lead to potentially very large numbers of false alarms. False alarms are a serious concern, as they would:

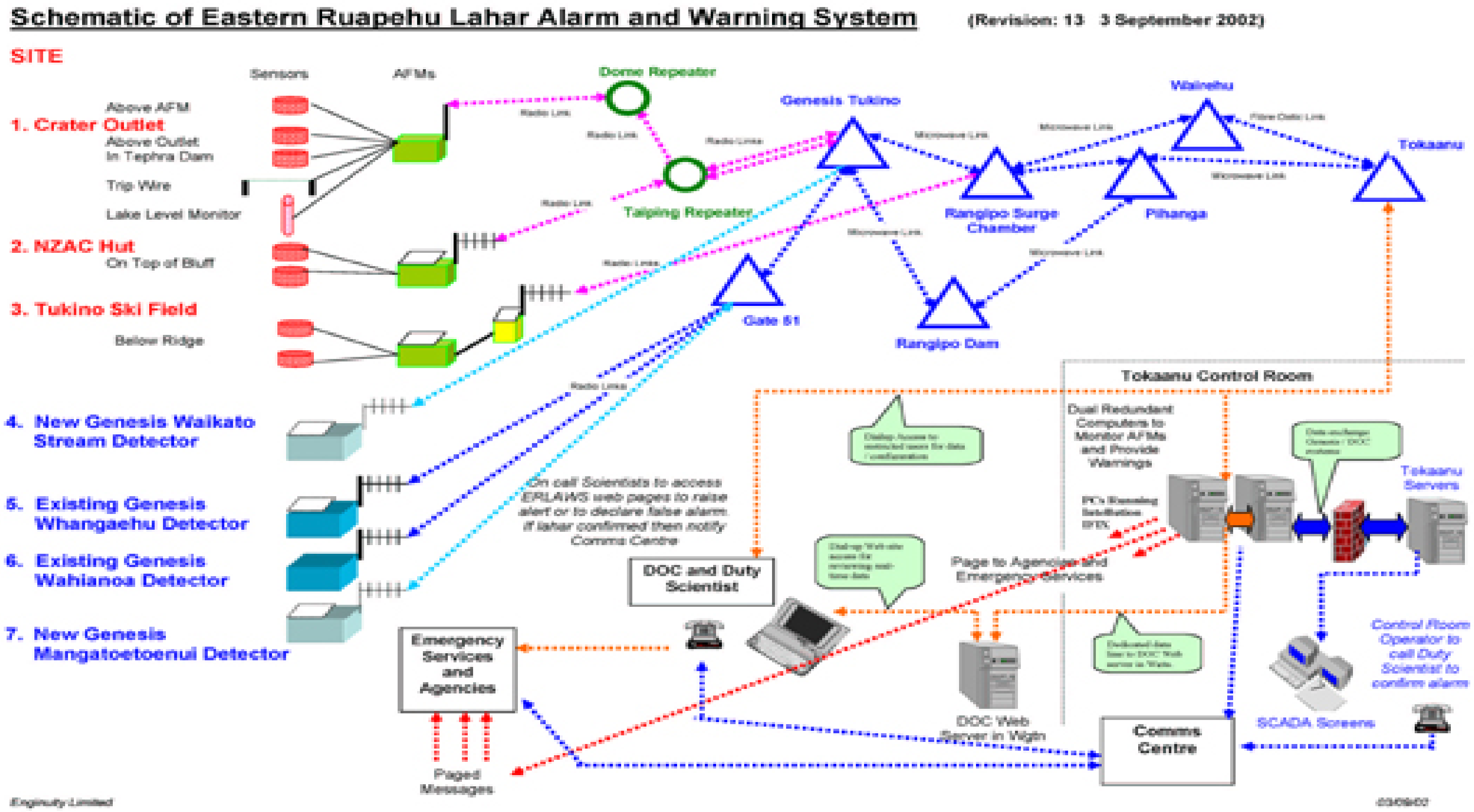
(a) diminish the vigilance and commitment of response teams

(b) have significant local economic impacts through interruption of local people's activity and of traffic through the area, and

(c) trigger Genesis actions in the Tongariro River that lead to significant loss of generation and a small additional hazard (within the range of river flow variations normally managed by Genesis) to people in the lower Tongariro River.

The risk (ie expected frequency) of false alarms should thus be an important factor in decisions regarding the operational arrangements for ERLAWS that will maximise its reliability.

Figure 18: Schematic of Eastern Ruapehu Lahar Alarm and Warning System
(DoC, Revision: 13 3 September 2002)



8.2 Responding to the Alarm – Local Response Plans

History is full of examples of situations in which a highly reliable alarm gave warning of an event, but the planned response failed for reasons associated with the unreliability or ineffectiveness of the response to the alarm. This is a well recognised possibility by all involved in responding to ERLAWS.

On the other hand, there has been a quite widespread presumption among many of those consulted in the course of this work that "*We will know when the lahar is coming, so of course we will be in a high state of readiness*". While this is true in terms of planning and preparation, it overlooks the possibility that we could be living for months or years in a state of "*The lahar could happen at any time*". The large uncertainty as to when the lahar will happen precludes many strategies for improving effectiveness of response which are routinely taken when an event is forecast for a particular time or date (eg stationing someone at the snow gates on the Desert Road when snow is forecast).

There is no response plan currently in place to address risks to users of the lower Tongariro River, though it is understood that Taupo District Council are currently considering such a plan. The absence of such a plan places significant constraints on Genesis' ability to protect their assets from lahars. More generally, it appears odd that so heavily used a river, subject to a wide variety of natural phenomena that could give rise to relatively sudden flow changes in its lower reaches, has no arrangements in place to warn and evacuate river users in the event of sudden floods. Genesis can and do manage those elements of this risk which are within their capacity to manage, but that is only a proportion of the types of hazardous event in question.

The response plan for all the other areas close to Mt Ruapehu where people are at risk is being developed and coordinated by RDC, in close cooperation with Ohakune Police. A note of the discussion held with RDC and Ohakune Police in the course of this assessment is provided as Appendix 8. Regional councils, and Wanganui District Council for lower parts of the Whangaehu River, are also actively involved in developing response plans.

The current RDC response plan as written is predicated on assembling a response team at Ohakune Fire Station once the ERLAWS pager alarms have been received. Ohakune Police will then issue instructions to groups of local volunteer fire fighters and police (and possibly the army at Waiouru) to attend and make safe various sites such as Tangiwai, parts of SH1, and locations downstream of Tangiwai. RDC will establish a communications centre and carry out a "*cascade*" of telephone warnings to people and businesses who live or work near the path of the lahar, to advise them it is coming.

RDC and Ohakune Police recognise the limitations inherent in this plan, and RDC have recently employed a project manager to lead the development of a more robust plan, who is now in place and making rapid progress. In discussion, it is clear that the ACTUAL plan that would be followed is not reliant on assembling a team in Ohakune, but would be led by telephone by the recipients of the pager alarms. The steps that would be followed are as shown in Figure 17 above, with a check that each of the recipients has received the alarm being followed by a call to the DoC duty scientist (also a single individual) to confirm that the lahar is "*for real*" and not a false alarm.

Obvious weaknesses in these response arrangements (these are a mix of the "*as written*" and "*as discussed*" versions) include:

(a) reliance on six individuals (one from RDC, one from Ohakune, Waiouru and Turangi Police one from DOC and the GNS Duty scientist) for response to the pager alarm

(b) reliance on the functioning of the telephone system in what is not a high reliability telecoms part of New Zealand

(c) the time involved in confirming receipt of the alarm, and that the alarm is real and not false

(d) the possibility that phone lines will quickly become clogged by incoming calls, whether from the range of people involved in the response or from others (eg the media), and

(e) the reliance placed on local volunteers for significant portions of the "*field*" parts of the activity.

All the people involved appear very capable and very committed to responding quickly to ERLAWS. The weaknesses are not to do with their competence and commitment, though, but with the inherent limitations of how reliably one person can respond to an alarm which might come at any time over a period of months or years. People have to sleep. Pager batteries have to be changed. People have other inevitable work and domestic crises to deal with. No high integrity system would rely on single individuals for such functions. Genesis and Tranz Rail, for example, have 365 days a year, 24 hours a day permanently manned control centres where staff work shifts to ensure that whoever is on duty is always fresh and able to devote their full attention to any crisis.

On the basis of the **written** RDC plan as it currently stands, this assessment is that there is almost no possibility of a successful response to the ERLAWS alarm within half an hour of its transmission via the pager system and (being generous) perhaps a 50% probability of a successful response being initiated within an hour.

Addressing the significant weaknesses identified above will have significant implications for people, systems and costs. Given the short time available for response, it is inevitable that any "*field*" response teams will have to be made up of people already in the area. It appears sub-optimal, though, to presume that the entirety of effort on the initial part of the response (receipt of pager alarms, confirmation of receipt, confirmation the lahar is real, issuing instructions to field teams), or indeed on the operational phase of response coordination (when large volumes of telephone calls may be being simultaneously made and received) MUST come from locations close to Mt Ruapehu.

It seems sensible for the "*first string*" option to be managed locally, but achieving very high reliability purely with local resources could involve very large costs in setting up call centres, reliable communication links, training and paying teams of people to share the burden of the response role (etc etc). The contrast is very notable between the circumstance of RDC and Ohakune Police with, say, Tranz Rail in their Wellington communication centre:

Ruapehu DC/Ohakune Police	Tranz Rail Wellington CC
No 24 hour manning	365 x 24 hours/year manned control centre
Single individuals relied on 365x24 hours	Three staff on duty at any one time, in shifts so always fresh
No back-up to public telecom systems	Own high reliability fibre optic system in addition to public telephony
Situated in Mt Ruapehu area (subject to harsh environmental conditions around the mountain)	Situated remotely (unlikely to be affected by conditions in Mt Ruapehu area)
Do not regularly issue telephone instructions to people to carry out safety-critical tasks in situations where ambiguity could lead to hazard	Do regularly issue and confirm responses to such instructions

This is not for a moment to argue that Tranz Rail or some other such organisation should be dragooned into providing a response service to civil emergencies. But the availability of such organisations, and the cost of replicating their advantages in the Mt Ruapehu environment, strongly suggests that using some existing organisation and systems to provide back-up to those in the front line of responding to the lahar event might be significantly more reliable, and less costly, than trying to replicate such functions locally.

Making response plans work reliably, based on large numbers of people doing things in a coherent way and confirming they have been done over a public telephone network, is inherently very difficult. With the significant weaknesses identified above addressed, it is considered that much better reliabilities could be achieved, perhaps of order 90% success in responding (ie issuing instructions to field teams to mobilise) within half an hour of receipt of the pager alarm, and 95%+ success in responding within an hour. In the former case, there is assumed to be at least a 10 minute interval from receipt of the ERLAWS "*red*" alarm to issuing of the first instructions to field teams to mobilise, to allow for the steps of confirming alarm receipt, and confirming lahar status.

We now move on to consider the implications of these response issues in terms of the time available for response at various locations where people are at risk, and the associated overall reliabilities of warning and response. In each case the reliability of a successful response is considered a) for response plans and related arrangements as they currently stand, and b) for what is considered realistically achievable, if good practice plans and related arrangements are put in place.

8.3 Locations at Risk: Reliability of Warning and Response

Times available between provision of an ERLAWS alarm and arrival of the lahar at the locations where people are potentially at risk, based on the lower times shown in Figure 2 (ie for lahars towards the larger end of the spectrum of possibilities), are as follows:

Location	**Time (minutes) from**		
	1st pour from Crater	**ERLAWS red alarm**	**1st instruction to field teams**
SH1 – Waikato Stream crossings	40	30	20
SH1 – Wahianoa Aqueduct	60	50	40
Tangiwai	90	80	70
Strachan's Bridge	110	100	90
Marae Bridge	130	120	110

These times are now compared with what would be needed for an effective response at each location where people are at risk.

SH1 – Waikato Stream or Wahianoa Aqueduct: Protection here involves preventing traffic gaining access to SH1 via variable message signs and snow gate closures, and such traffic as is already on the road getting out of the way. The time to clear the road should thus be approximately:

- time to closure of snow gates (taken as the more reliable closure mechanism), plus
- time for vehicles already past the gates to drive past the hazard sites

Transit's experience (see Appendix 3) is that the average time taken to close the snow gates is about 45 minutes from issuing an instruction to the contractor to do so. Traffic has around 30 km to drive to get from the farther snow gate to the hazard site, which might take, say, 20 minutes at best. Total time to effect a response, assuming an instruction to close the snow gates is issued instantaneously on receipt of the ERLAWS pager alarm, is thus likely to be around an hour or more. For the purposes of this assessment there is assumed to be no chance, with current arrangements, of a response aimed at protecting traffic on SH1 being effective.

This is not to say the snow gate closure is not a sensible precautionary measure. It a) prevents access onto potentially damaged roads after the path of the lahar, and b) recognises the possibility that, if the ERLAWS alarm is received very early, and police are in the vicinity and able to respond, the snow gates might be closed and vehicular access might be prevented within a few minutes of the start of the lahar, in which case there is a good chance that the number of vehicles at risk would be reduced. In recognition of this latter possibility, the realistically achievable assessment of the probability of failing to prevent vehicles being caught in the path of the lahar or of driving into it on SH1, GIVEN that the highway has been damaged by the lahar, is taken as 0.8.

Tangiwai: There are three important functions to be achieved by the response plan in relation at Tangiwai:

(a) to check and evacuate the Memorial site

(b) to close off road access, and

(c) to provide supplementary warning to Tranz Rail of the lahar, and to confirm the site status.

The first two roles each require response personnel to get to Tangiwai well before the lahar does so. The people involved would be coming from Ohakune and/or Waiouru, which are each within 10-20 km drive of Tangiwai via SH49. Once mobilised, the travel time should thus be no more than 10-15 minutes. Another 15-20 minutes needs to be added for mobilisation time, from receipt of a telephone instruction from Ohakune Police, through to being in a vehicle and setting off for the site (to allow for getting dressed, getting vehicle out, loaded and started etc). With arrangements as they are currently (ie before the planned improvements to the RDC response plan), it is considered that there is at best an 80% chance (ie 20% chance of failure) of field teams getting to Tangiwai in time to be effective within the 70 minutes or so available from receipt of the police instruction to mobilise. A realistically achievable success probability, with highly prepared field teams and vehicles and slick, well rehearsed response procedures, is considered to be over 90% (95% has been assumed for this assessment).

As regards overnight campers at the Memorial site, successful evacuation depends entirely on getting response teams to the site. With current arrangements, the assessed chance of failing to evacuate such campers is thus taken as 20%. For a realistically achievable assessment it has been assumed that the Memorial, the car park and the toilet facilities would all be effectively closed off to access (ideally relocated elsewhere to remove the incentive to get in and visit or use them), thus eliminating the possibility of response failure here.

As regards closing access to the SH49 road bridge, Transit are installing automated gates which would be activated an appropriate time after receipt of the ERLAWS alarm (to allow people time to get out of the way). These gates are not yet procured, installed or commissioned. Their reliability once commissioned is assumed to be better than 90%, and a failure probability of 5% has been assumed for this assessment (ie success probability of 95%). Given a successful ERLAWS alarm, the operation of the gates would be largely independent of the response teams getting to site (noting the possibility of extreme weather providing a circumstance in which neither the gates could open nor the response teams reach the site – but if the response teams were unable to reach the site it is unlikely anyone else would be traveling there either). The realistically achievable combined probability of failure to prevent access to the SH49 road bridge would thus be 0.05 x 0.05 or 0.0025 (0.25%), once the Transit gates and a good quality response plan are in place.

As regards the Tangiwai Rail Bridge, Tranz Rail have very reliable ways to stop trains reaching the bridge, but their system is limited by the reliability of getting a warning of the lahar to the control centre in Wellington. An important function of the response plan should therefore be to get such a warning to Tranz Rail at the earliest opportunity. This importance is not reflected in the current response plan, where Tranz Rail comes a good way down a long list of parties with whom to liaise. It should be a high priority to warn Tranz Rail of the lahar, and for response teams at site to advise Tranz Rail if there are any trains in the area (and as a secondary priority, once all else is made safe, for them or central response coordinators to liaise with Tranz Rail to confirm the status of the site).

With the current response arrangements, there is considered to be around a 20% chance of failing to provide such a supplementary warning to Tranz Rail. With a modest change to the arrangements (eg to provide Tranz Rail with an ERLAWS pager, or ensure they receive early telephone advice of an ERLAWS alarm), it is considered that this could realistically be reduced to around a 1% failure probability. Tranz Rail's own response arrangements are of sufficiently high reliability that this improved warning success would feed directly through to improved system success at preventing trains being at risk.

Downstream Whangaeu Valley Locations: Strachan's Bridge and the Marae Bridge have been treated as at equivalent risk of failure of response success to Tangiwai, the extra lahar travel time being balanced by the need for extra time to reach it from Ohakune or Waiouru. This assumes that telephone warning to the local farm or to the Marae would not be an effective response, which is a clearly pessimistic assumption (tantamount to assuming that there is no chance that the next person who would have used the bridges receives a telephone message of warning). Given the possibility that residents are all out at the time of the ERLAWS telephone warning from RDC, or of visitors who cannot be reached by RDC, this seems the safest assumption for this assessment.

Locations further downstream have additional warning time, and it is considered that even with the response arrangements as they currently stand, this should be sufficient to enable a 90% success probability of getting response personnel to close roads and make sites safe, given that the ERLAWS alarm is received.

A success probability for response of 95% is considered realistically achievable for all of these locations downstream of Tangiwai, if a high quality response plan is put in place with all the issues identified in section 8.2 above addressed.

Summary

The probabilities of failure to provide a warning (via ERLAWS) and of failing to respond as intended, are summarised by location in Table 8 overleaf. The overall probability of failure is given by:

$$P_{\text{failure, overall}} = 1 - (1 - P_{\text{fail, warn}}) \times (1 - P_{\text{fail, respond}})$$

(for small probabilities of failure this effectively is the same as saying the likelihood of overall failure is the sum of the likelihoods of warning and of response failure).

Table 8: Warning and Response Failure – Summary

location	Current Situation …..			Realistically Achievable ….		
	Probability of failure to WARN	Probability of failure to RESPOND	Overall probability of failure	Probability of failure to WARN	Probability of failure to RESPOND	Overall probability of failure
SH1 – Waikato Stream Crossings	0.1	1	1	0.02	0.8	0.804
SH1 – Wahianoa Aqueduct area	0.1	1	1	0.02	0.8	0.804
Tangiwai – evacuate Memorial site	0.1	0.2	0.28	0.02	0.05	0.069
Tangiwai – prevent traffic over SH49 bridge	0.1	0.2	0.28	0.02	0.0025	0.02245
Tangiwai – warn Tranz Rail	0.1	0.2	0.28	0.02	0.01	0.0298
Strachan’s Bridge	0.1	0.2	0.28	0.02	0.05	0.069
Marae Bridge	0.1	0.2	0.28	0.02	0.05	0.069
Other downstream locations	0.1	0.1	0.28	0.02	0.05	0.069

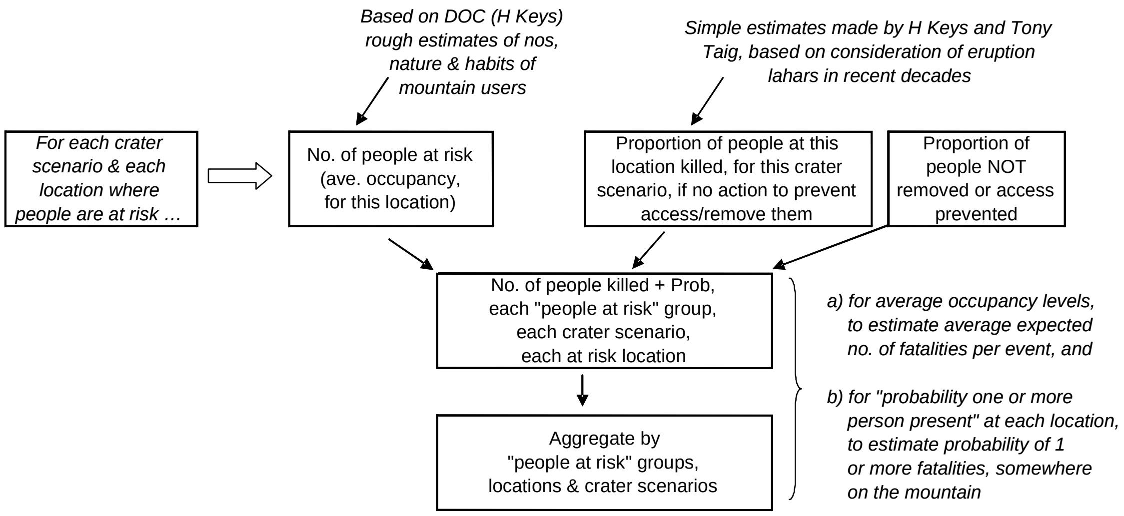
9 Risks on the Upper Mountain

An important group of people not so far considered in this assessment are those who visit and spend time on the upper parts of Mt Ruapehu for recreational, scientific and (when interesting events are impending) media purposes. These people are effectively the only people at risk from the relatively frequent eruption lahars experienced on Mt Ruapehu (ie for lahar scenarios E1 and E2 identified in Section 4 above). The primary purpose of this section is to present the basis on which risk to this group of people has been assessed for the dam collapse lahar. The secondary purpose has been to provide an assessment of risk associated with the eruption lahar scenarios E1 and E2, to provide a point of comparison with the overall safety impacts of the dam collapse lahar.

The assessment based here relies entirely on information as to the numbers and sorts of people who visit Mt Ruapehu, where they spend their time, and what risk would be involved for people at particular places in particular circumstances, which has been supplied by Harry Keys of DoC, whose assistance in developing this model and knowledge in providing it with data is gratefully acknowledged.

The basis of the assessment of risk for people on the upper parts of the mountain is shown in Figure 19 below:

Figure 19: Basis of Upper Mountain Risk Model



The groups of people considered, the factors (such as time of year) that affect how heavily the mountain is used, and where they spend their time on the upper mountain, are summarised in Figure 20. The occupancy levels, and various factors used to estimate proportions of time in critical locations (eg for skiers on the ski fields) are shown in Table 9. The synthesis of this information in terms of:

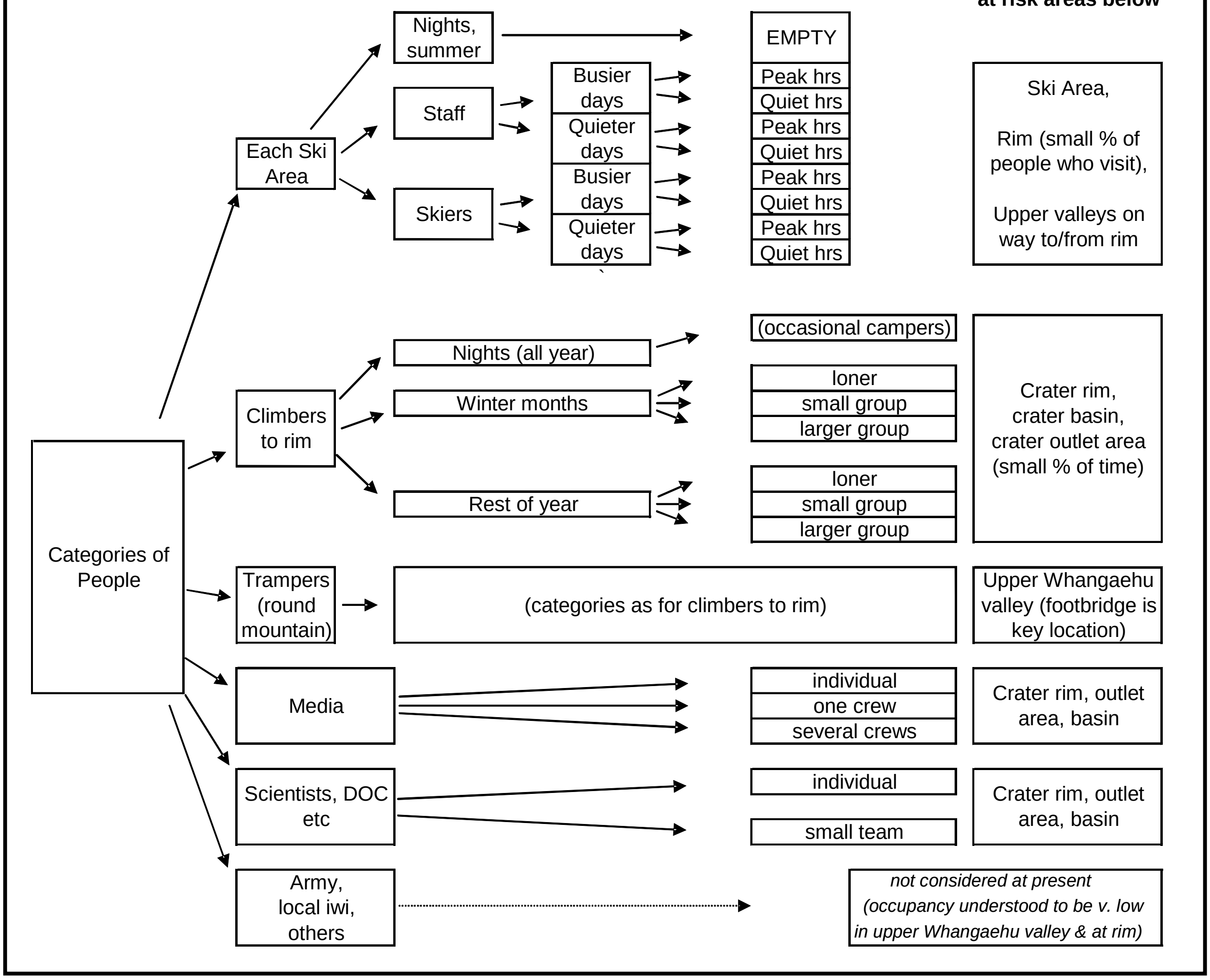
(a) where people, on average, spend their time on the mountain

(b) year-round average numbers of people present at each location, and

(c) year-round proportion of time one or more people are present at each location,

are shown in Tables 9(a) to 9(c) respectively.

Figure 20: Upper Mountain - People & Occupancy



The risk to people who are present at the critical locations considered (crater outlet, other parts of the crater rim, the crater basin, the upper Whangaehu Valley, the upper Whakapapa Valley and the Whakapapa and other ski fields) is presented in Table 10(a). This table was developed by consideration of the last eight major historic lahars, many of them related to eruptions, on Mt Ruapehu. For each such lahar, the risk that a person present at each location would have experienced (had they been there) was estimated based on knowledge of the extent and nature of the hazards involved. These historic lahar scenarios were then used as a basis for estimating the risk to hypothetical individuals at each location considered, under:

- the dam collapse lahar scenario (presents risk only to people at the crater outlet and in the upper Whangaehu Valley)
- an approximately 10 year return period eruption lahar scenario (presents risk primarily to people up around the crater rim area), and
- an approximately 20 year return period eruption lahar scenario, which presents significant risk at a wider range of locations (including, in particular, the Whakapapa ski field).

Table 11 shows the assumptions used as to the proportion of people who would NOT be prevented from accessing the relevant parts of the mountain, or would not be successfully evacuated given warning of an impending lahar (note – the warning times available are extremely short this near to the crater). The possibility of both “*blue skies*” eruptions and of events with forewarning is considered. Access prevention (eg by DoC posting signs on the mountain) is assumed to have some, limited effectiveness in reducing occupancy. Cessation of activity (eg Ruapehu Alpine Lifts ceasing guided rim walks) is assumed to be very effective. Warning and evacuation is assumed to have questionable effect given the short times available and previous experience in testing the response of skiers to warnings on the Whakapapa ski field[8].

These occupancy levels, fatality risks if present, and proportions of people not successfully got out of the way or prevented from access, are brought together to estimate the expected numbers of people killed and (for consistency with other parts of this assessment) the expected likelihood of one or more fatal accidents, GIVEN that the relevant lahar scenario has occurred, in Tables 12 and 13 respectively.

The simple conclusions of this part of the assessment are:

1. The risks on the upper mountain associated with the dam failure lahar are small in comparison with either the other (eruption) lahar scenarios, or the risks at other locations further down the mountain, and

2. The risks associated with the eruption lahars (the 20 year event in particular – roughly equivalent in scale to the 1975 event) are of similar order to the total risk to people associated with dam failure lahars.

The virtual impossibility of intervention after the event to mitigate these risks is also noted.

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[8] Private communication, D Johnston, Institute of Geological & Nuclear Sciences

Table 9: Occupancy: Input Data - Nos/Habits

Skiers

	Location	days open /yr	hrs open /day	hrs staff /day	Busy Days ……….. No/ yr	No skiers	No staff	Light Days …… No/ yr	No skiers	No staff	Of each day ………………………………… No. Busy hrs	Propn skiers (busy hrs)	Propn staff (busy hrs)	No. Quiet hrs (skiers)
	Whakapapa ski field	120	7	9	40	7500	300	80	1000	40	5	1	1	2
Ski Field Inputs	Turoa ski field	120	7	9	40	2000	100	80	500	15	5	1	1	2
	Tukino ski field	120	7	9	40	100	5	80	20	2	5	1	1	2

ALL Others

				Party size	No. trips /yr	Ave time @rim	Hrs/yr occupied	Prop Hrs/yr rim not occupied	Prop rim visits w. time @ outlet
	Climbers to rim (incl. RAL guided parties)	Nights (all year)	occasional groups	3	30	12	360		0.5
		Winter months	loner	1	20	2	40		0.2
			small group	3	20	2	40		0.2
Climbers			larger group	10	2	2	4	**0.881**	0.2
		Rest of year	loner	1	50	4	200		0.2
			small group	3	80	4	320		0.2
			larger group	10	75	1	75		0.1
	Trampers on round mountain track, crossing U. Whangaehu valley	Nights (all year)	(empty)			ave hrs @risk			
		Winter months	loner	1	30	0.166667	5		
			small group	3	20	0.166667	3.333333		
Trampers			larger group	10	10	0.166667	1.666667		
								0.989	
		Rest of year	loner	1	350	0.166667	58.33333		
			small group	3	150	0.166667	25		
			larger group	10	10	0.166667	1.666667		
	Media		individual	1	12	8	96		Note - land
Media			one crew	3	6	2	12	**0.987**	
			several crews	10	1	2	2		
	Scientists, DOC etc		individual	1	12	4	48		Visits will b
"Staff"								**0.984**	as high risk
			small team	3	24	4	96		(remote me

Table 9(a) Distribution of time spent across:

Who	Outlet	Crater Rim	Basin	U. Whangaehu (tootbridge)	U. Whakapapa	Whakapapa skil field	Other ski fields
Skiers-Whak		0.000395			0.00079	0.998815	
Skiers-Turoa		0.000236					0.999764
Skiers-Tukino		0.00023					0.99977
Climbers	0.05	0.4	0.45	0.05	0.05		
Trampers				1			
Media	0.5	0.5					
Scientists	0.1	0.2					

Table 9(b) (transfers to Results Sheet)

Collation of Occupancy Tables: Average Occupancy							
Who	**Year-round average no. of people present at …..**						
	Outlet	**Crater Rim**	**Basin**	**U. Whangaehu (tootbridge)**	**U. Whakapapa**	**Whakapapa skil field**	**Other ski fields**
Skiers- Whak	0.0000	0.1084	0.0000	0.0000	0.2169	274.1769	0.0000
Skiers- other	0.0000	0.0215	0.0000	0.0000	0.0000	0.0000	91.2105
Climbers	0.0182	0.1457	0.1639	0.0182	0.0182	0.0000	0.0000
Trampers	0.0000	0.0000	0.0000	0.0207	0.0000	0.0000	0.0000
Media	0.0087	0.0087	0.0000	0.0000	0.0000	0.0000	0.0000
Scientists	0.0038	0.0077	0.0268	0.0000	0.0000	0.0000	0.0000

Table 9(c) (transfers to Results Sheet)

Collation of Occupancy Tables: Proportion of time someone there							
Who	**Year-round proportion of time 1+ people present at …..**						
	Outlet	**Crater Rim**	**Basin**	**U. Whangaehu (tootbridge)**	**U. Whakapapa**	**Whakapapa skil field**	**Other ski fields**
Skiers- Whak		0.0701			0.0881	0.1233	
Skiers- other		0.0613					0.1233
Climbers	0.0041	0.1186	0.1186	0.0041	0.0041	0.0000	0.0000
Trampers	0.0000	0.0000	0.0000	0.0108	0.0000	0.0000	0.0000
Media	0.0063	0.0063	0.0000	0.0000	0.0000	0.0000	0.0000
Scientists	0.0013	0.0025	0.0088	0.0000	0.0000	0.0000	0.0000
OVERALL (MAX)	**0.0116**	**0.2588**	**0.1274**	**0.0149**	**0.0922**	**0.1233**	**0.1233**

Table 10(a): Characteristics of Historic Lahars

Event	Eruption & lahar characteristics:							Conditional Fatality Risk for anyone present at									Notes
Date	**Single event or episode?**	**Houghton**	**Sherburn**	**Otway**	**Max lahar, m^3**	**Direction of largest lahar**	**Warning?**	**Return Period**	**Outlet**	**Crater Rim**	**Basin**	**U. Whangaehu (footbridge)**	**Footbridge destroyed?**	**U. Whakapap**	**Whakapapa ski field**	**Other ski fields**	***Conditional fatality risk for individuals present corresponds to proportion of people killed. These estimates were made by Harry Keys & Tony Taig in discussion on 21 June 2002, of which this table is the record***
1988	S	3	3	M	13200	Whang	N	5-9	1	0.5	0.3	0.01	N	0	0	0	
1977	S	3	3	M	130000	Whang	N	5-9	1	0.5	0.3	0.1	?	0	0	0	not sure whether footbridge reinstated post-1975
1971	E	4	4	M	72000	Whang	Y	9	1	0.5	0.2	<.1	?N	0	0	0	not sure whether footbridge was there
1968	E	4		M	729000	Whang	Y	9	1	.8-.9	.3-.5	1	Y	<.1	0	0	
1995	E	5	5	L	2000000?	Whang	Y	18	1	1	0.5	1	Y	.5-1	0.01	0	
1975	S	5	5	L	1800000	Whak	N	18	1	1	1	1	Y	.2-.5	0.03	0	0.9m m3 lahar to Whakapapaiti & -nui; 0.6m to Mangaturuturu; baby towards Turoa
1969	S	5		L	117000	Whak	N	18	1	0.9	0.5	<.1	?N	.5-1	0.02	0	largest lahars towards Whakapapa; smaller to Whangaehu & Mangaturuturu
1945	E	5		L	10000?	Whang	Y	18	1	1	0.5	1	Y	.5-1	0.01	0	destroyed Strachan's Bridge, though no-one saw lahar; assumed similar to 1988 & 1971

Table 10(b): Risk Model Scenarios (derived by Tony Taig from consideration of above historic events & checked with H Keys 24/6/02):

E1	0.5	Medium	varied	varied	0.5	10-ish	1	0.5	0.3	0.5	0.5	0.03	0	0	Conditional probabilities of fatality are rough estimates, indicative rather than precisely representative of total risk associated with eruption lahars
E2	0.5	Larger	>100000	varied	0.5	20-30	1	1	0.6	1	1	0.5	0.02	0	

(~ Otway)

↑ *prob of warning*

Table 11: Proportion of People NOT successfully got out of way

Scenario	Proportion of people still here, with warning							P (warning by DOC signs or EDS)
	Outlet	**Crater Rim**	**Basin**	**U. Whangaehu (footbridge)**	**U. Whakapap**	**Whakapapa ski field**	**Other ski fields**	
Eruption 1	0.1	0.1	0.1	0.1	0.5	0.5	0.5	0.5
Eruption 2	0.1	0.1	0.1	0.1	0.5	0.5	0.5	0.5
Dam failure	0.2	0.2	0.2	0.1	0.1	1	1	1
Scenario	Proportion of people still here, "blue skies" event							*Note - ski areas assumed not to close in 50% of warned cases; other access prevention reasonable*
Eruption 1	1	1	1	1	1	1	1	
Eruption 2	1	1	1	1	1	1	1	
Dam failure	0.2	0.2	0.2	0.1	0.1	1	1	

Table 11a: Proportion of Times NOT EVERYONE successfully got out of the way

Scenario	Proportion of times SOMEBODY still here, with warning							P (warning by ERLAWS or EDS)
Eruption 1	0.1	0.1	0.1	0.1	0.5	0.5	0.5	0.5
Eruption 2	0.1	0.1	0.1	0.1	0.5	0.5	0.5	0.5
Dam failure	0.2	0.2	0.2	0.1	0.1	1	1	1
Scenario	Proportion of times SOMEBODY still here, "blue skies" event							*Note - ski areas assumed not to close in 50% of warned cases; other access prevention reasonable*
Eruption 1	1	1	1	1	1	1	1	
Eruption 2	1	1	1	1	1	1	1	
Dam failure	0.2	0.2	0.2	0.1	0.1	1	1	

SAME as Table 11, purely because in Table 11, reliability corresponds to having closed off access (given warning). Thus "getting people out of the way" results in either success (no-one present) or failure (everyone who would normally present is so), with no in-betweens

Table 12: Expected Average Fatalities, PER EVENT

Scenario	Average no. of fatalities, for one event, at ……							Total deaths, all locations
Eruption 1	**Outlet**	**Crater Rim**	**Basin**	**U. Whangaehu (footbridge)**	**U. Whakapap**	**Whakapapa ski field**	**Other ski fields**	
Skiers - Whak	0.0000	0.0298	0.0000	0.0000	0.0049	0.0000	0.0000	0.03
Skiers - other	0.0000	0.0059	0.0000	0.0000	0.0000	0.0000	0.0000	0.01
Climbers	0.0100	0.0401	0.0270	0.0050	0.0004	0.0000	0.0000	0.08
Trampers	0.0000	0.0000	0.0000	0.0057	0.0000	0.0000	0.0000	0.01
Media	0.0048	0.0024	0.0000	0.0000	0.0000	0.0000	0.0000	0.01
Scientists	0.0021	0.0021	0.0044	0.0000	0.0000	0.0000	0.0000	0.01
Total Erup1:	0.02	0.08	0.03	0.01	0.01	0.00	0.00	**0.14**
Eruption 2								
Skiers - Whak	0.0000	0.0596	0.0000	0.0000	0.0813	4.1127	0.0000	4.25
Skiers - other	0.0000	0.0118	0.0000	0.0000	0.0000	0.0000	0.0000	0.01
Climbers	0.0100	0.0801	0.0541	0.0100	0.0068	0.0000	0.0000	0.16
Trampers	0.0000	0.0000	0.0000	0.0114	0.0000	0.0000	0.0000	0.01
Media	0.0048	0.0048	0.0000	0.0000	0.0000	0.0000	0.0000	0.01
Scientists	0.0021	0.0042	0.0089	0.0000	0.0000	0.0000	0.0000	0.02
Total Erup2:	0.02	0.16	0.06	0.02	0.09	4.11	0.00	**4.46**
Dam Failure								
Skiers - Whak	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
Skiers - other	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
Climbers	0.0036	0.0000	0.0000	0.0018	0.0000	0.0000	0.0000	0.01
Trampers	0.0000	0.0000	0.0000	0.0021	0.0000	0.0000	0.0000	0.00
Media	0.0017	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
Scientists	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
Dam Total:	0.0061	0.0000	0.0000	0.0039	0.0000	0.0000	0.0000	**0.01**

9-year return period type event;

18-year return period type event

peak occupancies of rim ~ 40x ave; peak occupancy of skifields ~25 x ave

Table 13: Probability of One or More Fatalities, PER EVENT

Scenario	Proportion of events involving 1 or more fatalaties at …..							**Probability of the event involving 1 or more fatalities, any location**
	Outlet	**Crater Rim**	**Basin**	**U.Whangaehu (footbridge)**	**U.Whakapapa**	**Whakapapa ski field**	**Other ski fields**	
Eruption 1	0.0064	0.0712	0.0210	0.0041	0.0007	0.0000	0.0000	**0.1008**
Eruption 2	0.0064	0.1423	0.0420	0.0082	0.0346	0.0462	0.0000	**0.2545**
Dam Failure	0.0023	0.0000	0.0000	0.0015	0.0000	0.0000	0.0000	**0.0038**

Note: Table 13 is based on exactly the same assumptions as Table 12. Instead of using the average number of people present at each location (Table 9b), though, it uses the likelihood of there being someone at the location (Table 9c). The numbers thus calculated are directly comparable with the other risks estimated in this report, though it needs to be borne in mind that the eruption lahar incidents include scenarios affecting many people, whereas most of the dam failure scenarios leading to harm to people involve one or a few people.

10 Collation of Findings

The findings of the report are presented under two sets of assumptions. The first set is based on things broadly as they stand today. The second set is based on what should be realistically achievable, given that all the systems still under development are completed, and all the sensible, reasonable cost measures that have been identified in the course of this assessment are implemented effectively. The first assessment is thus "*unfair*" in that it does not take account of all the ongoing and planned arrangements, but is in my view important in that it provides a snapshot of where we realistically would be if all these actions were not progressed. Presenting both assessments is also useful in helping monitor progress in getting from where we are now, to the better state represented by the second assessment

10.1 Current Assessment

The current assessment bottom line result is that there is a chance of between a few per cent and a few tens of per cent **(could be up to 40% chance)** of the lahar resulting in one or more fatal accidents, given preparedness as it currently stands.

"*Current preparedness*" is taken for this assessment as involving:

- ERLAWS operating successfully at Site 3 but not yet fully commissioned at Sites 1 and 2
- local response plans in their current status (formal written response plans of almost zero effectiveness; informal arrangements acknowledged between the parties involved of higher effectiveness but significant unreliability)
- significant uncertainty as to the topography of the area around SH1 close to the Wahianoa Aqueduct, and no measures in place for protection of SH1 against lahar flows onto the road
- the Tangiwai Memorial and associated toilets, washing facilities and car park remaining open
- the Transit system for protection of the SH49 road bridge at Tangiwai not yet operational
- the Tranz Rail lahar protection system functioning as intended, but with no particular priority given to delivering additional ERLAWS warnings to Tranz Rail
- the significant possibility that, if lahar material were to flow down the Waikato Stream, some of it would follow the channel leading to the SH1 culvert and would overtop the road there, and
- Genesis' procedure in the event of an alarm from the Waikato Stream being applied as currently written, with absolute priority being given to prevention of contaminated flows into the Poutu Canal and management of lower Tongariro River flows having subsidiary status to that objective.

The assessment findings are presented in more detail in Table 14 and Figure 21 below. Table 14 provides upper and lower estimates, for each location, of:

(a) the risk of damage to assets, given the lahar has happened

(b) the risk of a fatal accident, GIVEN asset damage, with NO response/protection action

(c) the risk of a fatal accident, with NO response/protection, given the lahar has happened (= A x B above)

(d) the risk of failure of protection arrangements, OTHER than those initiated by ERLAWS (currently only Tranz Rail has such arrangements in place)

(e) the risk of a fatal accident, with NON-ERLAWS protection, given the lahar has happened (= C x D above)

(f) the estimated unreliability of ERLAWS (ie risk ERLAWS fails to provide a timely alarm)

(g) the estimated unreliability of the response to ERLAWS (ie risk that the response fails to protect people from harm at the stated location, given that an ERLAWS alarm was successfully raised)

(h) the overall estimated unreliability of ERLAWS-led warning and response
(= 1 – [1-F]x[1-G] above)

(i) the overall estimated risk of a fatal accident.

The table also shows the overall estimated residual risk of there being a fatal accident, added up over all the locations concerned.

Figure 21 provides the same overall residual risk information for each location, plotted graphically.

Table 14 and Figure 21 show that the dominant contributors to the risk of a fatal accident (of whatever sort) are:

1 the risk to people on SH1 in the vicinity of the Wahianoa Aqueduct (1-10%)

2 risk at Tangiwai to visitors to the memorial and users of SH49 (collectively 3-10%)

3 risk to road users at locations downstream of Tangiwai in the Whangaehu Valley (collectively 2-10+%)

There is then a group of lower risk locations contributing less than 1% each to the overall risk of there being a fatal accident (with the important proviso that for the rail bridge at Tangiwai the "*fatal accident*" involved might involve 50-200 people, whereas at other locations the risk is probably limited to a few people). These are:

(a) risk to railway users traveling over the Tangiwai Rail Bridge

(b) risk to road users at the Waikato Stream culvert under SH1, and

(c) risk to people in the lower Tongariro River, caused by sudden flow changes associated with Genesis' response to a lahar alarm from the Waikato Stream.

Table 14 and Figure 21 do not represent a "*best estimate*" of what should be achievable by the time the lahar happens. Such an assessment is developed in the following "*Realistically Achievable*" assessment, described below.

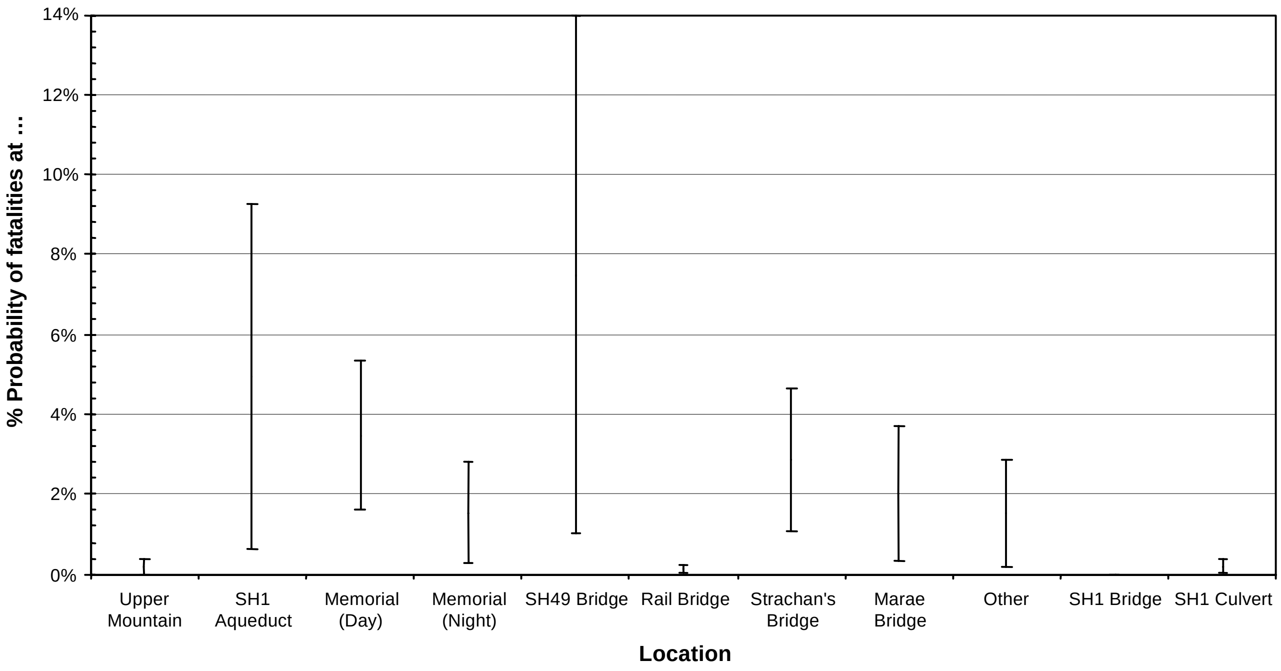
Table 14: Summary of Residual Risk to Life; Current Assessment

Location		**Hazard**	**Probability of asset damage GIVEN lahar**		**Conditional P of fatal accident, GIVEN asset damage, NO PROTECTION**		**RISK of a fatal accident, GIVEN lahar, NO PROTECTION**		**Conditional P that non-ERLAWS related protection arrangements fail, GIVEN lahar**		**RISK of a fatal accident, GIVEN lahar, no ERLAWS response**		**Warning and Response**			**RISK P of 1 or more fatalities, GIVEN lahar, AND ERLAWS & Response**	
													Unreliability of warning (usually ERLAWS)	Expected probability of unsuccessful response	Overall unreliability		
			A		**B**		**C**		**D**		**E**		**F**	**G**	**H**	**I**	
			min	max	min	max	min	max	min	max	min	max				min	max
Upper Mountain		*People caught in path of lahar*	*N/A*	*N/A*	*N/A*	*N/A*	*0*	*0.004*	*N/A*	*N/A*	*0*	*0.004*	N/A	N/A	N/A	*0*	*0.004*
Whangaehu Valley	Site G SH1 (Wahianoa Aqueduct)	Vehicles trapped in path of lahar	*0.10*	0.30	*0.062*	0.31	0.0062	0.093	1	1	*0.0062*	0.093	0.1	1	1	*0.0062*	0.093
	Site H Tangiwai - SH49	People/vehicles at Memorial trapped in path of lahar DAY	*1*	1	*0.058*	0.19	0.058	0.19	1	1	*0.058*	0.19	0.1	0.2	0.28	*0.016*	0.053
		People/vehicles at Memorial trapped in path of lahar NIGHT	*1*	1	*0.010*	0.10	0.010	0.10	1	1	*0.010*	0.10	0.1	0.2	0.28	*0.0028*	0.028
		People/vehicles otherwise trapped or drive onto damaged bridge	*0.30*	0.80	*0.12*	0.62	0.036	0.50	1	1	*0.036*	0.50	0.1	0.2	0.28	*0.010*	0.14
	Site I Tangiwai Rail Bridge	Train accident at damaged bridge*	*0.30*	0.80	*1*	1	0.30	0.80	0.005	0.01	*0.0015*	0.0080	0.1	0.2	0.28	*0.00042*	0.0022
	Site I Strachan's Bridge	People caught in path of lahar, and people driving into damaged roads	*1*	1	*0.038*	0.17	0.038	0.17	1	1	*0.038*	0.17	0.1	0.2	0.28	*0.011*	0.046
	Site L Marae Bridge		*0.30*	0.80	*0.038*	0.17	0.011	0.13	1	1	*0.011*	0.13	0.1	0.2	0.28	*0.0032*	0.037
	Other locations	As above (catch-all for all other locations downstream)	*0.30*	0.80	*0.030*	0.19	0.009	0.15	1	1	*0.009*	0.15	0.1	0.1	0.19	*0.0017*	0.029
Tongariro Catchment	Site A SH1 Bridge	People caught in path of lahar, and people driving into damaged bridge or road	*0*	0.0001	*0.12*	0.62	0	0.000062	1	1	*0*	0.000062	0.5	1	1	*0*	0.000062
	Site E SH1 Culvert		*0.0030*	0.010	*0.04*	0.36	0.00013	0.0036	1	1	*0.00013*	0.0036	0.5	1	1	*0.00013*	0.0036
	Tongariro River at Turangi	Flow surges - Genesis response to ERLAWS alarm	*1*	10	*0*	0	0	0	1	1	*0*	0	1	1	1	*0*	0
	Tongariro River at Turangi	Flow surges - Genesis response to Waikato Stream alarm	*0.0030*	0.010	*0.050*	0.30	0.00015	0.0030	1	1	*0.00015*	0.0030	1	1	1	*0.00015*	0.0030

* Approx 20% chance of the accident involving 50 to 200 people, 80% chance of it involving a single person

OVERALL RESIDUAL RISK of 1 or MORE FATAL ACCIDENTS											**16%**	**80%**				**5%**	**37%**

Figure 21: Current Fatal Accident Risk GIVEN a Lahar Event



10.2 Realistically Achievable Assessment

In the course of this assessment, many improvements have been described and discussed. Some of these are already firmly planned, budgeted for and should be completed in the next few months. Others are good ideas not yet implemented. None are yet in place on the ground and working reliably.

This second assessment is based on all of these improvements being implemented, in a consistent and coherent way, and being well managed so as to achieve a good level of reliability and effectiveness. On this basis the revised bottom line of the assessment of residual risk is that there is between 1% and several % (less than 10%) chance of a fatal accident associated with this lahar.

Table 15 and Figure 22 provide a breakdown of where this risk comes from in a format corresponding to that of Table 14 and Figure 21. The key changes, and their effects (referenced to the small superscript numbers in Table 15) are:

1 ERLAWS is assumed to be fully commissioned, and its reliability and availability to be actively managed, to achieve 98%+ success of providing an alarm, along with an acceptable frequency of false alarms. This will require good quality first principles assessment of ERLAWS unreliability in respect both of failure to provide alarms when it should, and of ERLAWS (and the protocol for its use and triggering of alarms) not providing excessive frequencies of false alarms, as well as continuation of the current monitoring and continuous improvement exercises.

2 The weak links in the current local emergency response plans are all successfully strengthened, so as to provide a 5% or less chance of failing to get emergency personnel to Tangiwai (and corresponding reliability of response at other locations) in time to take the necessary actions there. These weak links include:

  (a) reliance on a small number of individuals to receive and respond to pager messages
  (b) limited availability of effective communications in the Ruapehu area,
  (c) protocols for confirming receipt of the alarm, and that the alarm is real
  (d) risk of large numbers of false alarms, and
  (e) blocking of telephone lines by large volumes of incoming calls.

3 The uncertainty surrounding SH1 at the Wahianoa Aqueduct site is removed by either
a) a site topographic survey leading to conclusive evidence as to the very low risk of lahar material reaching the road, or (if the survey shows otherwise),
b) by effective measures to prevent any lahar material reaching the road (eg a suitable bund)

4 The Tangiwai Memorial, car park, toilets and washing facilities are effectively closed to public access (note – relocating them at a safer location would prevent the possibility of people seeking ways to get round barriers and visit these points of interest if they remain at their present sites)

5 Transit's plans for automated barriers on SH49 are implemented as intended, and the barriers achieve a 95% or better reliability of closing on demand

6 Tranz Rail is provided with reliable early warning of the lahar via ERLAWS (for example by being provided with a pager) instead of coming well down local emergency response teams' lists of parties to be contacted

7 Effective mechanisms are in place to provide 95%+ reliability of preventing accidents at Strachan's Bridge, the Marae Bridge and along the Field Track downstream of Tangiwai. It is also assumed that other downstream locations are reviewed in the light of this assessment, and that appropriate response mechanisms are in place for their protection.

8 The Waikato Stream culvert on SH1 is protected against the possibility of road inundation by lahar flow either by appropriate action to prevent flow down this channel (eg a small bund to ensure flow travels via the Waikato Stream channel under the SH1 bridge), or to replace the culvert with a bridge capable of passing the peak lahar flows projected.

9 Genesis EITHER provide convincing evidence that their response actions to a Waikato Stream lahar alarm will not cause significant risk to people in the lower Tongariro River (Note – this may involve development by/with Taupo District Council of arrangements for warning and evacuation of people using the lower Tongariro River, which would have benefits for a wide variety of other circumstances in which river flows can change suddenly, not solely for dealing with this lahar), OR make a modest change in their emergency procedures and in the instruction and training given to Genesis' operational staff, to ensure that primacy is given to protection of life in the lower Tongariro River over other, asset protection and environmental objectives.

The challenge of achieving these realistically achievable risk levels should not be underestimated. Providing 95%+ reliability of local responses, for example, will require significant investment in people and communications systems.

The order of likely risk management costs associated with this lahar is summarised in Table 16, which shows:

(a) the likely order of up-front costs associated with the above mitigation measures

(b) the scale of asset replacement costs associated with the various assets at risk, and

(c) the order of the consequential losses associated with those assets being out of service.

The total costs associated with the lahar, given protection to the realistically achievable levels of residual risk discussed above, are likely to be of the order of:

a) several $millions of reasonably certain costs, in terms of up-front assessments, protection systems, warning and response systems, and
b) of order $5-10 million of much less certain possible costs associated with the direct replacement value of assets at high risk, and
c) potentially of order $10 million + further costs if significant damage to power generation assets in the Tongariro catchment occurs.

The impression gained in the course of this assessment is that the scale and cost of what would be necessary to achieve a reasonably reliable warning and response to this lahar may not previously have been fully appreciated.

The acceptability of this realistically achievable level of risk, and the possibilities for further risk reduction, are discussed in Section 11.

Table 15: Summary of Residual Risk to Life; Realistically achievable

Location		Hazard	Probability of asset damage GIVEN lahar		Conditional P of fatal accident, GIVEN asset damage, NO PROTECTION		RISK of a fatal accident, GIVEN lahar, NO PROTECTION		Conditional P that non-ERLAWS related protection arrangements fail, GIVEN lahar		RISK of a fatal accident, GIVEN lahar, no ERLAWS response		Warning and Response			RISK of a fatal accident, GIVEN lahar, AND ERLAWS & Response	
			min	max	min	max	min	max	min	max	min	max	Unreliability of warning (usually ERLAWS)[1]	Expected probability of unsuccessful response[2]	Overall unreliability	min	max
Upper Mountain		*People caught in path of lahar*	*N/A*	*N/A*	*N/A*	*N/A*	*0*	*0.004*	*N/A*	*N/A*	*0*	*0.004*				*0*	*0.004*
Whangaehu valley	Site G SH1 (Wahianoa Aqueduct)[3]	Vehicles trapped in path of lahar	0	0	0.062	0.31	0	0	1	1	0	0	0.02	0.8	0.80	0	0
	Site H Tangiwai - SH49[4]	People/vehicles at Memorial trapped in path of lahar DAY	1	1	0	0	0	0	1	1	0	0	0.02	0.05	0.069	0	0
		People/vehicles at Memorial trapped in path of lahar NIGHT	1	1	0	0	0	0	1	1	0	0	0.02	0.05	0.069	0	0
		People/vehicles otherwise trapped or drive onto damaged bridge	0.30	0.80	0.12	0.62	0.036	0.50	1	1	0.036	0.50	0.02	0.0025	0.022	0.0008	0.011
	Site I Tangiwai Rail Bridge[5]	Train accident at damaged bridge [#]	0.30	0.80	1	1	0.30	0.80	0.005	0.01	0.0015	0.0080	0.02	0.01	0.030	0.000045	0.00024
	Site J Strachan's Bridge[6]	People caught in path of lahar, and people driving into damaged roads	1	1	0.038	0.17	0.038	0.17	1	1	0.038	0.17	0.02	0.05	0.069	0.0026	0.011
	Site L Marae Bridge[6]		0.30	0.80	0.038	0.17	0.011	0.13	1	1	0.011	0.13	0.02	0.05	0.069	0.00078	0.0091
	Other locations[6]	As above (catch-all for all other locations downstream)	0.30	0.80	*0.030*	0.19	0.009	0.15	1	1	0.009	0.15	0.02	0.05	0.069	0.0006	0.010
Tongariro Catchment	Site A SH1 Bridge	People caught in path of lahar, and people driving into damaged bridge or road	0	0.0001	0.12	0.62	0	0.000062	1	1	0	0.000062	0.02	0.8	0.80	0	0.000050
	Site E SH1 Culvert[7]		0	0	0.045	0.36	0	0	1	1	0	0	0.02	0.8	0.80	0	0
	Tongariro River at Turangi	Flow surges - Genesis response to ERLAWS alarm	1	10	0	0	0	0	1	1	0	0	1	1	1	0	0
	Tongariro River at Turangi[8]	Flow surges - Genesis response to Waikato Stream alarm	0	0	0	0	0	0	1	1	0	0	1	1	1	0	0

[#] Approx 20% chance of the accident involving 50 to 200 people

OVERALL RESIDUAL RISK of 1 or MORE FATAL ACCIDENTS *9%* 70% *0.5%* 5%

Figure 22: Realistically Achievable Fatal Accident Risk, GIVEN a Lahar Event

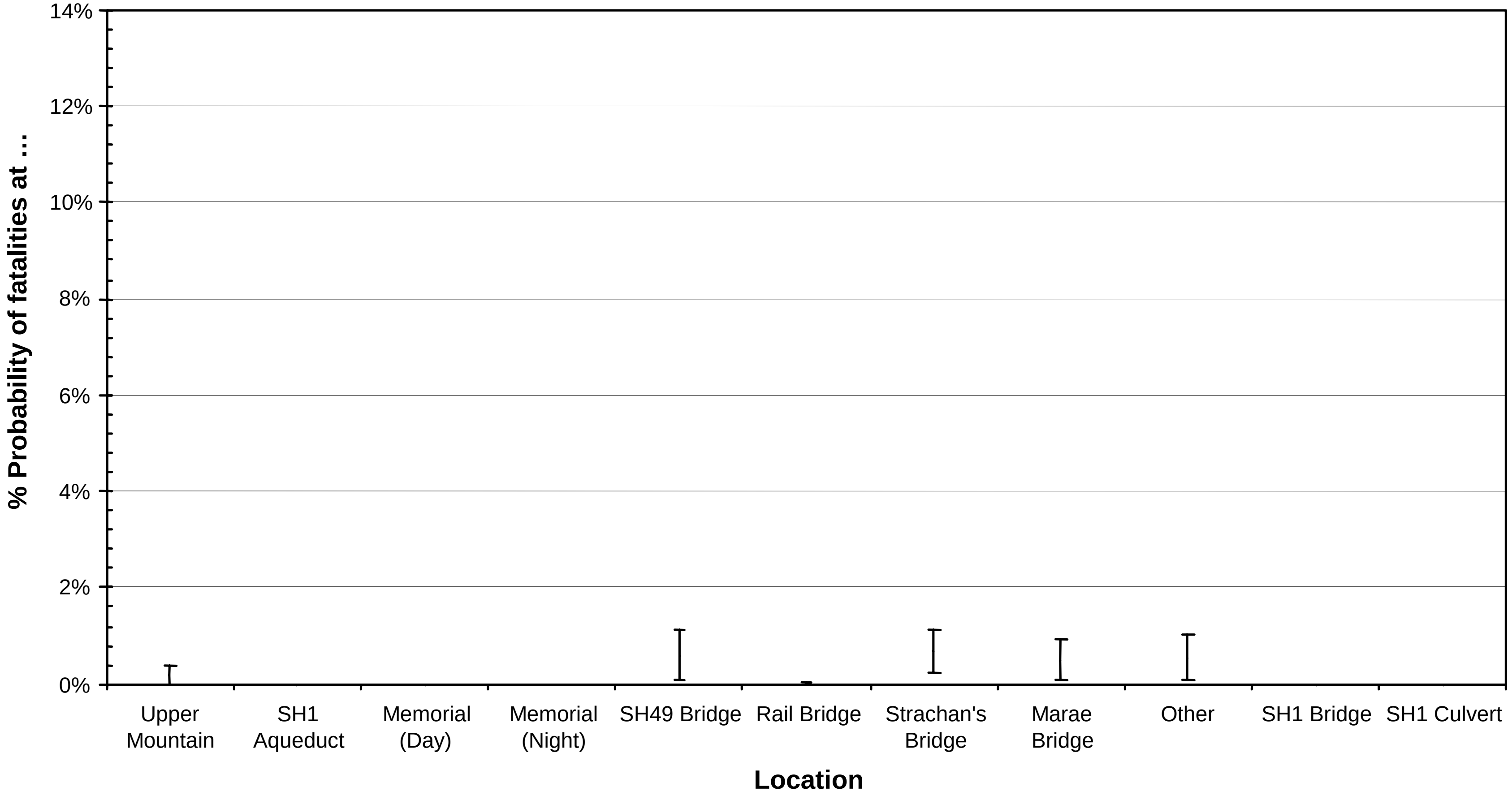


Table 16: Summary of Economic Impacts

	Location	Impacts via	Parties bearing costs	"Certain" costs	Uncertain costs		
				Prevention & mitigation measures + "certain" damage	**Risk**	**Asset restoration**	**Loss of Revenue/ other consequential**
	Upper Mountain	DOC precautionary measures + footbridge replacement	DOC	$100k+	H	(footbridge damage virtually certain)	Potentially significant tourism impact (not considered here)
Whangaehu valley	Wahianoa Aqueduct	Damage to Aqueduct	Genesis/ MRP	$100k's protective measures	H	(damage in "certain" category)	$5m
		Damage to L. Moawhango	Genesis/ MRP	$100k's protective measures	M	$100k's minimum	$20m
		Damage to pylons & transmission lines	Transpower	$100k assessments, protective measures	L	$100k's maximum ($50k approx per pylon)	??(NOT national disaster; ltd criticality of lines; quick to repair)
	Tangiwai Rail Bridge	Damage to bridge	Tranz Rail	$10k's (training, alarm upgrades)	H	$2m	Modest (some trains can use alternative routes; temporary bridge up in few days)
	Tangiwai - SH49	Damage to Memorial Area	Ruapehu DC?	0	H	$10k's?	0
		Damage to SH49 bridge	Transit	$200k+ New alarms, signs, auto barriers	H	$2m	Modest (alternative routes available; temporary bridge up in few days)
	Other locations	Damage to roads & other assets	Ruapehu DC, local people	? $200k+ emergency planning, testing, systems	H	$100k's road restoration	?? Impacts on local economy
Tongariro Catchment	SH1	Protection of/damage to road	Transit	$10k's assessment, planning etc	M	$100k's road restoration	?? Substantial impact, but quick to fix
	Rangipo Power Station	Damage to Station & associated assets	Genesis	$100k's assessment, planning etc	L	$7m	$10m
General		Overall costs of emergency plans, systems, impacts on local/national economy (many parties)		$ few millions on assessments, systems, response management	H	(considered above)	??? Impacts on tourism & economy (esp. if any fatalities)

11 Discussion and Way Forward

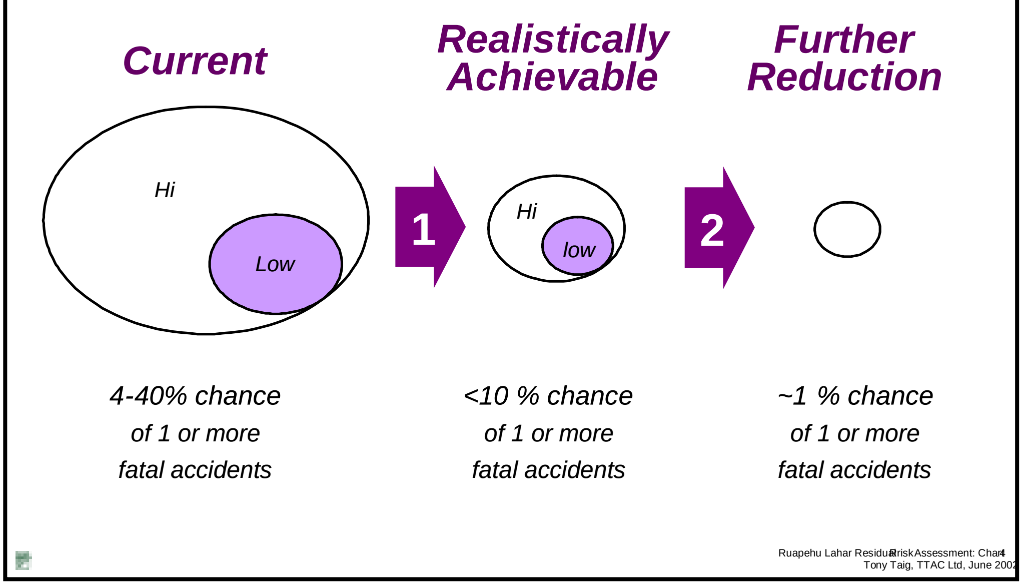
The discussion here addresses four key questions:

1. How acceptable are the assessed residual risk levels?
2. What do we need to do to gain assurance of reaching the realistically achievable residual risk levels?
3. Where should response plans concentrate their efforts to be most effective? and
4. What would be the most promising avenues for further reduction, beyond the realistically achievable levels of residual risk?

11.1 Acceptability of Risks

The estimates of residual risks contained in this report are very uncertain. It has been evident in discussions held during the course of this assessment that different parties have interpreted uncertainty differently, and that different perceptions have resulted as to the degree of risk to assets and people. The approach used throughout this report has been to try to make sure risks have not been underestimated, and to make clear the sources and scale of uncertainties as and when they arise. The numbers calculated by the assessment should not be treated as definitive. Figure 23 below provides a pictorial representation of three possible residual risk levels, which may be helpful in decision making.

Figure 23: Residual Risk Levels - Conceptual



Ruapehu Lahar Residual Risk Assessment: Chart 4
Tony Taig, TTAC Ltd, June 2002

What constitutes an acceptable level of residual risk is not a matter for this report. That is inherently a value judgment on which many different people will have different views, and is an inherently political decision. What can be done here is to help put the risks in Figure 23 in context to help those (ie elected politicians) who must make such difficult decisions.

Starting on the left of the figure, the current situation may involve as high as 40% chance of there being a fatal accident when the dam collapse lahar happens. On the other hand, the risk may be as low as a few per cent. This uncertainty is inherent in the situation; it will not go away if lots of other experts are consulted. It may be possible to find people who know a lot about geology and volcanoes who would offer an opinion vouching lesser uncertainty, but the tendency of experts to understate uncertainty, particularly where their own hypotheses and specialities are involved, is well known. For decision making purposes, it is probably most useful to note the real possibility that, within the bounds of what the best experts can currently tell, there could be as much as a 30 or 40 % risk of fatal accidents, when the lahar happens.

By almost any reckoning, a possible 30 or 40% chance of fatal accidents associated with an event which has been very well forecast, and on which government has made a very public decision to let the event happen when nature dictates it, rather than pursue other options to manage it[9], seems almost certain to be considered unacceptably high. Gaining confidence that risk is nearer to the realistically achievable levels of risk is thus assumed to be a high priority.

Acceptability or otherwise of the realistically achievable levels of risk is harder to gauge. The level of risk we are talking of now is less than a 10% chance of a fatal accident, and may be as low as 1% or lower. There are many risks we live with that are much bigger, and many comparisons might be made with government decisions (eg in allocation of health resources, or spending on the roads) that would imply lesser willingness to pay by society to avoid a given quantum of risk than is implied by sums already spent on the Ruapehu lahar risk.

The already tolerated risks associated with relatively frequent (every 10 or 20 year) eruption lahar type events on Mt Ruapehu's ski fields provide an interesting comparison case in point. The assessment in Section 9 suggests that the levels of "*risk of a fatal accident*" associated with the type of eruptions to be anticipated every 20 years or so on Mt Ruapehu is comparable to the "*as is, before improvements*" dam collapse lahar risk, and greater than the reasonably achievable levels of risk. Moreover, it could involve considerably more people.

On the other hand, people who ski on Mt Ruapehu know they are venturing onto a live volcano, and to some extent at least accept there is an element of risk, whereas people on the roads or on trains around the foot of the mountain make no such choice. There are special concerns about avoiding recurrence of the Tangiwai disaster of 1953. There are few precedents available to help establish what is an acceptable level of risk associated with an event known to be hazardous, where a deliberate, ministerial level decision has been made to allow that event to occur, for cultural, environmental and other good reasons.

The acceptability of the realistically achievable level of risk therefore appears more marginal. The discussion below focuses on: first, what needs to happen to provide government with assurance that we will actually achieve the realistically achievable risk levels, and second, on what might be the most promising avenues to pursue if further risk reduction were desired.

11.2 Assuring Realistically Achievable Levels are Reached

Attainment of this level of residual risk relies on timely and coherent implementation of the measures 1-9 presented above in Section 10.2.

These measures involve many parties, and many opportunities for failure because of either:

(a) insufficient awareness of what is required to make one party's part of the strategy work sufficiently reliably and effectively, or

(b) because of people making their own interpretation of what is required of them, or of what others are going to achieve, which are not consistent with other people's interpretations.

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[9] The decision to allow the lahar to happen, and to rely on a strategy of warning and response to mitigate associated safety risks, followed from the extensive assessment and consultation surrounding the Department of Conservation's *Assessment of Environmental Effects*, published in 1999.

MCDEM has an important leadership role in making all this happen. For a high degree of assurance to be obtained, there are important planning, delivery, funding and monitoring issues to be addressed – all four must be tackled; lack of any one would prevent a high degree of assurance from being possible.

Planning: The plethora of parties and differences of interests and perspectives make it vital that active, coordinated management of the whole response planning process is provided. RDC is well placed in terms of local knowledge and contacts, but there is an inherent difficulty in asking a small territorial authority to set priorities and devote significant resources to protecting (largely) people who do not live in the area from risks involved in traveling through or visiting it. It should be emphasised that RDC in discussions on this assessment appeared in no sense to be less concerned about people visiting or traveling through the district than about its own residents, but there is a clear difficulty in making resources available for a large scale planning and coordination task. MCDEM appear ideally placed to contribute expertise to assist in this task. The ideal would be to provide dedicated support; something more than facilitation is needed.

Delivery: Any response actions in the field (getting to a site to erect road blocks or evacuate people, for example), must be provided by people or organisations close to the places at risk or the travel times will be too long to be of any use. Given the time scales available for responding to the lahar, heavy reliance has to be placed on telephony and wireless communications for providing alarms and initiating response actions. At present, these are all being devised locally by RDC and Ohakune Police.

Given the strain on local resources and the inherent limitations on communications reliability in the Ruapehu area, it would seem well worth considering whether back-up communications capability (to provide back-up for tasks from initiating call-out of emergency teams on the ground, to handling potentially large volumes of incoming calls) might be provided from outside the area. For example, Tranz Rail in Wellington have a 365x24 hour control centre, with high reliability fibre optic telecommunications links backed up by Telecom systems, continuously triple manned by highly trained operators well used to issuing unambiguous instructions and confirming that they have been acted on[10].

A second point concerning delivery is the whole project management of this exercise. Besides devising and putting in place the systems and personnel to respond to pager alarms, initiate and manage the response, there will be a number of teams of local people (who might include volunteer firefighters, police, army and others) to be briefed, trained and rehearsed in exercises. There are important interfaces with the key utilities involved to be managed and monitored. Significant time and energy will be involved in all this; the appointment of a dedicated project manager by RDC is very much to be welcomed, but there will be an ongoing issue of available resource and costs to ensure the management challenge involved can be adequately handled.

Funding: The effect of adopting a "*Let it happen as nature dictates*" strategy to the lahar (rather than an "*Avoid by doing something to the tephra dam*" or "*Make it happen at a time of our choosing*" strategy) has been to place a heavy burden of responsibility and associated costs onto the local Territorial Authorities and emergency services, who are ill placed to accept it. There appears to be a strong case here for some form of central support and/or funding for the local bodies charged with leadership in this area.

Monitoring: Currently RDC are leading the response exercise, and MCDEM are supporting it. It seems likely that that support will become more active over the coming months. There is a clear need for:

- a well devised plan to address the key issues 1-9 in Section 10.2 above, and
- clear milestones against which to measure progress.

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[10] There is no suggestion here that Tranz Rail has any obligations for providing back-up emergency response support to territorial or regional authorities or should be imposed upon to assume such obligations, simply that they provide one example of an organisation much better placed to lead a telecoms-led "*instruct, monitor, inform and respond*" exercise than, for example, Ohakune Police.

There is also a strong case for the active involvement in a monitoring or review capacity of someone independent of the whole process to review progress from time to time. Given the likelihood of the lahar being a year or more away, it might make sense to plan now for reviews in (say) 6 and 12 months time. Within six months, most of the planned systems should be in place, with evidence emerging as to their performance, and protocols for their operation and use well established. Response planning should also be well advanced. Within 12 months there should be a high state of operational readiness, a good understanding of potential failures of parts of the whole system, and robust arrangements in place for dealing with them.

11.3 Targeting of Response Plans

Some simple but important priorities flow from this assessment for those developing response plans. The key points are:

1. The strategy for protecting people "*up the mountain*" (ie above the ring of main roads around Ruapehu of which SH1 and SH49 provide the Eastern, Southern and South-Western portions) should rely on prevention of access through appropriate warnings and restraint on activities such as taking guided walking parties to "*at risk*" parts of the crater rim (nearer the outlet area), or the upper Whangaehu Valley (eg across the footbridge on the round the mountain walk) once the lake levels become dangerous. Post-lahar intervention to send people up the mountain to search and rescue others is likely to be ineffective, and could be hazardous to those involved in the rescue attempt. It should not feature in response planning, other than in post-event recovery and checking for damage/people who need help.

2. The time available for getting to at-risk parts of SH1 is too short for any realistic protection strategy to be effective in getting people out of the way of at risk parts of the road. The strategy for protecting SH1 therefore has to rely on ensuring the lahar does not reach the road (which, if site surveys and consideration of the flow calculations in this report confirm a need for them, can be done through relatively simple, low cost engineering measures). Transit's arrangements to close the Desert Road in the usual way using the snow gates appear an appropriate precautionary measure, once a high degree of assurance that the lahar will not inundate any part of the road surface has been provided (ref points 3 and 8 in Section 10.2 above).

3. The primary focus for response planning, in terms of prevention of access and evacuation once the lahar is known to be on its way, should be on the lower parts of the Whangaehu Valley from Tangiwai and downstream. At Tangiwai, primary roles (given that the Memorial has been closed) would be to reinforce and enhance the reliability and effectiveness of the automated systems for protecting the SH49 road bridge and the railway bridge – to ensure the Transit barriers were working effectively to inhibit road traffic access, and to liaise with Tranz Rail to confirm the status of the rail bridge and absence of trains from the bridge and surrounding areas.

   It has not been possible in this report to consider in detail the roads and structures downstream of Strachan's Bridge and the Tirorangi Marae Bridge, but the flow calculations in Section 5 should assist local planners in assessing risk at specific locations. A useful approach in limiting how far downstream the lahar-specific plan is developed would be to consider at what point downstream the scale of the lahar (which is depositing material and diminishing downstream) becomes similar to or less than the scale of floods (which accumulate material and increase as they flow downstream) for which emergency plans are already available.

11.4 Further Risk Reduction Possibilities

A further factor of perhaps 2-5 reduction beyond the realistically achievable level of risk could be achieved by focusing on improving readiness and response effectiveness at Tangiwai, and higher risk locations downstream of Tangiwai, and by active reinforcement of access prevention measures higher on the mountain.

To go beyond this, into the realm of 1% risk of a fatal accident or lower, would require (in addition to appropriately strengthened response systems) a significant further step in reliability of warning systems. This would require either enhancing the reliability of ERLAWS, or providing some completely independent system.

Enhancing ERLAWS beyond 98% success performance would probably be expensive. Significant further improvement would have to tackle the fundamental limitations of the RF communications links high on the mountain. Genesis are in the process of spending about $1 million to install higher reliability microwave communications from Tukino Hut down to Tokaanu Power Station. To do something similar to connect the three ERLAWS sites to the Genesis System would probably cost considerably more.

Better value may be obtainable by applying the sound systems engineering strategy of building up high integrity systems from relatively cheap, moderate reliability components which are truly independent of each other. Mention has been made in the course of this assessment of the possibility of (for example) bringing together:

- the scientific value of having high quality photos or film of lahars
- the media value of having real time coverage of lahars, and
- the relatively high availability in New Zealand of interested, skilled people who might be prepared to spend a week at a time at some safe location (eg one end of the footbridge over the Whangaehu Gorge?)

into some lower key, modest reliability arrangement to provide the dual functions of access management, and operation of relatively simple but collectively robust (given a human presence) cameras and mobile communication links to monitor the status of the Whangaehu River high up the valley. We note, though, that even once the crater lake has filled to a level high up the tephra barrier, the time elapsed before dam failure is highly uncertain and could extend to many weeks or months, so that any such measures might have to be prolonged for very extensive periods to be effective.

Realistically, developing a response strategy which is more than 99% reliable is likely to prove prohibitively expensive. The primary focus of any further risk reduction is thus likely to be more on preparedness and structural measures from Tangiwai downstream along the Whangaehu Valley.

If a 1% risk of a fatal accident is not considered acceptable, or if the costs of achieving "*below 10%*" risk levels is considered excessive (once those costs have been realistically estimated, giving due account to what is needed to provide appropriate reliability), then the strategy of allowing the lahar to happen would have to be revisited. Consideration of alternative risk management strategies involving, for example, interventions at the crater rim, or triggering the lahar at a time of choice rather than allowing it to happen as nature dictates, is outside the scope of this report.

12 Conclusions

The decision not to remove the tephra dam over the rim of the crater of Mt Ruapehu and to allow the impending lahar to happen when nature decides it was made in the knowledge that there would be some residual risk to people, and that reliable warning and response arrangements would be needed to minimise that risk.

The nature of the lahar to be anticipated from failure of the tephra dam, and of its effects, is subject to considerable uncertainty. It was clear in the course of this assessment that these uncertainties have been interpreted differently by different people, and that different perceptions have thus arisen as to the likely scale of the lahar, and the risk it presents to assets and to people. The aim of this assessment has been to expose these uncertainties so as to reduce the potential for confusion, and to focus on the conclusions that are reasonably robust in the face of the uncertainties. Those conclusions are:

1 The range of possible dam failure lahar scenarios can be bracketed by considering a range of possible values for four key parameters:

   (a) the level of the crater rim below the tephra dam (three possibilities considered here)

   (b) the height of the crater lake up the dam when the dam fails (two possibilities)

   (c) how quickly the dam fails (two possibilities), and

   (d) the factor by which the flow bulks up by entrainment of solid material (three possibilities).

2 The experts are reasonably confident that the lahar would lie within the span of the 24 lahar scenarios corresponding to the 2x2x2x3 combinations of the above factors considered in this assessment, though recognise the possibility of larger or smaller associated lahars. They are reluctant to express a view as to the relative likelihood of various values of the parameters a-d above, except for (b). The consensus view is that the lake is likely to reach near the top of the dam before the dam fails. This is important; it is by no means a "*worst case*" outlying possibility that the lake will reach the top of the dam before the lahar happens. On the contrary, that is one quite possible outcome. When the dam will fail is uncertain; that it will fail rapidly when it does fail is more generally agreed.

3 For most of the 24 lahar scenarios considered, predicted flows down the Whangaehu Valley are higher than those thought to have occurred during the 1953 lahar which led to the Tangiwai Disaster (the last occasion on which a relatively sudden failure of lake containment, as opposed to volcanic activity, led to a major lahar). The range of predicted flows at Tangiwai for these 24 scenarios ranges from about 300 m^3/sec to about 1800 m^3/sec, compared with the estimated flow in the 1953 event of about 600 m^3/sec. The importance of the four key lahar factors is in the reverse of their order in 1(a) to 1(d) above, ie bulking factor creates the largest, and crater rim level the lowest, uncertainty in flows further down the Whangaehu Valley.

4 The bund constructed at the bottom of the Whangaehu Gorge to prevent flows into the Waikato Stream would be effective in achieving that purpose in all but the two largest of the 24 lahar flow scenarios considered. In those scenarios (corresponding to rapid failure of the dam, with the lake full to the top of the dam, and a maximum bulking factor of 5) the flow calculations performed for this assessment predict no overtopping of the dam using "*central estimate*" assumptions, but modest overtopping using worst case assumptions. Even in these two extreme scenarios, using worst case flow assumptions, the peak lahar flows reaching the Tongariro River are estimated to be of the order of a few cubic metres per second (and certainly well below the flows of order of 100 m^3/sec which had been estimated in the absence of the bund)[11].

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[11] We noted earlier the importance of a field survey to confirm the information on elevation of the Whangaehu/ Waikato watershed above the Whangaehu stream bed on which this conclusion is based.

5 Assets at risk where people might also be put at risk from the lahar can be divided into the following groups:

(a) virtually certain to be severely damaged: Tangiwai Memorial and Strachan's Bridge

(b) at high risk (0.3 to 0.8 probability) of severe damage: rail and SH49 bridges at Tangiwai, and the Marae Bridge

(c) at uncertain risk: SH1 near the Wahianoa Aqueduct

(d) at lower risk: SH1 at the bridge and culvert where the Waikato Stream crosses it.

Risk at road locations downstream of the Marae Bridge has not been explicitly assessed. An additional risk to people is present in the Tongariro River, associated with Genesis' response to lahar alarms in the Waikato Stream and not with the lahar itself. Electricity generation and transmission assets are also at risk from the lahars considered here (in particular the Wahianoa Aqueduct, Lake Moawhango, Rangipo Power Station, and a small number of Transpower pylons from one of the three transmission lines which run broadly parallel to SH1).

6 If arrangements were to remain in their present state (with ERLAWS part commissioned, Transit arrangement on SH49 not yet in place, rudimentary local response plans etc), the likelihood of one or more fatalities following the tephra dam collapse lahar could be as high as 40%.

7 With measures already in progress or planned, and other practicable, reasonable cost measures identified in this assessment put in place, a reduced likelihood of less than 10% of a fatal accident due to the lahar should be realistically achievable.

8 The "*current arrangements*" risk as in (6) above is dominated by:

(a) the risk to people on SH1 in the vicinity of the Wahianoa Aqueduct (1-10%)

(b) risk at Tangiwai to visitors to the memorial and users of SH49 (collectively 3-10%)

(c) risk to road users at locations downstream of Tangiwai in the Whangaehu Valley (collectively 2-10+%)

9 The realistically achievable risk as in (7) above is dominated by the risk to road users at Tangiwai on SH49, and on bridges and roads further downstream the Whangaehu Valley, with a small residual risk to people high on Mt Ruapehu (climbers and trampers around the Upper Whangaehu valley).

10 The risk of a passenger train accident at Tangiwai is significantly lower than the other risks of a fatal accident (less than 0.1% chance with current arrangements, realistically reducible to less than a 0.01% chance), but could involve many more people.

11 A high priority is assumed to attach to progressing from the "*current arrangements*" to the realistically achievable risk. This will require considerably greater effort from many parties than the completion of the ERLAWS system and of Transit's automated closure gates for SH49 at Tangiwai. Considerable and well-coordinated effort and resources will be required to realise the realistically achievable level. The required measures have been described in detail (Section 10.2) and can be summarised in terms of five strategies for key groups of locations:

(a) Remove risk on SH1 by protecting the road from lahars (not practicable at other locations).

(b) Close the high risk Tangiwai Memorial site and car park.

(c) Enhance warning and response at Tangiwai to supplement Transit and Tranz Rail automated systems.

(d) Enhance warning and response (and readiness) at locations downstream of Tangiwai.

(e) Put people before assets and the environment in the Tongariro River (see 13 below).

12 Priorities for emergency response planning should focus on 10(c) and (d) above; search and rescue parties should not be sent to at risk locations up Mt Ruapehu until after the lahar risk has passed. Precautionary road closure of SH1 is a sensible and proportionate response, but further measures (eg carrying out a "*sweep*" of the road and nearby locations to remove straggler motorists or campers) are unlikely to be very effective. They are worth planning in anticipation of the possibility of a relatively generous warning time being available, but should have a lower priority than the SH49 and downstream responses.

13 The assessed risk to people in the Tongariro River from the dam collapse lahar itself is very small. The risk associated with Genesis' response to alarms is a separate matter (which involves many other possible lahar scenarios, not just a dam collapse). Achievement of the realistically achievable risk level is predicated on the uncertainty surrounding this risk being removed, either by appropriate assessment of river flows and hazards, or by alterations to Genesis' lahar response procedures to give primacy to protection of human life in the lower Tongariro River.

14 Progressing below the realistically achievable level of risk would require concerted further measures to improve readiness, warning and response at Tangiwai and other downstream locations. Trying to push ERLAWS above about 99% availability is likely to be costly; if higher reliability is required it may be better to consider a modest reliability but fully independent supplementary warning system. Achieving better than 99% reliability of response is also likely to be extremely difficult and costly. With substantial investment over and above that required to achieve the realistically achievable levels discussed above, risk might thus be reducible to around a 1% chance of the dam collapse lahar resulting in a fatal accident. A 1% risk would represent about the lowest for which a high degree of assurance could be provided.

15 If risk at the realistically achievable level (<10% chance of the dam collapse lahar resulting in a fatal accident) is not considered tolerable, then significant further investment might possibly reduce the risk to around 1%. If this were not considered tolerable, or if the costs (realistically estimated with regard to the required reliability and effectiveness) of achieving either the <10% or the ~1% level were considered excessive, then the strategy of allowing the lahar to happen when nature dictates it would have to be revisited. Consideration of alternative risk management strategies is beyond the scope of this assessment.

16 Whichever strategy is adopted, coherent and properly resourced planning, delivery, and monitoring of progress in achieving the desired levels of risk from this lahar will be required. One outcome of this assessment should be a better shared appreciation of the costs and resources involved in devising and implementing high reliability warning and response measures for this event.

17 Some significant factors relevant to the original decision to allow the lahar to happen when nature dictates it have been revealed in the course of this assessment. In particular:

(a) Different people had made quite different interpretations of the qualitative assessments of risk associated with the lahar and of consultees' responses to DoC's AEE report (ranging, for example, from "*not really putting assets significantly at risk*" to "*some important assets are at high risk*").

(b) There does not appear to have been a shared appreciation of what would be involved, and what it would cost, to provide a high reliability of warning and response to protect life.

(c) Some people appear to have had a false sense of security as to the effectiveness of response arrangements, based on an incorrect perception that we will know with a good degree of precision when the lahar is going to happen.

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October 2002