BEFORE A HEARING PANEL: WHAKATĀNE DISTRICT COUNCIL AND BAY OF PLENTY REGIONAL COUNCIL

IN THE MATTER	of the Resource Management Act 1991
AND	
IN THE MATTER	of submissions and further submissions on Plan Change 1 (Awatarariki Fanhead, Matatā) to the Operative Whakatāne District Plan and Plan Change 17 (Natural Hazards) to the Bay of Plenty Regional Natural Resources Plan

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STATEMENT OF EVIDENCE OF TIM DAVIES ON BEHALF OF WHAKATĀNE DISTRICT COUNCIL

RISK ANALYSIS AND OPTIONS ASSESSMENT

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1. EXECUTIVE SUMMARY

1.1. Many steep erodible catchments generate debris flows from time to time in severe rainstorms. However, any given catchment will generate debris-flows fairly rarely (perhaps a few times per century), so many such catchments show only subtle signs that they can generate debris flows.

1.2. The alluvial fan of a debris-flow capable stream represents the possible impact zone of the next debris flow, because the fan has been built up by past debris flows – including those that occurred before recorded history.

1.3. Any dwelling sited on a debris-flow fan and impacted by a debris flow is liable to be destroyed, as shown by the 2005 Matatā event; and anyone inside is at high risk of death (no fatalities occurred in Matatā in 2005, but experts agree this was exceptionally fortunate; there are many instances of debris-flow deaths both in New Zealand and overseas).

1.4. Debris flows can be managed by engineering structures, and this is commonly attempted overseas. However design of such structures is based on data such as impact forces that are still being researched, and there are no accepted design criteria for debris-flow defences. Even in Japan, where structural defences are common, scores of people are killed by debris-flows every year. Intensive investigation have found that no reliable and affordable engineering management possibilities exist at Awatarariki.

1.5. The alternative risk reduction strategy is to zone the debris-flow fan so that areas of different risk-to-life are delineated, and can be assessed for their suitability for dwellings on this basis. This has been done at Awatarariki.

1.6. Because there is only a single recorded debris-flow event at Matatā, and because risk analysis requires a magnitude-frequency distribution to generate the required statistics, numerical modelling was carried out using a specific debris-flow module of the Swiss “RAMMS” model suite. This was calibrated against the known deposit area of the 2005 event, which had a volume of about 300,000 m^3; the model was used to delineate the deposit areas of debris flows with volumes from 50,000 m^3

to 450,000 m^3. These volumes were assigned return periods based on the best estimates of the return period of the 2005 event, which is 200-500 years.

1.7. The risk analysis was carried out according to international best practice. Because of the sparseness of the basic data (volume and deposit distribution for the 2005 event only, and a very rough estimate of return period), the risk analysis was inevitably accompanied by substantial potential errors. A precautionary approach was taken to delineating risk levels on the Awatarariki fan because lives are at risk if dwellings are permitted there; in the event of a death, decision makers need to demonstrate that they have used an appropriate level of risk that recognises the imprecisions of the available analysis. For the same reasons the extreme levels of acceptable risk-to-life recommended in international literature have been used.

1.8. The proposal for a ring-net debris flow detention structure was peer-reviewed in 2010. It was found that "Overall, the concept is reasonable but is a substantial departure from international experience in terms of the size of the structure, which at 13.7 m net height was more than twice as high as any previous structure of this type. Detailed design considerations will be required to achieve satisfactory performance." Subsequently it was decided that the detention structure was unjustified on cost and performance grounds.

1.9. In 2015 the feasibility of protecting individual dwellings on the Awatarariki fan with engineering structures was investigated; it was found that such measures could not reliably reduce risks to acceptable levels.

1.10. The possibility of constructing a concrete chute to transfer debris flows across the fan from the fanhead to the sea was investigated in 2012; in 2015 I peer-reviewed the resulting design. I found that there was insufficient gradient available on the Awatarariki fan to allow any such channel to ensure transfer of debris-flow material to the sea. Thus a debris flow would be likely to halt in the channel, blocking it and causing the following material to overtop the channel and flow onto the "protected" fan.

1.11. In 2017 I investigated the possibility of implementing an early warning-evacuation system that could in principle eliminate risk to life if all inhabitants could evacuate to safety when a debris-flow was either forecast or detected in the catchment. I found that the time taken for a debris flow to reach the fan following its detection at feasible locations was too short to allow reliable evacuation of the fanhead area. Evacuations based on catchment moisture and forecast rainfall, which could provide more warning time, require location-specific data on catchment conditions and debris-flow occurrence that are not available at Matatā. I thus concluded that a reliable early-warning system was not feasible.

1.12. In 2017 I assessed the possibilities for reduction of the debris-flow hazard in Awatarariki Stream, focussing in particular on the suggestion that log-jam dams may have exacerbated the magnitude of the 2005 event. Based on reports of the dimension of log-jam dams provided by Young (2017), I found that the maximum potential volume of debris in such dams was 40,000 – 50,000 m^3. This is within the margin of error of the best available estimates of the volume of the 2005 event, so it is not evident that removing log-jam dams frequently would make any significant difference to a future event. I also considered the possibility of building artificial check-dams in the catchment, as is common practice in Europe, to store debris and prevent channel-bed erosion. In the Awatarariki Stream on the order of 100 such structures, each 5 m high, would be required, and the cost and environmental disturbance required to build and maintain them would be extremely high. It has been found in Europe that such systems are not fool-proof; domino-style failures of many check dams have occurred resulting in devastation of towns downstream. The benefits of such a strategy are thus dubious and the costs probably unsustainable.

2. INTRODUCTION

2.1. My full name is Timothy Reginald Howard Davies.

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

(a) Proposed Plan Change 1 (Awatarariki Fanhead, Matatā) to the Operative Whakatane 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 scientific aspects of the Proposed Plan Changes. My evidence will cover:

(a) Alluvial fan hazards;

(b) Debris flow phenomena including variabilities such as size, behaviour and predictability *(Overlap with evidence of Dr McSaveney);*

(c) Debris flow triggering mechanisms including the complex inter-relationships between rainfall intensity, soil pore pressure, geology, slope angle etc that make it difficult to identify when a debris flow might occur in a specific location (*Overlap with evidence of Dr McSaveney);*

(d) Debris flow numerical modelling (Overlap with evidence of Mr Hind);

(e) Debris flow risk:

i. Risk assessment;

ii. Acceptable levels of risk;

iii. Use of AGS (2007) as an appropriate risk management framework to assess debris flow risk from the Awatarariki catchment;

iv. Challenges with modelling long recurrence interval high consequence natural hazard events, including managing uncertainties (e.g. probabilistic analysis), underestimating the level of risk, and appropriateness of using a precautionary approach *(Overlap with evidence of Mr Blackwood);*

(f) Risk management;

(g) Debris flow risk management, including hazard mitigation;

(h) Updated estimate from 200,000 m^3 to 300,000 m^3 as being the volume of solid material deposited on the Awatarariki fan from the 2005 debris flow (as increased by Tonkin and Taylor Ltd and factored in to the risk assessment that Mauri and you later peer reviewed);

(i) Likelihood of future debris flows and area of risk;

(j) Peer review of the Tonkin and Taylor Ltd Supplementary Risk Assessment– Debris Flow Hazard, Matatā (2015), including confirmation of the high, medium and low debris flow risk areas delineation and conclusion that the high risk area is unsafe for residential use;

(k) Debris detention structure peer review;

(l) Awatarariki debris flow design factors that were provided to MBIE during Determination 2016/034 process and their implication for building design; including international feedback received on building on debris fans;

(m) Investigation of Chute to Sea option;

(n) Investigation of the viability of early warning systems to reduce debris flow risk to properties on the Awatarariki fan to an acceptable level;

(o) Investigation of the viability of proactive catchment management processes to reduce debris flow risk to properties on the Awatarariki fan to an acceptable level.

3. QUALIFICATIONS AND EXPERIENCE

3.1. I hold the position of Professor in the School of Earth and Environment, University of Canterbury, Christchurch.

3.2. My qualifications include:

(a) PhD , Southampton University UK (1973);

(b) MSc , Southampton University UK (1968); and

(c) BSc(Hons) in Civil Engineering from Southampton University, UK (1966)

3.3. I have been actively researching debris-flow behaviour, processes, impacts and management since the early 1980s, and was for 20 years a member of the 5 person International Advisory Committee for the four-yearly international conference series on Debris Flow Hazard Management.

3.4. I was the Recipient of a Distinguished International Fellowship, Durham University, UK in 2011

3.5. I have published 22 research papers on debris flows in the international literature.

3.6. I have been involved in a number of consulting projects assessing risks from natural hazard events to developments in the mountain areas of New Zealand. These include:

(a) An assessment of debris-flow hazard at Aoraki/Mt Cook for DoC in 1997 that resulted in construction of a diversion wall protecting the Hermitage hotel;

(b) Assessment of debris-flow risk to a proposed development at Mitchells, Lake Brunner, Westland for Grey District Council in 2005;

(c) Investigation of debris-flow processes at Pipson Creek, Otago for Otago Regional Council in 2008;

(d) Assessment of debris-flow hazard at Bowen Creek, Queenstown for Otago Regional Council in 2014.

3.7. I have been involved in the Matatā situation since shortly after the debris-flow event of 2005.

3.8. In the context of comprehensive hazard and risk assessments at Franz Josef Glacier, Westland, I have also been involved in intensive community engagement processes as well as acting as a consultant for West Coast Regional Council (1997 to present).

3.9. I have been involved as an expert witness in Environment Court proceedings in the context of river behaviour and management on behalf of Environment Southland and Otago Regional Council, and have acted as an expert witness on river sediment behaviour for river conservation groups at hearings about the Rakaia, Waimakariri, Waitaki and Wairau rivers.

4. MY ROLE

4.1. I have prepared a number of reports in the context of the 2005 event. The first was an unsolicited article entitled "Debris Flow Emergency at Matatā, New Zealand, 2005: Inevitable Events, Predictable Disaster", and the last was a paper for the 7th International Debris-Flow Hazard Management conference in Golden, Colorado USA in 2019, co-authored with Jeff Farrell of WDC, entitled "Debris flow risk management in practice: A New Zealand case study".

4.2. In between these I have authored and co-authored several reports for Whakatane District Council, including peer reviews of the debris-flow modelling, risk analysis and engineering feasibility of the ring-net concept, and analyses of the feasibility of the chute-to-sea proposal, the feasibility of an early-warning-evacuation system and the contribution of log-jam dams to the 2005 event.

4.3. I have visited Awatarariki fan on half a dozen or so occasions since 2006, and flown over the catchment in a helicopter recently. I also inspected the lower 1 km or so of Awatarariki Stream on foot in about 2007.

4.4. I have attended a large number of meetings with council officials and/or scientists/consultants and/or locals in both Whakatane and Auckland.

4.5. I participated as a debris flow expert in a Consensus Development Group, explaining and clarifying to the group the processes of debris-flow initiation and motion; the hazards to life posed by debris flows; and the basis and process of the risk analysis for the Awatarariki Fanhead (Awatarariki Debris Flow Risk Management Programme) (2015).

4.6. In preparing this evidence I have reviewed the documents and reports listed in **Annexure 1** to my evidence.

5. CODE OF CONDUCT

5.1. Although this is a Council hearing 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 Hearings Panel. 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. SCOPE OF EVIDENCE

6.1. This statement of evidence covers the following:

(a) An overview of the scientific issues relevant to the Plan Changes (**Assessment of the Plan Changes**);

(b) Response to issues raised in submissions and further submissions (**Response to Submissions**); and

(c) Conclusions.

7. ASSESSMENT OF THE PLAN CHANGES

Preamble

7.1. I first present an outline of the water and sediment flow phenomena relevant to the Awatarariki hazard, because basic knowledge of the behaviour of alluvial fans and debris flows is key to appreciating what science can and cannot tell us about the likely nature, magnitude and occurrence of future events in the Awatarariki Stream.

Alluvial Fans

7.2. Wherever a stream flowing from a steep, erosion-prone catchment spreads onto flatter land, the water flow slows down and spreads out so that some of the sediment it carries settles out of the water flow to build up a sloping, fan-shaped deposit called an "alluvial fan" (e.g. Fig. 1).

Fig. 1 An alluvial fan

7.3. The fan-like shape results from the stream moving to and fro across the surface of the fan, depositing sediment where it flows. This is a fundamentally aggradational landform (that is, it continues to grow in extent and elevation over time), growth of which will continue as long as the fan toe is not maintained in a constant position by a river or the sea. If the fan toe is trimmed in this way, the fan is called an “equilibrium fan” and, although the stream can continue to avulse to any position on the fan, it no longer builds up in the long term because local, temporary aggradation of the fan is balanced by local, temporary erosion elsewhere on the fan surface. This is the situation at Matatā where the Awatarariki fan has been built up over the last several thousand years by deposition of sediment transported by the Awatarariki Stream, and its toe has been maintained in the same position by coastal processes since sea level stabilised several thousand years ago.

7.4. In rainstorms sediment is brought into the stream by landslides and bank erosion in the steep, erodible catchment. The coarser component of this sediment (gravels and sands) is dragged along the stream bed by the force of the water flow, while finer particles (sands and silts) are carried along in suspension, dispersed in the whole volume of the flow. Deposition of both coarse and fine material onto the bed of the stream occurs when the flow reduces again; if, during the storm, the river changes course to flow across a different part of the fan, then sediment can be deposited in the new stream bed. Thus any development on the active surface of an alluvial fan is at some risk from flooding and sediment deposition by the stream during storms.

7.5. Many large alluvial fans, however, have incised fan heads; that is, the river flows across the upper part of the fan in a channel well below the fan surface level. In this case it is difficult for the river to flow across the fan head, because massive sediment deposition is needed to elevate it to the level of the fan surface, and the fan head area is not normally at high risk from flooding.

7.6. Small fans can also have incised fan heads (e.g. Fig. 1), but the land adjacent to the incised stream may nevertheless be at high risk from flooding and sediment deposition. This is because, in some small, steep catchments with erodible rock, a quite different type of sediment transport process can occasionally occur; this is a “debris flow”, and it was an occurrence of this phenomenon that devastated parts of Matatā in 2005.

Debris flows

7.7. A debris flow occurs when enough fine sediment enters a steep stream (e.g. from a hillslope failure) to turn the stream flow into a thick, muddy slurry; in this state the flow is able to erode and transport rocks and boulders of virtually any size. The whole flow transforms into the consistency and density of wet concrete, and moves down-valley as a wave or surge carrying boulders and trees. A debris flow can also be generated by a landslide blocking the stream temporarily, and washing away when it is overtopped by the flow. However it is caused, a debris flow differs from normal flood flows in the following ways:

(a) it does not flow steadily – the flow forms a series of discrete surges comprising large boulders and trees (Fig. 3). These surge waves are much deeper and faster than the normal flow of flood water, and in between them the flow is much lower and carries only fine sediment;

(b) it is able to transport virtually all the solid material available to it – e.g. trees, boulders, houses – and often scours its channel to bedrock, thus increasing its volume with additional sediment;

(c) because of the internal flow mechanics the larger solids (boulders, trees) are carried at the front of the surges, forming a battering ram with large destructive ability;

(d) a surge that halts is able to block an incised fanhead channel very quickly, and subsequent surges can then travel to any part of the fan;

(e) surges may not follow the stream course, especially at bends;

(f) the flow event occurs very quickly with no reliable precursors.

7.8. A debris flow can occur in a catchment if:

(a) the average catchment steepness is sufficient;

(b) there is sufficient sediment available; and

(c) a sufficiently intense rainstorm occurs.

7.9. The catchment steepness criterion determines catchments which can, under appropriate circumstances, generate debris flows. A steepness criterion often used is the "Melton Ratio", which is the ratio of catchment relief (the highest elevation in the catchment minus the fanhead elevation) to the square root of catchment area above the fanhead. It has been found by several studies (e.g. Watts and Cox, 2010; Welsh and Davies, 2011; Page et al., 2012) that in New Zealand the catchments that are known to have generated debris flows have Melton ratio values greater than about 0.5. However, as emphasised by Welsh and Davies (2011), the Awatarariki and Waitepuru catchments at Matatā which generated debris flows in 2005 have Melton Ratio values much lower than this, about 0.2; the reason for this remains as yet unknown. This discrepancy does not, however, in any way cast doubt on the nature of the 2005 event, which all qualified observers have classified as a debris flow, nor does it in any way affect the risk analysis which is based on the 2005 event.

7.10. The initiation of a debris flow can occur either as a result of increasing streamflow over a bed of suitable material causing intense bed erosion; or as a slope failure (landslide) that enters a stream channel in flood and delivers large volumes of fine sediment that turns the stream flow into a slurry; or as a landslide that forms a temporary dam and soon overtops causing the dam to collapse. In any of these cases, whether or not a debris flow occurs depends on complex inter-relationships among antecedent soil moisture, soil structure and shear strength, vegetation root reinforcement of the soil, the temporal sequence of rainfall intensity and the detailed topography of a specific site. Hence it is not surprising that, in spite of a large volume of research, there are no values of rainfall amount and intensity, or of sediment availability, which reliably quantify the conditions under which debris flows can occur at any given location (in addition, sufficiently intense rain can itself cause landslides and thus increase sediment availability). If such values did exist then forecasts of debris flow occurrence would be feasible provided that rainfall amount and intensity could be forecast, but they do not. Thus, a debris-flow can be expected to occur in any future storm in a catchment known to be capable of generating them.

7.11. An alluvial fan formed by a catchment that generates debris flows will contain evidence of their past occurrence in the form of boulders (possibly buried) too large for the stream to transport in normal floods; this is the only fully reliable way to identify a debris-flow capable catchment and fan. The extent of the boulder distribution (buried or not) thus indicates the area at risk of debris flows. As explained above, no location on a fan that can experience debris flows can be considered to be free of risk of damage due to debris-flow impact.

7.12. Because debris-flows require a steep catchment in order to form, they generally occur in small catchments, say less than 10 - 20 sq km or so. Thus the alluvial fans downstream of these catchments are also small. This, together with the high speed of debris flows (several metres per second) means that a debris flow can affect any development on a fan within a few minutes of its initiation in the catchment.

Management of debris flows

7.13. Countries like Japan, Taiwan and Austria have long experience of debris-flow hazards; moreover, having high population densities they are forced to use engineering structures to attempt to control the debris-flows themselves, because relocation is usually not an option.

Fig. 2 Debris-flow structures. A: Masonry dam. B: Ring-net. C: Check-dams. D: Grill.

7.14. Japan in particular has long experience of constructing dams to manage debris-flow behaviour. The dams are designed to prevent the valley-bottom erosion which debris flows can cause, and which can greatly increase their volume; and to temporarily retain debris-flow material thus reducing the volume flowing onto the occupied fans downstream. In spite of this experience, scores of fatalities occur every year in Japan as a result of debris flows. One reason for the unreliability of debris-flow control structures is the lack of accurate design data; the density, volume and velocity of future debris-flows cannot be accurately predicted and thus their impact on structures is difficult to quantify. This latter point is emphasised by the fact that the 2018 post-fire debris flows in California far exceeded the volumes expected from such an event, leading to retrospective doubling of the officially-delineated hazard zone area.

7.15. In the western USA debris basins are commonly used to store debris-flow material before it can impact developments downstream. Again, these are effective if large enough, but because increase in size increases both cost and environmental impact, the capacity of such basins is frequently exceeded by events with consequential damage downstream.

7.16. A recent development is the ring-net barrier (Fig. 2B), effectively a flexible dam that catches the larger debris by deflecting as a surge impacts it; the retained coarse debris then acts as a mass dam to retard the following material. While environmentally desirable when compared to rigid structures, these barriers are at an early stage of development and have been proven effective only against debris flows much smaller than the 2005 Matatā event. For example, a full-scale ring-net structure was tested at Illgraben experimental catchment, Switzerland in 2005-2007 (Wendeler, 2016); during this period the largest debris-flow had a volume of 55,000 m^3 (about one-sixth of the 2005 Matatā event) and a maximum depth of 2.7 m (about one-fifth of the proposed net height at Awatarariki). Three versions of the ring-net structure were tested during this period. Wendeler (2016) also demonstrate the design procedure for a 4 m high ring-net designed to contain a debris-flow of 5000 m^3 volume. A ring-net structure was investigated as a management structure at Awatarariki Stream but was found to be not feasible for technical reasons, as Mr Hind's evidence will describe.[1]

7.17. In any given location the potential for management of debris-flow events needs to be assessed on information specific to that location. For example, a deflection wall such as that installed at Aoraki-Mt Cook as a result of a 1997 risk assessment is not necessarily a realistic strategy elsewhere. In general, structural control measures have been found to be unreliable in reducing debris-flow risks, especially for major events (Davies, 1997), because of the lack of reliable data on which to base a design.

Debris flow numerical models

7.18. Computer-based numerical modelling is an increasingly common technique for representing and predicting the behaviour of complex phenomena such as debris flows. Such models specify materials (in terms of their density, viscosity and other properties) that are thought to behave in the same way as debris flows, then keep account of the forces on, and hence motion of, given volumes of these materials across specified terrain. Models such as these are very reliable for simple materials such as water or dry granular materials (e.g. sand), because the constitutive relationships of such materials are well-known. However debris-flows comprise dense slurries of fine sediments in water, carrying

[1] Letter from Aecom New Zealand Ltd. to Jeff Farrell, 25 February 2011

high concentrations of coarser materials up to boulder-size – and often trees. Hence the constitutive relationships of debris-flows are poorly-known, and materials are specified for use in models that in fact behave differently from debris-flows. This means that without reliable field data to calibrate the model its predictions are likely to be unrealistic.

7.19. Most debris-flow models incorporate "tuning-knobs" which are factors whose values can be varied to give different behaviours. These are especially valuable in a situation where a debris-flow event has been observed and, for example, its deposit extent is known; a model can then be run with a range of values of the tuning factors, and the values that give the correct deposit extent can be assumed to realistically represent the deposit extent for different debris-flows of the same material – for example the deposit extents of smaller and larger volumes can be found. The model is then said to be calibrated for that type of material.

7.20. For the Matatā project, a model called RAMMS developed in Switzerland was used to determine the deposit extents for various flow volumes, as the evidence of Mr Hind will describe. This generalised mass movement model has a module specifically developed to represent the behaviour of debris flows. At the time (2008) when Mr Hind used it this was one of the most sophisticated debris-flow models available, and it remains widely-used today; even so, it could only approximately represent the behaviour of the 2005 Matatā debris flow. The material used in the model was a pure plastic fluid, not a boulder-soil-water-tree mix like the real debris flow. Nevertheless, the model was able to be calibrated against the known behaviour of the 2005 event so that the correct model volume (300,000 cubic metres) deposited in the correct locations on the Awatarariki fan. Hence this model was able to produce predictions of the deposit extents of larger and smaller volumes, and of the performance of various structural control measures such as ring-nets and overflow channels. Although these predictions were the best available, they are inevitably prone to errors whose magnitude is unknown.

Debris-flow risk

7.21. In the modern world many decision-making processes make use of the concept of risk. In this context "risk" has a specific meaning:

Risk = the probability of an event times the consequence of the event (UNISDR, 2017)

7.22. Here the *probability* (which is also sometimes called "likelihood") is the number of times that a specific event is expected to occur in any given year, assessed as an average over a very long time period. So if an event occurs about 100 times every 10,000 years its annual probability is 100/10,000 = 0.01, or 1%. This is also known as the *annual exceedence probability* or "AEP", because the occurrence of an event is equivalent to the exceedence of the specified event magnitude.

7.23. The event *consequence* is the cost of the event to society, in terms of economic costs (including asset damage, commercial disruption and recovery), human costs (deaths and injuries) and societal costs (e.g. community disruption, environmental disturbance, commercial costs, psychosocial costs). Where loss of life is a possible consequence, as is usually the case with a debris-flow event, "loss-of-life" risk is usually assessed separately from economic and societal costs.

7.24. Debris flows have caused deaths in New Zealand in the past. For example, such an event at Peel Forest, Canterbury in 1975 killed four children in a holiday home during an intense rainstorm (Davies & Hall, 1992); and a tramper was killed in Otago by a debris flow in 2002 (McSaveney & Glassey, 2002). Four people in a tent were killed near Arthur's Pass by a debris flow in 1979; three people were killed by a debris flow at Te Aroha in 1985; while 3 people were killed when trains ran into debris-flow deposits on railway tracks in the North Island in 1936 and 1946.

Risk assessment

7.25. The purpose of a risk assessment is to show how risk (in the Awatarariki case, risk-to-life from occurrence of a debris-flow event) is distributed spatially so that, in particular, locations where the risk is unacceptably high can be identified. This information can then inform decisions around strategies for reducing the risk to acceptable levels, strategies that range from modification of the debris-flow event, through warning and evacuation systems, to relocation of people out of the unacceptably-high-risk area.

7.26. Risk assessment procedures are commonly specified (in codes of practice accompanying legislation, e.g. the Buildings Act 2004) for a range of particular hazards, such as seismic (earthquakes), landslide and flood risks. There are no procedures specified for debris-flow risk, so the procedures used at Matatā were adapted from the Australian Geomechanics Society's (AGS) 2007 guidelines (Fell et al., 2008) for landslide risk assessment. More recently, Jakob et al. (2016) stated: "Three fundamental components of debris-flow risk assessments include frequency-magnitude analysis, numerical scenario modelling, and consequence analysis to estimate the severity of damage and loss."

7.27. In more detail, risk assessment involves (a) deriving or generating a relationship between the magnitude or intensity of an event (for a debris flow, its volume is the obvious quantity corresponding to intensity) and its AEP; (b) deriving or generating a relationship between debris-flow volume and its impact on people in the deposition area (i.e. how many people does each event volume kill?); (c) for all feasible event volumes, calculating the product of deaths per event and event probability, giving deaths per year due to events of that volume; and (d) adding together the deaths per year for all the event volumes. This yields the total deaths per year due to all debris flow event volumes, spatially distributed across the area in question (e.g. AGS, 2007).

Acceptable risk

7.28. The level at which risk-to-life becomes unacceptable is evidently a critical criterion in basing risk reduction decision-making on a risk assessment. As with many factors in risk management, however, it is a topic fraught with uncertainty, but recent experiences following the Christchurch earthquakes have led to a noticeable convergence of opinion.

7.29. A useful basis is the diagram below (Figure 3), which is commonly cited in risk research (e.g. AGS (2007), Clague and Stead (2012)).

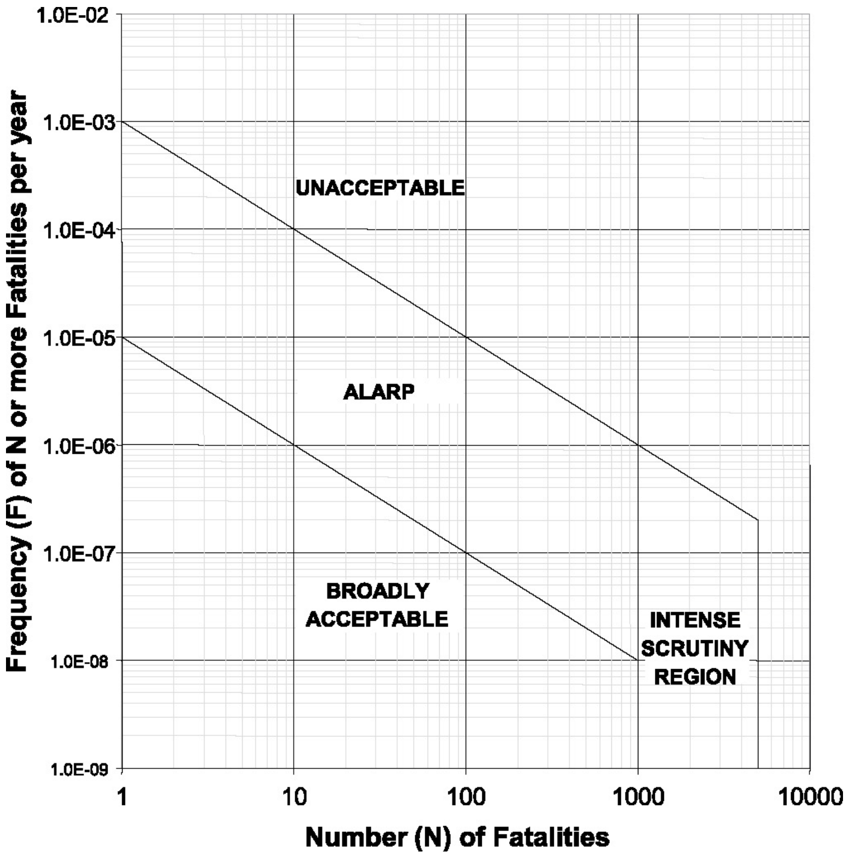

Figure 3 Limits of acceptable risk (Clague & Stead, 2012)

7.30. Although this is derived from surveys of people exposed to risk-to-life due to failure of a dam, it is applicable to a debris-flow situation because, as with a dam failure, (a) the likely future occurrence of the event at the location is known and (b) it is recognised that fatalities may occur. The diagram shows that one fatality every 1000 to 100,000 years (risk-to-life of 10^{-3} to 10^{-5} per year) is the upper limit of acceptable risk, and this and lower levels are only tolerable if everything possible has been done to reduce the risk (As Low As Reasonably Practicable = ALARP) – anything higher (e.g. one fatality every 100 years, or 10^{-2}) is unacceptable. The acceptable risk level also reduces in direct proportion to the number of lives lost, so that 100 deaths in an event is only acceptable every 100,000 to 10 million years.

The AGS framework

7.31. In 2007 the Australian Geomechanics Society published its “Guidelines for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning” which were developed as a result of the 1998 Thredbo disaster. This 20-page document recommends the use of the risk analysis procedure shown in Figure 4 below. This procedure is essentially similar to the general process outlined above for risk assessment, leading on to assessment of tolerability/acceptability and consideration of risk reduction strategies, so the AGS procedure is certainly acceptable as a framework for risk assessment at the Awatarariki fan.

7.32. The risk analysis procedure outlined above is acknowledged as the proper way to consider uncertainties when making decisions on which lives may depend. Nevertheless there are ways in which the process may seem less than perfect, especially in the context of the frequency of hazard events at a given location when compared with the time-scale of the planning horizon for human society. This is because the probabilistic approach is only reliable when applied to a large number of hazard event occurrences – that is, the probability of events occurring is only matched by actual occurrences when large numbers of events over long time periods are considered. So while an event with a probability of 10^{-2} (1 in 100) will occur about 100 times in 10,000 years, there is no guarantee that it will occur once and once only in any 100-year period; it may well not occur at all, or it might occur several times. When we are considering events that occur only a few times per millennium the situation is worse.

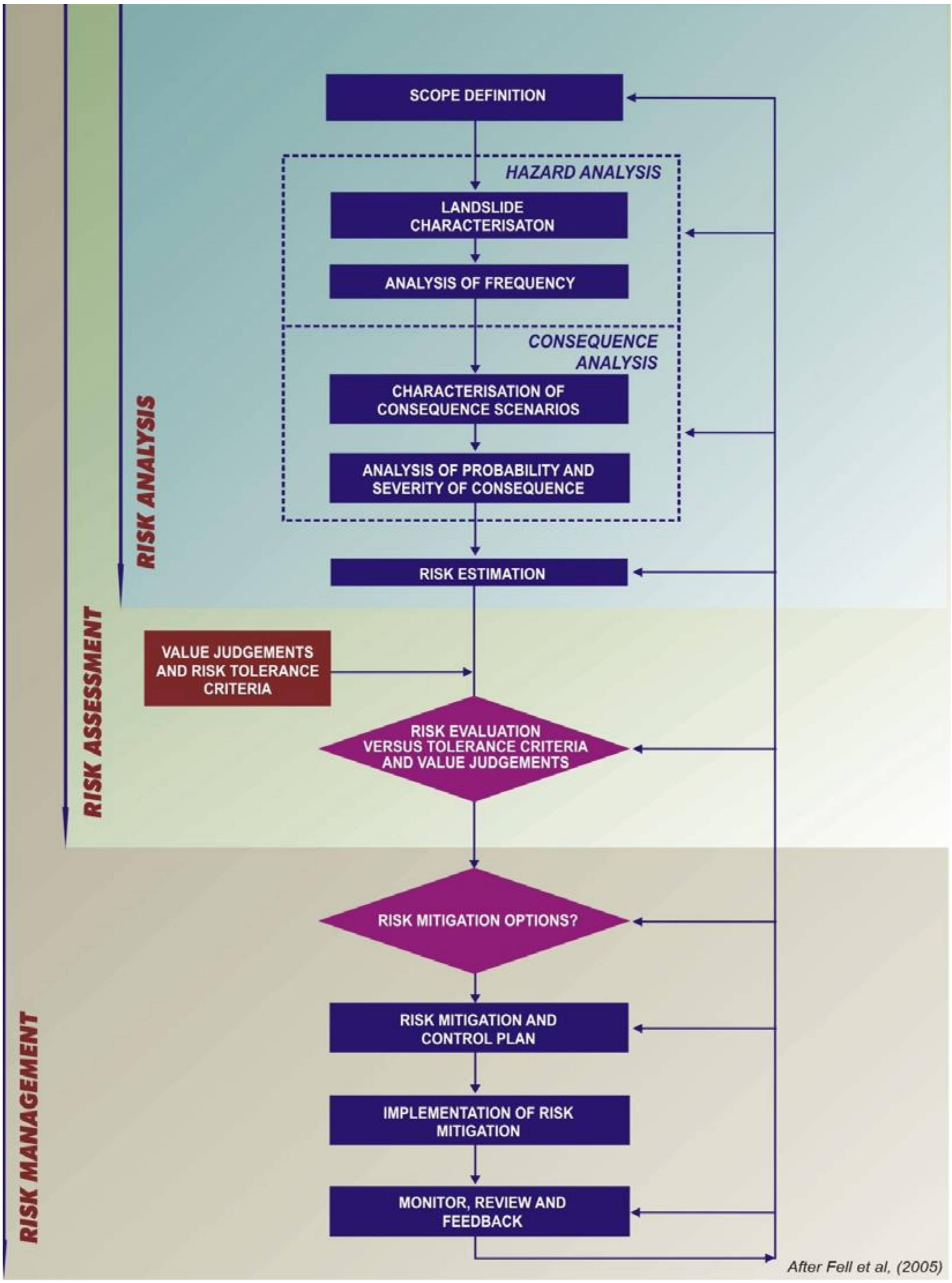

Figure 4 Risk management framework (AGS 2007)

7.33. Further, available data on event occurrences are usually based on a very small number of recorded events (at Matatā, a single event), so the probabilities of different–sized events can only be estimated roughly. It is also more likely than not that recorded events are not extremely large ones, because those events occur relatively rarely – so it is likely that our sample of event sizes will underestimate the event magnitudes in the low-frequency, high-magnitude part of the range.

7.34. Looked at another way, if measures can be taken that will reduce the risk to a development sufficiently then the development is considered safe for occupancy. Note however that this does not guarantee that deaths will not occur in the development due to an event in the near future – it implies that any such deaths are acceptable because their probability was sufficiently low, so no responsibility is attributed for those deaths.

7.35. Conversely, when deaths occur in a location where the assessed risk-to-life is greater than the acceptable level, these deaths are considered unacceptable, and responsibility for this unacceptable occurrence lies with the organisation that permitted the occupation.

7.36. It thus follows that if organisations are responsible for managing risk-to-life, they will only permit people to be present where the risk is assessed to be at or less than the acceptable level, so that they cannot be found responsible for the deaths. It follows that the organisations' assessment of risk will necessarily be conservative or precautionary; that is, any demonstration that the risk is greater than their assessment will imply their responsibility, so they will assess the risk at the highest realistic level. Therefore they will err on the side of caution (precautionary approach) when assessing risk to life.

7.37. It is my professional opinion that in cases where lives are at risk, and the available risk data are imprecise, it is necessary to take a precautionary approach so that if lives are lost it can be demonstrated unequivocally that the risks being run were definitely within the range considered acceptable by the relevant decision-making authority.

7.38. If it can be shown that specific measures can reduce risk-to-life to acceptable levels, a further decision is required on whether or not the measure is affordable for the community.

Debris-flow risk management

7.39. Risk management is the entire process outlined above, from risk assessment, through establishment of the acceptable level of risk, to the implementation of strategies to reduce risk to below the acceptable level. Added to this is the ongoing monitoring of the situation to detect changes in risk (due either to changes of hazard event probability or magnitude, or to changes in the assets exposed to damage by events) so that the strategy can be updated as required to maintain the risk at acceptable levels – in principle in perpetuity. This is the process that underpins disaster risk reduction globally, and was confirmed by the Sendai Declaration of 2015 (Sassa, 2015) as the paradigm to apply until 2030. New Zealand is a signatory to the Sendai Declaration, and therefore risk management is the basis of disaster management in New Zealand.

7.40. It must be acknowledged, however, that while perfectly rational, the risk management approach is only guaranteed to yield benefits at a given location over very long time periods. For example, to reduce debris-flow risk to acceptable levels at Matatā in the near future will require investments (in the form of the social cost of residents to relocate) to be made now. There is no guarantee that those investments will prove to be necessary within the lifetimes of those making them – there may well be no more debris flows in the Awatarariki Stream in that time, or for a hundred years thereafter, this being the nature of natural events and of risk assessment. One day there will be a repeat of the 2005 event, but we cannot know when; it may be next week, next month, next year, or it may not be until 2200. This makes risk management seem somewhat theoretical to locals whose period of involvement is short.

7.41. This problem of debris-flow risk management is exacerbated by the paucity of data on debris flows at any given location. At Matatā, for example, there is one well-described event, that of 2005. GNS Science (2005) found evidence for previous events at Matatā within the past century, but there is no information on their magnitude; thus no statistical information can be derived from them. That is why numerical debris flows were generated in a computer to approximate the magnitude-frequency relationship for Matatā, so that the risk management framework could be applied. We do not know how accurately the computer-generated statistics represent past events in Awatarariki Stream, but they are the best approximation presently available.

7.42. Debris-flow hazard mitigation by structural modification of debris-flow events has been shown in 7.7 above to be not feasible in the Awatarariki

Catchment; the further investigations detailed later in my evidence and in the evidence of Mr Hind, Dr Massey, and Dr Phillips, conclude that (a) no fanhead structures are capable of reducing risk-to-life reliably; and that (b) no early-warning-evacuation system can provide enough warning time to allow reliable evacuation of people in the high-risk zone, so risk cannot be reduced by such a system. Neither can a combination of these be shown to be reliable in reducing risk.

7.43. The only remaining option for reducing risk-to-life reliably in the high-risk zone is to reduce the exposure of people to debris-flow events there, by reducing the number of people in the zone. Unless this number is reduced to zero, however, the possibility remains that someone will be killed by a debris flow there. While this might be theoretically and professionally acceptable, it demonstrates that the exposure of any individual to the hazard has not been reduced.

7.44. A critical factor in the calculation of risk-to-life is the debris-flow magnitude-frequency relationship, which represents the probability of occurrence in any given year of debris flows of a range of magnitudes (volumes). This relationship depends on the estimated volume and probability of occurrence of the 2005 event.

7.45. The 2005 event volume was initially estimated as 200,000 m^3 (GNS Science 2005). By 2008 Tonkin & Taylor (2008) had increased this to 250,000 m^3, and the risk assessment by Tonkin & Taylor (2013a, 2013b) was based on 300,000 m^3 as the 2005 event volume. The specific event volumes investigated by numerical modelling were 50,000m^3, 150,000m^3, 300,000m^3 and 450,000m^3.

7.46. The probability of the 2005 event has been estimated on the basis of the probability of the rainfall event that triggered it, and Mr Blackwood's evidence deals with this in more detail. There is general agreement among experts that the return period of the 2005 rainfall event is probably greater than 100 years, and possibly less than 1000 years; the Tonkin and Taylor (2013b) risk assessment was based on return periods of 200 and 500 years, equivalent to annual probabilities of 0.005 (5×10^{-3}) and 0.001 (10^{-3}) respectively. The shorter the return period of a given volume, the higher the total risk (due to all flow volumes) at any given location. As Mr Blackwood shows, climate change is expected to reduce the return periods of specific events over the next century.

7.47. RAMMS modelling, calibrated on the 2005 event, has been used by Tonkin and Taylor to delineate the risk distribution associated with specific event volumes (50,000 m^3 to 450,000 m^3) and for return periods of 200 years and 500 years; this is described in the evidence of Mr Hind.

7.48. In 2015 Dr McSaveney and I carried out a peer review of the T&T risk distributions and recommended the extent of the area that we considered represented a high risk. That area corresponded to the 10^{-5} (or 1 in 100,000) modelled annual risk-to-life area delineated in the T&T report. We also recommended that a retreat policy be applied to the high-risk area, removing the possibility that persons would be killed in the high-risk area in future events. We chose this area because:

(a) The limit of acceptable per person life-risk is commonly taken to be 10^{-5} (e.g. Fig. 1; AGS, 2007). While it is often noted that higher values (up to 10^{-3}) can be acceptable if they conform to the ALARP criterion (ALARP = “As Low As Reasonably Practical”: meaning that all reasonable steps have been taken to reduce the risk from its original unmodified level), this cannot apply in a situation where no measures are feasible to reliably reduce the original risk. Hence in the Matatā situation we consider the modelled 10^{-5} to be the baseline acceptable risk limit.

(b) The analysis in the T&T report is based on data, in particular return periods, that are unavoidably poorly constrained, and we considered that a precautionary approach should extend the area beyond the 10^{-4} AEP zone identified by the T&T modelling, which might normally be considered the unacceptable-risk zone (e.g. Fig. 3 section 7.11 above). The area of high risk is considerably increased by selecting the T&T 10^{-5} line as the limit of acceptable risk, indicating that the modelling is particularly susceptible to data imprecisions in this range.

(c) The 10^{-5} AEP line corresponds closely with the mapped limit of deposited boulders in the 2005 event, which we consider to accurately represent the extent of high risk-to-life due to persons being impacted by boulders during that event. This correspondence to some extent reduces the dependence of the high-risk zone on the AEP data; designating the boulder deposit area as high-risk effectively eliminates the possibility that persons will be killed by boulder impact in a repeat of the 2005 event, and indicates that the boulder deposit zone of that event is unsafe for future residential use. The significance of this recommendation is that the boulder extent is the only precise data available for the 2005 event, so is a solid basis for zoning.

Debris detention structure peer review

7.49. In 2010 Colin Newton of Aecom and I carried out a Peer Review of the Resource Consent Application Technical Proposal for the Awatarariki Stream Debris Flow Control System for Whakatane District Council. The review is summarised in a letter dated 25 February 2011 from Aecom to WDC. The review noted that:

(a) "Key issues to the success of the net include the need to ensure that the buried skirt remains secured during initial loading, that the final level of the debris dam is sufficiently high to ensure flow over the spillway, that deposition of the coarser material does not impact on the approach to the spillway and the net is maintained to ensure it remains effective throughout its operational life."

(b) "No modelling or assessment of the sediment deposition at the base of the spillway has been undertaken. The deposition of material in this location may impact on the flow path of the diverted material."

(c) "Regular inspection and maintenance of the net will be required. This will include repairs to any damage to the corrosion protection system and the removal of any retained sediment on a periodic basis."

(d) "Public safety issues require further consideration "

(e) “Overall, the concept is reasonable but is a substantial departure from international experience [in terms of the size of the structure, which at 13.7 m net height was more than twice as high as any previous structure of this type. Detailed design considerations will be required to achieve satisfactory performance.”

Building Act Determination

7.50. During 2015 WDC applied to the Ministry of Building, Innovation and Employment (MBIE) for a Building Act Determination which Mr Farrell discusses in his evidence. WDC investigated the possibility that damage to individual dwellings located in the debris-flow path could be avoided by either making them strong enough to be undamaged by impact from a debris flow, or by building the dwellings atop raised platforms so that the flows would pass underneath.

7.51. I, together with Mr Hind, participated at a hearing to provide expert advice to the MBIE Hearing Panel. On 1 May 2015, after the hearing and prior to the Determination being finalised[2], WDC provided MBIE (by email) with the following table (Table 1) of debris-flow parameters, with accompanying notes, that would be relevant for structural design of individual buildings at 100 Arawa Rd and 6 Clem Elliott Drive to avoid or resist the design flow impact:

Descriptor	**Parameter**
Event magnitude (volume)	300,000 m^3 (approximates the 2005 event)
Return period	200-500 years
Flow parameters · Flow density (ρ) · Coulomb-type friction (μ) · Viscous-turbulent friction (Xi) · Earth pressure coefficient (λ)	 1700 kg/m^3 0.02 1500 m/s^2 1.75
Flow velocity at the southern boundary of 100 Arawa Road	3 m/s
Minimum height to underside of floor support structure at 100 Arawa Road	7-10 m
Flow velocity at the southern boundary of 6 Clem Elliott Drive	1 m/s

[2] Ministry of Business, Innovation and Employment Determination 2016/034

Minimum height to underside of floor support structure at 6 Clem Elliott Drive	4.0 m or 6.0 m

Table 1 Debris-flow design parameters

Notes: The 7.0m and 4.0m minimum height reflect a factor of safety of 2.0 on boulder dimension, whereas the 10 m and 6.0 m reflect a factor of safety of 3.0. Note that the heights of 10 m and 6 m are the maximum necessary value - in other words, something less might be acceptable but research would be required to support a reduction.

Note also that removal of debris following any future event would be required to restore the factor of safety.

The Council's position is that unless MBIE provides guidance on what the minimum height should be, the higher value should apply in the absence of further research.

7.52. MBIE responded with a series of questions which Mr Hind, Mr Farrell and I collaborated on and which Mr Farrell answered by email on 18 August 2015. These questions and responses are in **Annexure 2** to my evidence.

7.53. The questions probed the possibilities of reducing the uncertainties in the relationship between debris-flow volume and return period, and in the required height of a platform to allow debris-flows to pass below. The answers emphasised that the parameters of future debris-flows on the Awatarariki fan cannot be predicted accurately. There is only a single (2005) event for which any information is available, and even for that event both the large-scale parameters (volume), and the smaller-scale ones (depth, velocity, density, viscosity) are extremely poorly constrained; in this respect, engineering design for debris flows at Awatarariki is very different from most geotechnical engineering designs. A further uncertainly in modelling future flows is that, because individual surges can alter the underlying topography by erosion and deposition, the elevation distribution of the topography over which any specific surge model must be run is itself uncertain by of the order of metres. The following quotes from the WDC answers to the MBIE questions emphasise these points:

> "It is noteworthy that, despite high-level international collaboration, we have been unable to locate any other jurisdiction in the world that provides debris flow design standards for residential structures on debris flow fans."

> "A high level of uncertainty exists in unconfined debris flow events."
>
> "A high level of uncertainty exists in debris-flow modelling."
>
> "In the case of the Awatarariki catchment, we have [only] one dataset to calibrate our modelling against."
>
> "To say anything sensible about the required floor height needs a fair bit of research, so anything we come up with prior to that being done is necessarily liable to considerable error."
>
> "The front face of a debris flow surge may be several boulders high."
>
> "Debris flows include fairly big trees that are even more difficult to design for because they float very high in a dense debris flow or hyperconcentrated flow."
>
> "The Council's experts conclude by saying there is a common theme in the questions provided that we can somehow treat this with a degree of certainty akin to a standard engineering problem, which this most certainly is not. The experts are very uncomfortable with the overall direction of the questions. Their considered view is that the moment we began to zoom in from an overview position to looking at individual properties is the time this process has lost its way. Notwithstanding, they recognise the legislation we must work under demands quantification of risk on a property-by-property basis, so this must be done but they want to state clearly they would be very uncomfortable with any risk assessment other than the highest that our very poor data allows."

7.54. The overall outcome of this information is that the risk-to-life assessment at Awatarariki is necessarily based on poor data with unquantifiable uncertainties; therefore the risk assigned to any specific location on the fan must be the highest possible in order to avoid potential liability for future deaths.

Investigation of Chute to Sea option

7.55. As part of assessing the options for managing debris flow risk at Awatarariki Stream, Matatā, the ability of a chute to the sea to deal effectively with a debris flow of the size and type of the 2005 event was considered. The intention was to provide an artificial channel that would carry the debris flow directly to the sea without it affecting assets outside the channel. In December 2012 AECOM provided a design report (AECOM Awatarariki Stream Options 20 December 2012) for such a structure with associated costs. On 21 September 2015 I reported on the adequacy of that design to WDC.

7.56. The AECOM design was intended to carry a maximum flow rate of 66 cumecs of water from the Awatarariki fanhead to the sea, for which it required a width of 15 m, a depth of 2.5 m and a longitudinal gradient of 1.4%; these dimensions were found by HEC-RAS modelling assuming that the flow is steady and comprises clean water (i.e. carrying no sediment). However, the 2005 debris flow had a maximum equivalent flow rate estimated as 700 cumecs (Tonkin & Taylor, 2013), for which the AECOM design is evidently inadequate. Further, debris flows commonly flow not in a steady fashion but as a series of surges interspersed with very low flows, and the 2005 event certainly had these characteristics; so the maximum surge flow rate will be much greater than 700 cumecs. Finally, the 2005 surges were not clean water, they were composed of a muddy slurry carrying large boulders and tree-trunks; the resistance to flow of such a composite fluid, even along a smooth concrete channel, will be much greater than that of water, indicating even greater inadequacy of the design.

7.57. In summary, it is clear that the channel proposed by AECOM (2012) would not satisfactorily mitigate the risk posed to the assets on the Awatarariki fan by debris flows of the magnitude of the 2005 event.

7.58. In order to be effective, such a channel would need to be much steeper (at least 9%, according to McSaveney et al., 2005) in order to ensure that the flow would not stop and block the channel. Over the approximately 300 m distance between the fanhead and the sea this means 27 m of fall, which is not available because the fanhead is at about 10 m asl. Thus, irrespective of the dimensions of a channel, the debris flow material would deposit and block it, leading to overtopping and serious risk to fan assets. This conclusion is supported by the fact that in the 2005 event no boulders reached the sea, and the majority deposited on the upper half of the fan.

Investigation of the viability of early warning systems to reduce debris flow risk to properties on the Awatarariki fan to an acceptable level

7.59. In December 2017 I reported to WDC on the potential for an early warning-evacuation system to reduce the risk-to-life to dwellings on Awatarariki fan (Davies, 2017a).

7.60. Critical factors in the assessment of a debris-flow warning system are:

(a) The reliability of the debris-flow detection or inference system (frequency of occurrence of false alarms and false negatives)

(b) The impacts of a debris-flow on the assets exposed and consequences for the lives of inhabitants

(c) The time between the warning being issued and the debris-flow impacting the asset

(d) The time taken to evacuate people from the hazard zone when the warning has been issued

(e) The residual risk once the system is operational

(f) System cost – setup, operation, insurance and maintenance.

7.61. Reliability – that is, the correspondence of alarms to the presence of debris-flows - is possibly the most critical issue. If a debris flow occurs but is not detected or inferred, there is a high life-risk to those exposed. Conversely, false detection or inference when no debris flow occurs leads to a false alarm; if a series of false alarms occurs the unnecessary evacuations may lead to desensitisation of the evacuees and likely failure to respond to future alarms.

7.62. Types of debris-flow detection systems were investigated. The outcome was that the only available, calibration-free system that is well proven is trip-wires. This has the advantage of being simple to install and operate. (Table 2).

Sensors	Operation	Advantages	Limitations
Ultrasonic, radar and laser sensors.	Measurement of the flow stage.	Easy to set warning thresholds.	Ultrasonic sensors have to be hung over the channel; installation can prove difficult if the channel banks are unstable.
Geophones and seismometers.	Measurement of ground vibrations caused by debris flow.	Easy and safe installation (the sensors are buried in safe places on stream banks).	Setting warning thresholds can be quite complicated. Risk of false alarms due to other sources of ground vibration (passage of trains or trucks, rockfalls, etc.). The need to filter the signal may increase system complexity.
Pendulums.	Detection of the debris-flow from the tilting of the pendulum.	Simple and robust device.	The pendulum must be hung over the channel; installation can prove difficult if the channel banks are unstable.
Wire sensors.	Detection of the debris-flow from wire breaking.	Simple and robust device.	Need for restoration after activation. Risk of false alarms due to accidental circumstances (passage of animals, falling trees, etc.).
Photocells (infrared photobeams, etc.).	Detection of debris-flow passage.	Non-contact detectors: do not need restoration after activation.	A careful installation is needed to avoid having the sensors come into contact with the flow.
CCD camera for machine-vision detection.	Recognition of debris flows.	Safe installation (the camera can be placed beside the channel).	The presence of fog or the occurrence of debris flow at night may complicate the use of the system and its workability.

Table 2 Principal debris-flow sensors (Arratano & Marchi, 2008)

7.63. The possibility of predicting debris-flow occurrence by monitoring rainfall was also investigated. In such systems an alarm is triggered when rainfall (and/or intensity) exceeds the threshold beyond which it is believed that a debris flow will be present in the channel. This system has a major issue: setting a reliable trigger threshold requires sufficient catchment-specific data on debris-flow occurrence related to rainfall, in order that there are not excessive false alarms and that there are no false negatives (i.e. a debris flow occurs but is not inferred). These data are not available for Awatarariki Stream, and, given the rarity of debris-flows in this system, would take decades or centuries to acquire. This type of system has recently been found to be too risky for those responsible to be able to purchase insurance against its failure (Jakob et al., 2012; http://www.nsnews.com/news/dnv-re-engineers-slide-warning-system-1.352521).

7.64. A hybrid system was also considered, in which meteorological data (antecedent, anticipated and measured) are used to establish readiness and warning, with evacuation then based on event detection. Rainfall monitoring (synoptic, radar, rain-gauge data) can be the basis of all but the final step in a sequence of *readiness* (catchment moisture status) -> *warning* (synoptic/radar indication of intense precipitation) -> *critical* (threshold exceeded) -> *evacuate* (event detected). A major advantage of a hybrid system is that the sequence of preparatory states allows reduced total evacuation time following the alarm; individuals may choose to evacuate before an event is detected and the alarm activated. However, this system depends on the alarm giving sufficient time to evacuate safely.

7.65. In order to maximise reliability (minimising false alarms and eliminating false negatives) and to avoid the need for calibration for Awatarariki Stream, the **trip-wire detector** type is preferred. This consists of one or several wires installed across the stream at a height above the channel bed greater than that of the water surface in a flood but lower than the depth of a debris-flow surge. The wire(s) is/are connected to an electrical circuit such that an alarm is triggered if a wire breaks. False alarms due to wire breakage by e.g. falling trees or animal motion can be avoided by setting up two detectors say 100 m apart along the stream, breakage of both being required to trigger an alarm. Obviously such a system would need regular inspection and testing, but is relatively robust and inexpensive to install and maintain.

7.66. The obvious locations for trip-wire detectors are immediately downstream of the two major confluences in the lower part of the catchment (Fig. 5). A detector downstream of confluence 1 will detect all debris flows in the system, but is close to the assets at risk so provides shorter warning times. A detector downstream of confluence 2 provides longer warning times but will not detect debris flows generated in the approximately 35% of the catchment downstream of it.

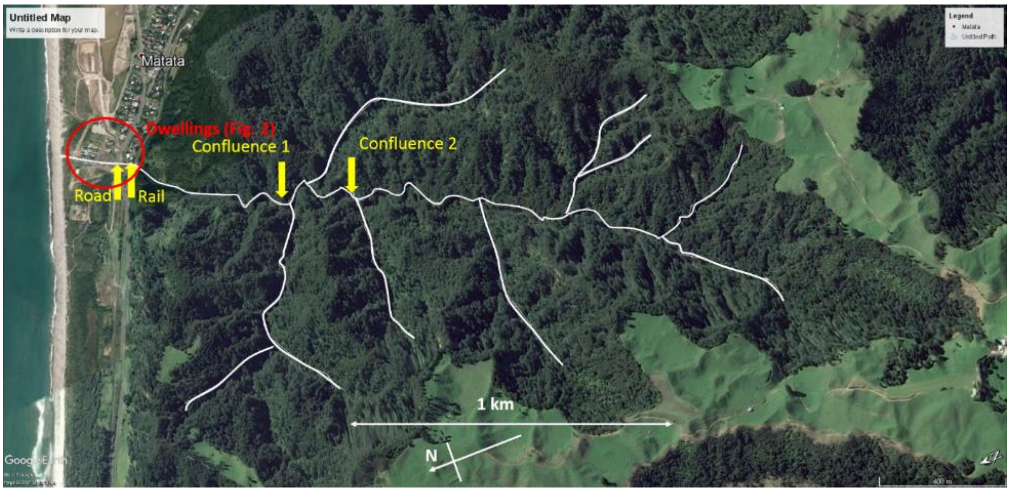

Fig. 5 Awatarariki Stream channel system and assets at risk (Google Earth image).

7.67. Based on likely debris-flow front velocities (5 m/s in the catchment, 3 m/s on the fan), the following total warning times (in seconds: **bold**) are estimated:

Asset	Confluence 1 (m)	Warning time (s)	Confluence 2 (m)	Warning time (s)
Rail crossing	740	**148**	1440	**288**
Road crossing	740 + *75*	148 + *25* = **173**	1440 + *75*	288 + *25* = **305**
Farthest dwelling	740 + *230*	148 + *77* = **225**	1440 + *230*	288 + *77* = **365**

7.68. The distance from the farthest dwelling to safety is 660 m. Assuming best-case conditions (a healthy person evacuating during daylight in good visibility), an average walking speed of about 1.3 m/s can be assumed (http://lermagazine.com/article/self-selected-gait-speed-a-critical-clinical-outcome; accessed 12 December 2017). Thus in the 365 seconds available, and *assuming no delay in leaving the dwelling*, a distance of 474 m can be covered. This is clearly inadequate. Assuming more realistically that it takes say 2 minutes to leave the dwelling, the distance able to be covered will be only 318 m. Taking into account the need for less fit and healthy people to evacuate, the available warning time is clearly inadequate for the dwellings farthest from the safe location.

7.69. Evacuation by vehicle is an alternative. To drive 660 m at 50 km/hr takes about a minute, but to this must be added the time to exit the dwelling, get in the car, start it, reverse it out of a garage and drive to safety. Whether these actions can be safely completed in five minutes is uncertain; under ideal circumstances (residents awake and dressed, keys immediately to hand, car starts immediately) it is clearly feasible, but it is not difficult to envisage circumstances in which it would not be accomplished (for example in the middle of the night, involving the sick or elderly or families with young children). Further, not every dwelling may have access to a vehicle nor every resident be able to drive.

7.70. While detailed study of the escape routes from other individual dwellings has not been undertaken, the closest dwellings to the fanhead have warning times similar to those for rail and road crossings, about 300 seconds maximum. Again, accepting that there will be a significant delay in leaving a dwelling especially if an alarm is activated at night when residents are likely to be asleep, this is insufficient time to guarantee that any given resident can reach safety before the debris flow impacts the dwelling or escape route.

7.71. The conclusion from these considerations is that although it is technically feasible to set up a warning-evacuation system that is 100% reliable in detecting debris flows, that system gives inadequate warning time for evacuation to take place reliably. Systems that give more warning time are much less reliable, with probabilities of both false alarms and of failure to detect a debris flow.

7.72. Investigation of the viability of proactive catchment management processes to reduce debris flow risk to properties on the Awatarariki fan to an acceptable level

7.73. As outlined earlier, debris flows are initiated by intense rain causing slope failures that deliver large quantities of sediment to the stream channel; these combine with the high streamflow rates caused by the rainfall, and erosion of the sediment already present in the stream channel bed, to form debris flows. The question arises, whether the Awatarariki catchment itself can be modified by management so that the risk of debris flow impacts on the fan is reduced.

7.74. There are in principle two possibilities for such management:

(a) Reduction of rainfall-induced slope failures

(b) Reduction of stream-bed sediment erosion

7.75. The first of these is not feasible in the Awatarariki catchment. The slopes are covered in native forest, so are already reinforced by tree roots, a condition which minimises slope failure frequency.

7.76. The second possibility could be achieved by constructing check-dams along the whole length of the 7.5 km length of the Awatarariki Stream and its tributaries, as is commonly done in European mountain catchments. This would, if successful, prevent the severe stream-bed degradation that occurred in 2005 and contributed a large (but unknown) proportion of the sediment volume of that event. However, to be successful, concrete dams would need to be constructed, with foundations extending to bedrock, along the full catchment system. Assuming a dam height of say 5 m, dams would be needed every 50-100 m along the channel network, meaning between 75 and 150 dams. As well as the environmental considerations, the cost of constructing and maintaining these dams would undoubtedly run into many millions. In any case, the volume reduction achievable in this way is unknown; the dams would not prevent slope-erosion-derived sediment from forming debris flows in an event like that of 2005. Finally, every dam in the system would need to be 100% failure-proof, because each dam would store sediment behind it which would, if the dam failed, add to the sediment in motion.

7.77. A further possibility for reducing the sediment volume involved in a 2005-type event would be to ensure that no natural sediment dams formed in the stream system between storms. Douglas (2017) reports that such features, formed by log-jams causing accumulation of sediment upstream of them, were certainly present in the stream during his inspections since 1993. He recalls climbing over debris dams 6-8 m high which retained sediment to form a flat plain upsteam of the dam, upstream of which again was usually a lake before the stream-bed appeared again. He recalls finding about 10-12 such dams in the Awatarariki Stream. If these dams stored a significant proportion of the 2005 sediment volume, then it is in principle possble to significantly reduce the volume of such an event by clearing such dams on a regular basis.

7.78. Based on Douglas' (2017) data I carried out an analysis to estimate the maximum volume that natural dams could have contributed to the 2005 event (Davies, 2017b). My estimate was that the upper limit of such a contribution would be about 40,000 – 50,000 m^3. While substantial, this lies within the margin of error of the estimate of the 2005 event volume, for which Costello (2005) had estimated 390000 ± 100000 m^3; subsequent estimates have not reduced the error value. In order for removal the 50,000 m^3 of stored natural dam sediment to be significant in total volume estimates, the error in the total volume needs to be much less than ± 25000 m^3. This is not the case, so the contribution of sediment dam removal (even if possible, reliable and economic) to fan risk is negligible.

8. RESPONSE TO SUBMISSIONS

Plan Change 17 - the Awatarariki Residents Society re risk modelling uncertainties

8.1. It is accepted that the information on which the risk-to-life modelling is based is too sparse to allow precise delineation of risk across the Awatarariki fan. Nevertheless, legislation requires risk, calculated as specified by internationally-accepted procedures, to be the basis of decisions such as that required at Matatā. Where lives are at risk, any future event that resulted in death of an inhabitant would be analysed to see whether the life-risk to that person was at or below the acceptable limits. If any case could be made, for example by using the worst extreme of the risk range estimate that the data sparsity allows, that the risk exceeded the acceptable range, decision-makers would be liable for the outcome. Therefore the precautionary principle must apply to risk zoning at Matatā, and the risk zones are at the upper limit of what the data allow.

Both Plan Changes - Matatā Residents Association re combination of bunding and EWS

8.2. It has been conclusively demonstrated that neither early warning systems (EWS: evidence of Dr Massey and myself) nor bunding for individual dwellings (my evidence) can reliably reduce the risk-to-life on the Awatarariki fan to acceptable levels. As noted in the response to the submission of Keith Sutton and Nola Neale below, bunding of individual dwellings is both unreliable and has the potential to transfer the impact to adjacent properties; it is not apparent that a combination with EWS will alter this conclusion significantly. If the proposition is that bunding and EWS are both unreliable, but if they were both used the combination would necessarily be more reliable, then the answer is in the affirmative, but the degree of increase in reliability cannot realistically be estimated given the sparseness of basic data available. Thus it cannot be demonstrated that the suggested combination of EWS and bunding will result in acceptable life risk to the particular dwellings.

Plan Change 17 - Katherine Stevens re catchment management

8.3. Before the 2005 event occurred, aerial imagery shows virtually undisturbed forest throughout the Awatarariki catchment. This suggests that the susceptibility of the area to landsliding and erosion was at its minimum at the time of the 2005 event. There is no evidence that "better managed" farming or forestry in the catchment would further reduce this vulnerability.

Plan Change 1 - Keith Sutton and Nola Neale re feasibility of an engineering solution to 28 and 32 Clem Elliott Drive and that hazard maps are based on flawed information

8.4. To the best of my knowledge, nowhere in the world is there a successful example of protection of individual dwellings on a high-risk debris-flow fan by individual bunds or elevated building platforms. Debris flows are highly energetic phenomena, even on a fanhead after leaving the confined headwater channel, carrying large boulders and logs which are able to redirect the flow across the fanhead in a completely unpredictable, and unmanageable, fashion. Further, even if a bund or building platform were to divert a flow away from a "protected" building, the diverted flow might well then impact another building with greater impact than if it had not been diverted.

8.5. The risk maps are based on the best available information and conform to international practice. The information on which they are based is sparse, and allows a range of interpretations in delineating the risk-to-life zones. In this case, where the consequence of permitting dwellings will one day be loss of life, it is imperative to be able to demonstrate unequivocally that the risk-to-life was at or below acceptable levels, which means that the highest possible risk that the data allow is that chosen to delineate risk.

Glenn Baker's Further Submission to PC 1 – provide engineered floodway and improve riparian management

8.6. An engineered floodway from the Awatarariki fanhead to the sea was considered in detail (Mr Bassett's and my evidence). While this might work satisfactorily for clear-water flood flows, it will not be able to control a debris flow because the available gradient is insufficient to ensure transfer of the debris flow to the sea. This means that the front of the flow would halt in the channel, blocking it, and the rest of the flow would spill over the channel banks onto the rest of the fanhead.

9. CONCLUSIONS

9.1. The debris-flow processes, hazard and risk distribution at Matatā have been studied to best international standards, on the basis of the sparse data available.

9.2. The 2005 debris flow at Awatarariki fan had a volume of about 300,000 m^3 and a rainfall return period of about 200-500 years.

9.3. Intensive investigations have established that there are no affordable and reliable engineering options for reducing the risk-to-life on Awatarariki fan to internationally acceptable levels, either for protecting the whole fan with a detention structure or chute-to-the-sea or for protecting individual dwellings with bunds or elevated building platforms.

9.4. Detailed risk analyses using internationally-accepted practice show that risk-to-life on much of the Awatarariki fan exceeds that categorised as “acceptable”, if a precautionary approach is used to the sparseness of the basic data and the correspondingly wide spread of possible risk distributions.

9.5. Neither early-warning-evacuation systems, nor improved catchment management, have the potential to reliably reduce the risk-to-life to acceptable levels.

9.6. The only realistic and affordable way to reduce risk-to-life at Awatarariki fan to acceptable levels is to relocate present occupants to locations outside the high-risk zone.

Timothy Reginald Howard Davies

15 January 2020

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ANNEXURE 2 – MBIE QUESTIONS AND RESPONSES

"Questions and Responses

1. Can the design parameter uncertainties be quantified even if only in approximate terms?

Response: Any such quantification would be subjective rather than objective because we only have a single recorded event at Matatā and that does not give any indication of uncertainty. Applying data from other sites would be grossly optimistic because the Awatarariki is very unusual as a debris-flow catchment (Welsh & Davies, 2010). In any case, probabilistic prediction of any of the characteristics of the next event at Matatā means applying statistics to a single event, which is illogical.

This means that we do not believe design data can be reliably quantified for any future event – even one with close similarity to the 2005 event. In addition there is very large uncertainty about the return period. In normal engineering design terms we quantify uncertainty with respect to variations in geotechnical factors such as soil or rock strength, groundwater pressures etc. We can undertake sampling, make reasonable estimates and then apply factors of safety. Debris flows from the Awatarariki catchment are a totally different beast. The major uncertainties are in event size and return period. We have one event whose magnitude (in terms of volume) is only understood in the very broadest terms and has always been in dispute. The return period for this same event is even more poorly known. Although we often seem to assign a return period of 200 years or so to the 2005 event, a more realistic perspective is to consider it a being more than decades and less than millennia. This is our biggest problem, as this has a direct result on the risk calculations. If pushed to quantify uncertainties, the best we can do is to suggest a return period range of more than 200 years and ± 30%-50% on the volume. Unfortunately we have so little information for this single event that there are big uncertainties around this range of values. In other words we are very uncertain as to what the uncertainties are, and are loath to be too numerical for this issue as it is poorly suited for it. This leads us to conclude that on the basis of risk-aversion we recommend using the shortest feasible return periods and largest volumes.

Further, we do not know whether or how the other design parameters vary with event volume. Again, given that lives are potentially at risk, the precautionary approach requires that conservative (i.e. worst-case) values are used.

2. We cannot tell from the information precisely what a 'safety factor of 3.0' means. We note that you refer to "boulder dimension" so our assumption is that you noted a boulder near 100 Arawa Road of maximum dimension 3.5 m and said 2 x 3.5 = 7 m and 3 x 3.5 = 10.5 m (about 10.0 m). Similarly, the maximum boulder dimension noted on or near 6 Clem Elliott Drive is 1.8 m double of which is about 4 m and trebling is about 6 m. If this assumption is correct it seems that it is simplistic – and very conservative - to assume double or treble the boulder size is the same as a factor of safety of two or three if that is what has been done because the distribution of boulders carried and deposited is unlikely to be a linear relationship. Have we understood this correctly? And if yes, do you have any comments on the apparent conservativeness we observe?

Response: It depends on which particular Factor of Safety (FoS) is referred to. Many are possible - e.g. on flow volume, on peak flow, on peak flow depth, on boulder volume, on boulder size, etc... [note that a FoS of 3 on boulder volume means a much smaller FoS (about 1.4) on boulder size]. We disagree with the idea that we can consider an increase in boulder volume as some sort of factor of safety as we do not see this having any basis in fact. For example, a 1m diameter boulder has a volume of 0.52 m^3, where as a 3m diameter boulder has a volume of $14m^3$. It should be possible to discover the boulder size available in the catchment. The 2005 GNS report contains an illustration of a boulder ~ 7m in diameter.

We don't think there is any way to establish a purely rational design elevation for a building platform so that boulders carried by a debris flow will pass (sufficiently) safely beneath it; "expert judgement" would be needed. The thrust of the question implies a need for a design platform elevation, so there needs to be some debris-flow factor that leads to this; but how to arrive at this on the basis of what we know about debris-flows at Awatarariki or elsewhere is a major research project in itself. It is noteworthy that, despite high-level international collaboration, we have been unable to locate any other jurisdiction in the world that provides debris flow design standards for residential structures on debris flow fans.

3. It would be useful to articulate the drivers behind the differences between the (velocity and boulder size) for the two properties. We certainly understand that it relates to the height differential of the two properties. Unpicking this may be useful not only for other properties but also may gave an insight on other strategies that could be considered to mitigate some risk (e.g. land contouring to direct flows and/or velocity reduction devices). Do you have any information about the height/boulder size dynamic?

We do not have information on the how the ground elevation relates to boulder size. It depends (in an unknown way) on a number of complex factors, including the flow rate from the catchment as a function of time; the spatial distribution of boulders in the specific future flow; the topographic contours of the land it is flowing over (which are likely to differ, in an unknown way, from the present contours because previous surges deposit material non-uniformly on the existing land); the way in which the boulder-laden flow distributes itself over these contours; and so on.

What happened in 2005 and where material went or did not go on that day were specific to the circumstances of that day. A whole lot of mechanical events happened which provided the specific outcome; but our understanding of these events and their interactions is so poor that the outcome is effectively random. What happened in 2005 would not happen in the same way if the debris-flow event was repeated. We would not go further than to say that any part of the fanhead could be impacted by a future debris flow and that the 2005 event gives us an insight into the general nature of this impact. Trying to finesse what may happen at any specific property is unrealistic.

4. In the information you have provided we can't tell from the information what is going on wrt the 'increased difference'. We remember in the hearing the Tonkin Taylor expert said that the May 2005 event had changed the profile (contours) of the land by depositing material land and this then would influence future debris flows and direct them away from the

property at 6 Clem Elliott Drive to some degree. Also, I think I remember the owners at 6 Clem Elliott Drive saying they'd raised their property since the 2005 event. Is our understanding correct?

Response: Your understanding is only partly correct. As stated in 3 above, it is not reasonable to assume that the present land surface will remain unaltered during the course of a future event. We know the form of the land before 2005, and also after the 2005 event - but we do NOT know what erosion and deposition occurred during that event. The land surface elevation at any particular point may have gone up and down during the event. The Lidar data post-2005 indicated a complex mixture of deposition and erosion in different places. Whether some change in terrain will impact future flows will depend on the nature of that flow. Some hyper-concentrated flows may well be directed away from some more slightly elevated areas whereas a large boulder-filled event will more likely just go where it wants and not show any real response to subtle changes in terrain. Every bit of elevation increase helps to reduce impact, but we cannot say that a property without a physical barrier will not be impacted by a future flow (or even that it will be less impacted) just because it has a slightly higher elevation.

The questions provided imply that we can somehow treat this situation with a degree of certainty akin to a standard engineering problem; this implication is incorrect. The considered view of the Council's experts is that when we start to move from an overview position to looking at individual properties, the process has lost its way. Nevertheless, legislation demands quantification of risk on a property-by-property basis, so this must be done; but the experts want to state clearly they would be very uncomfortable with any risk assessment other than the highest that our very poor data allows."