BEFORE THE ENVIRONMENT COURT **ENV-2020-AKL-000064**
AT AUCKLAND

I MUA I TE KOOTI TAIAO O AOTEAROA
TĀMAKI MAKAURAU ROHE

IN THE MATTER	of an appeal under the first schedule of the Resource Management Act 1991 (**RMA**)
BETWEEN	**AWATARARIKI RESIDENTS INCORPORATED** Appellant
AND	**BAY OF PLENTY REGIONAL COUNCIL** First Respondent
AND	**WHAKATĀNE DISTRICT COUNCIL** Second Respondent and Requestor of Plan Change 17

STATEMENT OF EVIDENCE OF KEVIN HIND ON BEHALF OF WHAKATĀNE DISTRICT COUNCIL

ENGINEERING

10 August 2020

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1. EXECUTIVE SUMMARY

1.1. Following the 2005 debris flow event in the Awatarariki Steam, a range of in-stream debris detention barriers were assessed as possible mitigation against future debris flow events. The intent was to protect the residential community located on the Awatarariki fanhead from a future debris flow event of equal magnitude to that of 2005.

1.2. In 2008 Whakatāne District Council (**the District Council or WDC**) approved the engineering design of a flexible “ring net” debris detention barrier (**DDS**) to be constructed upstream of the Matatā Escarpment.

1.3. The concept was for the DDS to retain approximately 100,000 m^3 of debris behind the barrier, with approximately 50,000 m^3 of fine-grained material passing through it. A further 150,000 m^3 of excess coarser debris was to be diverted away from the DDS to the fanhead via a spillway. The debris would then be directed away from the residential area through the use of earth barriers or bunds. This is referred to as the partial containment option.

1.4. Commencing in 2009, a series of computer analyses (RAMMS) were undertaken to assist in the design of the barrier, spillway and fanhead bunds. The modelling was initially calibrated to the 2005 event (back analysis) and then used to assess the performance of the DDS, spillway and fanhead bunds (forward analysis).

1.5. Difficulties in getting the fanhead bunds to work as required (because of land use restrictions) led to the partial containment option being abandoned. Design subsequently moved towards a full containment option using a larger DDS.

1.6. A number of factors, including the unique size of the barrier, barrier performance uncertainty, difficulties in construction and maintenance, as well as cost, ultimately saw the DDS being abandoned in 2012 as being non-viable.

1.7. By not constructing the DDS, the hazard and risk from a future debris flow event(s) remained for the Awatarariki fanhead. In order to assess what this level of hazard and risk was, Quantitative Landslide Risk

Assessments (**QLRA**) were undertaken by myself between 2013 and 2015.

1.8. An initial debris flow hazard and risk assessment was undertaken in 2013 as part of a broader assessment of the Matatā Escarpment. The results from this assessment were general in nature.

1.9. A detailed QLRA consisting of deterministic risk analyses for debris flows of variable return period and magnitude was subsequently undertaken. Loss of Life Risk contours were developed across the fanhead for both short return period and longer return period events. These were considered to bracket the likely range of a future event and were the best estimated for the 2005 event.

1.10. The modelling showed that the Loss of Life Risk on the majority of the fanhead west of the Awatarariki Stream was well in excess of 0.01%, as was a smaller area east of the stream. Subsequent probabilistic analyses, which were not reliant on singular values for input parameters effectively gave the same result.

1.11. The adoption of unconservative values as input into the calculations was unable to bring the estimated Loss of Life Risk for the affected properties to less than 0.01% per annum, let alone 0.001%. This was confirmed by the probabilistic analyses.

1.12. The effect of climate change will only increase the frequency and intensity of storm events capable of generating debris flows in the Awatarariki catchment.

1.13. The results of the risk analyses were provided to WDC, however the acceptability or otherwise of the risk was not determined as part of this work. As part of a peer review of T+T’s work, McSaveney and Davies (2015) recommended that the minimum area of retreat be aligned with the 0.001% modelled annual risk contour, on the basis that this best represented the area exposed to high risk bearing in mind the imprecision of the data.

1.14. WDC adopted Societal Risk (i.e. the risk of multiple fatalities) was assessed for both the current fanhead population as well as for a future larger population. The Societal Risk was determined to be intolerable/unacceptable in both cases.

2. INTRODUCTION

2.1. My full name is Kevin Joseph Hind.

2.2. My evidence is given on behalf of the Whakatāne District Council (the **District Council**) in relation to:

(a) Proposed Plan Change 1 (Awatarariki Fanhead, Matatā) to the Operative Whakatāne District Plan; and

(b) Proposed Plan Change 17 (Natural Hazards) to the Bay of Plenty Regional Natural Resources Plan (a private plan change request from the District Council)

(together referred to as the **Proposed Plan Changes**).

2.3. My evidence relates to the debris flow modelling and risk assessment aspects of the Proposed Plan Changes. My evidence will cover:

(a) The assessment of potential debris flow mitigation options for the Awatarariki Fanhead;

(b) Modelling of debris flows from the Awatarariki catchment and replication of the 2005 event;

(c) Modelling of a proposed flexible Debris Detention Structure (**DDS**) within the Awatarariki Stream and its related debris diversion structures;

(d) Assessment of engineering solutions to protect the Awatarariki fanhead from future debris flow events;

(e) Use of the Australian Geomechanics Society's guidelines (AGS, 2007)[1] as an appropriate risk management framework to assess debris flow risk from the Awatarariki catchment;

(f) Quantitative debris flow hazard and risk assessment at Matatā;

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[1] Australian Geomechanics Society. Landslide Risk Management. Australian Geomechanics, Vol. 42, No. 1, March 2007.

(g) Confirmation of the different debris flow risk areas;

(h) Confirmation of the different Loss of Life Risk areas and confirmation that the fan is unsafe for residential use;

(i) Confirmation that no viable engineering detention solution on the upper catchment exists (as outlined in letter to CPG dated 28 Feb 2012); and

(j) Confirmation that fanhead solutions of bunds and raised building platforms alone (i.e. without upper catchment detention) are inadequate to mitigate the risk.

2.4. I attended the public hearing of submissions to the Proposed Plan Changes held in March 2020 and presented expert evidence to the Hearing Commissioners.

3. QUALIFICATIONS AND EXPERIENCE

3.1. I hold the position of Technical Director (Engineering Geology) at Tonkin & Taylor Ltd (T+T) in Auckland. I have been employed at T+T since 2006.

3.2. My qualifications include a B.Sc. and an M.Sc. (Hons) in Earth Sciences, both from the University of Waikato.

3.3. I have 33 years of post-graduate experience, all within engineering geology and geotechnical engineering. I am registered with Engineering New Zealand as a Professional Engineering Geologist (PEngGeol) and I am a member of the New Zealand Geotechnical Society and the International Association for Engineering Geology and the Environment.

3.4. I have specialist skills in engineering geological investigations, natural hazards and Quantitative Landslide Risk Assessments (**QLRA**). I have worked on many large natural hazard and civil engineering projects ranging from feasibility studies and investigations, consent applications through to detailed design and construction monitoring. My experience has been gained on projects undertaken in New Zealand, Australia, Burma, Indonesia, Japan, Jordan, Papua New Guinea, Philippines, Pitcairn Island, Saudi Arabia, Singapore, Switzerland, United Kingdom, United Arab Emirates and Vanuatu.

3.5. Previous work experience applicable to this project include detailed QLRA undertaken for the Matatā, Whakatāne and Ohope escarpments, two large hydroelectric dams in the Philippines, rock fall hazard risk assessments for Herepuru Road on the Matatā Escarpment as well as a residential area at Aranga Beach in Northland. I have designed multiple landslip and rockfall debris detention structures, including in Whakatāne and Ohope, between 2012 and 2019.

4. MY ROLE

4.1. My first involvement with the Awatarariki debris flow mitigation project was the finalisation of a DDS options assessment report, which was issued in August 2008[2]. This report summarised the options assessment process that commenced shortly after the 2005 event.

4.2. I subsequently undertook three major phases of work:

(a) Numerical debris flow modelling to aid design of the flexible barrier, spillway and fanhead diversion structures (2009 – 2010);

(b) Debris flow hazard and risk assessments of the Awatarariki Stream fanhead (2013) as part of a broader landslide risk assessment of the Matatā Escarpment; and

(c) Detailed numerical modelling and risk assessment of the Awatarariki Stream fanhead including preparation of risk contour maps (2013-2015).

4.3. The first phase of work was detailed numerical modelling of the proposed DDS and debris diversion earthworks. I undertook all modelling using the software RAMMS (Rapid Mass Movement). The mitigation scheme originally modelled was a 12 m high flexible barrier with a spillway and fanhead diversion bund. This was subsequently modified to a larger 14 m high flexible barrier designed to contain all debris from the design event, with no requirement for a spillway or

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[2] Tonkin & Taylor, 2008. Matatā Regeneration Project, Awatarariki Stream Debris Detention. Report prepared for Whakatāne District Council dated August 2008.

fanhead bunds or building platforms. Although only 2m higher than the original barrier design, the higher barrier was substantially wider and able to retain a much greater volume of debris due to the topography of the site.

4.4. Once the WDC resolved not to proceed with an engineering solution, the focus of my work shifted to assessing the debris flow hazard and risk on the Awatarariki Fanhead.

4.5. The first hazard and risk assessments were general in nature, being reliant on the numerical modelling that I had undertaken in 2009. The resultant report presented broad assessments of debris flow hazard and risk across the Awatarariki fanhead[3]. The report was issued in November 2013 following a peer review by Mr Dick Beetham (GHD) in May 2013.

4.6. I was subsequently commissioned by WDC to undertake a detailed debris flow risk assessment which specifically addressed the issue of Loss of Life Risk across the Awatarariki fanhead. This second QLRA, which was commenced in 2013, was based on additional detailed numerical modelling of debris flows. It resulted in the preparation of Loss of Life Risk contours across the Awatarariki fanhead[4].

4.7. The debris flow risk report[5] was finalised and issued to WDC in July 2015. The report was subsequently issued to Professor Tim Davies (University of Canterbury) and Dr Mauri McSaveney (GNS Science) for independent peer review.

4.8. As a result of a peer review workshop held in September 2015, I undertook additional probabilistic risk analyses based on the results of the numerical modelling undertaken in 2013. This work was undertaken to confirm the robustness of the results of the 2013 analyses with respect to the uncertainties of the input parameters.

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[3] Tonkin & Taylor, 2013a. Quantitative Landslide Risk Assessment, Matatā Escarpment. Report to Whakatāne District Council dated November 2013.

[4] Tonkin & Taylor, 2013b. Supplementary Risk Assessment, Debris Flow Hazard, Matatā, Bay of Plenty. Draft report to Whakatāne District Council dated November 2013.

[5] Tonkin & Taylor, 2015a. Supplementary Risk Assessment, Debris Flow Hazard, Matatā, Bay of Plenty. Final report to Whakatāne District Council dated July 2015.

4.9. Known as Monte Carlo simulation, the probabilistic analyses involved the calculation of risk in the same manner used in the deterministic analyses but the input parameters (such as event return period, probability of physical impact and vulnerability to impact etc) are selected randomly from normal distributions bound by estimated minimum and maximum values. The result is a distribution of risk rather than a single value.

4.10. The probabilistic work resulted in a slightly modified Loss of Life Risk contour map for the Awatarariki fanhead, although it confirmed that regardless of what value was assigned to the parameters (within reason) the level of risk was similar to that previously calculated. The outputs were included in a letter report issued to WDC in October 2015[6] and represent the Loss of Life Risk calculations forming the basis of the proposed plan change.

4.11. I also participated in a Ministry of Building, Innovation and Employment Building Act determination hearing providing expert debris flow modelling advice to the Hearing Panel (2015)[7].

4.12. In preparing this evidence I have reviewed the following documents and reports:

(a) Australian Geomechanics Society, 2007. Landslide Risk Management. Australian Geomechanics, Vol. 42, No.1, March 2007;

(b) AECOM, 2010. Awatarariki Stream Debris Flow Control System. Peer Review of Resource Consent Application Technical Proposal. Letter report to Whakatāne District Council dated 23 June 2010;

(c) AECOM, 2011. Awatarariki Stream Debris Flow Control System Peer Review of Resource Consent Application Technical Proposal 2011 dated 25 February 2011;

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[6] Tonkin & Taylor, 2015b. Awatarariki Debris Flow Peer Review Workshop. Letter report to Whakatāne District Council dated 2 October 2015.

[7] Ministry of Building, Innovation and Employment Building Act Determination 2016/034

(d) Bickers, 2012. Review of Awatarariki Catchment Debris Control Project. Report to Whakatāne District Council dated June 2012;

(e) CPG, 2012. Matatā Debris Flow Mitigation Structure – Overview Review. Report to Whakatāne District Council dated 1 March 2012;

(f) McSaveney, M.J., Beetham, R.D. and Leonard, G.S., 2005. The 18 May 2005 debris flow disaster at Matatā: causes and mitigation suggestions. Report prepared for the Whakatāne District Council dated July 2005;

(g) McSaveney, M.J. and Davies, T.R.H., 2015. Peer Review: Awatarariki debris-flow-fan risk to life and retreat zone extent. Letter report to Whakatāne District Council dated 17 November 2015;

(h) Tonkin & Taylor, 2008. Matatā Regeneration Project, Awatarariki Debris Detention Options. Report prepared for Whakatāne District Council dated October 2007.Tonkin & Taylor, 2008. Matatā Regeneration Project, Awatarariki Stream Debris Detention. Report to Whakatāne District Council dated August 2008;

(i) Tonkin & Taylor, 2009a. Debris Flow Numerical Modelling, Awatarariki Stream, Matatā. Report to Whakatāne District Council dated May 2009;

(j) Tonkin & Taylor, 2009a. Debris Flow Numerical Modelling, Awatarariki Stream, Matatā. Report to Whakatāne District Council dated May 2009;

(k) Tonkin & Taylor, 2011. Awatarariki Stream Barrier Design Report. Report to Whakatāne District Council dated 11 October 2011;

(l) Tonkin & Taylor, 2013a. Quantitative Landslide Risk Assessment, Matatā Escarpment. Report to Whakatāne District Council dated November 2013;

(m) Tonkin & Taylor, 2013b. Supplementary Risk Assessment, Debris Flow Hazard, Matatā, Bay of Plenty. Draft report to Whakatāne District Council dated November 2013;

(n) Tonkin & Taylor, 2015a. Supplementary Risk Assessment, Debris Flow Hazard, Matatā, Bay of Plenty. Final report to Whakatāne District Council dated July 2015; and

(o) Tonkin & Taylor, 2015b. Awatarariki Debris Flow Peer Review Workshop. Letter report to Whakatāne District Council dated 2 October 2015.

5. CODE OF CONDUCT

5.1. I confirm that I have read the Code of Conduct for Expert Witnesses contained in the Environment Court Consolidated Practice Note 2014. I also agree to comply with the Code when presenting evidence to the Court. I confirm that the issues addressed in this brief of evidence are within my area of expertise, except where I state that I rely upon the evidence of another expert witness. I also confirm that I have not omitted to consider material facts known to me that might alter or detract from the opinions.

6. ASSESSMENT OF THE PLAN CHANGES

Debris Flow Mitigation Option Selection

6.1. Following the May 2005 debris flow event, WDC commissioned T+T to assess potential debris flow mitigation options for the Awatarariki Stream. WDC adopted a DDS as the preferred mitigation option in August 2005, although the type of DDS had yet to be determined. T+T subsequently assessed a number of different possible DDS types including embankment dams, open grid structures, pier barriers and flexible “ring net” barriers.

6.2. At the time of the initial DDS options assessment in 2005, a design debris volume of 330,000 m^3 was adopted for initial planning purposes, although the then-best estimate of the volume of debris deposited on the fanhead was 200,000 m^3. This design event essentially replicated what had occurred in 2005.

6.3. An assessment of the fanhead debris volume undertaken jointly in early 2007 by T+T and GNS resulted in a revised debris volume estimate of 250,000 m^3 for the debris deposited on the fanhead and adjacent lagoons.

6.4. It was recognised early in the DDS assessment process that the physical constraints of the catchment meant that a DDS of the size anticipated to be constructible within the channel of the Awatarariki Stream would only be able to capture approximately 100,000 m^3 of debris, i.e. less than half of the design event. The design concept subsequently adopted was for debris in excess of what could be captured by the DDS to be directed around the true-left bank of the DDS via a spillway and into unoccupied parts of the fanhead and broader coastal strip. Fine grained (sandy/muddy) material would pass through the barrier and remain in the stream channel.

6.5. The various DDS options were summarised in a report prepared for WDC in October 2007 (T+T, 2007)[8]. This report identified the two most cost-effective options as being: 1) a flexible barrier and 2) an embankment dam with a culvert. No preferred or recommended option was identified in T+T (2007), although it was noted that the flexible barrier option had a significantly smaller construction impact on the valley floor and watercourse compared to an embankment dam.

6.6. A flexible “ring net” barrier was approved by WDC as the preferred type of DDS on 23 July 2008. This reflected engineering considerations as well as community feedback to WDC.

6.7. The engineering assessments that informed the decision to adopt the flexible DDS as the preferred mitigation option were subsequently presented in a summary report prepared by T+T in August 2008 (T+T, 2008). The intent of that report was to document the assessment process undertaken to that date.

Flexible DDS and Associated Earthworks

Proposed Scheme

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[8] Tonkin & Taylor, 2007. Matatā Regeneration Project, Awatarariki Debris Detention Options. Report prepared for Whakatāne District Council dated October 2007.

6.8. The fundamental design elements of the proposed debris flow mitigation scheme were as follows:

(a) The DDS would consist of a flexible ring net barrier located in the lower section of the Awatarariki Stream.

(b) The volume of debris requiring management by the DDS in the design event was 250,000 m^3. An additional volume of fine-grained material (potentially up to 50,000 m^3) would pass through the barrier in the form of a slurry and remain in the channel of the Awatarariki Stream.

(c) The DDS would retain approximately 100,000 m^3 of debris at maximum capacity based on the likely maximum height of the structure.

(d) The approximately 150,000 m^3 of excess debris would be directed into a spillway located on the true left bank of the DDS. The spillway channel would deliver this debris onto the fanhead via the State Highway No. 2 (SH2) underpass; and

(e) In order to prevent that debris emerging out of the spillway channel from inundating the nearby residential area, it was proposed to construct an earth bund on private land bounded by McPherson St, Kaokaoroa St and Clem Elliot Drive. Figure 1 presents the conceptual layout of the diversion bund as presented in T+T (2008).

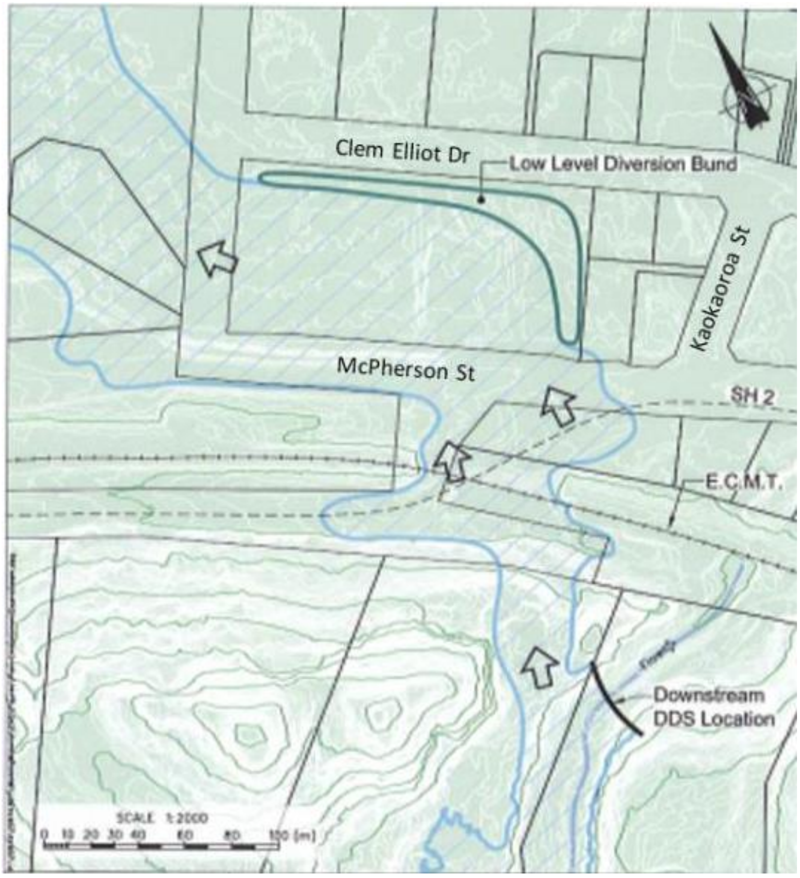

Figure 1: The mitigation scheme as presented in T+T (2008)

Detailed Design

6.9. In early 2009, WDC commissioned T+T to undertake the detailed design of the debris flow mitigation scheme. The first part of this work consisted of computer-based debris flow modelling to provide assurance that the proposed scheme would achieve its objectives.

Debris Flow Modelling

6.10. Debris flow modelling was required to:

(a) Confirm the debris impact velocity on the barrier.

(b) Confirm the volume of debris that would be stored upstream of the DDS and the volume that would be discharged onto the fanhead via the spillway.

(c) Gain an understanding of how the barrier and spillway would interact and from this determine an appropriate elevation for the spillway crest.

(d) Determine the effectiveness of an on-fanhead diversion bund and from this confirm its location and size; and

(e) Confirm that the scheme would provide adequate protection for the residential properties on the fanhead.

6.11. All of the debris flow modelling was undertaken by me using RAMMS, a numerical continuum code then undergoing final development by WSL Forschungsanstalt, the Swiss Federal Institute for Forestry, Snow and Landscape Research. WSL is recognised as a world leader in debris flow research.

6.12. I travelled to Zurich in February 2009 to attend WSL for a week to learn how to use RAMMS in the company of those who developed it, as well as to discuss matters of debris flow behaviour and modelling with some of the world's best experts in the subject.

6.13. RAMMS model's debris flows as a three-dimensional, single-phase Voellmy-fluid whose overall properties approximate those of the real-life flow. The movement of a debris flow within RAMMS is governed by the slope of the terrain down which the debris moves and the frictional forces resisting such movement. In a Voellmy-fluid, flow behaviour is a function of fluid density (ρ), basal friction angle (δ) (represented by μ where $\mu = \tan(\delta)$), the viscous resistance factor (ξ) and the lateral pressure coefficient (λ).

6.14. The pre and post-2005 digital elevation (terrain) models (**DEM**) used in RAMMS were developed predominantly from LiDAR data. As the higher reaches of the Awatarariki catchment were not covered by LiDAR at that time, the DEM in those areas was developed from elevation contours published by Land Information New Zealand.

6.15. A range of suitable values for each RAMMS input parameter was obtained from discussions with WSL which had conducted considerable research into the properties of debris flows. This included direct in-field measurements of debris flow physical properties. Subsequent parametric studies were undertaken within these recommended upper-bound and lower-bound limits.

6.16. The debris flow modelling was undertaken in three phases: 1) parametric studies; 2) back analysis of the 2005 event and 3) forward analyses of the proposed scheme.

Parametric Studies

6.17. The first phase of RAMMS modelling consisted of parametric studies in which each of the different input parameters in RAMMS were systematically varied in order to gain an understanding of how each parameter affected the results and which were the most important in governing the outcome.

6.18. It was found that the basal friction (μ) and the lateral pressure coefficient (λ) were the two variables that most significantly affected debris flow movement and depositional characteristics. The former controlled the frictional behaviour of the flow whereas the latter determined the viscosity of the flow i.e. whether the debris behaved more or less water-like when flowing. Variations in ξ and ρ were found not to materially affect the results.

Back Analysis of the 2005 debris flow

6.19. The second phase of RAMMS modelling was the undertaking of a back analysis of the 2005 debris flow event. By modifying the input parameters, and in particular those that the parametric study had shown to be of greatest importance in determining flow behaviour, it was possible to broadly replicate the characteristics of the 2005 event. From this the best estimate of the RAMMS input parameters was obtained.

6.20. The most significant departure that the RAMMS output had from the observed behaviour of the 2005 event was in the distribution of the different materials making up the flow. Post-event observations showed a distinct distribution of finer-grained and coarser-grained components (i.e. boulders/timber) across the fanhead. However, as RAMMS models debris flows as a single phase, it was not able to replicate the detailed depositional patterns observed.

6.21. The primary output from the RAMMS modelling was flow thickness and velocity data across the fanhead. It was concluded based on this output that RAMMS sufficiently replicated the 2005 event that it served as a basis for investigating the DDS scheme.

6.22. It is characteristic of debris flows to be composed of two or more surges. Eye witness accounts of the 2005 event reported two or more surges of debris onto the fanhead, although the nature and timing of these surges is complicated by the fact that debris was held up for a period of time by the temporary blockage of the channel by timber debris at the railway bridge/culvert. A large surge of debris onto the fanhead occurred when the culvert failed, releasing the material trapped behind it.

6.23. A series of RAMMS analyses were undertaken to determine whether the number of flow surges and their relative size affected outcomes in terms of debris flow behaviour and deposition on the fanhead. At this time RAMMS required the debris flows to be initiated as landslides within the upper catchment. The surges were modelled by starting an initial landslide within the catchment, adding the resultant debris deposits to the DEM and then initiating another landslide to represent a subsequent surge.

6.24. The results indicated that neither the thickness nor distribution of the final deposits were materially affected by whether the overall event is modelled as single or multiple flows or whether the first surge was the smaller or larger of the sequence.

6.25. The primary difference between a single or multi-surge event was the peak height that the flow could attain within the constricted section of the Awatarariki Stream, as this directly reflected available volume of debris. The only noticeable difference in terms of deposition was that the initial surges tended to exhibit a greater variation in deposit thickness as a result of the underlying topographic irregularities. Subsequent surges flowed over a more regular surface of deposited material.

6.26. A debris flow sequence of two surges of equal volume was found to adequately represent the observed behaviour of the 2005 debris flow event.

Forward Analyses

6.27. The third phase of modelling was forward analyses in which the performance of the barrier, spillway and fanhead diversion bund was assessed using debris flow parameters derived from the back analysis. Essentially the mitigation scheme was being tested against the 2005 event. The following describes each of these elements.

RAMMS Model Configuration

6.28. Forward analyses were undertaken using two surges of equal volume, giving a total of 250,000 m^3 that would either be captured by the DDS or diverted over the spillway. The additional 50,000 m^3 of muddy debris that was assumed to pass through the porous barrier could not be modelled.

Spillway Performance

6.29. The RAMMS modelling allowed the most-appropriate spillway level to be determined relative to the crest of the DDS. This allowed the DDS to reach its maximum possible containment volume without debris spilling over the top of the barrier or for debris to access the spillway prematurely. Modelling showed that the spillway commenced to transmit debris prior to the DDS being full. As the barrier continued to fill towards its maximum height, a greater volume of debris entered the spillway. When correctly configured, the spillway commenced to transport 100% of the debris reaching the barrier just as the retained debris reached the top of the barrier.

6.30. The RAMMS modelling also allowed the optimum width and gradient of the spillway to be determined. The spillway gradient needed to be sufficient steep to prevent debris from stopping and blocking it, yet not so steep as to generate debris velocities greater than could be managed by the fanhead diversion bund.

Fanhead Debris Diversion Bund

6.31. While the RAMMS modelling was being undertaken, owners of the properties on which the diversion bund was proposed to be constructed (Figure 1) declined permission for their land to be used for this purpose.

6.32. As a result of this, the diversion bund was moved onto a thin parcel of public land (McPherson Street) located immediately north of the SH2 underpass (Figure 2). This revised location was significantly less desirable because of its much closer proximity to the outlet of the spillway (by approximately 70 m). This resulted in the following disadvantages:

(a) A higher debris impact velocity, as the debris did not have as far to travel before reaching the diversion bund. This resulted in an increased tendency for debris to pass up and over the bund and into the residential area beyond.

(b) A greater debris flow thickness at time of bund impact, as there was a significantly reduced ability for the debris flow exiting the narrow confines of the spillway to spread out and dissipate.

(c) The open space available between the SH2 underpass and the diversion bund was significantly smaller for the revised location. This placed limitations on both the footprint and maximum height of the bund.

(d) The significantly reduced area of open space in front of the bund restricted the quantity of debris that could be deposited before the debris either inundated the bund or affected debris movement within the spillway; and

(e) The proximity of the bund to the SH2 underpass required the debris to undertake a near 90-degree change in direction in order for debris to continue flowing (Figure 2). This slowed the debris flow down, likely resulting in premature deposition of debris at the toe of the bund.

6.33. A series of RAMMS analyses showed that a diversion bund of sufficient height could not be constructed at the proposed McPherson Street location to prevent debris from overtopping it and entering the residential properties near Clem Elliot Drive.

6.34. It was subsequently proposed to excavate a channel immediately in front of the bund as a means of both effectively increasing the height of the bund and to assist in the westward flow of the debris. RAMMS modelling indicated that the bulk of the debris flow could be diverted to open ground by a bund and channel system provided that the critical section near the spillway had a height above existing ground level of 4 m and a channel depth of 1.5 m. This was reliant however on the larger debris not being deposited and infilling or blocking the channel. This was considered to be an event of not-insignificant likelihood and was something that RAMMS was unable to model.

6.35. Furthermore, in order to prevent the more fluid debris from flowing around the eastern end of the bund into existing residential areas, the bund had to be considerably more laterally extensive than was originally conceived (Figure 2). This bund blocked the entrance to Kaokaoroa Street, effectively preventing any access to the Clem Elliot Drive area from SH2.

6.36. Typical output from the RAMMS modelling of the diversion bund is presented in Figure 3.

6.37. The results of the RAMMS modelling were presented to WDC in a report dated May 2009[9].

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[9] Tonkin & Taylor, 2009a. Debris Flow Numerical Modelling, Awatarariki Stream, Matatā. Report to Whakatāne District Council dated May 2009.

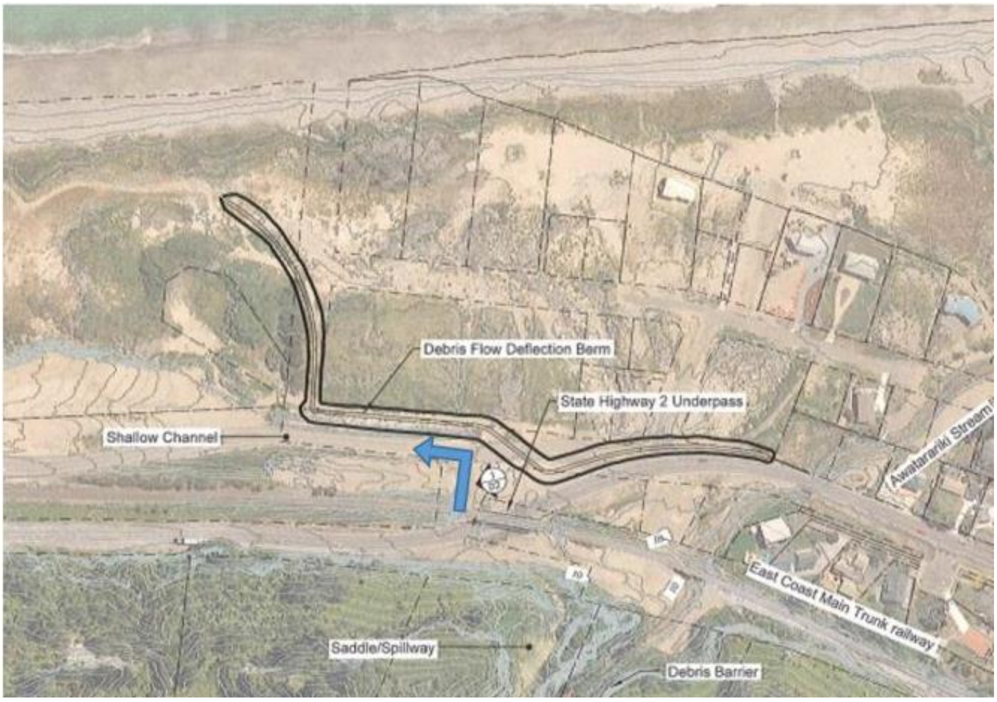

Figure 2. Extent of diversion bund necessary to prevent ingress of debris into the residential areas of the fanhead. The blue arrow indicates the extreme left-hand change in direction that the debris passing through the SH2 underpass would need to achieve in order for ongoing diversion of debris to the west to be achieved. Substantial deposition of debris at this turning point would potentially result in the channel and bund becoming ineffective, with debris subsequently overtopping the barrier and entering the residential area.

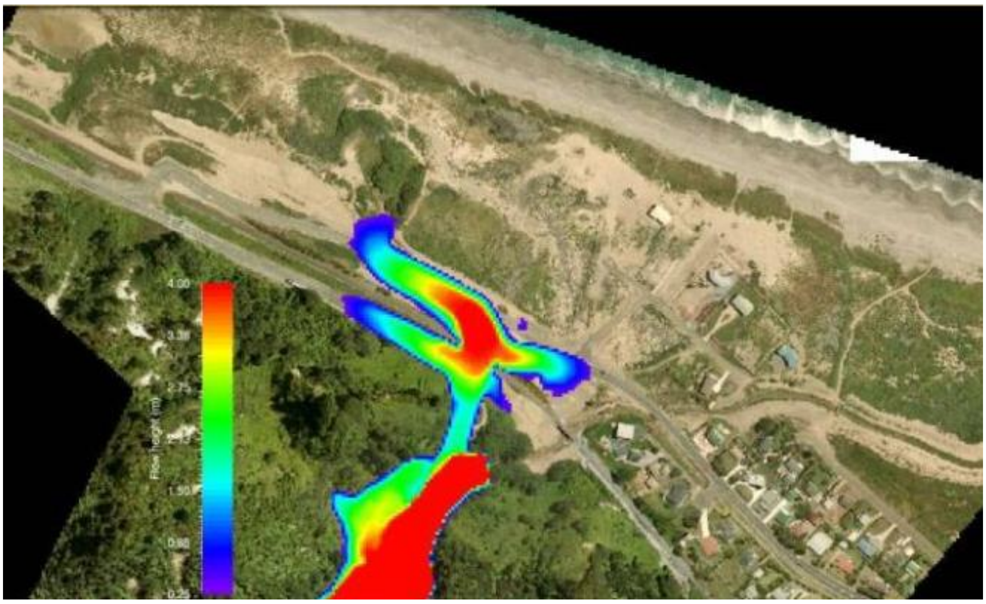

***Figure 3:* Output of RAMMS modelling showing the flow of excess debris material down the spillway and up against the fanhead bund. The red zone in front of the diversion bund indicate an increase in debris thickness at this turning point. Whilst RAMMS tended to indicate that this single-phase material continued to flow to the west, in reality it was expected that substantial coarse debris deposition would occur at this turning point, potentially rendering the channel and bund inoperative or less effective than required.**

Engineering Design

6.38. Once the RAMMS modelling had been completed, T+T prepared a design report covering the proposed design of the completed debris flow mitigation scheme[10].

6.39. Because full protection of the residential area of the fanhead required the construction of a very laterally extensive bund, WDC proposed a partial diversion option. This consisted of a bund extending only as far as Kaokaoroa St and three raised building platforms constructed behind the bund in those areas not then occupied by dwellings.

6.40. The proposed partial diversion option is shown in Figure 4.

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[10] Tonkin & Taylor, 2009b. Debris Flow Control System, Awatarariki Stream, Matatā. Report to Whakatāne District Council dated June 2009.

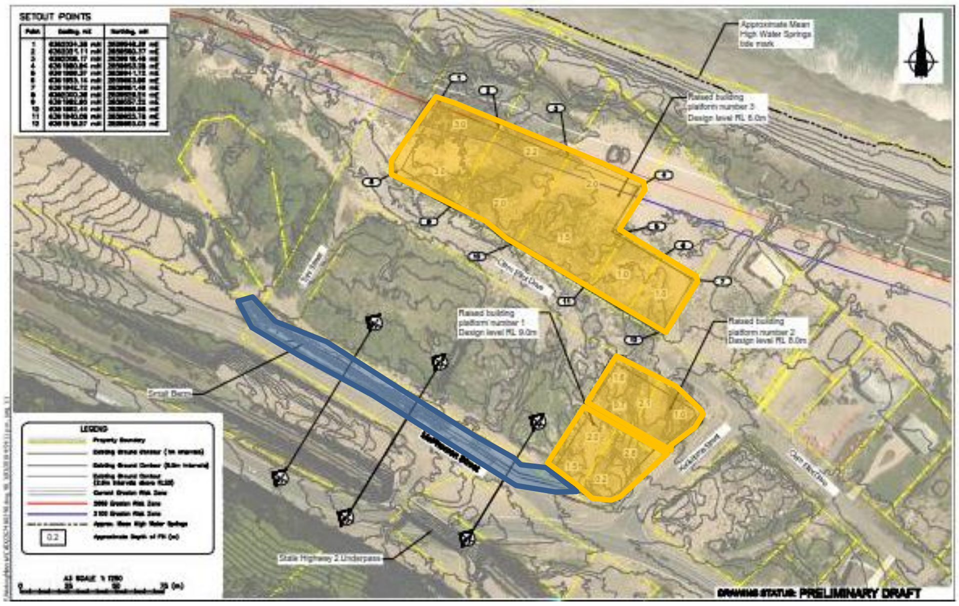

Figure 4: Partial diversion option with a short bund (blue) and three building platforms (orange)

6.41. Additional RAMMS modelling was undertaken to assess the effectiveness of the partial diversion option. It was found that building platforms approximately 2 to 3 m above existing ground level were still subject to some debris inundation. Further increases in the elevation of the building platforms resulted in a corresponding loss of debris containment volume in the area in between and a tendency of the debris to inundate the top of the building platforms.

6.42. The RAMMS modelling also demonstrated that building platforms only partially mitigated debris inundation for those properties that had yet to be built on. The use of the lower bund also increased the inundation hazard of already existing dwellings located at lower elevations and unable to be placed on raised building platforms.

6.43. In 2010, a decision was made to no longer pursue a partial containment option as the performance of the spillway could not be assured and the area available for a diversion bund immediately to the north of the SH2 underpass was insufficient for effective performance.

6.44. The preferred solution was then changed to a single flexible DDS structure large enough to contain the design event volume of 250,000 m^3 i.e. complete in-stream capture of all but the 50,000 m^3 of fine-grained material expected to pass through the barrier and remain in the stream channel. This significantly simplified the overall nature of the scheme, however it resulted in a large increase in retained debris volume as well as the forces acting on the DDS and its supporting anchorages. The DDS would have been the largest ever constructed worldwide at that time.

6.45. T+T prepared a draft Design Report in October 2011 intended to support the application for a building consent for the DDS[11]. This was presented at a pre-Building Consent application meeting on 19th October 2019. The major elements of the revised DDS were:

(a) A barrier height of 14 m and width of 39 m;

(b) A 71 m long supporting cable;

(c) Design retained volume of 250,000 m^3;

(d) Maximum loads on the support cable of 40 MN (20 each end); and

(e) A complex array of ground anchors up to 27 m in length to form the anchorages for the support cable.

6.46. No spillway or fanhead diversion structures were required. In the event of a debris flow event greater than the design, the excess debris would spill over the top of the DDS.

6.47. A single building platform was to be constructed north of Clem Elliot Drive, however this was required for Resource Consent conditions unrelated to the debris flow mitigation scheme.

Peer Reviews

6.48. A peer review of the proposed scheme was undertaken on a periodic basis through 2009 and 2010 by Professor Tim Davies (University of Canterbury) and Mr Colin Newton (AECOM NZ Ltd). Dialogue continued between T+T and the reviewers in order to reach agreement as to the design philosophy, flow characteristics and system performance.

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[11] Tonkin & Taylor, 2011. Awatarariki Stream Barrier Design Report. Report to Whakatāne District Council dated 11 October 2011.

6.49. The final peer review report[12] raised concerns regarding assurance that the barrier and spillway would perform as proposed. These concerns were unable to be addressed due primarily to the uncertainty associated with debris flow behaviour and the unique nature of the proposed scheme. These concerns, amongst others, contributed to the DDS-spillway-bund scheme being abandoned and the single large DDS being adopted as the preferred design.

6.50. AECOM was retained by WDC to undertake a peer review of the proposed mitigation works for a resource consent application which was centred on the construction of a large DDS without spillway or fanhead earthworks. The peer review report[13], undertaken in conjunction with Prof. Davies, concluded that the overall concept was reasonable but was a substantial departure from international experience. There were specific concerns with regards to corrosion of the DDS and its support system and the need for periodic removal of retained material.

Abandonment of an Engineered Solution

6.51. In early 2012, I expressed concern to the new CEO of the WDC as to the uncertainties of success with respect to the scheme centred on the single large flexible DDS and that the scheme had evolved into something very different to what had originally been envisaged. These concerns centred on:

(a) The unique size of the flexible barrier, especially now that it was intended to fully capture the design debris flow event;

(b) The likely difficulty in being able to construct anchorages of sufficient capacity within the extremely weak rocks at the DDS location;

(c) Issues with trying to investigate the anchorage locations sufficiently for design; and

(d) The escalating cost of the project.

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[12] AECOM, 2010. Awatarariki Stream Debris Flow Control System. Peer Review of Resource Consent Application Technical Proposal. Letter report to Whakatāne District Council dated 23 June 2010.

[13] AECOM, 2011. Awatarariki Stream Debris Flow Control System Peer Review of Resource Consent Application Technical Proposal 2011 dated 25 February 2011.

6.52. WDC subsequently commissioned CPG to "*confirm or otherwise the T+T concerns and recommendation [not to proceed] and assess if there is a current feasible solution which adequately mitigates risk to people and property*". CPG subsequently concluded that "*there is no financially viable proposal which adequately mitigates risk to people and property and resolves the cultural and environmental concerns over a 120-year design life*"[14].

6.53. An independent review of the project by Alan Bickers in 2012[15] recommended that no further action be taken to implement the proposed debris flow control system.

6.54. In December 2012, WDC resolved to not proceed with an engineering solution to manage the debris flow hazard for residential properties on the Awatarariki Fanhead on the basis that there were no viable engineering solutions to manage the debris flow risk that met the community engagement outcomes, engineering viability or feasibility.

6.55. WDC resolved to investigate and develop a planning framework to manage the hazard and risk.

Quantitative Hazard and Risk Assessments

6.56. With the abandonment of an engineered solution, WDC moved to a risk management approach. I subsequently undertook two hazard and risk assessments in 2013:

(a) A general Quantitative Landslide Risk Assessment (QLRA) of the Matatā Escarpment and its environs. This followed on from similar assessments I had completed for the Whakatāne and Ohope Escarpments. The Matatā QLRA included an assessment of the debris flow hazard and risk on the Awatarariki Fanhead in general terms, however it was of insufficient detail to determine the level of risk at specific properties; and

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[14] CPG, 2012. Matatā Debris Flow Mitigation Structure – Overview Review. Report to Whakatāne District Council dated 1 March 2012.

[15] Bickers, 2012. Review of Awatarariki Catchment Debris Control Project. Report to Whakatāne District Council dated June 2012.

(b) A detailed QLRA of the Awatarariki Fanhead based on extensive new debris flow modelling. This work allowed the calculation of risk on a property-specific level.

General Risk Principles

6.57. The general process of risk management is defined by AS/NZS 31000:2009 *Risk Management – Principals and Guidelines*. According to the Standard, risk management involves a stepwise process in which risks are identified, analysed, evaluated, and then treated. The steps required for the management of specific risks such as landslides are not provided in AS/NZS 31000:2009.

6.58. New Zealand currently does not have its own formal system of assessing landslide risk. In 2007 GNS Science published *Guidelines for assessing planning policy and consent requirements for landslide prone land* (Saunders and Glassey, 2007). This document outlined the general principals of identifying and assessing landslide risk with a specific emphasis on applying the results to land use planning applications.

6.59. The most widely adopted basis for the undertaking of landslide risk assessment in NZ is *Landslide Risk Management* (AGS, 2007), published by the Australian Geomechanics Society.

AGS (2007): Landslide Risk Management

6.60. AGS (2007) sets out the framework for landslide risk assessment, as well as providing detailed susceptibility, hazard and risk classifications. AGS (2007) is a recognised risk assessment methodology in the Regional Policy Statement Assessment User Guide.

6.61. The theoretical basis of the methodology presented in AGS (2007) is the result of international collaboration that can be traced back to the pioneering work of Varnes & IAEG (1984)[16], Fell (1994)[17] and Fell & Hartford (1997)[18].

6.62. Claims that AGS (2007) is not relevant to the assessment of debris flow risk in New Zealand because of its Australian origin are entirely without merit. AGS (2007) sets out a set of principles for landslide risk assessment that are entirely independent of geology, climatic conditions, or legal framework. AGS (2007) simply documents well established principles of landslide risk assessment previously provided in authoritative texts such as Lee and Jones (2004)[19].

6.63. AGS (2007) follows the principles of AS/NZ 31000:2009 in that it divides the risk management process into the following three basic elements:

(a) *Risk analysis*: where the nature of the landsliding hazard is assessed and the numerical value of risk estimated;

(b) *Risk assessment*: where value judgements are made as to whether the calculated risks are acceptable, tolerable or intolerable/unacceptable; and

(c) *Risk management*: where risk mitigation measures are assessed and implemented.

6.64. AGS (2007) provides commentary on what level of risk corresponds to “acceptable”, “tolerable” and “intolerable”. Not being defined in New Zealand law, the adoption of specific risk values to populate risk categories is subjective and often argued. It has been shown however that the Loss of Life Risk present on the Awatarariki fanhead is sufficiently high, even when adopting unconservative assumptions, that the risk must be considered intolerable.

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[16] Varnes, D.J. and the International Association of Engineering Geology Commission on Landslides and Other Mass Movements, 1984. Landslide hazard zonation: A review of principles and practice. Natural Hazards, Vol. 3, Paris, France. UNESCO.

[17] Fell, R. 1994. Landslide risk assessment and acceptable risk. Canadian Geotechnical Journals, 31, 261-272.

[18] Fell, R. and Hartford, D. 1997. Landslide risk management, in “Landslide Risk Assessment, Cruden and Fells (Eds.), Balkema, Rotterdam, 51-110.

[19] Lee, E.M. and Jones, D.K.C., 2004. Landslide Risk Assessment. Second Edition. ICE Publishing.

6.65. Although debris flows have more in common with floods than typical landslides, they are nevertheless the product of landslides and are included as one of the major landslide types in AGS (2007). The basis for assessing risk is the same for debris flows as landslides, although it is necessary to consider the particular physical properties of debris flows when assessing issues such as travel distance, velocity etc.

Definitions

6.66. Discussions concerning hazard and risk are commonly hampered by inaccuracy with respect to terminology. The following are definitions of the terms used in the work reported here.

6.67. **Likelihood**: AGS (2007) defines likelihood *"as a qualitative description of probability or frequency."* Descriptors of likelihood and corresponding annual probability of occurrence used in AGS (2007) are presented in Table 1.

6.68. Probabilities are typically presented in scientific notation (e.g. 10^{-4}). This was the form adopted throughout the T+T reports referred to in my evidence. As this format can be nonintuitive to many people, my evidence presents probabilities in terms of equivalent percentages. This has necessitated the modification of tables referenced from AGS (2007). A table of equivalent probabilities is presented in the evidence of Professor Tim Davies.

6.69. The likelihood descriptors are presented by AGS (2007) in terms of the potential that an event will occur during the design life of a residential structure. AGS (2007) considers a design life of 50 years to be *"reasonable for permanent structures used by people"*. This is also in line with the New Zealand Building Regulations (1992).

Table 1: Qualitative Measures of Likelihood (modified from AGS, 2007)

Annual Probability of Occurrence[1]	Implied Recurrence Interval (years)	Description	Descriptor
10%	10	The event is expected to occur over the design life	Almost certain
1%	100	The event will probably occur under adverse conditions over the design life	Likely
0.1%	1000	The event could occur under adverse conditions over the design life	Possible
0.01%	10,000	The event might occur under very adverse circumstances over the design life	Unlikely
0.001%	100,000	The event is conceivable but only under exceptional circumstances over the design life	Rare
0.0001%	1,000,000	The event is inconceivable or fanciful over the design life	Barely credible

6.70. The return period or recurrence interval does not imply that natural events such as debris flows occur in strict cyclical fashion with a predictable and regular frequency of occurrence. The probability that an event will have occurred over a particular time period increases with each passing year, however the potential for an event to occur in any particular year does not increase with the passage of time. There is an approximately equal probability that an event can occur in any given year (within the physical constraints of sediment supply etc) within the recurrence interval, potentially even on consecutive years.

6.71. **Hazard:** AGS (2007) defines hazard as *“A condition with the potential for causing an undesirable consequence”.* The classification of hazard severity for large[20] landslides is based on the likelihood that the event in question (in this case, a debris flow) will occur. AGS (2007) does not provide a hazard classification specifically related to debris flows,

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[20] Not defined by AGS (2007) but can be considered to be single events of significant potential consequence.

however its classification for large landslides, presented in Table 2 is considered here to be applicable.

6.72. It can be seen that hazard and likelihood are equivalent, in that they both reflect the annual probability of debris flow occurrence. The greater the annual probability of a debris flow occurring, the higher the hazard. Hazard, as it is defined in risk assessments such as AGS (2007) is not a function of event magnitude. Whilst this would appear illogical on the basis that a large event should be "more hazardous" than a small one, in fact what we are doing in this scenario is comparing the consequence of the two events, rather than the hazard. This is an example of how difficult it can be untangling common usage of language around hazard, consequence, and risk.

Table 2: Hazard Classification for Large Landslides (AGS, 2007)

Hazard Descriptor	**Annual Probability of Active Sliding**	**Equivalent Return Period (years)[1]**
Very High	10%	10
High	1%	100
Moderate	0.1% to 0.01%	1,000 to 10,000
Low	0.001%	100,000
Very Low	<0.0001%	>1,000,000

Notes:

1) Equivalent return periods have been added to the original table in AGS (2007).

6.73. **Consequence:** AGS (2007) defines consequence as *"the outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively or quantitatively in terms of … loss of life*." Consequence is represented by the probability that a negative outcome occurs as a result of a debris flow actually occurring. Consequence can be defined either in terms of a fatality or degree of property damage.

6.74. The potential consequences of future debris flow events on the Awatarariki fanhead were informed by the level of destruction observed in the immediate aftermath of the 2005 event, as illustrated in Figure 5.

These observations contributed to the definition of the Debris Flow Intensity Zones (**DFIZ**) defined in paragraph 6.109.

Figure 5: Photographs illustrating the degree of devastation on the Awatarariki fanhead from the May 2005 debris flow event

6.75. **Risk** is defined in AGS (2007) as "*the product of probability and consequences."* This can equally be described mathematically as hazard x consequence. Risk can be assessed in terms of loss of life or property loss.

6.76. **Loss of Life Risk:** AGS (2007) defines Loss of Life Risk as "*the annual probability that the person most at risk will lose his or her life taking account of the landslide hazard and the temporal spatial probability and vulnerability of the person.*"

6.77. Loss of Life Risk is the product of a number of variables that determine the likelihood that a fatality will occur. It is calculated as follows:

Loss of Life Risk = Likelihood x Consequence

$$= P_{(H)} \times [P_{(S:H)} \times P_{(T:S)} \times V_{(D:T)}]$$

Where:

$P_{(H)}$ is the annual probability of a debris flow event occurring

$P_{(S:H)}$ is the probability that, should a debris flow occur, it will impact the subject property

$P_{(T:S)}$ is the probability that the "person most at risk" will be present when the debris impact occurs

$V_{(D:T)}$ is the vulnerability of the person most at risk i.e. the probability that a fatality will result should impact occur

6.78. The methodology by which AGS (2007) calculates the Loss of Life Risk to an individual differs from that presented in the BOPRC RPS Appendix L – Methodology of Risk Assessment. An analysis of the two approaches is provided in the evidence of Dr Massey.

6.79. The classification used by AGS (2007) to define zones of different Loss of Life Risk are presented in Table 3. It is based on the annual probability that a fatality will occur.

Table 3. Risk Descriptors using Loss of Life Criteria (modified from AGS, 2007)

Risk Zoning Descriptors	Annual Probability of Death of the Person Most at Risk in the Zone	Criteria for Existing Developments
Very High	>0.1%	Unacceptable
High	0.1% to 0.01%	Unacceptable
Moderate	0.01% to 0.001%	Tolerable (if as low as reasonably practicable)
Low	0.001% to 0.0001%	Acceptable
Very Low	<0.0001%	Acceptable

6.80. **Vulnerability:** AGS (2007) defines vulnerability for people as the probability that a particular life will be lost given that the person is impacted directly by the debris flow or from the collapse of a structure in which they are located.

6.81. **Person most at risk**: The ”person most at risk” represents the individual with the greatest spatial temporal probability i.e. the person with the greatest site occupancy rate.

6.82. **Societal Risk:** The assessment of potentially multiple fatalities from a single event is termed Societal Risk. The probability that one or more lives may be lost as a result of a debris flow event depends on, amongst other things, the number of people present, where they are located relative to the flow, and their ability to move out of danger.

Initial Debris Flow Hazard and Risk Assessment

6.83. In early 2013 I undertook a QLRA of the Matatā Escarpment for the WDC (T+T, 2013a). Whilst most of the work involved landslide hazard and risk assessments for the escarpment and the properties located near its base, a general assessment of debris flow hazard and risk on the Awatarariki fanhead was also undertaken.

6.84. The work was based on my understanding of the 2005 debris flow event and the RAMMS modelling that I undertook in 2009. No project-specific RAMMS modelling was undertaken. The following explains the process undertaken.

Initial Debris Flow Hazard Zoning

6.85. The first debris flow hazard map prepared for the fanhead is presented below as Figure 6. It divides the Awatarariki Fanhead into low, moderate and high hazard zones. The zoning represents the assessed likelihood that a particular area will be impacted by a debris flow in the future.

6.86. This early assessment of hazard was based on the assumption that the 2005 event had a return period of between 200 and 500 years and that a similar event could be expected to occur again within the same 200 to 500 year time frame. This was considered to represent a conservative estimate of the hazard as it excluded other possibly smaller, but nevertheless potentially destructive events, of shorter return period.

6.87. The return period of the 2005 debris flow event is uncertain. Whilst it is the only well documented occurrence of a debris flow on the Awatarariki Fanhead, there is anecdotal and geomorphologic evidence for debris flows having occurred periodically on the fanhead over the past few thousand years (McSaveney *et al*, 2005)[21].

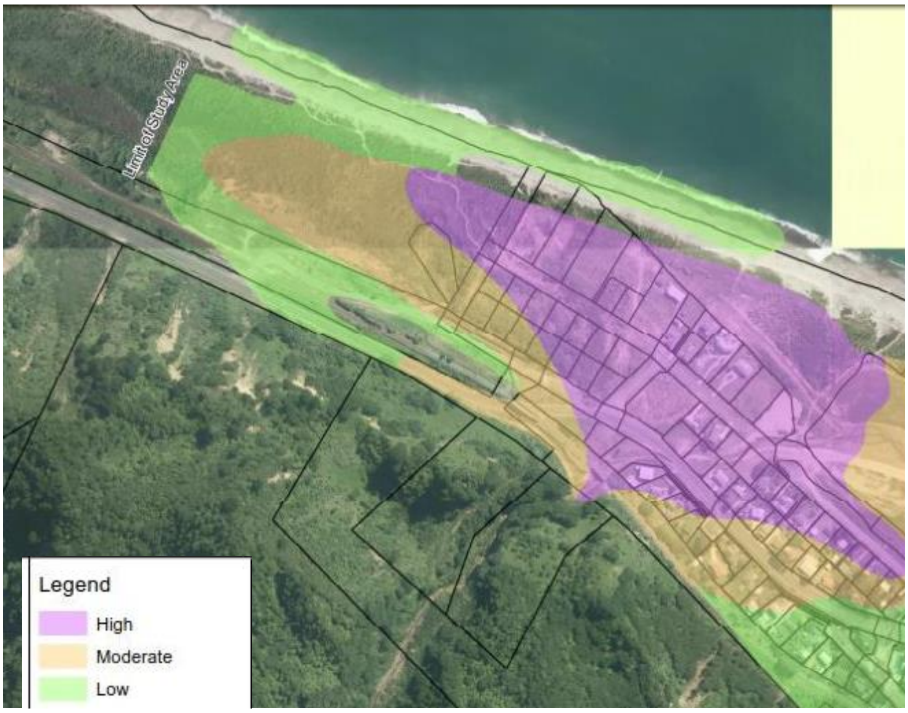

Figure 6: Initial debris flow hazard map for the Awatarariki fanhead (T+T, 2013a)

6.88. Rainfall records indicate that the storm that initiated the Awatarariki Stream debris flow had a return period of between 200 and 500 years. Although rainfall and debris flow return periods are not directly linked, it was assumed by T+T that the 2005 event would have had a return period greater than decades but less than millennia i.e. several hundred years. For the purposes of subsequent analyses, the 2005 debris flow event was assumed to have a return period of between 200 and 500 years.

6.89. My evidence will show that even if the 2005 debris flow event had a significantly longer return period, in the order of 15,000 years, the outcome that the Loss of Life Risk on the Awatarariki Fanhead remains intolerable/unacceptable. As such the issue of return period for the event or events being considered is essentially academic.

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[21] McSaveney, M.J., Beetham, R.D. and Leonard, G.S., 2005. The 18 May 2005 debris flow disaster at Matatā: causes and mitigation suggestions. Report prepared for the Whakatāne District Council dated July 2005.

6.90. By considering the return periods and likelihood descriptors presented in Table 2, the debris flow hazard was considered to be “High” based on a 200 year return period, or “High to Medium” for a 500 year return period. Given this, and the observed level of destruction that occurred in 2005, the central area of the fanhead was subsequently classified as having a high hazard (Figure 6).

6.91. Those more distal areas which suffered demonstrably less damage in the 2005 event were mapped as having moderate and low hazard ratings. This downgrading of the hazard away from the central fanhead was based on the observed effects of the 2005 event. This is not strictly correct, as hazard is simply a measure of likelihood, not consequence, therefore the same hazard rating (High or High to Medium) should apply to the entire fanhead affected to any degree by the 2005 event. However, the purpose of the hazard map was to broadly identify those areas most likely to be significantly impacted by a future large debris flow event and so this modified hazard zonation approach was adopted.

Initial Debris Flow Risk Zoning

6.92. The initial risk assessment of the fanhead undertaken in 2013 (T+T, 2013a) looked at risk in three forms:

(a) Qualitative Risk;

(b) Quantitative Loss of Life Risk; and

(c) Qualitative Property Loss Risk.

Qualitative Risk

6.93. This assessment used the qualitative risk matrix included in AGS (2007) (Table 4 below) which is general in nature, i.e. it is not equivalent to a Loss of Life Risk which is quantitative in nature and considers specific elements of consequence. Based on the estimated return period for the 2005 event of between 200 and 500 years, a similar event is considered “likely”. Based on this, together with the severity of damage observed in 2005, qualitative risk was applied to the debris flow hazard zones (Figure 6) as follows:

(a) The high hazard zone had a corresponding high to very high risk;

(b) The moderate hazard zone had a moderate to very high risk; and

(c) The low hazard zone had a low to high risk.

Table 4: Qualitative Risk Matrix (modified from AGS, 2007)

Relative Likelihood	Consequences				
	Catastrophic	**Major**	**Medium**	**Minor**	**Insignificant**
Almost Certain	VH	VH	VH	H	L
Likely	VH	VH	H	M	L
Possible	VH	H	M	M	VL
Unlikely	H	M	L	L	VL
Rare	M	L	L	VL	VL

Quantitative Loss of Life Risk

6.94. In an attempt to broadly quantify the risk posed by debris flows on the Awatarariki fanhead, Loss of Life Risk calculations were undertaken based on the 2005 event. A single representative value was selected for each of the risk parameters defined in Section 6.77 apart from return period which assumed two values: 200 years and 500 years. The values adopted for the risk parameters were those considered applicable to the central part of the fanhead mapped earlier as having a high debris flow hazard.

6.95. The annual Loss of Life Risk was estimated to be between 0.05% and 0.1% depending on the return period assumed (Table 5). This classified the central fanhead as having a high to very high risk according to AGS (2007) (see Table 3 above).

Table 5: Annual Loss of Life Risk for the 18 May 2005 Debris Flows

Assumed Event Return Period (years)	Factors						$R_{(LOL)}$
	$P_{(H)}$	$P_{(S:H-1)}$	$P_{(S:H-2)}$	$P_{(T:S-1)}$	$P_{(T:S-2)}$	$V_{(D:T)}$	
200 years	0.5%	100%	100%	100%	25%	75%	0.1%
500 years	0.2%	100%	100%	100%	25%	75%	0.05%

Notes:

In these initial calculations, $P_{(S:H)}$ was divided into two components ($P_{(S:H-1)}$, the probability that the dwelling is located below the landslide and $P_{(S:H-2)}$, the probability that the landslide debris can travel as far as the dwelling). This was necessary to account for the position of a dwelling located at the toe of the Matatā escarpment relative to those areas generating landslides. As this was not an issue when considering debris flows alone, P(S:H) would subsequently be treated as a single parameter for the detailed risk assessment of the fanhead debris flows (see Table 9 below).

$P_{(T:S)}$ was similarly divided into two components ($P_{(T:S-1)}$, the probability that someone is home and $P_{(T:S-2)}$, the probability that the person, if home, is in a position that would allow them to be physically impacted). These would subsequently be treated as a single parameter for the detailed risk assessment, with $P_{(T:S-2)}$ being accounted for as part of vulnerability (see Table 9 below).

Qualitative Property Loss Risk

6.96. Property Loss Risk was assessed in accordance with the AGS (2007) classification. As the Property Loss Risk has not been a basis on which the proposed plan changes have been developed, it is not considered further in my evidence even though the analytical work was completed.

Peer Review

6.97. A peer review of the QLRA undertaken for the general Matatā area (T+T, 2013a) was undertaken by Mr Dick Beetham of GHD.

Detailed Debris Flow Risk Assessment

6.98. The initial quantitative Loss of Life Risk assessment was general in nature, as it relied on observations made of the 2005 event, as well as the debris flow modelling undertaken as part of the DDS design. Given the high level of risk indicated by the initial assessment, WDC commissioned T+T to undertake additional detailed debris flow modelling to serve as the basis of a detailed Loss of Life risk assessment. I undertook this work in 2013. The results were presented in a draft report in November 2013 (T+T, 2013b). A final report was issued in July 2015 (T+T, 2015a).

Debris Flow Modelling

6.99. The use of RAMMS allowed those areas of the fanhead inundated by debris to be identified for debris flows of any magnitude (volume). The most significant technical challenge in the modelling was determining the consequences of inundation, and in particular, the probability of a fatality occurring.

6.100. It was assumed that the greatest potential for adverse consequences was associated with those areas impacted by large numbers of boulders and trees. This was considered reasonable given that these were the areas where the greatest physical damage to dwellings was observed in 2005 (see Figure 5). Conversely, those areas inundated primarily with sand, mud and muddy water were assumed to have a significantly reduced risk, at least with respect to dwelling occupancy.

6.101. The approach to the detailed modelling had the following three elements:

(a) Back analysis of the 2005 event with the purpose of determining the flow characteristics that correlated with the different types of debris transport and deposition observed.

(b) Identification of a parameter that could adequately represent flow intensity and debris transportation type; and

(c) Forward analyses to identify those areas likely to be subject to inundation by boulders and high energy flows for a range of different debris flow return periods and magnitudes.

6.102. RAMMS had undergone further development by WSL since the original analyses undertaken in 2009. The most significant of these changes were:

(a) RAMMS now included an analysis module specifically designed for the analyses of debris flows; and

(b) The debris flow was able to be initiated at any location within the stream channel, with the discharge characteristics being defined by a hydrograph. This allowed the two surges previously adopted for design to be included within a single model. Previously individual landslides had to be initiated on the slopes of the DEM catchment and the results combined.

Debris Distribution

6.103. Observations of the fanhead made after the May 2005 event showed that the debris field could be separated into three different zones. These zones were:

(a) Areas with significant accumulations of boulders and/or timber.

(b) Areas where there were an abundance of boulders and timber within a sand, silt and gravel matrix; and

(c) Areas of predominantly sand, silt and gravel with a variable boulder and timber content.

6.104. Each of these areas represented different risk to people and property as could be seen by the level of destruction that occurred within each zone in 2005.

6.105. These three zones were distributed approximately radially across the fanhead with the central fanhead being overlain by the greatest accumulation of boulders and timber. The debris distribution reflected the decreasing ability of the debris flow to continue to transport the larger debris as the flow spread out across the fanhead, thinning out, slowing down and losing momentum and destructive power as it did so.

6.106. The mapped distribution of debris is shown on Figure 7.

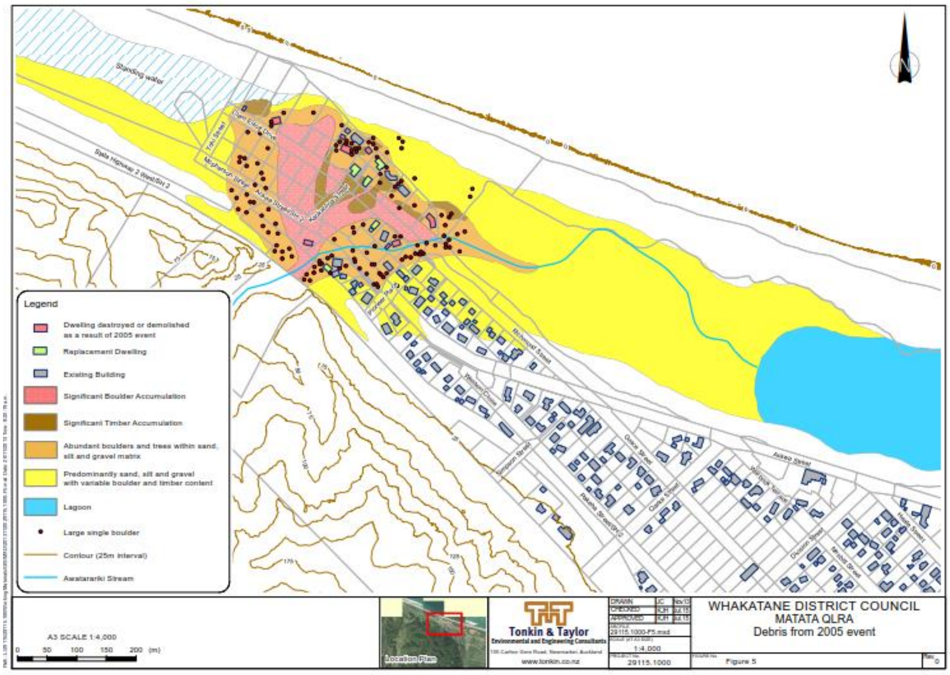

Figure 7 Distribution of various debris types during the 2005 event (T+T, 2013)

Flow Intensity Zonation

6.107. T+T (2013) used a measure of flow energy called the Debris Flow Intensity Index (DFII)[22]:

$$DFII = dv^2$$

Where:

d = depth of debris flow

v = flow velocity

6.108. The DFII is a measure of the kinetic energy passing through a particular area in a unit of time and hence the momentum flux of the flow and impact force on an obstacle. As can be seen from the form of the equation, the DFII is particularly responsive to changes in velocity. As a result, a slowing debris flow rapidly losses its momentum and therefore its ability to carry the larger and heavier debris enclosed within it.

6.109. By extracting flow depth and velocity data from RAMMS for the 2005 back analyses, it was possible to determine both the distribution of DFII across the fanhead and its relationship to the type of debris deposited in 2005. By comparing the distribution of the different debris types across the fanhead in 2005 with the DFII, it was possible to identify four debris flow intensity zones (DFIZ), as defined in Table 6. Photographs indicative of each DFIZ are presented in Figure 8.

Table 6: Definition of Debris Flow Intensity Zones

Debris Flow Intensity Zone DFIZ No.	**Debris Flow Intensity Index DDII**	**Debris Description**
1	>15	Mass boulder passage and deposition. Abundant boulders of several metres in diameter with large

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[22] Jakob, M., Stein, D. and Ulmi, M. 2012. Vulnerability of buildings to debris flow impact. Natural Hazards, 60(2), pp 241-261.

		trees. Deposits several metres thick, boulders commonly being clast supported (boulder to boulder contact)
2	15 - 5	Abundant boulders and trees within a matrix of sand silt and gravel. Boulders up to several metres in diameter but typically less than 1m. Boulders are matrix supported
3	5 – 0.5	Predominantly sand, silt and gravel with occasional boulders, typically less than 0.5m in diameter, although occasional boulders up to 2m in diameter may enter this zone
4	<0.5	Predominantly silt and sand-laden water (debris flood) with minor coarse material. No or rare boulders present.

DFIZ 1, DFII >15

DFIZ 2, DFII 15 - 5

DFIZ 3, DFII 5 – 0.5

DFIZ 4, DFII <0.5

Figure 8 Photographs from 2005 illustrating the debris types associated with each of the DFIZ and DFII

6.110. With DFII being able to be calculated directly from the output of RAMMS, it became possible from this point to map the estimated distribution of debris across the fanhead for debris flow events of any magnitude, with DFII substituting for debris types. Figure 9 presents a debris flow intensity zonation map for a 300,000 m^3 event as predicted by RAMMS.

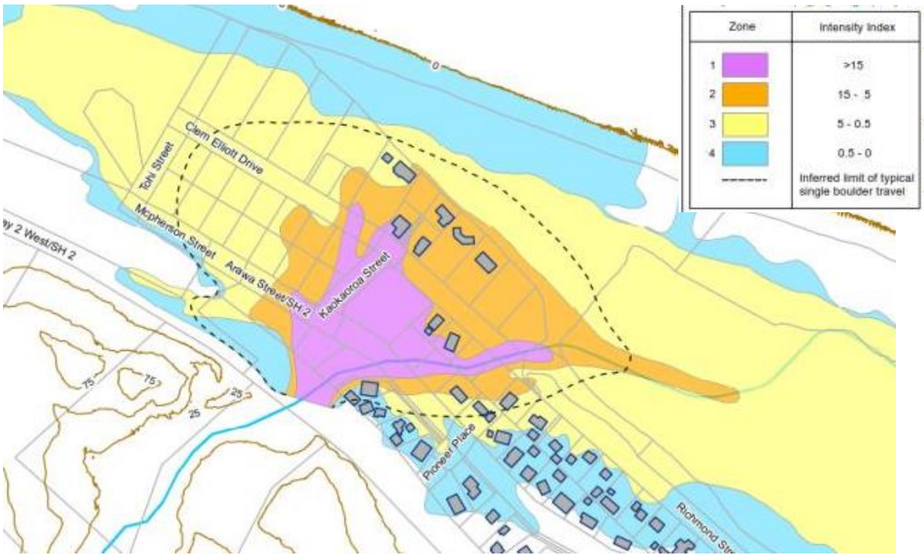

Figure 9 Example of intensity index mapping (300,000 m^3 example)

Loss of Life Risk Estimation Methodology

The Likelihood-Consequence Curve

6.111. Risk is the product of likelihood and consequence. When assessing the risk arising from a single event such as the 2005 Awatarariki Stream debris flow, risk may be represented graphically, as shown in Figure 10, as the area enclosed by Likelihood (y-axis) and Consequence (x-axis).

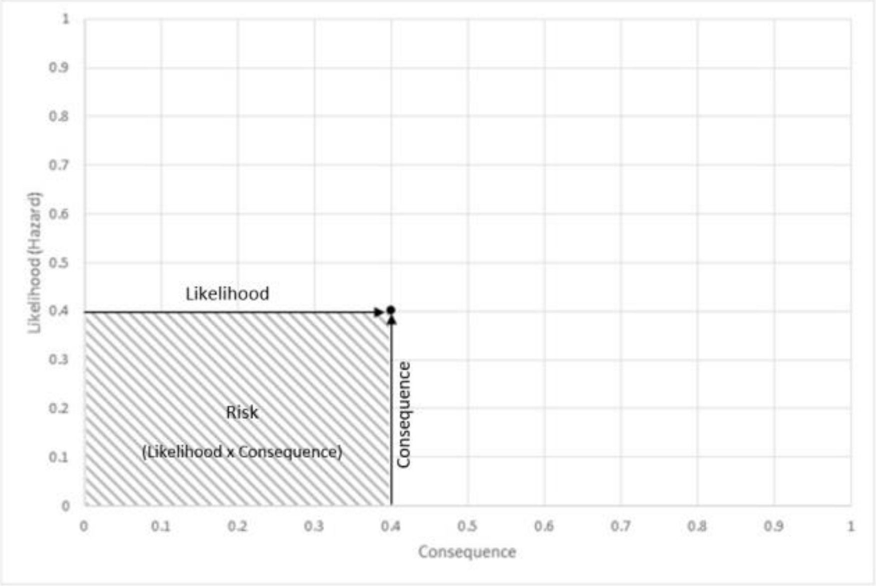

Figure 10: Graphical representation of Risk as the product of Likelihood and Consequence

6.112. It was on this basis that the Loss of Life Risk associated with the 2005 debris flow event was estimated to be between 0.1% and 0.05% depending on whether the return period of the event was either 200 years or 500 years respectively (see Table 5).

6.113. This risk however was limited to a single one-off future event. In reality, a catchment such as that of the Awatarariki Stream has the ability to continue to generate debris flows of different magnitudes and return periods, such that the risk posed to residents or property is greater than that from a single debris flow. Smaller events will occur more often but potentially have lesser consequence over a smaller area, whereas larger magnitude events will occur more rarely but likely be of greater consequence over a larger area. The rapid regeneration of debris for subsequent events is described by Dr McSaveney in paragraph 10.4 of his evidence.

6.114. When estimating the long-term Loss of Life Risk on the Awatarariki Fanhead it is necessary that this be based on the cumulative risk of all potential debris flows. AGS (2007) notes *"that a full risk analysis involves consideration of all the landslide hazards for a site. For comparison with tolerable risk criteria, the individual risk from all landslide hazards affecting the person most at risk, or the property, should be summed."*

6.115. Figure 11 is a graphical representation of the risk associated with events that are both smaller and larger than that represented by the single event in Figure 10. It is axiomatic that those events with a higher annual likelihood of occurrence will have a smaller magnitude and therefore lower consequence. This is represented by area "A" on Figure 10. Likewise, those events that are less likely to occur will be of greater magnitude and therefore greater consequence. These events are represented by area "C" on Figure 11.

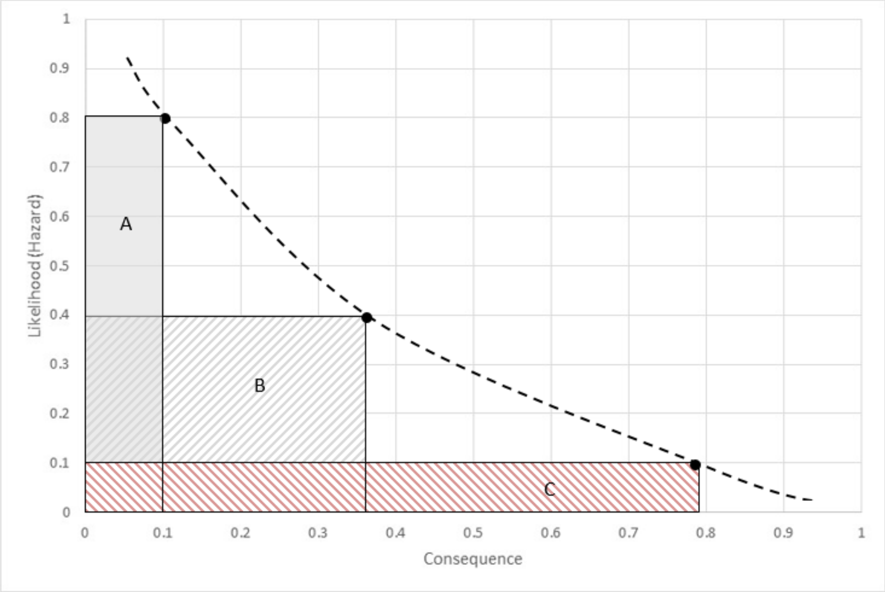

Figure 11: Inverse relationship between Likelihood and Consequence, with high probability events having a low consequence (A) and low probability events having a high consequence (C). Intermediate likelihood and consequence events (B) will often have the largest resultant risk (B). The dashed line represents that general hazard-consequence relationship for all potential events. Total risk from all possible events is represented by the area under the curve.

6.116. When considering a natural phenomenon such as debris flows, there is a continuum of potential magnitude (and return periods) events from the smallest to the largest. Each event will plot along the curved line on Figure 11 as a Likelihood-Consequence pair. The total risk from all events is represented not by a summation of each individual event but by the area beneath the curved line. If total risk was the simple summation of risk from all individual events, then risk would tend towards the infinitely large as the number of events being considered increases.

Limitations on a Likelihood-Consequence Curve for the Awatarariki Stream

6.117. In theory a likelihood-consequence curve developed for the Awatarariki Fanhead would enable Loss of Life risk to be estimated at all locations for all potential future events. In reality it was found that a number of issues prevented the development of such a curve. These included the following:

(a) Only one data point on the likelihood-consequence curve is known (i.e. the 2005 event). Even then there is uncertainty as to what the return period (i.e. likelihood) of that event actually was;

(b) The likelihood of events with magnitudes both smaller and larger than the 2005 event is unknown as they have not been adequately witnessed nor documented. They have been estimated on the basis of magnitude relative to the 2005 event;

(c) Limitations in the knowledge of the minimum and maximum magnitude events that could be generated within the Awatarariki catchment; and

(d) There is no single likelihood-consequence curve applicable to the entirety of the Awatarariki Fanhead as the consequences are location-specific. For instance, a property located at the top of the fanhead (i.e. near the railway bridge) would likely be severely impacted by small, medium and large debris flows, whereas a property located at the coastal limit of the fanhead may be impacted significantly only by large events.

6.118. Given the limited information available with which to construct a reliable likelihood-consequence curve and the variability of this relationship across the fanhead, a simplified approach was adopted in which a small number of debris flow events of distinctly different magnitudes were modelled in RAMMS and the estimated risks from each were summed.

6.119. Simple summation of risk from many events, rather than calculating the area beneath the Likelihood-Consequence curve, will tend to overestimate the total risk, potentially by a significant amount. This can be demonstrated graphically by considering the three different events shown on Figure 11. The risk of each individual event is represented by the enclosed area. However, as can be seen on Figure 11, there is overlap of the three events, particularly towards the origin of the two axes. In such cases, the risk is essentially being erroneously accounted for twice or possibly three times. This double or triple counting of risk near the axes is offset however by the non-inclusion of the large triangular areas immediately beneath the curve. The accuracy of the risk estimate depends on the relative proportion of overcounting and undercounting.

6.120. The use of a single event will therefore greatly underestimate the total risk. As the number of events being considered increases, the greater is the potential overestimation due to overlapping and the smaller is the compensating none-counted area. At some point, the summation process stops underestimating the risk and it begins to overestimate it. An effective estimate of total risk relies on the number of individual events being considered being neither too few nor too many.

Identification of the appropriate number of debris flow events

6.121. In order to determine the appropriate number of debris flow events of different magnitude with which to undertake the risk assessment, Loss of Life risk was calculated for four events of different magnitude. The four events modelled in RAMMS were 50,000 m^3, 150,000 m^3, 300,000 m^3 and 450,000 m^3. The 300,000m^3 event represents a debris flow of approximately the magnitude of the 2005 event. The 150,000 m^3 and 450,000 m^3 events represent debris flows that are 50% smaller and 50% larger than the 2005 event respectively. The 50,000 m^3 event represented the smallest likely magnitude event.

6.122. The Loss of Life Risk was calculated for each of these events and the Likelihood-Consequence curve developed. The results varied from location to location, however the area north of Clem Elliot Drive (Area E1 – see Figure 14) is an area where there is a different calculated consequence for each of the four magnitude events. It was noted during the undertaking of this work that not all areas could be represented by a standard Likelihood-Consequence curve, as the two largest events may have the same extreme consequence for a particular area, even though the largest event nevertheless does have the greatest consequence in terms of area adversely affected.

6.123. The Likelihood-Consequence pairs for each of the four events for Area E1 are presented on Figure 11. The individual and cumulative Loss of Life Risk for this area is presented in Table 7.

Table 7: Debris Flow Magnitude and Loss of Life Risk for Clem Elliot Drive (Zone E1) assuming Shorter Return Periods

Debris Flow Volume (m3)	Likelihood	Consequence	Annual Loss of Life Risk
450,000	0.2%	15%	0.03%
300,000	0.5%	0.75%	0.004%
150,000	1%	0.1%	0.002%
50,000	2%	0.0075%	0.0002%
Cumulative Risk			**0.036%**

6.124. The true total risk, which is the area beneath the Likelihood-Consequence curve in Figure 11, can be found by integrating the curve, which in this case is best estimated by the power function $y = 0.0012x^{-0.309}$ (Figure 12). Integration of this curve between the limits of the smallest and largest events yielded a Loss of Life Risk of 0.047%. This compares well to the 0.036% estimated from the simple summation of the 4 events.

6.125. Based on this, it was considered appropriate to proceed with risk zoning across the fanhead using the summation of the four different debris flow magnitudes.

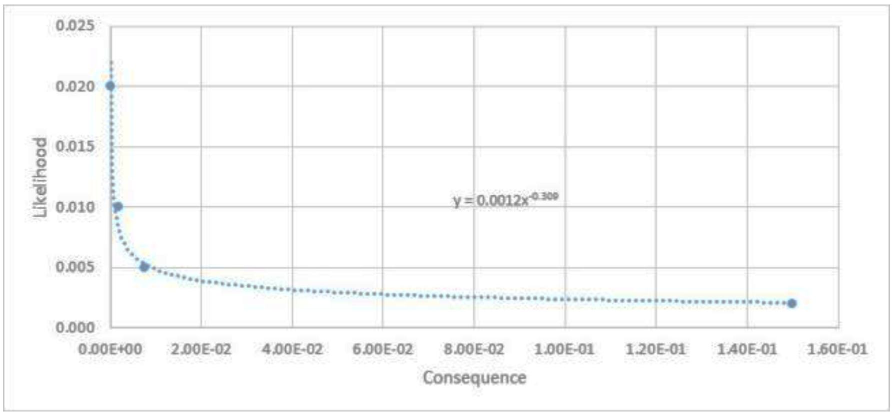

Figure 12: Likelihood-Consequence pairs for the four design debris flow events north of Clem Elliot Drive, Zone E1 (shorter return periods)

Detailed Loss of Life Risk Calculations

6.126. The process by which the Loss of Life Risk was calculated was as follows:

Step 1: Select Design Events

6.127. Four debris flow events of different magnitude were defined, ranging from much smaller than the 2005 event (50,000 m^3) to half as large again (450,000 m^3). The four design debris flow events are identified in Table 8. The 300,000 m^3 event was considered to represent an approximation of what occurred in 2005.

6.128. As described previously, four events of very different likelihood and magnitude were considered to provide a more realistic estimate of total debris flow risk than a single design event (Table 8). However it will be shown that the Loss of Life Risk for that part of the fanhead subject to the Plan Changes can be considered unacceptable (0.001% or 10^{-5} as per McSaveney and Davies, 2015) without having to include the effects of these other magnitude events.

Table 8: Return periods used for design debris flow events

Event Volume (m3)	**Shorter Return Period (yr)**	**Longer Return Period (yr)**
50,000	50	100
150,000	100	250
300,000	200	500
450,000	500	1000

6.129. The 300,000 m^3 event retained the 200 year and 500 year return period range previously described. Those events that were either smaller or larger than the 300,000 m^3 event were assigned return periods generally relative to this (Table 8). The smallest event was limited to a return period of no less than 50 years on the basis that such events may have happened on the fanhead once or twice in recorded history (T+T, 2008). An overlap was applied to the two mid-sized events to account for uncertainty in the return period of the two events considered to be the most likely to be substantially destructive.

Step 2: Determine the extent and severity of impact

6.130. RAMMS was used to define the extent and severity of impact across the fanhead for each of the four magnitude events. This was undertaken by mapping the DFII across the fanhead based on the peak depth and velocity pairs determined from RAMMS (see Table 6).

6.131. An example of the output for the 300,000 m^3 event is presented in Figure 13.

Step 3: Assign Risk Factors to the Debris Flow Intensity Zones

6.132. Each DFIZ was considered to represent different levels of consequence based on the nature of the flow intensity and entrained debris characteristic of them. The three components of consequence ($P_{(S:H)}$, $P_{(T:S)}$ and $V_{(D:T)}$) were varied to reflect the intensity of each DFIZ as per the debris descriptions given in Table 6.

6.133. The consequence values selected for each DFIZ are presented in Table 9. The most significant consequences were assigned to DFIZ 1 and DFIZ 2, as these represent areas that are located within the main accumulation of large boulders and trees (as calibrated by the 2005 event). More distal areas characterised by finer-grained debris with occasional (DFIZ 3) to rare boulders (DFIZ 4) had significantly lower consequences. The total consequence values for DFIZ No. 1 and No. 2 (i.e. within the main boulder debris field) are two orders of magnitude greater than for DFIZ No. 3 and No. 4 which are located beyond it.

6.134. Assumptions made in selecting these values were as follows:

(a) $P_{(T:S)}$, the probability that the Person Most at Risk will be present when the debris impact occurs was assumed to be 75% for all locations. AGS (2007) does not provide a recommended value for $P_{(T:H)}$, however it does recommend that occupancy should consider *“an average family on a full-time residential basis”*. In their assessment of rockfall risk in Christchurch, GNS (Massey *et al*, 2012)[23] assumed an occupancy rate of 67%, although recognising *“in reality the most exposed person is still likely to be present 100% of their time”*;

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[23] Massey, C.I., McVerry, G., Gerstenberger, M. and Litchfield, N. 2012. Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Additional assessment of the life-safety risk from rockfalls (boulder rolls). GNS Consultancy Report 2012/214, September 2012.

(b) The vulnerability of the Person Most at Risk was varied between 1% and 75% depending on the DFIZ in order to reflect the overall greater probability of a fatality occurring in an area subject to higher velocity flows and significant boulder impact compared to more distal areas subject largely to fine-grained debris-floods. In general, those properties located landward of Clem Elliot Drive are located within DFIZ 1 and were assigned a vulnerability of 75%, whereas those properties located seaward of Clem Elliot Drive are within DFIZ 2 and were assigned a vulnerability of 20%. GNS (Massey *et al*, 2012) adopted a uniform vulnerability of 50% for the rockfall hazard in the Port Hills; and

(c) The probability that the subject property would be impacted ($P_{(S:H)}$) was varied in a manner similar to $P_{(T:S)}$, to reflect the greater consequence of a potentially fatal impact within an area inundated by large boulders (DFIZ1 and DFIZ 2) compared to more distal areas affected largely by debris floodwaters and occasional boulders. $P_{(S:H)}$ was therefore used to reflect the probability that an impact of significance would occur rather than just any impact. This provided a lower overall risk as a result.

Table 9: Design Loss of Life Risk Factors

Flow Intensity Zone		**Boulder Impact Zone**	**Probability of structural impact** **P(S:H)**	**Probability that the PMR will be present** **P(T:S)**	**Vulnerability** **V(D:T)**	**Comments**	**Total Consequence**
1		Inside main boulder field	100%	75%	75%	Certain to be impacted by mass boulders	56%
2		Inside main boulder field	100%	75%	20%	Certain to be impacted by mass boulders	15%
3	3a	Inside main boulder field	20%	75%	5%	Risks associated with single boulders	0.75%

	3b	Outside main boulder field	5%	75%	5%	Risks associated with rare boulders	0.19%
4	4a	Inside main boulder field	10%	75%	5%	Risks associated with rare single boulders	0.38%
	4b	Outside main boulder field	1%	75%	1%	Risks associated with very rare boulders	0.0075%

Step 4: Calculate Loss of Life Risk for Each DFIZ

6.135. The assigning of return periods to each magnitude event and probabilities to each of the consequence parameters allowed Loss of Life Risk to be calculated for each DFIZ and each magnitude event. The matrix of results is presented in Table 10.

6.136. The upper rows of Table 10 show the calculation of risk associated with each risk zone, which in turn reflect the intensity of debris impact. The lower tables indicate the DFIZ associated with each event magnitude.

6.137. By overlaying the DFIZ maps for all four magnitude events (Figure 13 being an example of just one event) it was possible to identify a total of 22 areas with a unique combination of DFIZ for the four events. Each of these areas (designated A1 to J) has a single Loss of Life Risk for each of the two return periods.

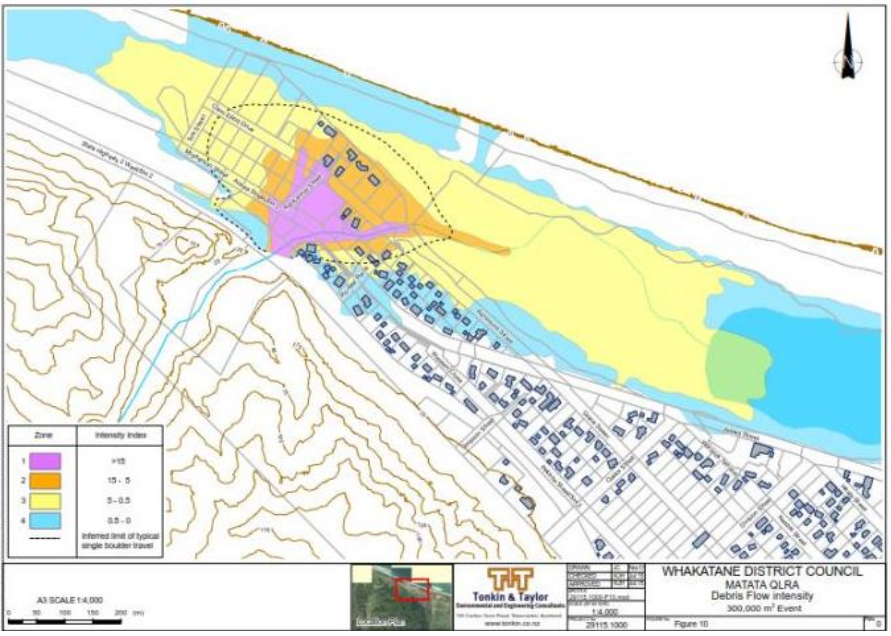


Figure 13: **DFII distribution for a 300,000 m^3 debris flow event *(T+T, 2015a)***

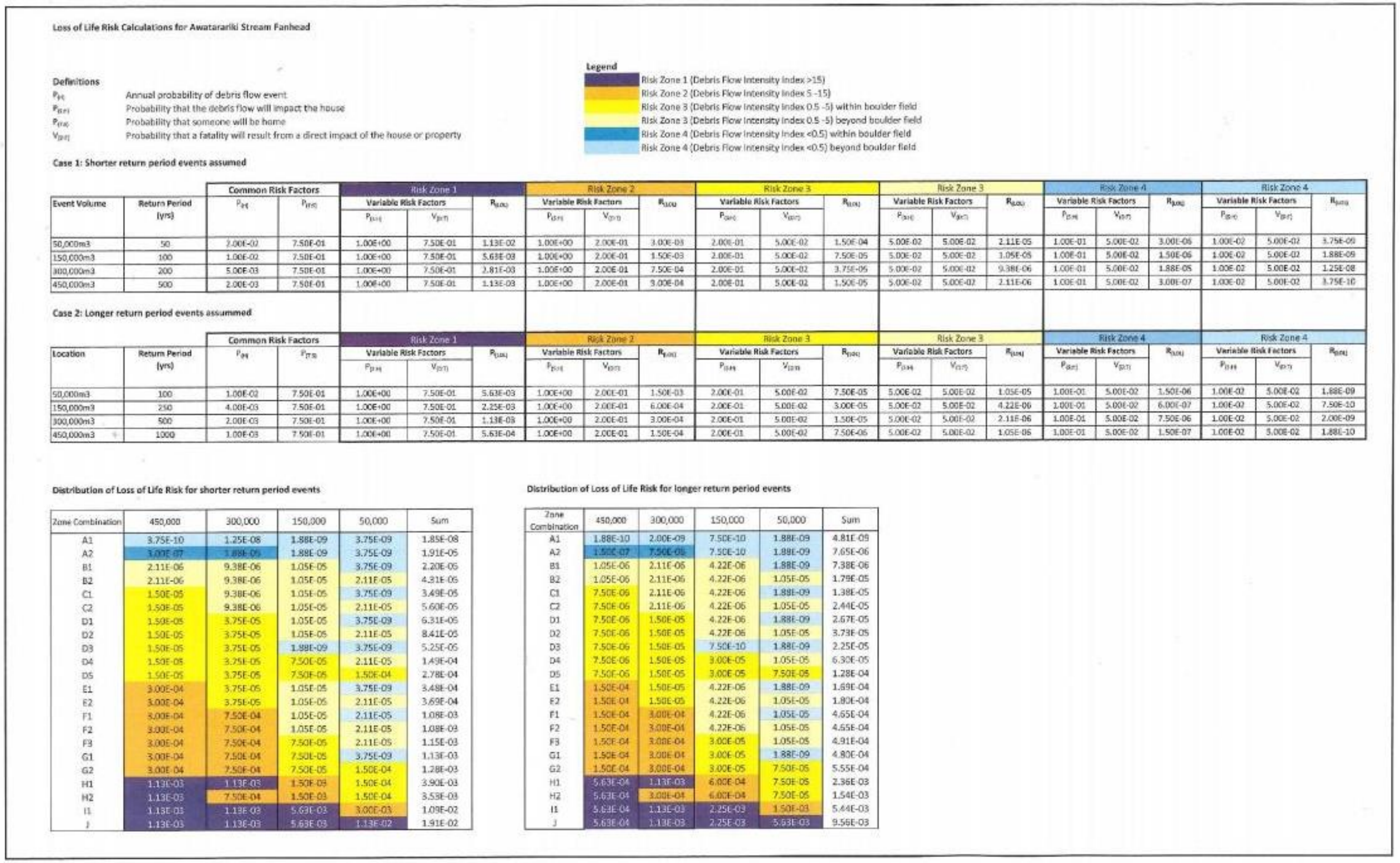
6.138. The Loss of Life Risk appropriate to any particular property was a function of the DFIZ in which it was located, as determined by RAMMS. For any given property, the relevant DFIZ would vary depending upon its location on the fanhead. Those properties located at the seaward end of the fanhead may be within a different DFIZ for each magnitude event whereas a property located at the top of the fanhead near the railway bridge may be within DFIZ 1 for all four events.

6.139. Figure 14 illustrates the distribution of the 22 DFIZ combinations. Table 10 identifies the DFIZ associated with each area, the Loss of Life Risk calculated for each event and the total Loss of Life Risk derived from summing the risk for each of the four events.

Step 5: Generation of Loss of Life Contours

6.140. To enable Loss of Life risk to be determined more readily, the singular risk associated with each of the 22 DFIZ areas was converted to a risk contour map. These contours reflect the boundary between the DFII zones that were greater than and less than 0.01% and 0.001% respectively. There is a separate contour map for the shorter return periods and longer return periods. These are presented as Figure 15 and 16, respectively.

Table 10: Loss of Life Risk Calculation Matrix



Loss of Life Risk Calculations for Awatarariki Stream Fanhead

Definitions

$P_{(H)}$	Annual probability of debris flow event
$P_{(S:H)}$	Probability that the debris flow will impact the house
$P_{(T:S)}$	Probability that someone will be home
$V_{(D:T)}$	Probability that a fatality will result from a direct impact of the house or property

Legend

■	Risk Zone 1 (Debris Flow Intensity Index >15)
■	Risk Zone 2 (Debris Flow Intensity Index 5 -15)
■	Risk Zone 3 (Debris Flow Intensity Index 0.5 -5) within boulder field
■	Risk Zone 3 (Debris Flow Intensity Index 0.5 -5) beyond boulder field
■	Risk Zone 4 (Debris Flow Intensity Index <0.5) within boulder field
■	Risk Zone 4 (Debris Flow Intensity Index <0.5) beyond boulder field

Case 1: Shorter return period events assumed

		Common Risk Factors		Risk Zone 1			Risk Zone 2			Risk Zone 3			Risk Zone 3			Risk Zone 4			Risk Zone 4		
Event Volume	Return Period (yrs)	$P_{(H)}$	$P_{(T:S)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$
				$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$	
50,000m3	50	2.00E-02	7.50E-01	1.00E+00	7.50E-01	1.13E-02	1.00E+00	2.00E-01	3.00E-03	2.00E-01	5.00E-02	1.50E-04	5.00E-02	5.00E-02	2.11E-05	1.00E-01	5.00E-02	3.00E-06	1.00E-02	5.00E-02	3.75E-09
150,000m3	100	1.00E-02	7.50E-01	1.00E+00	7.50E-01	5.63E-03	1.00E+00	2.00E-01	1.50E-03	2.00E-01	5.00E-02	7.50E-05	5.00E-02	5.00E-02	1.05E-05	1.00E-01	5.00E-02	1.50E-06	1.00E-02	5.00E-02	1.88E-09
300,000m3	200	5.00E-03	7.50E-01	1.00E+00	7.50E-01	2.81E-03	1.00E+00	2.00E-01	7.50E-04	2.00E-01	5.00E-02	3.75E-05	5.00E-02	5.00E-02	9.38E-06	1.00E-01	5.00E-02	1.88E-05	1.00E-02	5.00E-02	1.25E-08
450,000m3	500	2.00E-03	7.50E-01	1.00E+00	7.50E-01	1.13E-03	1.00E+00	2.00E-01	3.00E-04	2.00E-01	5.00E-02	1.50E-05	5.00E-02	5.00E-02	2.11E-06	1.00E-01	5.00E-02	3.00E-07	1.00E-02	5.00E-02	3.75E-10

Case 2: Longer return period events assummed

		Common Risk Factors		Risk Zone 1			Risk Zone 2			Risk Zone 3			Risk Zone 3			Risk Zone 4			Risk Zone 4		
Location	Return Period (yrs)	$P_{(H)}$	$P_{(T:S)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$	Variable Risk Factors		$R_{(LOL)}$
				$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$		$P_{(S:H)}$	$V_{(D:T)}$	
50,000m3	100	1.00E-02	7.50E-01	1.00E+00	7.50E-01	5.63E-03	1.00E+00	2.00E-01	1.50E-03	2.00E-01	5.00E-02	7.50E-05	5.00E-02	5.00E-02	1.05E-05	1.00E-01	5.00E-02	1.50E-06	1.00E-02	5.00E-02	1.88E-09
150,000m3	250	4.00E-03	7.50E-01	1.00E+00	7.50E-01	2.25E-03	1.00E+00	2.00E-01	6.00E-04	2.00E-01	5.00E-02	3.00E-05	5.00E-02	5.00E-02	4.22E-06	1.00E-01	5.00E-02	6.00E-07	1.00E-02	5.00E-02	7.50E-10
300,000m3	500	2.00E-03	7.50E-01	1.00E+00	7.50E-01	1.13E-03	1.00E+00	2.00E-01	3.00E-04	2.00E-01	5.00E-02	1.50E-05	5.00E-02	5.00E-02	2.11E-06	1.00E-01	5.00E-02	7.50E-06	1.00E-02	5.00E-02	2.00E-09
450,000m3	1000	1.00E-03	7.50E-01	1.00E+00	7.50E-01	5.63E-04	1.00E+00	2.00E-01	1.50E-04	2.00E-01	5.00E-02	7.50E-06	5.00E-02	5.00E-02	1.05E-06	1.00E-01	5.00E-02	1.50E-07	1.00E-02	5.00E-02	1.88E-10

Distribution of Loss of Life Risk for shorter return period events

Zone Combination	450,000	300,000	150,000	50,000	Sum
A1	3.75E-10	1.25E-08	1.88E-09	3.75E-09	1.85E-08
A2	3.00E-07	1.88E-05	1.88E-09	3.75E-09	1.91E-05
B1	2.11E-06	9.38E-06	1.05E-05	3.75E-09	2.20E-05
B2	2.11E-06	9.38E-06	1.05E-05	2.11E-05	4.31E-05
C1	1.50E-05	9.38E-06	1.05E-05	3.75E-09	3.49E-05
C2	1.50E-05	9.38E-06	1.05E-05	2.11E-05	5.60E-05
D1	1.50E-05	3.75E-05	1.05E-05	3.75E-09	6.31E-05
D2	1.50E-05	3.75E-05	1.05E-05	2.11E-05	8.41E-05
D3	1.50E-05	3.75E-05	1.88E-09	3.75E-09	5.25E-05
D4	1.50E-05	3.75E-05	7.50E-05	2.11E-05	1.49E-04
D5	1.50E-05	3.75E-05	7.50E-05	1.50E-04	2.78E-04
E1	3.00E-04	3.75E-05	1.05E-05	3.75E-09	3.48E-04
E2	3.00E-04	3.75E-05	1.05E-05	2.11E-05	3.69E-04
F1	3.00E-04	7.50E-04	1.05E-05	2.11E-05	1.08E-03
F2	3.00E-04	7.50E-04	1.05E-05	2.11E-05	1.08E-03
F3	3.00E-04	7.50E-04	7.50E-05	2.11E-05	1.15E-03
G1	3.00E-04	7.50E-04	7.50E-05	3.75E-09	1.13E-03
G2	3.00E-04	7.50E-04	7.50E-05	1.50E-04	1.28E-03
H1	1.13E-03	1.13E-03	1.50E-03	1.50E-04	3.90E-03
H2	1.13E-03	7.50E-04	1.50E-03	1.50E-04	3.53E-03
I1	1.13E-03	1.13E-03	5.63E-03	3.00E-03	1.09E-02
J	1.13E-03	1.13E-03	5.63E-03	1.13E-02	1.91E-02

Distribution of Loss of Life Risk for longer return period events

Zone Combination	450,000	300,000	150,000	50,000	Sum
A1	1.88E-10	2.00E-09	7.50E-10	1.88E-09	4.81E-09
A2	1.50E-07	7.50E-06	7.50E-10	1.88E-09	7.65E-06
B1	1.05E-06	2.11E-06	4.22E-06	1.88E-09	7.38E-06
B2	1.05E-06	2.11E-06	4.22E-06	1.05E-05	1.79E-05
C1	7.50E-06	2.11E-06	4.22E-06	1.88E-09	1.38E-05
C2	7.50E-06	2.11E-06	4.22E-06	1.05E-05	2.44E-05
D1	7.50E-06	1.50E-05	4.22E-06	1.88E-09	2.67E-05
D2	7.50E-06	1.50E-05	4.22E-06	1.05E-05	3.73E-05
D3	7.50E-06	1.50E-05	7.50E-10	1.88E-09	2.25E-05
D4	7.50E-06	1.50E-05	3.00E-05	1.05E-05	6.30E-05
D5	7.50E-06	1.50E-05	3.00E-05	7.50E-05	1.28E-04
E1	1.50E-04	1.50E-05	4.22E-06	1.88E-09	1.69E-04
E2	1.50E-04	1.50E-05	4.22E-06	1.05E-05	1.80E-04
F1	1.50E-04	3.00E-04	4.22E-06	1.05E-05	4.65E-04
F2	1.50E-04	3.00E-04	4.22E-06	1.05E-05	4.65E-04
F3	1.50E-04	3.00E-04	3.00E-05	1.05E-05	4.91E-04
G1	1.50E-04	3.00E-04	3.00E-05	1.88E-09	4.80E-04
G2	1.50E-04	3.00E-04	3.00E-05	7.50E-05	5.55E-04
H1	5.63E-04	1.13E-03	6.00E-04	7.50E-05	2.36E-03
H2	5.63E-04	3.00E-04	6.00E-04	7.50E-05	1.54E-03
I1	5.63E-04	1.13E-03	2.25E-03	1.50E-03	5.44E-03
J	5.63E-04	1.13E-03	2.25E-03	5.63E-03	9.56E-03

Figure 14: Distribution of the DFIZ combinations, each representing a unique set of Loss of Life Risk results.

Figure 15: Loss of Life Risk contours for shorter return period events. The yellow box identifies the properties assessed as part of subsequent probabilistic analysis

Figure 16: Loss of Life Risk contours for longer return period events.

Results of Detailed Loss of Life Risk Analyses

6.141. The Loss of Life Risk contour plans (Figures 14 and 15) showed that all of the dwellings located to the west of the Awatarariki Stream, and a narrow area east of the stream had an annual Loss of Life risk in excess of 0.01% . A number of vacant properties located in the north-west part of the subdivision are located outside of the modelled 0.01% contour, although still within the modelled 0.001% contour recommended by McSaveney and Davies (2015) as the minimum retreat area. WDC adopted this as the High Risk Zone. The detailed risk calculations (Table 10) show that the single most significant contribution to the total risk is the 300,000 m^3 event, which effectively represents a repeat of the 2005 event.

Consequences of Parameter Selection

6.142. The results of the risk assessment are ultimately the product of the various parameters that make up the calculation. The following considers the potential for alternative outcomes to have been obtained had alternative parameters or assumptions been adopted.

Number of debris flow events

6.143. Each additional debris flow event included in the risk assessment increases the cumulative or total risk. The assessment presented here is based on four events of different magnitude. The minimum risk that can reasonably be calculated for the Awatarariki fanhead is a single event of 300,000 m^3 (i.e. a repeat of the 2005 event).

6.144. Figure 17 presents the 0.01% and 0.001% Loss of Life Risk contours resulting from the 300,000 m^3 event alone, conservatively assuming that the longer return period (i.e. 500 years) applies. The assumption that other events of different magnitude are possible (in addition to a repeat of the 2005 event) only increases the risk above this level. Therefore, it is possible to conclude that the Loss of Life Risk is unacceptable across the fanhead simply based on the potential for the 2005 event to be repeated.

Return Period

6.145. The Loss of Life Risk is sensitive to the assumed return period of the design event. The seaward-most dwellings on Clem Elliot Drive are calculated to have a Loss of Life Risk for just the 300,000 m^3 event of 0.03% for a 500 year return period and 0.075% for a 200 year return period event (see Table 10). In order for these properties to be beyond the 0.01% risk contour, a future debris flow event equivalent to that of 2005 (i.e. 300,000 m^3) would need to have a return period of no less than 1,500 years, all else being equal. In order for these same properties to lie beyond the 0.001% risk contour (the maximum risk level recommended by McSaveney and Davies (2015)), the return period would need to be at least 15,000 years.

6.146. The effect of climate change will be to increase the frequency and intensity of storm events of the type that could generate debris flows in the Awatarariki catchment[24]. This subject is considered in detail in the evidence of Mr Peter Blackwood.

6.147. Given that 0.001% has been adopted by WDC as the basis for identifying the high risk area subject to retreat, the very long return period required to achieve a Loss of Life Risk less than this means that the acknowledged uncertainties associated with the event return period are effectively irrelevant to the final result, as the Loss of Life Risk associated with the 2005 event is simply too high for reasonable variations within this ,and other selected parameters, to affect the overall outcome.

6.148. My risk assessment report (T+T, 2015a) provided some discussion around the annual Loss of Life risk that is typically considered to be intolerable/unacceptable, however the report did not provide a recommendation as to which risk contour would identify any proposed area of potential retreat. This matter was considered by McSaveney and Davies (2015) whose recommendations were subsequently adopted by the Council.

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[24] Ministry for the Environment. 2020. National Climate Change Risk Assessment for Aotearoa New Zealand: Main report. Wellington: Ministry for the Environment.

Figure 17: ***Lines enclosing areas with a Loss of Life risk greater than 0.001% (red) and 0.01% (orange) based only on the 300,000 m^3 event, assuming a 500 year return period.***

6.149. The detailed risk analysis was reported in draft form in November 2013 (T+T, 2013b). Following receipt of public comments on the draft, a final report was issued in July 2015 (T+T, 2015a).

Societal Risk

6.150. The basis for the assessment as to whether the risk of fanhead occupation was intolerable (or otherwise) was based on the Loss of Life Risk for an individual (the “person most at risk”). In addition to this, T+T (2015a) presented an assessment of Societal Risk, which is an assessment of the total number of lives that could be lost in the event of another debris flow event.

6.151. The Societal Risk was calculated for the then estimated current population density of the fanhead as well as a future higher density model that assumed that dwellings would be present on all residential properties west of the Awatarariki Stream.

6.152. The estimated number of fatalities ranged from 1 to 8 depending upon the time frame being considered (i.e. the number of individual events that might occur within the time frame) and the assumed population density.

6.153. By applying the same methodology to the fanhead with the housing density estimated to be present in May 2005, it is possible to estimate the number of fatalities that could have been expected based on the magnitude of the actual event.

Assuming that one resident was present within each of the houses located within DFIZ 1 and 2 during the 2005 event (see Figure 9), it is estimated that approximately 3 deaths could have occurred.

6.154. Whilst in actuality no fatalities occurred on the day, the extent and severity of the destruction, as illustrated by the photographs presented in Figure 5, would suggest that a death toll of 3 would not be an unreasonable estimate. It is my opinion that it was only luck that prevented one or more fatalities from occurring.

6.155. By plotting the results onto the cumulative frequency-number of fatalities (F-N) chart presented in AGS (2007) it was found that the Societal Risk was classified as “unacceptable” for both the lower and higher population density cases (Figure 18).

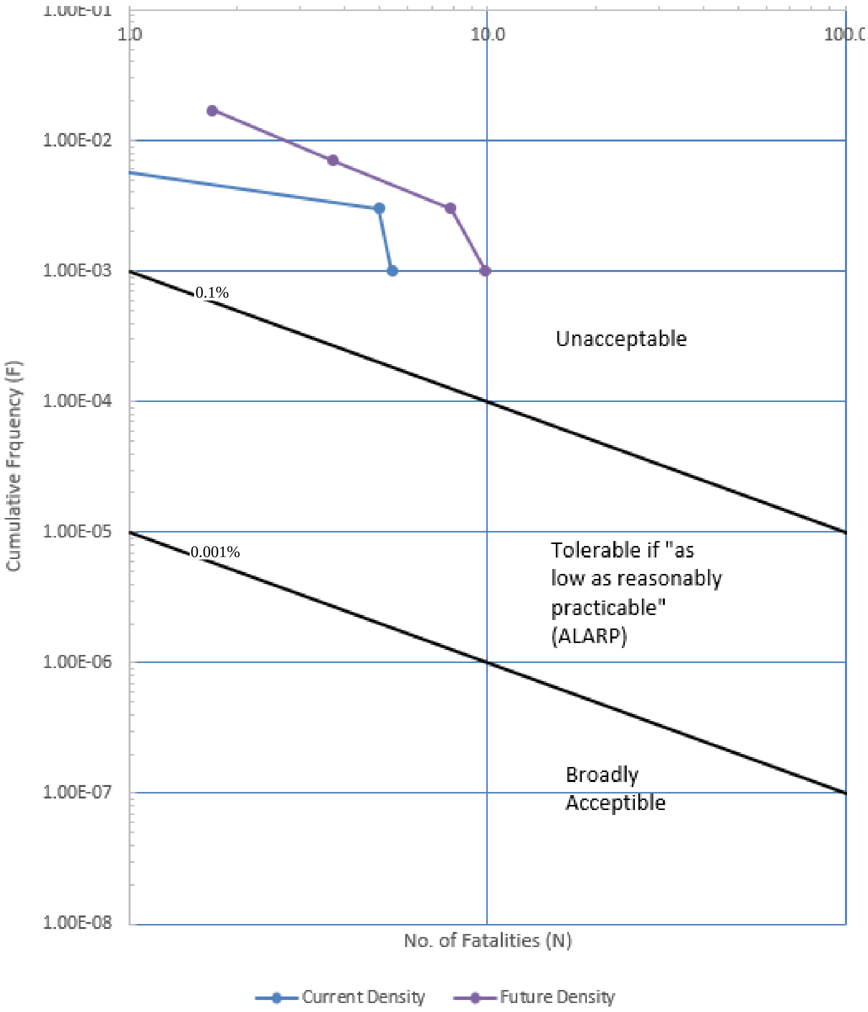

Figure 18: Societal risk chart from T+T (2015a). Source of base chart: AGS (2007)

6.156. Reducing the number of residents on the fanhead would result in a lower Societal Risk (i.e. the number of fatalities for any given event would be expected to be lower). The Loss of Life Risk to any individual, including the Person Most at Risk, however, does not reduce with a reduction in population. This risk can only realistically be lowered by reducing the time that the individual spends on the fanhead, lowering the probability of impact or lowering the vulnerability through engineering works etc.

6.157. The outcome of this assessment was noted in T+T (2015a), however Societal Risk was not the basis on which continued occupancy of the fanhead was considered intolerable/unacceptable, nor was it used to estimate the annual individual fatality risk (AIFR) as defined by the RPS.

Peer Review

6.158. WDC issued T+T (2015a) to Prof Tim Davies of University of Canterbury and Dr Mauri McSaveney of GNS Science for peer review. As a result of a workshop held in September 2015, the peer reviewers recommended the following (McSaveney and Davies, 2015)[25]:

(a) Probabilistic analyses be undertaken to determine how sensitive (or otherwise) the Loss of Life Risk calculations are to variability of the input parameters; and

(b) That the 0.001% risk contour be *used "to delineate the minimum retreat area"*. This means that the modelled 0.001% per annum risk contour defined the limit of what was unacceptable, compared to the 0.01% risk level used by AGS (2007).

6.159. The Bay of Plenty Regional Council issued T+T (2015a) to GHD for peer review. The results of probabilistic analyses undertaken after completion of T+T (2015a) were contained within McSaveney and Davies (2015), which was also reviewed by GHD. The review (GHD, 2019)[26] was prepared by Mr Greg Kotze and reviewed by Mr Andrew Leventhal. It is noted that Mr Kotze was on the Landslide Task Force and Mr Leventhal was chair of the Steering Committee for AGS (2007).

6.160. GHD provided the headline conclusions that the Loss of Life Risk assessment carried out by T+T was "*robust*" and "*in accordance with industry best practice*".

6.161. GHD (2019) was of the opinion that the approach adopted by T+T (2015), in which a single value was used uniformly across the fanhead for some of the factors that contribute to Loss of Life risk, "*may have resulted in a degree of conservative generalisation in some risk calculation outcomes*" and "*that this may have resulted in Loss of Life calculation outcomes that are potentially higher for some properties than would be the case if property-specific parameters were adopted.*"

6.162. I note that the values of the various parameters used to calculate Loss of Life Risk (see Table 9) did in fact vary across the fanhead in response to DFIZ and DFII. Specifically, the probability of impact and the vulnerability of anyone present to that impact both decreased significantly with distance across the fanhead. Uniform parameter values applied only to each of the DFIZ, which as shown in Figure 14, are of relatively limited spatial extent.

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[25] McSaveney, M.J. and Davies, T.R.H., 2015. Peer Review: Awatarariki debris-flow-fan risk to life and retreat zone extent. Letter report to Whakatāne District Council dated 17 November 2015

[26] GHD, 2019. Technical assessment, debris flow risk management, Awatarariki fanhead, Matatā, Bay of Plenty. Letter report to Bay of Plenty Regional Council dated 31 October, 2019.[Appendix X to s.42A report]

6.163. Based on the potential for Loss of Life Risk to be reduced as a result of using property-specific values, GHD (2019) state that there was a possibility that certain properties would change from being in a high risk zone to a medium risk zone. This is the equivalent of changing from unacceptable to tolerable according to guidance in AGS (2007). I note that for GHD this meant a property changing from a Loss of Life risk of greater than 0.01% to one that is between 0.01% and 0.001%. McSaveney and Davies (2015) however still considered a risk between 0.01% and 0.001% as unacceptable and sufficiently high for retreat to be recommended.

6.164. As GHD (2019) do not provide any property-specific calculations or examples of where such a change in risk classification could potentially occur, it must be taken that they have offered this as a general possibility and not something that could reasonably be expected to result.

6.165. Purely from a technical standpoint, it can be demonstrated that not only is a property-specific risk assessment approach not realistic, it doesn’t materially change the outcomes of the risk assessment presented in T+T (2015a) and T+T (2015b). The input parameters simply cannot vary sufficiently for any of the properties subject to retreat being classified as having a Loss of Life Risk of less than 0.001% should a property specific assessment be attempted.

6.166. GHD (2019) consider that some of the accumulated debris from the 2005 event could provide some protection to certain properties during a future event. That any protection would result from this has not been demonstrated, nor has there been any consideration given to a potential increase in Loss of Life Risk and property damage at adjacent properties as a result of additional debris being diverted in their direction. Furthermore, future development of the fanhead would almost certainly see this debris removed.

6.167. GHD (2019) argue that individual properties may have occupancy rates below the 75% assumed by T+T (2015a and 2015b) for the “*person most at risk*” and that Loss of Life Risk is over-estimated as a result. If we assume that there is a property on the fanhead that currently has a Loss of Life risk greater than 0.01% which would drop below this on the basis of a lower occupancy rate (as a matter of fact, there isn’t), it could be rerated as “high risk” simply by the process of change such as a change in a family member’s employment status or by selling the property to an owner with a higher occupancy rate. The Loss of Life Risk level for such a property would require not only re-evaluation whenever the occupancy status changed but it could result in the farcical situation of a property being acceptable for occupancy one day but unacceptable the next.

6.168. Whilst it is probable that most people do not spend 75% of their time at home, the Loss of Life Risk is not intended to reflect the risk to such people. It is specifically intended for the Person Most at Risk, for which 75% can be considered reasonable, if not actually conservative.

6.169. The Loss of Life Risk calculations from T+T (2015b) were rerun adopting the modified parameter values suggested by GHD (2019). There was a reduction in Loss of Life Risk, as there must be, however the magnitude of this reduction was insufficient to produce any material change in the outcomes of the original assessment. Figure 19 illustrates the change in 0.01% and 0.001% Loss of Life Risk contour lines that would result from conservatively adopting all of the GHD (2019) proposed parameters at the same time, even though some of these parameters are valid only for some areas, not all.

6.170. There are no properties that were assessed by T+T (2015b) as having a Loss of Life Risk level greater than 0.01% that end up below this level as a result of adopting the GHD (2019) parameters i.e. all high risk areas remain as such, simply because the level of risk is so great that even with substantial reductions in numerical value they do not cross the threshold to moderate risk. All but one property (32 Clem Elliot Drive) on the fanhead remain inside the 0.001% Loss of Life Risk contour adopted by WDC as the High Risk Zone. This confirms my earlier conclusion that the high risk classification of the fanhead cannot be downgraded simply by modifying the values of the input parameters.

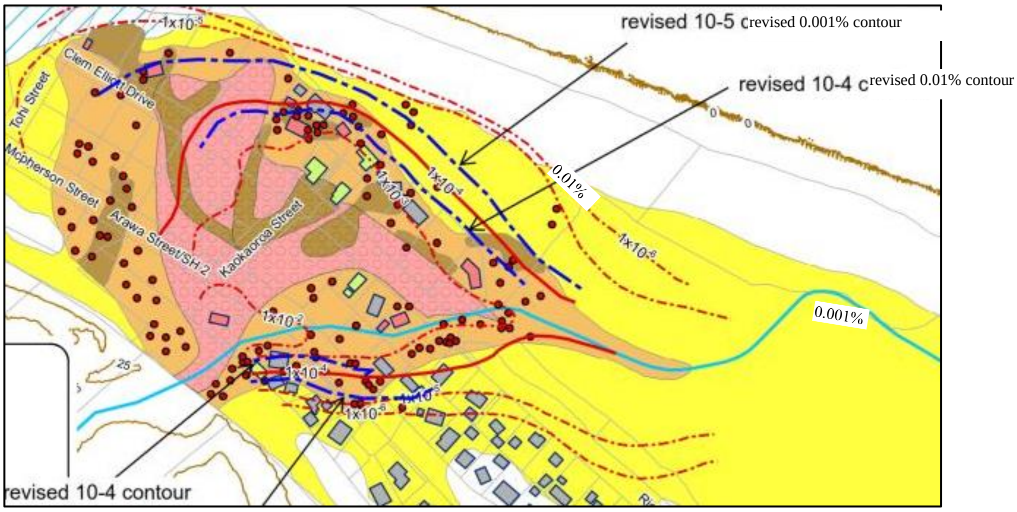

Figure 19: ***Shift in Loss of Life risk contours. Red contours are from T+T (2015b) whereas the blue contours are those that result from using the GHD parameters****.*

Adoption of 10^{-5} as the annualised risk for retreat

6.171. One of the effects of adopting 0.001% as the basis for defining the minimum extent of retreat on the Awatarariki Fanhead (McSaveney and Davies, 2015) was a reduction in the dependence of the outcome on the return periods chosen for the design debris flow events.

6.172. I therefore consider that the outcome of the risk analysis (i.e. that the residential properties on the Awatarariki fanhead within the proposed High Debris Flow Risk Policy Area have an intolerable/unacceptable level of Loss of Life risk) is robust and that the outcome would not change given the use of reasonable alternative values for the input parameters. It would take entirely unrealistic assumptions to be adopted in order for anything other than unacceptable Loss of Life Risk to be determined for the vast majority of the fan head as well as the eastern stream bank.

Probabilistic Loss of Life Risk Assessment

6.173. The annualised Loss of Life Risk contours presented in T+T (2015a) were in the form of shorter return periods and longer return periods assigned to each event magnitude (volume). These effectively bracketed the range of Loss of Life Risk for the fanhead, with a “best estimate” of risk represented by some intermediate value. The other potential variables in the risk calculation such as vulnerability were fixed on what were considered to be best estimates.

6.174. In order to determine the effect that choosing alternative input parameters could have on the outcome of the risk analyses, a Monte Carlo simulation was undertaken in which the input parameters (return period, probability of impact and vulnerability) were chosen at random from distributions of potential values. A normal distribution was chosen in each case.

6.175. The Monte Carlo simulation was run by generating input parameters and output for a single risk calculation. The output of this analysis was saved and the process repeated. A total of 100 analyses were undertaken. This generated a distribution of risk values rather than a single outcome. The extreme values of the distribution represent the calculations undertaken with the most conservative and least conservative values respectively.

6.176. To assess the effects that the Monte Carlo simulation may have had on the outcome of the previous risk analysis, an assessment was made for the seaward dwellings No. 8 to 18 Clem Elliot Drive (see Figure 15).

6.177. The original calculations had the Loss of Life Risk = 0.1% contour passed through these properties for the shorter return periods (Figure 15) whereas they lie between the 0.1% and 0.01% contours for the longer return period, at approximately the 0.3% risk level (Figure 16).

6.178. The Monte Carlo simulation does not provide a single design Loss of Life Risk estimate but many estimates in the form of a normal distribution. For the seaward properties, the Loss of Life Risk ranged from a minimum of 0.05% to a maximum of 0.1%. The mean risk estimate was 0.07% per annum (Table 11).

6.179. By comparing the probabilistic and deterministic results (Table 11) it can be seen that the mean probabilistic risk estimate is closer to the longer return period deterministic estimate. The probabilistic results confirmed that the minimum Loss of Life Risk for the seaward properties was 0.05%, 50 times greater than the 0.001% recommended by McSaveney and Davies (2015) as the basis for determining a minimum retreat area. This provided further confirmation that 1) the high risk classification of the fanhead is not simply a function of the parameters that were chosen by T+T and 2) the selection of realistic alternative values will not generate an alternative outcome.

Table 11: Comparison of Loss of Life Risk Estimates for Seaward Properties on Clem Elliot Drive

Short Return Period Deterministic Analyses	Longer Return Period Deterministic Analyses	Probabilistic Analyses		
		Minimum	Mean	Maximum
0.1%	0.03%	0.05%	0.07%	0.1%

Risk Tolerability Assessment

6.180. The various T+T reports that presented the results of the Loss of Life Risk analyses did not make a judgement as to whether risk on the fanhead was intolerable/unacceptable, tolerable or acceptable. As noted above, McSaveney and Davies (2015) recommended to WDC that the 0.001% Loss of Life Risk contour be adopted as the minimum retreat area.

Tolerability of Risk

6.181. Whether a particular Loss of Life Risk is acceptable, tolerable or intolerable/unacceptable is a matter of considerable debate, as this is not quantified in New Zealand legislation. T+T (2013a) noted that the calculated Loss of Life Risk for the fanhead was greater than the 0.01%/annum level adopted by AGS (2007) as the tolerable-unacceptable boundary. However, T+T (2013a) did not make a determination that the debris flow risk on the fanhead was intolerable, as this was considered to be a matter for WDC to decide.

6.182. It should be noted that in 2016, after the debris flow risk assessment had been completed, the natural hazard provisions of the Bay of Plenty Regional Council Regional Policy Statement quantified an annual Loss of Life Risk greater than 0.01% as “high” – refer Appendix L, Step 5(b).

7. RESPONSE TO APPEAL GROUNDS

7.1. Reasons provided as grounds for appeal, in so far as they relate to my area of expertise are a) risk assessment and b) assessment of alternative options. These are addressed separately below:

Risk assessment

7.2. The risk assessment described in detail in my evidence is claimed to have used incorrect inputs including, but not limited to the following:

(a) *"An overly conservative or 'precautionary' approach not justified by the factual matrix"*. This is addressed in paragraphs 7.3 and 7.4.

(b) The *"scale of risk assessment (whether inner property features are assessed or risk assessment is at zonal scale only)"*. This is addressed in paragraph 7.5.

(c) *"options for lesser forms of risk management that do not involve prohibiting or restricting residential activity (such as early warning systems or other management)"*. This is addressed in paragraph 7.6.

(d) *"The risk assessment is uncertain…"*. This is addressed in paragraphs 7.7 to 7.9.

(e) PC17 adopts AGS (2007) *that "include significant qualifiers as to relevance and application for existing use scenarios where sensitive users already occupy land identified as subject to potential hazard, and reasonably available alternative methods exist for hazard mitigation"*. This is addressed in paragraphs 7.10 and 7.11.

7.3. Quite contrary to the claim, the risk assessments have not been undertaken in a conservative manner. All input parameters have been best estimates with no additional conservatism added. The probabilistic analyses have also shown that even when non-conservative inputs are used, the risk is still high.

7.4. The term "precautionary approach" refers to the adoption of the 0.001% Loss of Life Risk Contour by McSaveney and Davies (2015) as the minimum extent of the area to be retreated from. This does not relate to my risk assessment work which did not provide any recommendations as to what was or was not an unacceptable or intolerable risk.

7.5. The initial risk assessment reported in T+T (2013a) was undertaken in a manner that provided only a general or zonal classification. The subsequent detailed risk assessment reported in T+T (2015) was however undertaken in a manner in which Loss of Life Risk was able to be calculated for any location and at any scale, including that of individual properties. It is not true that the analyses that allowed the

Loss of Life Risk contours to be generated were zonal or general in nature and therefore insufficiently robust for individual properties to be considered. However, they do not account for individual circumstances such as occupancy rate.

7.6. A range of different engineering mitigation options were considered, as described in paragraphs 6.1 and 6.31 to 6.35, but found to be impractical, as described in paragraphs 6.51 to 6.55. The efficacy of early warning systems is addressed in the evidence of Professor Davies and Dr Chris Massey.

7.7. The outcome of a risk assessment is entirely dependent upon the values selected for each parameter involved. As there is a level of uncertainty around each of the parameters, there is also uncertainty associated with the resulting magnitude of risk calculated. This uncertainty has always been acknowledged in both the execution of the risk calculations as well as the interpretation of the outcomes.

7.8. The greatest uncertainty in the risk assessment was the return period and volume of future debris flow events. This variability was accounted for initially by adopting four events of different magnitude (volume) and two different return periods, one typically twice the size of the other. This is described in detail in Sections 6.125 to 6.133. T+T (2015b) took a more detailed account of the parameter uncertainty by adopting a probabilistic approach using the Monte-Carlo simulation methodology. Described in Sections 6.176 to 6.182, the probabilistic approach looks at all possible outcomes, some more likely, some less likely, to determine whether the selection of input parameters has the potential to affect the overall conclusions derived from the assessment. It was found that the probabilistic approach was unable to identify a credible scenario in which the risk category of the fanhead was less than that derived from the deterministic methodology.

7.9. Great consideration was given to the range of values used as input into the risk assessment. I consider them to be robust, comparable to those adopted by others, and account for the potential variability and uncertainty. Whilst there are some scenarios where the outcome of a risk assessment could be quite different depending on the choices made in terms of the input parameter, in the case of the Awatarariki fanhead, the Loss of Life risk is simply so high from a repeat of the 2005 event that tinkering around the edges with different parameters values does not produce a different result.

7.10. AGS 2007: AGS (2007) is a Risk Management Framework. It provides guidance on the process that should be followed when undertaking susceptibility, hazard and risk assessments. It presents the fundamental mathematical equation used to calculate risk as well as definitions of its components. The methodology is universally applicable and is based on principles of hazard and risk management that long pre-date AGS (2007). Local geological or climactic effects are accounted for by the values one selects for the relevant parameter. There is nothing “Australian” about the AGS (2007) methodology other than it was an Australian organisation that secured the funding and had the motivation to publish the guidelines. It could just as easily have been prepared and published in New Zealand, or anywhere for that matter. The source of the risk management framework is irrelevant and does not diminish its applicability.

7.11. The issue of alternative methods of risk mitigation is addressed in paragraph 7.6.

8. CONCLUSION

8.1. A debris flow event in the Awatarariki Steam in May 2005 initiated the assessment of a potential debris flow detention structure to protect the residential community located on the Awatarariki fanhead from a future debris flow event.

8.2. Commencing in 2009, a series of computer analyses was undertaken to first calibrate the software to the 2005 event and then to assess the effectiveness of variation barrier, spillway and fanhead barrier configurations.

8.3. A number of factors including land access limitations, the unique size of the barrier, barrier performance uncertainty, difficulties in construction and maintenance as well as cost ultimately saw the barrier option being abandoned in 2012.

8.4. A detailed Quantitative Landslide Risk Assessment (QLRA) was undertaken between 2013 and 2015. The purpose of the QLRA was to determine the Loss of Life Risk for current and future residents of the Awatarariki fanhead.

8.5. The QLRA consisted of deterministic risk analyses for debris flows of variable return period and magnitude. Loss of life risk contours were developed across the fanhead for both short return period and longer return period events. These were considered to bracket the likely range of a future event.

8.6. Probabilistic modelling was subsequently undertaken to ensure that the outcome of the deterministic analysis was not a function of data uncertainty.

8.7. The effect of climate change will be for the type of rainfall event that could generate a debris flow in the Awatararariki catchment to become more frequent than they have been to date.

8.8. The modelling showed that the loss of life risk was in excess of 0.01% per annum for the vast majority of the Awatarariki fanhead, as well as a smaller area east of the stream. The 0.001% per annum risk contour, which was adopted by McSaveney and Davies (2015) as the recommended minimum limit of retreat, extends marginally further.. Subsequent probabilistic analyses, which were not reliant on selected return periods for events, essentially gave the same result.

8.9. The level of Loss of Life risk on the fanhead was considered to be intolerable/ unacceptable.

8.10. An independent peer review confirmed the same.

8.11. Societal risk was assessed for both the current fanhead population as well as for a future larger population. The loss of life risk was determined to be intolerable/unacceptable in both cases.

Kevin Joseph Hind

10 August 2020