11 November 2022

E: Anna@scoped.nz
T: 021 0869 1484

Te Tai o Poutini Plan Team
PO Box 66
Greymouth 7805

info@ttpp.nz

Dear Sir/Madam,

Te Tai o Poutini Plan – Submission to Publically Notified Plan

Name of Submitter – Scoped Planning and Design Limited

This is a submission on the Proposed Te Tai o Poutini Plan 2022 (TTPP) by Scoped Planning and Design Limited which has been prepared in accordance with Clause 6 of Schedule 1 of the Resource Management Act 1991 (the Act).

It is confirmed that Scoped Planning and Design Limited could not gain an advantage in trade competition through this submission.

The specific provisions of the proposal that the submission relates to, the submission points, reasons and decisions sought are detailed in the following report and tables. Scoped Planning and Design Limited seeks that the decision sought as set out in the attached table are adopted, or any other such relief and/or consequential amendments that achieves an equivalent outcome.

Scoped Planning and Design Limited does wish to be heard in support of this submission.

The following accompany this letter

1. Submission report and tables, including relief sought
2. Franz Josef Relocation – Relative Risks Final Draft
3. Potential Landslide Risk at Franz Josef Glacier Township
4. Submission form

Yours faithfully,
Scoped Planning and Design Limited

Anna Johnson
Principal Planner
BEP, M. NZPI

1. The following submissions are made to ensure that there is a practical and workable planning regime for the implementation of resource use throughout the West Coast region. The submission requests that either:

- The specific relief as set out in the table below is adopted; or
- Such other relief to a similar effect is adopted to address the matters outlined in the submission to the submitter's satisfaction; and
- In relation to the above, any consequential amendments necessary as a result of the decision to grant the relief sought.

2. The submitter's address for service is:

   Scoped Planning and Design Limited
   165 Jollie Street
   Hokitika 7810

3. Documents for service on the submitter may be sent to the above address for service or may be emailed to anna@scoped.nz. Service by email is preferred.

Item One: Lot 2 DP 2816, PT RS 1613, RS 1614, RS 1615, RS 1594 and RS 1622 – Zone Change

4. The above properties are located primarily within the Future Urban Zone (FUZ) adjacent to the General Residential Zone (GRZ) within Greymouth located between various transport corridors, including Arnott Heights East, Town Belt South and Marlborough Street. The site itself is intersected by paper road, Glen Road, as shown within the below Figure 1.

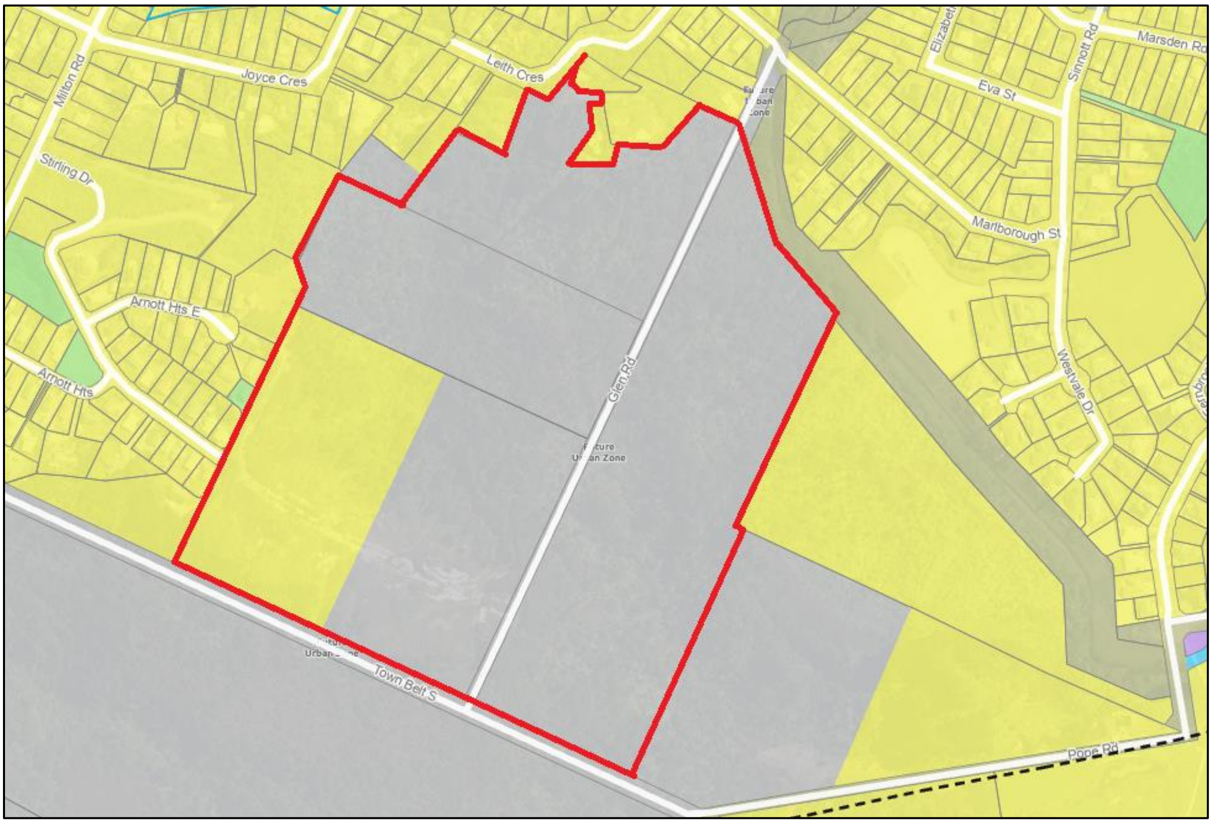


Figure 1: Subject Site – TTPP Eplan Maps 2022

5. The purpose of this submission is to request the proposed zoning is amended to **convert the above FUZ properties to Large Lot Residential Zone (LLRZ)** for the reasons hereunder discussed.

6. The site was excluded from the GRZ in the original draft of the TTPP due to topographical restrictions and the potential for servicing complications for traditional density residential, which is provided for within the GRZ. The site contains areas of steep topography and a ridgeline that runs through the property in a north to south trajectory. The site is also located within the Land Stability Hazards and Risk Area. No alternative hazard overlay is applicable to the site.

7. As a result of the FUZ, the proposed TTPP demonstrates that the residential use of the site is not inappropriate where a Structure Plan or Plan Change is adopted by Council. Either of these processes will involve the requirement for the applicant to demonstrate that the use of the site is practicable from an engineering perspective.

8. The land owner has taken steps to address land stability concerns. Investigations have been advanced which demonstrate the site ability to accommodate vehicle access and subsequent large lot residential allotments as demonstrated within the following Figure 2, which depicts topography and a transport corridor providing connectivity to Stirling Drive and Leith Crescent. An additional connection has been demonstrated to the east of the site.

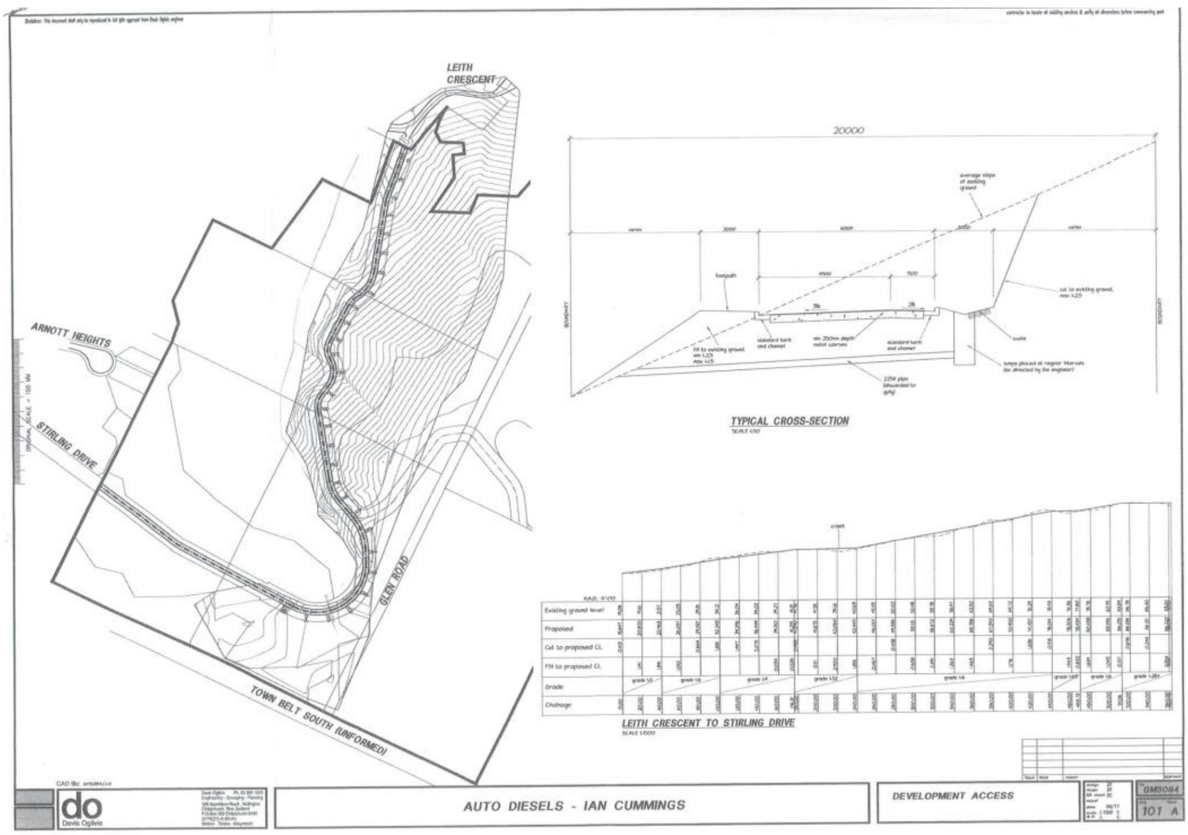


Figure 2: Subject Site and Roading Cross Section Including Stormwater Disposal - Davis Ogilvie Engineering, Surveying and Planning 2022

9. The land owner has absorbed considerable cost to date in undertaking investigations to confirm the suitability of the site for development. There are no known reason for onsite servicing in the form of wastewater and stormwater disposal to ground to not be achieved where reticulated services are not available. This is consistent with FUZ-P4. The investigations have demonstrated areas suitable for residential use without extensive earthworks or land stabilisation.

10. Through the landowner's investigations, undertaken by suitably qualified professionals, they have demonstrated that the site is suitable for residential development at a reduced density as compared to the GRZ. It is considered that Large Lot Residential Zoning is more appropriate for this site.

11. The character of the surrounding environment includes residential activity of varying densities. The property is not affected by any Natural Environmental Values or Open Spaces Zoning. The use of the site for the purpose of large lot residential activity will achieve cohesion with the surrounding environment which will not put additional pressures on the receiving environment in respect to both infrastructural capacity and land stability. Due to the Land Stability overlay, Council will maintain discretion over any future LLRZ subdivision of the site via SUB – R23, which will ensure engineering, servicing, natural hazard and character concerns can be addressed in a pragmatic way via the resource consent process as opposed to the uncertainty which stems from the FUZ.

12. The conversion of the site from FUZ to LLRZ will not adversely affect the ability for any future subdivision or land use to be consistent with the applicable provision of RESZ O1 to O3 and P1 to P-17. The density provided for by the LLRZ has been considered more appropriate to the use of the site due to topographical restrictions as opposed to any future intensive residential density enabled by the present FUZ overlay where it is adopted by Council through a Plan Change or Structure Plan.

Relief Sought

13. It is requested that RS 1615, RS 1622, RS 1594, PT RS 1613 and Lot 2 DP 2816 are rezoned to Large Lot Residential Zone. Intensive preliminary investigations have demonstrated that this is appropriate from an engineering perspective. RS 1614 shall remain GRZ. Residential character will be maintained and the rezoning will assist in achieving cohesion between two presently segregate residential environments. Where the LLRZ is adopted, valuable connectivity will be achievable and the social and economic wellbeing of the community will be supported.

14. It is intended that Glen Road will be closed in future. This will be appropriate as the alignment of the road presently in not practicable due to the existing topography. It is unlikely that this road will ever be utilised to form a transport corridor for public use due to the considerable works which would be required to construct a formation to NZS 4404.

15. Through the LLRZ Council will still maintain discretion over the subdivision of the site due to the presence of the Land Stability overlay, which will ensure the site is not subject to inappropriate development which has the potential to effect land stability. The Council will be able to ensure areas of vegetation and steep slopes are retained and protected by way of s. 221 Consent Notices or land covenants which will be informed by engineering recommendations through any future subdivision process as a part of a resource consent application.

Item Two: Future Urban Zone

Proposed District Plan Provision	The Submission is that: Oppose/Support	Reasons	Decisions Sought:
FUZ – O4	Support	This objective is supported as it allows for more than one process in achieving development within the FUZ. This submission supports the potential for the adoption and implementation of a Structure Plan to undertake appropriate subdivision and development within the FUZ, as opposed to a Plan Change process.	
FUZ – P4	Support	This submission is in support of this Policy as it provides for the potential to implement necessary infrastructure within the FUZ by any individual or the Council. It also provides explicitly for the disposal of wastewater to ground where reticulated connections are not	

		available, which will ensure appropriate development may proceed where infrastructural projects may be subject to unresolvable delay.
FUZ – P5	Support	This Policy provides for a pragmatic approach to the implementation of a Structure Plan.
FUZ – R10	Support	This Rule provides for development where a Structure Plan has been adopted by Council, which will ensure activities provided for within the structure plan may be implemented in accordance with alternative zone standards without the need for a private plan change.

16. In summary, this submission is in support of the provisions of the FUZ which enable subdivision and development of a site in accordance with alternative suitable zoning within the TTPP where Council has approved a Structure Plan. This submission supports that the TTPP does not require limited or full notification of the adoption of a Structure Plan.

Item Three: Rural Zone Subdivision

Proposed District Plan Provision	**The Submission is that:** **Oppose/Support**	**Reasons**	**Decisions Sought:**
B – S1	Oppose	B-S1(h) provides for subdivision within the GRUZ where minimum lot sizes are 4ha, except where the site is located in a highly productive land precinct. This does not provide for one of the most common forms of rural subdivision which occurs throughout the district. It is highly common for productive rural land holdings to be subdivided off from existing lawfully established dwellings, resulting in one smaller title with the existing dwelling and one larger productive land holding. This allows for a range of scenarios which are typically appropriate in respect to subdivision within the rural zones which will not result in further fragmentation of productive land holdings. This form of subdivision allows for retirees or families to remain in the house they feel connected to without the responsibility or pressure of operating a productive farm. This form of subdivision will also allow for a modern dwelling to be built on the productive land holding for the purpose of residential occupation in support of the productive use. This will help support and stimulate agricultural activities whilst providing for the wellbeing of residents. This form of subdivision can also provide financial relief for people under pressure where they do not wish to relocate from their community or family home. In the above circumstances, it is often the case for the land owner to want a small, low maintenance land holding to be subdivided off with the dwelling. 4ha would be an inappropriate size, and would detract from the	It is sought that an additional subdivision trigger is provided for the subdivision of one smaller title within the GRUZ, which can occur once. The following standard is recommended for Restricted Discretionary subdivision within the GRUZ: **General Rural Zone subdivision must comply with all of the following standards:** ***(i)*** *General Rural Zone 4 hectares, except that it is 20 hectares in the Highly Productive Land Precinct; or* ***(ii)*** *The Record of Title to be subdivided must be at least 8 hectares in area;* ***(iii)*** *The Record of Title(s) to be subdivided must have an issued date of no later than 31 December 1999;* ***(iv)*** *The proposed subdivision must create no more than one additional Record of Title, excluding an access allotment;* ***(v)*** *The additional lot must have a proposed area of between 5,000m^2 and 1.6 hectares.* This will allow for rural subdivision as originally proposed in the TTPP, but will also offer a one off alternative for people to subdivide one smaller Lot. This can only occur once due to the title date trigger and therefore won't result

		balance farm lot. A smaller lot size must be provided for in the rural zones, which can only be subdivided once.	in continued fragmentation of productive rural land holdings.

Item Four: Visitor Accommodation

Proposed District Plan Provision	The Submission is that: Oppose/Support	Reasons	Decisions Sought:
GRZ – R6	Oppose in part	Visitor accommodation is permitted where the following standards are met: **1.** The accommodation is ancillary to a residential activity. **7.** In the Buller District the accommodation is homestay accommodation with a permanent resident living on site. All Districts should be able to undertake visitor accommodation in an ancillary building (which excludes self-contained minor residential units) where the permanent resident lives within the primary dwelling or flat on site. All Districts should be able to provide for homestay accommodation, which by definition is visitor accommodation contained within the primary dwelling or flat with a permanent resident living within the dwelling or flat.	GRZ – R6 shall be amended as follows: **1.** The accommodation is undertaken within: **i** A building ancillary to the primary dwelling on site, which is occupied by a permanent resident, or **ii** The accommodation is homestay accommodation with a permanent resident living within the dwelling or flat. GRZ-R6(7) shall be deleted.

Item Five: Vegetation Clearance

Proposed District Plan Provision	The Submission is that: Oppose/Support	Reasons	Decisions Sought:
ECO – R1	Oppose	This submission is in opposition of permitted vegetation clearance standards, specifically the following: ***5.** Within the Buller and Westland Districts:* ***i** It is the removal or clearance of mānuka, kānuka and bracken only that is not part of any wetland and which is under 15 year old, not exceeding 5ha per site over any continuous three year period, subject to provision of notice to the relevant District Council at least 20 working days prior to the proposed clearance, including:* ***a.** Details of the location of the proposed clearance;* ***b.** Area of the proposed clearance; and*	This submission seeks to transfer rule ECO-R1(5)(i)(a-b) to a controlled activity status as opposed to permitted. Matters of control are to include but are not limited to: • Adverse effects upon ecological integrity are avoided, remedied or mitigated. • Sedimentary controls and management are planned and implemented. • Adverse effects upon amenity are avoided, remedied or mitigated. • Landscape character is maintained.

		c. *Verification by documentary, photographic or means that the vegetation is less than 15 years old and not part of any wetland, or* ***ii*** *It is a maximum area of 5000m² per site, in total, over any continuous three year period.* This rule is very permissive and in practice, will be likely to encourage uncontrolled vegetation removal which can result in considerable adverse effects where mitigation measures are not implemented. The rule does not consider impacts of sediment dispersal, streams and overland flow paths, impacts upon fauna, etc. Juvenile forests may still contain significant species, including birds and galaxias within waterways. 5,000m² of removal permitted per every three years with no controls or mitigation required has the potential to have a significant impact on the Westland District and its environmental quality, particularly where significant species can be found. This rule may also result in issues in practice as it does not provide for Council to request further information or question the information required by Rule ECO-R1(5)(i)(c), including its source. The rule also does not require this information to come from a reputable source. It will be difficult to confirm the evidence provided by the individual is in fact the site they refer to and is likely to result in tension and dispute with land owners. There are no legal mechanisms Council can rely on to improve information quality. It is considered that this form of information gathering is more suitable as part of a resource consent process.	This submission also seeks to remove ECO-R1(5)(ii) from the permitted activities list. It is sought that the above Rule ECO-R1(5)(ii) is omitted entirely from the TTPP. This will mean that this level of indigenous vegetation clearance (5,000m² per three years) will result in an activity status of a minimum of Discretionary. This will ensure Council has the opportunity to address vegetation clearance of mature forests on a case by case bases and take practical measures to protect delicate ecosystems and involve the relevant potentially affected parties.

Item Six: Coastal Hazards and Zoning

Proposed District Plan Provision	**The Submission is that:** **Oppose/Support**	**Reasons**	**Decisions Sought:**
MDRZ Revell Street	Oppose	167- 241A of the western side of Revell Street, Hokitika are Zoned Medium Density Residential which allows for increased investment and residential occupation within immediate proximity of the coastal environment.	This submission seeks that the Medium Density Residential Zone covering the 167- 241A of the western side of Revell Street is removed and replaced with General Residential Zone. The GRZ will allow for the use of existing structures for those activities permitted within the zone.

		It is noted that protection works do not yet exist within immediate proximity of these properties. The seawall proposed from Richards Drive to Stafford Street has not been granted resource consent to be undertaken. The proposal is not in accordance with the central directive of the New Zealand Coastal Policy Statement and is only proposed to be in situ for 15 years. 15 years post construction, the wall shall be removed. This zoning appears to be based of non-existent protection works. It is also noted that the maintenance and retention of any coastal protection works is not a statutory requirement. The wall or any associated protection works will continue to be managed by an external party, being the West Coast Regional Council. The maintenance of the wall may be removed from the annual plan in future and therefore the reliance on its existence for residential intensification is incredibly poor practice. Further investment in areas affected by or projected to be affected by coastal process should be heavily discouraged. The above zoning is contrary to national level legislation and will make it very difficult for territorial authorities to fulfil their duties pursuant to s. 31 of the Act.	Please see the following paragraphs 17 and 18 for further generalised relief sought for property located within immediate proximity of the coastal environment.
NH-R1	Oppose	Reconstruction and replacement of lawfully established buildings within natural hazard overlays are permitted where the standards of NH-R1(1-5) are met. This will mean that land owners will be forced to rebuild in the same spot where a natural hazard caused property damage as opposed to relocating the activity to a more suitable location where available. This is likely to result in issues with insurance for property owners and is poor planning practice. Existing use rights pursuant to s. 10 the Act will still apply where applicable. This will continue to affect redevelopment within hazard overlays. The above standard is unnecessary and too permissive.	This submission seeks to ensure that no reconstruction or replacement of buildings is permitted within natural hazard overlays. Where reconstruction does not occur in accordance with s. 10 of the Act (within 12 months), the activity shall be assessed as a new activity. Existing use rights will still be applicable in some instances and therefore people will have the opportunity to rebuild, so removing this rule will not alter people rights under the Act.

NH-R4	Oppose	This standard allows for the construction of new natural hazard protection works, such as groynes, stop banks, and seawalls where a site is not affected by any Overlay Chapter Area identified in Schedules 1-8. It is acknowledged that the structure still has the potential to require consent pursuant to any applicable Regional Council Plan, however, the activity should not be permitted. The District Councils should continue to be involved in this process to ensure locals have a say in the processes through s. 95 of the Act as protection works can reshape natural environments and surrounding processes, which can compromise natural character and amenity indefinitely. This form of activity also encourages further investment within areas through offering a temporary fix. Immovable structures within coastal environments are discouraged through central legislation. This rule contravenes the intent of the present nation direction.	This submission seeks to remove NH-R4 from the permitted activities list. The construction of new natural hazard mitigation structures should be discretionary at a minimum. It is recommended that NH-R4 is moved in full to a discretionary activity status.
NH-R7	Oppose	This rule allows for all non-habitable buildings to be constructed as a permitted activity in the Flood Severe and Flood Susceptibility Overlays. This rule allows for continued investment in areas where natural hazards can have considerable impacts upon property and people. This is likely to encourage continued development which will become progressively difficult to insure where it is constructed in areas potentially subject to significant natural hazards.	This rule should be amended to state *unoccupied buildings of no more than 50m^2.* This will allow for small structures to be erected, with the remaining buildings falling into either Restricted Discretionary or Discretionary with controls around demonstrating the structure is not at risk of significant natural hazards.
NH-R10	Oppose	This rule allows for buildings for sensitive activities to be constructed as a permitted activity within the Flood Susceptibility Overlay where the finished floor level is 500mm above the 1% AEP flood event level. This rule is too permissive and requires that all builds are constructed to 500mm, whereas some constructions may involve engineer advice which recommends a raised floor level in excess of 500mm above the 1% AEP flood event level.	This rule should be shifted to controlled, with matters of control including (but not limited to) the avoidance of significant natural hazards. The wording should also be altered to state the following: *Any new buildings or additions and alteration have a finished floor level **a minimum** of 500mm above the 1% AEP flood event.*
NH-R38 & NH-R39	Oppose	These standards provide for further investment within areas of coastal hazards,	This submission seeks to ensure that no reconstruction or replacement of buildings is permitted within natural

		including reconstruction and new construction of non-habitable buildings. New investment and reconstruction should be discouraged within coastal hazard overlays. As noted above, s. 10 existing use rights will still remain for the reconstruction of buildings within 12 months of removal or destruction. NH-R38 is too permissive in this respect and will result in insurance issues for private property owners. Allowing any building within severe coastal hazard areas is not best planning practice.	hazard overlays. Where reconstruction does not occur in accordance with s. 10 of the Act (within 12 months), the activity shall be assessed as a new activity. Existing use rights will still be applicable in some instances and therefore people will have the opportunity to rebuild, so removing this rule will not alter people rights under the Act. Rule NH-R38 should be removed. NH-R39 should be amended to say unoccupied buildings of no more than $50m^2$. This will allow for small structures to be erected, with the remaining buildings falling into either Restricted Discretionary or Discretionary with controls around demonstrating the structure is not at risk of significant natural hazards.

17. Further relief is sought in regards to coastal hazards and zoning. It is noted that the TTPP prohibits some activities within areas affected by severe earthquake natural hazards, however, no similar controls have been proposed in respect to areas of the coastal environment which are at significant risk to tsunamis (which are likely to occur during the same event) or areas affected by coastal erosion which may be vulnerable to storm surge in the short term and land loss in the long term.

18. This submission seeks to ensure new sensitive activities are prohibited within the Coastal Severe Overlay. It is vital that territorial authorities are given the tools to meet their obligations pursuant to s. 31 of the Act without the opportunity for challenge or human error resulting in poor decisions. By prohibiting sensitive activities within the Coastal Severe Overlay, the Plan will promote managed retreat in a way that will still allow for minor developments within areas affected by alternative Coastal Hazard Overlays.

Item Seven: Franz Josef Landslide Risk and Associated Provisions

19. This submission aims to ensure landslide risk is considered and provisions are adopted to prevent development within areas at risk. It is considered that the devastating effects associated with landslide risk within Franz Josef have not been considered or provided for via appropriate prohibitive zoning and associated provisions. It is acknowledged that during an earthquake, the likelihood of a landslide (rock avalanche) occurring from the steep hillslope south-east of the existing township is high. This event has the potential to result in catastrophic loss of life.

20. Attached is the draft Comparative Hazard and Risk Assessment report for Franz Josef, prepared by Tim Davies of the School of Earth and Environment, University of Canterbury. This is presently still only available in a draft form as the document is being peer reviewed. This report discusses landslide risk in the form of the collapse of the steep hillslope to the southeast of the township, as well as landslide result in dam-break flooding from the Callery and Tatare Rivers. This report acknowledges that the ranges of return periods considered vary between hazards. Thus, for example, the area

affected by a 100,000-year return period rock avalanche is delineated because, although it has a very low probability (10^{-5}) of occurring in any given year, it poses a significant risk to life because it can kill a very large number of people (80% of people in the present town site, 35% of those in the proposed new town site). The occurrence of earthquakes, however, is dominated by the Alpine fault earthquake which currently is a 50 – 100-year return interval event and is also the maximum conceivable event for the area, and is expected to kill only a small proportion of those present. Thus, the ways in which earthquakes and landslides contribute to risk are very different, because they have very different magnitude-frequency-impact distributions. It is considered that landslides have the potential to result in the most significant loss of life without the potential for warning or evacuation. It is important to note that the landslide may occur where the slope fails catastrophically without an earthquake trigger.

21. The extent the landslide/rock avalanche is likely to affect the existing township of Franz Josef has been demonstrated within the attached report as shown within the following Figure 3. This does not include landslides and associated dam-break mentioned above.

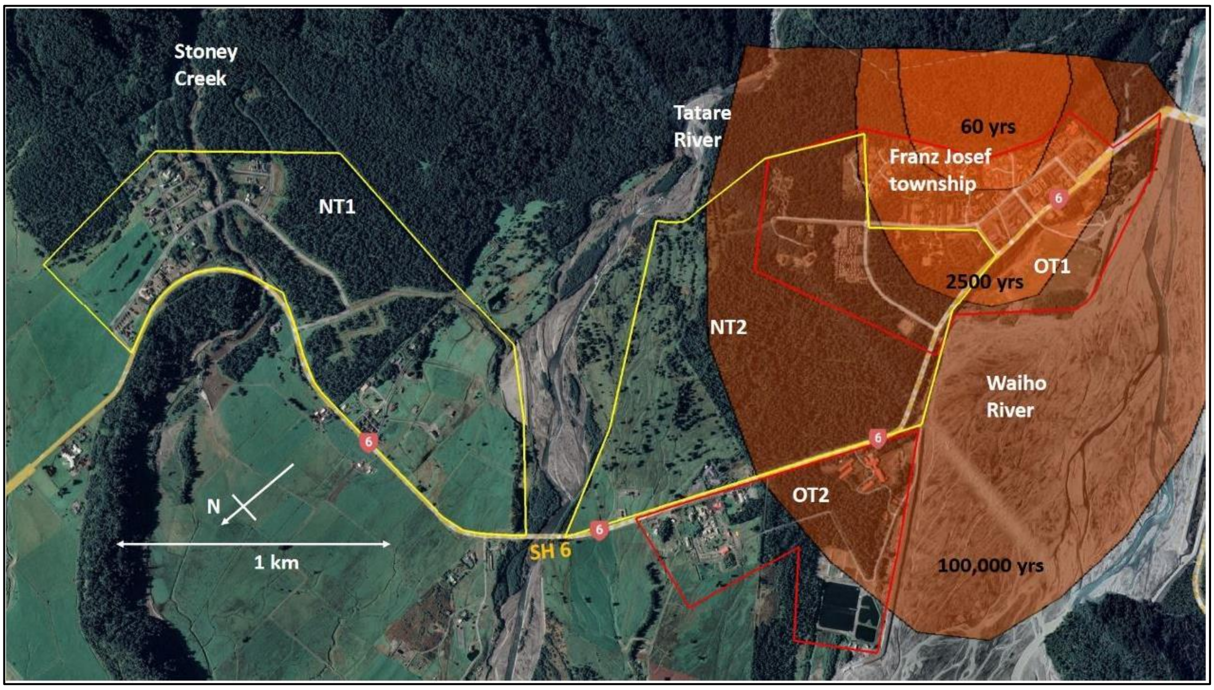


Figure 2: Landslide (Rock Avalanche) Hazard at Franz Joseph – Tim Davis 2022

Relief Sought

22. This submission seeks that the information within the attached reports is utilised to inform alternative zoning/overlays which prohibits development within areas at immediate risk of landslide natural hazards. The TTPP does not provide enough consideration to landslides within Franz Josef. An additional overlay needs to be included in the Plan and associated maps. As noted above, this overlay needs to prohibit all development in this area with a blanket vetoing of new structures and additions to existing structures that will result in the capacity for additional guest (commercial) or additional gross ground floor area (residential and other). This amendment to the TTPP is required in order for the Westland District Council to administer its duties pursuant to s. 31 of the Act and to achieve the purpose of Part II of the Act. This amendment is also required to assist in preventing considerable loss of life and discouraging further development within an area which is clearly at substantial risk. The outcome cannot be subject to political influence.

COMPARATIVE HAZARD AND RISK ASSESSMENT OF EXISTING AND PROPOSED FRANZ JOSEF TOWN SITES: REPORT FOR WESTLAND DISTRICT COUNCIL

September 2022

Tim Davies
School of Earth and Environment, University of Canterbury

EXECUTIVE SUMMARY

Franz Josef Glacier township is known to be subject to a number of natural hazards that threaten both assets and lives:

1. river flooding from the Waiho-Callery river system and the Tatare River;
2. earthquake (surface rupture, ground shaking and liquefaction), predominantly from the Alpine fault;
3. failure (probably earthquake-triggered) of the steep hillslope immediately south-east of the existing township, causing a rock avalanche;
4. landslide dambreak flooding from the Callery and Tatare Rivers; and
5. debris-flows at Stoney Creek.

The threats from Waiho River flooding and an Alpine fault earthquake are widely-recognised, and official and societal concerns about them are such that it has been proposed to relocate the township to an alternative site in the same vicinity but more distant from both the Waiho and the Alpine fault.

New Zealand legislation requires that land-use decisions in respect of natural hazards are based on the concept of risk (defined as the annual probability of an event multiplied by its cost), therefore it is necessary to assess the degree to which the proposed relocation will alter all natural-hazard risks to assets and to life at Franz Josef.

This report estimates and compares the risks to the existing and proposed town sites that arise from all these hazards. Due to the sparsity of data on individual hazards, estimates of absolute risk are subject to potentially large errors. The ratios of risks in the two sites, however, are more robust because errors will tend to be similar at both sites and may largely cancel each other out.

The outcomes are that:

- Overall risks to life in the existing town are of the order of 10-20 times higher than those to the same population in the proposed town site.
- Risks to assets are of about the same order of magnitude over both existing and proposed sites, but somewhat greater over the former.
- In particular, the individual risk-to-life from rock avalanche hazard at the present town site appears to be about an order of magnitude higher than globally-accepted levels, but is much closer to acceptable levels in the relocated site.
- Societal risks-to-life due to rock avalanche, dambreak flood and debris flow appear to be unacceptably high by global standards across parts of the present and proposed town sites.

It is noted, however, that a number of assumptions underlie these results:

(a) That assets and people are uniformly spatially distributed across both existing and relocated town sites at equal spatial densities corresponding to pre-Covid population and tourist numbers. This means that the spatial distribution of hazards determines the risk distribution.
(b) That risks due to hazards 1, 3, 4 and 5 are only those that exist prior to the occurrence of a major earthquake. This is because hazards 1, 3, 4 and 5 are likely to be altered significantly following a major earthquake, but this alteration cannot be quantified realistically.
(c) That the rock avalanche hazard is real; this is presently somewhat uncertain. A detailed geotechnical assessment is needed to assess this, because rock avalanche risk is the main cause of the much higher risk-to-life at the existing town site.
(d) That flood control banks are in place as planned in 2020 (Figs. 3 & 4), and these will not fail before 2040. This is because aggradation of the Waiho River is assumed to continue at the pre-2020 rate, and this will result in bank failure becoming much more likely after 2040.

Climate change has not been factored into present hazard and risk estimates, because the extent of its impacts on weather and river flows prior to 2040 have yet been defined sufficiently reliably.

It follows from (b) and (d) that the relative risks calculated herein are valid only until the next major earthquake or until 2040, whichever comes first; the probability of an Alpine fault earthquake occurring before 2040 is about 30-40%. A qualitative outline of risk changes after 2040 and/or after an earthquake is provided in Appendix C.

The risks to the proposed relocated town site can be reduced by concentrating assets and people in locations less vulnerable to hazards. The part of the proposed town site east of the Tatare River and north of State Highway 6 stands out as the least threatened area.

Further work is needed to assess

(i) the reality of the rock avalanche hazard;
(ii) how the relocated township layout will affect risks to lives and assets, and how these compare to risks to the present township layout;
(iii) how hazard frequency will change following the occurrence of a major earthquake; and
(iv) how flood frequency will change due to increased risk of stopbank overtopping after 2040.

When reliable estimates of the locations of assets and population of the proposed relocated township become available, further detailed work could be carried out to reassess the relative risks using the actual distribution of assets and people in the present town site. However the base data on hazard magnitude, frequency and spatial distribution are recognised to be approximate, and will limit the reliability of any precise risk estimates.

It is also important to note that no estimates of risk can predict the extent to which specific areas of land will be affected by hazards prior to 2040. Risk is a probabilistic concept that does not apply reliably to any small sample of events; only over a very long time period can outcomes be expected that correspond reliably to the present hazard and risk estimates.

CONTENTS

1. Introduction

On 20 December 2020 Westland District Council contracted University of Canterbury to provide a comparative hazard impact assessment of the existing and proposed Franz Josef town sites (Fig. 1, 2). This work is to be carried out by Dr Tim Davies and MSc thesis student Nandhini R.

Reported data required include

i. the approximate footprints of the identified hazards over a range of magnitudes and frequencies on both present and proposed town sites;
ii. a comparison of the average annual hazard impact on the present town site with that of the proposed new site, assuming the same degree of development at each site;
iii. identification of specific areas requiring more detailed investigation.

A Progress Report dated May 2022 dealt with the first of these.

The MSc thesis (R, 2022) was submitted at the end of June 2022, and provides an account of the project and a quantitative comparison of the hazard exposure of the sites. The main contribution of the thesis was to develop a GIS-based superposition of the hazard magnitude zones and to quantify their overlaps with the present and proposed town sites, and to find values for specific hazard mortality rates. The thesis was examined and passed by two external referees; the comments of the referees have been incorporated in the present report where appropriate.

This Final Report outlines the basis of, describes and summarises the outcomes of, the MSc thesis and other work completed for this project.

2. Background

Franz Josef Glacier township in Westland (Fig. 1) was, pre-Covid, a rapidly-developing centre forming a key component of South Island tourism; in the future it is expected to resume that role. However it has for some time been of increasing concern that the township and its ca 400 permanent inhabitants, together with hundreds of seasonal workers and some thousands of daily tourists, are at serious risk from the natural hazards that threaten the area. The sublime beauty of the natural landscape that attracts tourists to the area results from its extremely active tectonic setting, which gives rise to rapid landscape uplift and spectacular mountains, and from its intense hydrological regime with ca 10 000 mm of rain per year and spectacular rivers. These same factors, however, also cause the occasional lethal earthquakes, landslides, floods and debris flows that can devastate Franz Josef with little or no warning. Although no such catastrophe has occurred in recorded history, this only dates back to the mid-19th century, and landscape evidence suggests that many major events have occurred prehistorically; these will certainly be repeated in the future. No location on Earth is risk-free, however, and Franz Josef can continue to live more safely with its exciting environment if it acknowledges its predicament and plans to avoid the future events that can be foreseen.

New Zealand legislation requires that natural hazards threatening assets and lives are considered when locating developments, and that this consideration is framed in terms of risk. In this context, risk is defined as the annual probability that a specific natural event will occur, multiplied by its impact on society in terms of deaths and costs. Thus risk is a criterion that must be used in decision-making about where to locate societal assets and, hence, people. In particular, if an event occurs that kills people, those responsible for permitting people to be in the fatal area must be able to demonstrate that the risks to the deceased were in the societally-acceptable range.

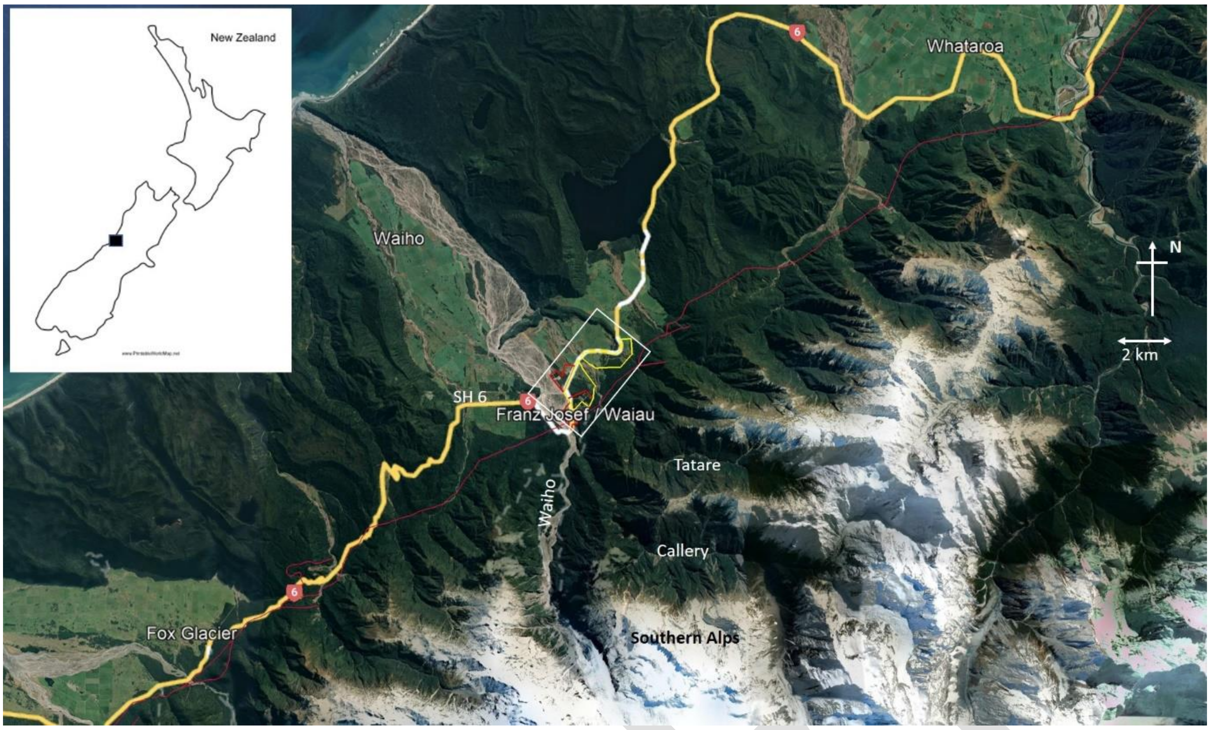


Fig. 1 Franz Josef area, Westland showing Alpine fault (red line), SH 6 (yellow line), Southern Alps and major rivers. White square is area of Fig. 2. Modified Google Earth image.

It has been proposed that Franz Josef township can reduce its hazard exposure, and hence risks, if its assets and population are relocated to a different site in the same general area. The purpose of the present work is to estimate and compare the risks from natural hazards to both the present town site and to the proposed relocation site. The existing (OT1 and OT2) and proposed (NT1 and NT2) town sites, each comprising two distinct areas, are shown in Fig. 2.

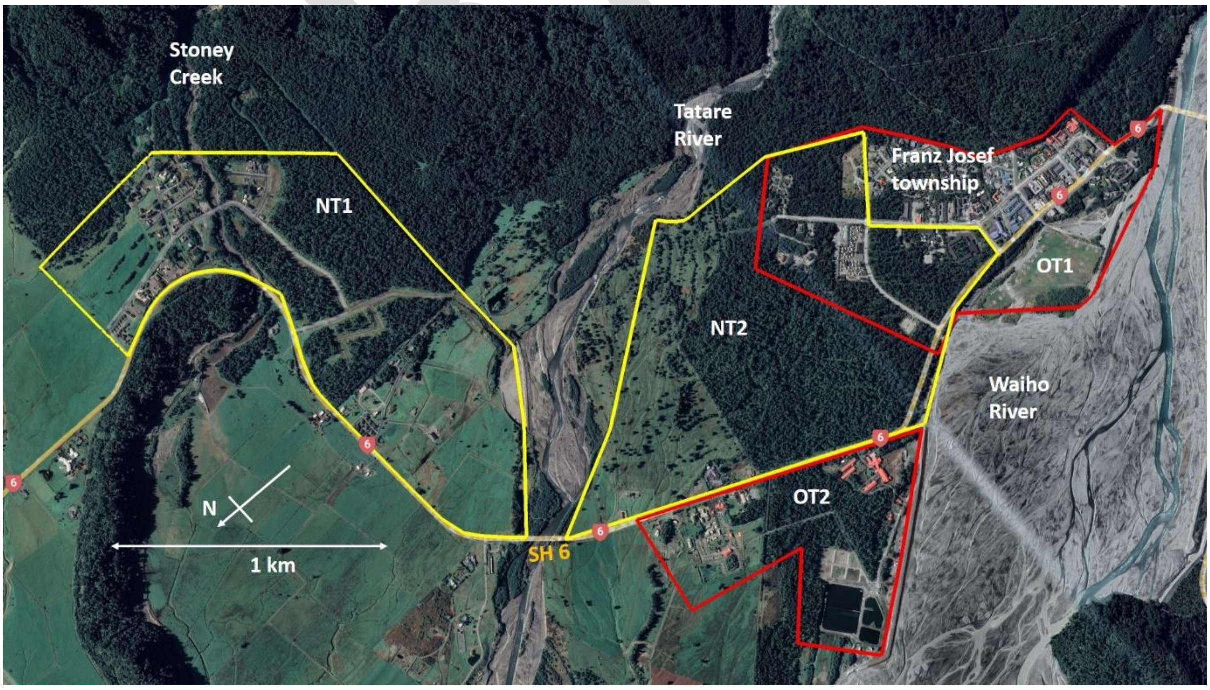


Fig. 2 Close-up of Franz Josef township area showing present town sites (red lines: OT1 and OT2) and proposed town sites (yellow lines: NT1 and NT2). Modified Google Earth image.

3. Previous hazard and risk assessments

McSaveney and Davies (1998) carried out the first natural hazard assessment for Franz Josef Glacier township and its environs, which however considered only the flood hazard due to the Waiho River and the earthquake hazard due to the Alpine fault. At that time the latter hazard had only recently been generally acknowledged, prior controversy over whether the Alpine was indeed seismogenic or moved by slow slip having been resolved in the mid-1990s. Since then considerable progress has been made in understanding seismic hazard in Westland and its likely impacts (e.g. Robinson et al., 2016; Howarth et al., 2021; Blagen et al., 2022). The 1998 hazard assessment focussed mainly on Waiho River flooding, using a geomorphic approach because of the lack of flow and sediment transport data.

Langridge et al. (2016) incorporated post-1998 work on the Alpine fault (Langridge et al., 2011; Howarth et al., 2014) and the Waiho River (Land River Sea Ltd, 2014), and considered in addition threats due to alluvial fan flooding; to landslide-dambreak flooding from the Callery River, which had caused relocation of a holiday park in 2003 following research by Davies (2002) and OptimX (2002); to coseismic and aseismic landsliding based on work by Hovius et al. (1997), Stark and Hovius (2001) and Robinson et al. (2016); and to rock avalanche based on work by Barth (2013) and Davies (2014). Areas susceptible to ground rupture, seismic shaking, Waiho flooding and liquefaction were delineated but without associated probabilities. Hazards due to debris flows at Stoney Creek and to landslide dambreak floods from the Tatare River were not mentioned, despite their consideration by Welsh and Davies (2011) and Davies and Korup (2007) respectively.

Tonkin and Taylor (2017) summarised hazard knowledge and presented options for risk management. Davies and Loew (2019) and Davies and Moretti (2021) estimated the likely size and annual probability of rock avalanche hazard at Franz Josef, and Dunant et al. (2021) derived a magnitude-frequency relationship for landslide-dambreak floods from the Callery River. In addition, R (2021) carried out a magnitude-frequency analysis of landslide dambreak floods from the Tatare River.

4. Methodology

The present report draws on the previous work centred on the Alpine fault for estimating earthquake-related hazards and risks. Waiho River flood hazard and risks assessments utilise data from the most recent modelling by Land River Sea (Gardner, 2021) and the aggradation analysis of Beagley et al. (2020). The areas affected by landslide dambreak floods from the Callery and Tatare Rivers are delineated for a range of return periods by modelling carried out specifically for this project by GNS Science Ltd under their Endeavour programme, while the areas affected by rock avalanches of a range of return periods are delineated using the empirical relationships of Davies (1982) and Korup and Clague (2009). To generate an impact-frequency relationship for debris flows at Stoney Creek, empirical relationships from the literature were assumed to apply, together with the assumption that debris flows result from aseismic landslides in the catchment. These analyses and the resulting impact-frequency data are outlined in Appendix A.

Using GIS, R (2022) has calculated the overlap of each hazard type and frequency with the old and new town sites. Assuming that assets and people are uniformly and equally spatially distributed across each town site, at the pre-Covid permanent and tourist populations, the asset risks and risks-to-life for each hazard, and the total for all hazards, are calculated.

5. Assumptions and implications

It is assumed that:

5.1 The spatial distribution of assets within the town sites is uniform. Thus the impact of each hazard event is characterised only by the spatial distribution of the hazard event itself, not by the location of any specific asset. The hazard spatial distribution, however, provides information that may be useful in deciding where to locate assets across the relocation sites in order to reduce impacts. Similarly, risk-to-life estimates are based on assumed uniform distributions of people across the two sites at pre-Covid permanent, itinerant and tourist populations. Asset and people distributions are assumed uniform in time.

5.2 Stopbanks are present as planned in 2020 (Figs 3, 4), including raising of existing banks and installation of a bank to prevent the Waiho avulsing into the Tatare downstream of the oxidation ponds. These stopbanks are also assumed to operate as designed (i.e. not fail).

5.3 The Waiho River continues aggrading. Beagley et al. (2020) showed that if the Waiho behaves over the next century as it has during the last 50 years, its bed will aggrade by about 17 m at the SH6 bridge by 2120, assuming that it remains confined in its present bed by raising stopbanks. To address this situation, the West Coast Regional Council medium-term strategy is to relax/remove the western stopbanks (on the true left of the Waiho River) so that the flood threat to the east bank (true right) land is greatly reduced (Gardner, 2021). Thus the eastern stopbanks only need to function until this strategy is implemented; they have been designed to cope with about 20 years of aggradation (Gardner, 2021), so this is the corresponding time-scale over which the present work applies. Note also that the probability of a major earthquake in the next 20 years is about 30-40%; this event will drastically alter (increase) the subsequent flood risk due to large coseismic landslide sediment input to the river (Robinson et al., 2016; Briggs et al., 2018; Appendix C). The present work therefore only applies until that event occurs.

5.4 The rock avalanche hazard described is real. As outlined by Davies and Loew (2019) there remains some doubt about this, to resolve which needs detailed geotechnical investigation.

Earthquake hazard at Franz Josef is dominated by the expectation of a major earthquake on the Alpine fault. This probability of this event is about 75% in the next 50 years, according to Howarth et al. (2021). Following this earthquake, or one on a different fault within the Southern Alps, the hazard probabilities at Franz Josef over the following decades to century will change significantly, because of the large volume of earthquake-generated landslide sediment that will be deposited in rivers and the severe aggradation and increased flooding this will cause (Blagen et al., 2022; Orchiston et al., 2018). It is not presently feasible to anticipate quantitatively how the hazardscape will be affected by the next major earthquake. The present work therefore considers only the current, pre-earthquake hazard distribution (which however includes the immediate impacts of the earthquake itself) in comparing the hazard exposures of the two town sites.

The present risk calculations thus apply only until the planned stopbanks become unreliable due to river aggradation in about 2040, or until the next major earthquake, whichever comes sooner.

Future hazards at Franz Josef are expected to alter with time due to climate change. Climate change has however been ignored in the present work because, first, it is a relatively slow process whose impacts will take many years to become fully apparent and in the meantime it is sufficiently accurate to predict future climate-related hazards based on past experience of these; and, second, climate change impacts, while still seriously debated, are likely to be rather similar for both present and proposed town sites and so will not significantly affect the relative hazard vulnerability of the sites.

When consideration extends to longer-term timeframes climate change will be a much more serious factor (Appendix C).

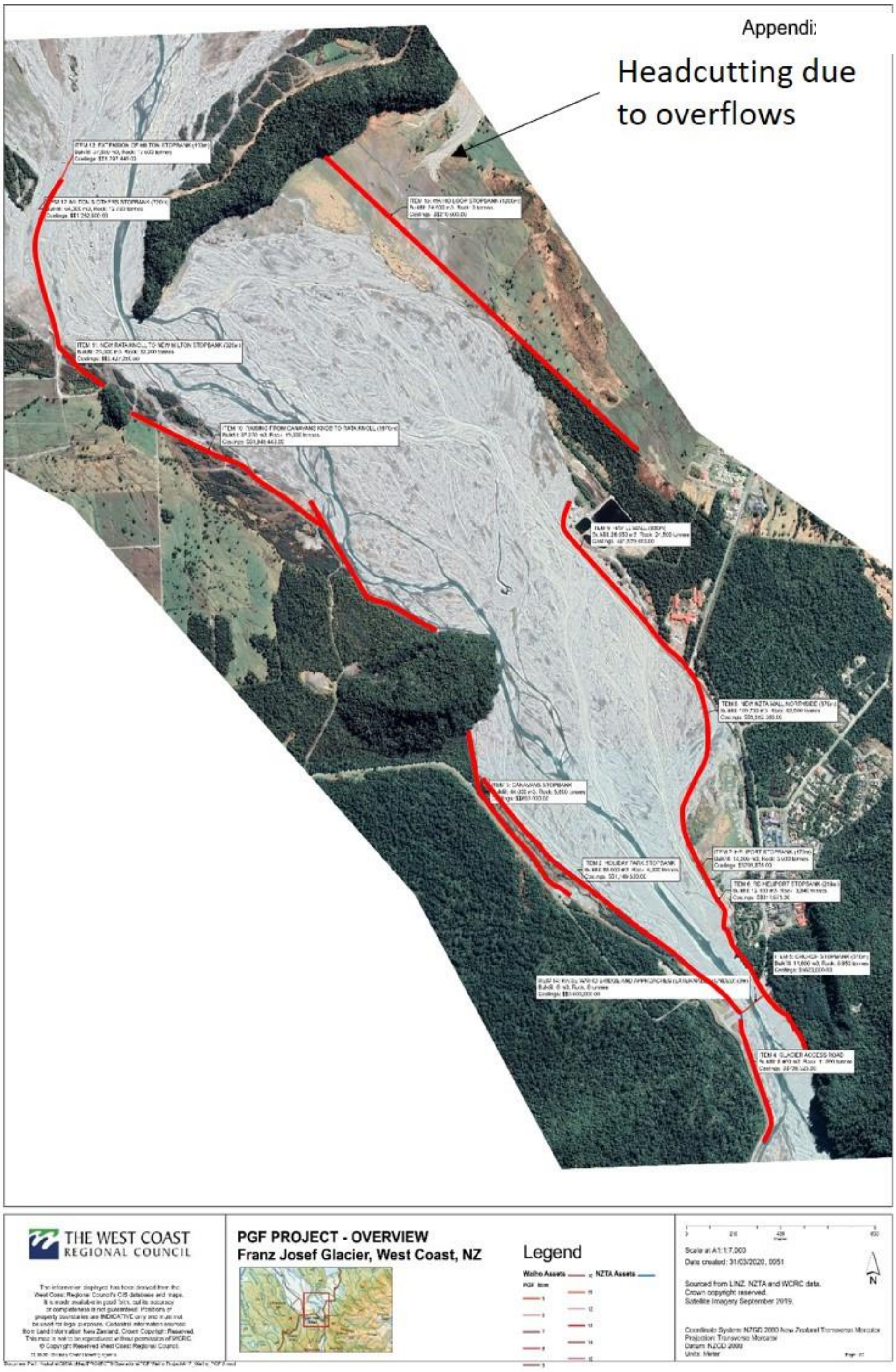
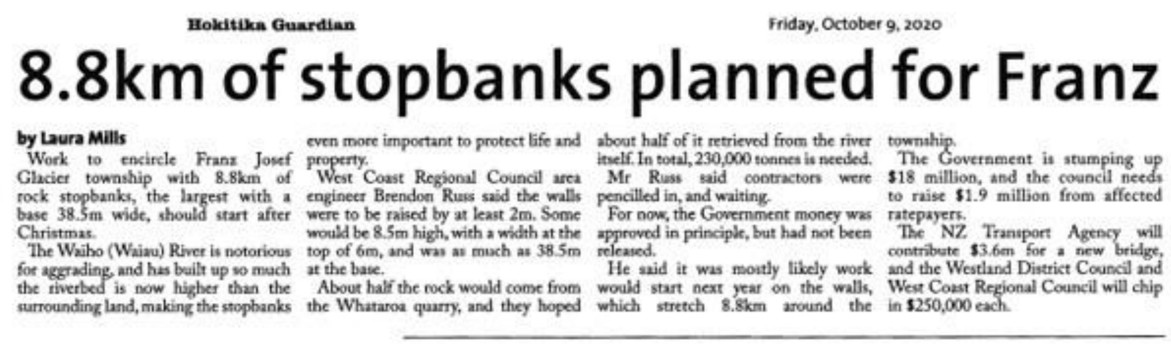


Fig. 3 Existing and planned stopbanks at Franz Josef (West Coast Regional Council).



Hokitika Guardian Friday, October 9, 2020

8.8km of stopbanks planned for Franz

by Laura Mills

Work to encircle Franz Josef Glacier township with 8.8km of rock stopbanks, the largest with a base 38.5m wide, should start after Christmas.

The Waiho (Waiau) River is notorious for aggrading, and has built up so much the riverbed is now higher than the surrounding land, making the stopbanks even more important to protect life and property.

West Coast Regional Council area engineer Brendon Russ said the walls were to be raised by at least 2m. Some would be 8.5m high, with a width at the top of 6m, and was as much as 38.5m at the base.

About half the rock would come from the Whataroa quarry, and they hoped about half of it retrieved from the river itself. In total, 230,000 tonnes is needed.

Mr Russ said contractors were pencilled in, and waiting.

For now, the Government money was approved in principle, but had not been released.

He said it was mostly likely work would start next year on the walls, which stretch 8.8km around the township.

The Government is stumping up $18 million, and the council needs to raise $1.9 million from affected ratepayers.

The NZ Transport Agency will contribute $3.6m for a new bridge, and the Westland District Council and West Coast Regional Council will chip in $250,000 each.

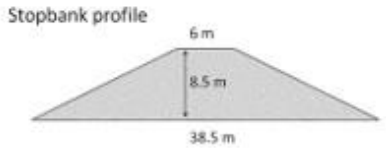


Fig. 4 Information and cross-section of planned stopbanks (Hokitika Guardian, 2020)

6. Hazards affecting town sites

Outlined herein are the estimated spatial extents and recurrence intervals for the known hazards whose areas of impact overlap with either or both the present and proposed town sites:

1. rainstorm-generated flooding from the Waiho-Callery river system and the Tatare River;
2. earthquake (surface rupture, ground shaking and liquefaction), predominantly from the Alpine fault;
3. earthquake-triggered landslide (rock avalanche) from the steep hillslope south-east of the existing township;
4. landslide dambreak flooding from the Callery and Tatare Rivers; and
5. debris-flows at Stoney Creek.

A number of natural hazards that can affect Franz Josef Glacier township, but are either insufficiently localised in impact or localisation of their impacts cannot be predicted, are not considered because they are likely to affect both present and proposed town sites equally. These include windstorms, hailstorms, snowstorms, surface flooding from rainfall, lightning strikes and wildfire.

Because few reliable data exist describing the magnitude-frequency relationships of the considered hazard events the quantities used and derived in the following analyses are necessarily approximations. Hence the areas delineated as affected by events of specific return periods, though as realistic as possible, are also approximations and must be acknowledged as such in any use of this report. Even if these delineations were ideally accurate, however, they could not reliably predict the areas affected by any specific future events because they are statistical descriptions of what can occur over very long time periods. Nevertheless, they are useful for comparing the hazard exposures and risk levels in the existing and proposed township areas.

The areas delineated as affected by events of different return periods are in some cases the result of state-of-the-art numerical simulations (Waiho River flooding; landslide dambreak flooding from the Callery and Tatare), while others (rock avalanche, debris flow, earthquake) are based on empirical data from within New Zealand and from overseas. The data sources and analyses underlying the hazard assessments are detailed in Appendix A.

The ranges of return periods considered vary between hazards. Thus, for example, the area affected by a 100,000-year return period rock avalanche is delineated because, although it has a very low probability (10^{-5}) of occurring in any given year, it poses a significant risk to life because it can kill a very large number of people (80% of people in the present town site, 35% of those in the proposed new town site). The occurrence of earthquakes, however, is dominated by the Alpine fault earthquake which currently is a 50 – 100-year return interval event and is also the maximum conceivable event for the area, and is expected to kill only a small proportion of those present. Thus the ways in which earthquakes and landslides contribute to risk are very different, because they have very different magnitude-frequency-impact distributions.

6.1 River flooding:

(a) Waiho River

The area of land threatened by flooding from the Waiho River has been modelled by Gardner (2021), based on the stopbanks planned in 2020, but omitting consideration of the new bank planned to extend from the vicinity of the oxidation ponds to the Waiho Loop (Fig. 3); this is designed not to overtop at flows below 2500 m^3s^{-1}. These stopbanks are designed on the basis of current bed levels plus 20 years' ongoing aggradation at about 0.18 m/year (Gardner, 2021). The flooded areas have been modelled for discharges of 500 to 3500 m^3s^{-1}, and Fig. 5 indicates the flooding extent for 2500 m^3s^{-1}, which is about a 200-year flood; it is notable that there is no substantial threat to either town site as long as the stopbanks remain functional.

Table 1 Flood magnitude and frequency, Waiho River (derived from Gardner, 2014)

Return period, years	Discharge, m^3s^{-1}
20	1857
50	2128
100	2330
400	2735
500	2800
1000	3000
5000	3300
10000	3500

(b) Tatare River

Flooding of the Tatare River has not been an issue historically because its river bed is incised well below the general land surface from the SH6 bridge downstream, with the depth of incision increasing to over 10 m at the Waiho Loop. However parts of the western new town site (NT2) adjacent to the Tatare upstream of the SH6 bridge are close to the river-bed elevation and likely to be prone to flooding in severe rainstorms, especially if there are substantial sediment inputs from the Tatare catchment. In the absence of detailed rainstorm-generated flood modelling for the Tatare River the return period of this extent of inundation is arbitrarily assigned as 100 years.

As pointed out by Davies et al. (2013), overflows from the Waiho into the Tatare immediately upstream of the Waiho Loop are increasing during high flows as the Waiho bed aggrades, and the ca 10 m lower elevation of the Tatare bed causes headward erosion that causes these flows to increase over time (indicated in Fig. 2). If a large proportion of Waiho floods in due course enters the Tatare then substantial aggradation of the Tatare is to be expected, which can then progressively cause its upstream bed level to increase. Modelling by Davies et al.

(2013) indicated that flooding from the Tatare upstream of the SH6 bridge may eventually be exacerbated due to this aggradation. To prevent this scenario the planned stopbank upgrades include a bank extending from the oxidation ponds to the Waiho Loop (Fig. 3) designed to contain Waiho flows of 2500 m^3s^{-1} (Gardner, 2021) which is about a 200-year event (Table 1). We assume that this bank will prevent such overflows as designed.

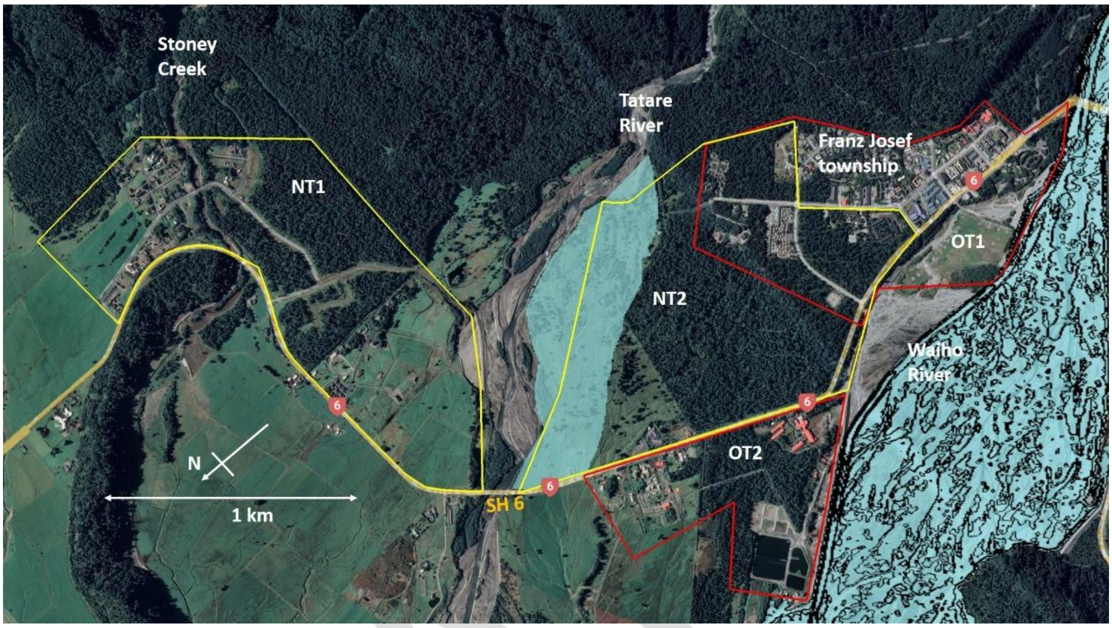


Fig. 5 Flood hazards (blue) at Franz Josef from Tatare (left) and Waiho (right) Rivers, ca 100-200-year return interval. Modified Google Earth image.

With the planned stopbanks in place, only minor flooding of any of the town sites from the Waiho is anticipated over the next 20 years. After that (Appendix C), ongoing river aggradation will increase the probability of stopbank failures; however it is not feasible to generally model that situation because the flooding location, intensity and extent will depend on the location and nature of the stopbank failures, which are not predictable.

6.2. Earthquake: Alpine fault

The Alpine fault marks the boundary between the Pacific and Australasian tectonic plates and delineates the western rangefront of the Southern Alps (Fig. 1). It is known to have ruptured several times per millennium with earthquakes of M_w 8 or greater over the past 8000 years (Berryman et al., 2012); Howarth et al. (2021) estimated that the next such earthquake has a 75% probability of occurring in the next 50 years, with a current annual probability of 1-2%.

The surface trace of the last (1717 AD) rupture of the Alpine fault passes through the present township site and is delineated by the Fault Rupture Avoidance Zone (FRAZ; Langridge et al., 2011; Toy et al., 2020; brown area in Fig. 6) that was designated by WDC in 2010 but rescinded in 2016. In this zone severe ground rupture is expected to occur during the earthquake, with consequent destruction of assets and corresponding risk to life. This affects only the present town site OT1 (Fig. 6).

The other major consequence of the earthquake is ground shaking. This is shown by Langridge et al. (2016) to be essentially uniform across all of the town sites, with a peak ground acceleration of greater than 0.75g (7.5 ms^{-2}, corresponding to Modified Mercalli Scale X – XII, which means severe damage to buildings and possible loss of life). This aspect of earthquake hazard is thus identical across both present and proposed town sites.

While earthquakes on other smaller faults in the region can undoubtedly cause shaking at Franz Josef, the threats due to Alpine fault rupture far outweigh these and so they are not considered herein.

6.3 Liquefaction and lateral spreading

Earthquake shaking may also cause liquefaction to occur at one location (white area in Fig. 6) identified by Langridge et al. (2016). This location is within both the present and the proposed town sites, so its impact is identical to both. Given the relatively coarse gravels that make up the alluvial sediments in the area, however, liquefaction seems unlikely to contribute significant additional shaking-derived damage in Franz Josef. Because of this and its very localised distribution, liquefaction is not considered in the comparison of hazards and risks between the town sites. If liquefaction is most likely during Alpine fault earthquakes then the return period is the same as that of ground rupture, or about 50-100 years

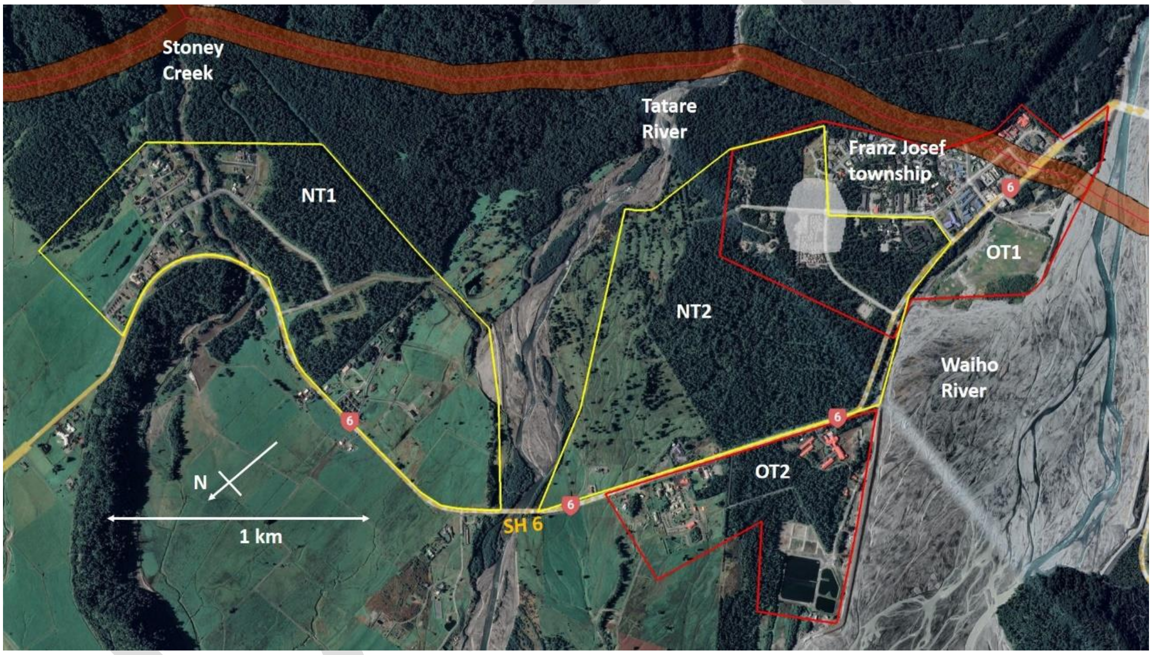


Fig. 6 Earthquake-related hazard at Franz Josef. Brown = surface rupture zone; white area = risk of liquefaction. The whole area shown is expected to be affected by shaking > 0.75g. Return period for rupture and shaking ca 50-100 years. Modified Google Earth image.

Lateral spreading due to severe shaking will affect earth structures, especially all river stopbanks which will subside and spread thus reducing their crest level and ability to contain floods. While this will not cause immediate damage to other assets or loss of life, it will severely impact on flood risk and river behaviour post-earthquake (Appendix C).

6.4 Earthquake-triggered landslide (rock avalanche)

Following its earlier identification by Barth (2014), Langridge et al. (2016) describe a potential major landslide (rock avalanche) that could fall from the hillslope overlooking Franz Josef, most likely during an earthquake on the Alpine fault that crosses the foot of the slope. Davies and Loew (2019) and Davies and Moretti (2021) estimated a potential failure volume of the order of 10^7 m^3 for this event, and an annual probability of the order of 10^{-5}, or 1 in 100,000. We have derived a relationship between landslide volume and probability from New Zealand data (Korup and Clague, 2009), and the corresponding runouts (Table 2) from an empirical volume-runout relationship (Davies, 1982); these are shown in Fig. 7. A 10^8 m^3 rock avalanche would affect all of the town sites except the northern half of NT2, but the ability of the source slope to yield such a large event is extremely doubtful, and it would have a return period of about 4 million years, so is not considered a realistic hazard.

It is worth noting that Davies and Moretti (2021) estimated the societal risk-to-life presented to the present town site OT1 by the 10^7 m^3 event (with an assumed 100,000-year return interval) to be about 10^{-2} per year, which is about 100-1000 times higher than internationally-used levels of acceptable risk. The present, more detailed, work confirms these orders of magnitude.

Table 2 Rock avalanche volume, runout distance and return period

Volume, m^3	Probability, a^{-1}*	Runout, km**	Return period, (yr)
10^5	1.6×10^{-2}	0.5	60
10^6	4×10^{-4}	1.0	2,500
10^7	1×10^{-5}	2.1	100,000
10^{8***}	2.5×10^{-7}	4.6	4,000,000

*Korup and Clague (2009) based on $p(10^7\ m^3) = 10^{-5}\ a^{-1}$.
**Davies, 1982; runout = $10(\text{volume})^{1/3}$.
*** statistical fiction

It is important to note that Davies and Moretti (2022) raised the possibility that this slope could also fail catastrophically without an earthquake trigger, most likely (but not necessarily) during a severe rainstorm. The probability of this is unknown but likely to be low.

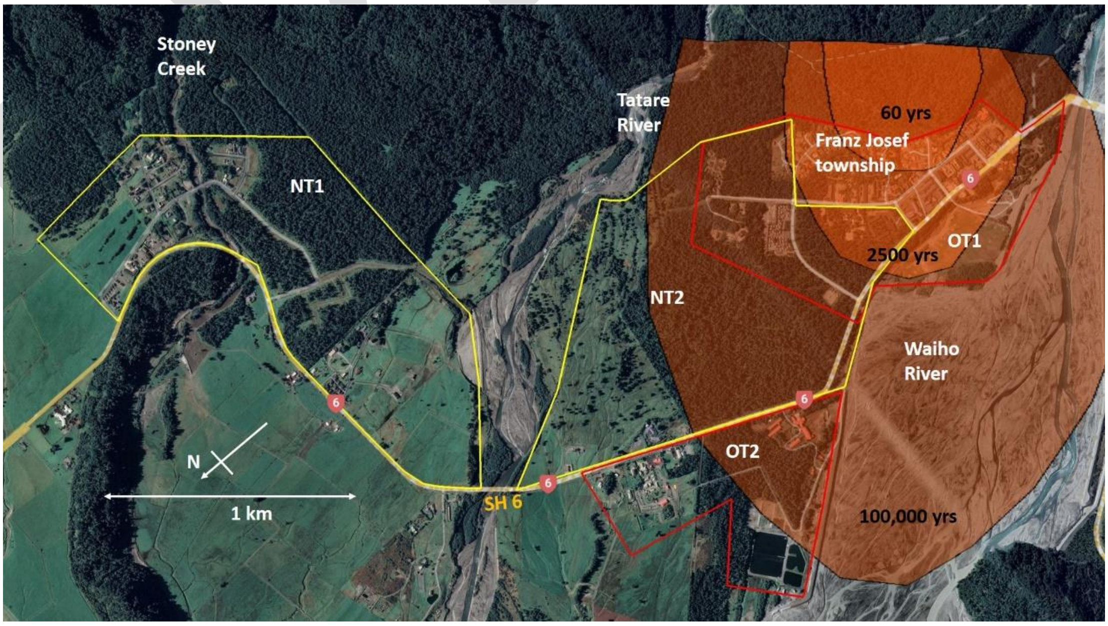


Fig. 7 Landslide (rock avalanche) hazard at Franz Josef. Modified Google Earth image.

6.5 Landslide dambreak flooding

Landslides in the mountains east of the Alpine fault take place in steep terrain through which run deeply-incised rivers. A major landslide in this terrain has a high probability of blocking a river by forming a temporary "landslide dam". The lake formed behind this will overtop the dam and can cause it to fail, either immediately or some time later; the release of the impounded lake water will cause a severe but short-lived flood to move through the downstream river system, carrying large quantities of sediment and woody debris. Such an event in the Poerua River in 1999 took place several days after the landslide occurred and caused extensive damage to farmland downstream. This landslide was neither earthquake- nor rainfall-triggered. Dambreak flood peaks are usually much higher than those of normal floods (though durations are much shorter), and correspondingly affect larger areas; an event of this type affecting Franz Josef township would cause severe damage and threaten lives (Davies, 2002).

Franz Josef is vulnerable to landslide dambreak floods in the Callery and Tatare Rivers, both of which flow between steep, high slopes for much of their catchment lengths. The Callery is a major tributary of the Waiho with its confluence about 1 km upstream of the township (Fig. 1). Ollett (2001), Davies (2002) and OptimX (2002) quantified the risk-to-life due to landslide dambreak flooding in the Callery River (Table 3), as a result of which the Franz Josef Holiday Park was relocated from its riverside site in 2003; Dunant et al. (2021) subsequently refined this analysis. R (2021) quantified the landslide-dambreak flood hazard from the Tatare River (Table 4), which had not been investigated previously. GNS Science, through its Endeavour research programme (Massey, C.I., GNS Science Ltd, PO Box 30368 Lower Hutt, *pers. comm.* 2022), used a RAMMS model to simulate dambreak flood flows of a range of return intervals from the Callery and Tatare Rivers, together with the areas these events would impact (Figs 8 - 10). Note that these dambreak discharges assume only minor background flows; in the unlikely event that they coincide with substantial flood flows the total discharges could be correspondingly higher.

Table 3 Callery-Waiho landslide dambreak flood magnitude-frequency (from Dunant et al., 2021).

Peak discharge m^3s^{-1}	1000	2000	3000	4000	5000	6000	7000	8000	9000
Return period years	5	15	25	45	75	100	175	300	2000

Table 4 Tatare landslide dambreak flood magnitude-frequency (R, 2021)

Peak discharge m^3s^{-1}	1000	2000	3000	4000	5000	6000	7000	8000	9000
Return period years	40	75	100	330	500	700	950	2100	4000

These simulations used the unmodified 2016 digital elevation model for the area, and thus the 2016 stopbank levels. Therefore the areas shown flooded by the dambreak flows (Figs 8 & 9) are not constrained by the planned stopbanks (Fig. 3). This is a realistically conservative scenario because a landslide dambreak flood differs considerably from a normal rainstorm flood, in particular because it assumes some of the characteristics of a debris flow surge with a high, tree-and-boulder laden main surge that may overtop stopbanks designed to contain normal floods. The simulations accounted for the higher mean sediment concentration of a dambreak flood, but not for its rapidly-varied flow. The highest return period events would in any case overtop the planned stopbanks.

Note that Davies and Korup (2007) found evidence of intense sedimentation close to the liquefaction site (Fig. 6) which they interpreted as caused by a prehistoric dambreak flood from the Tatare.

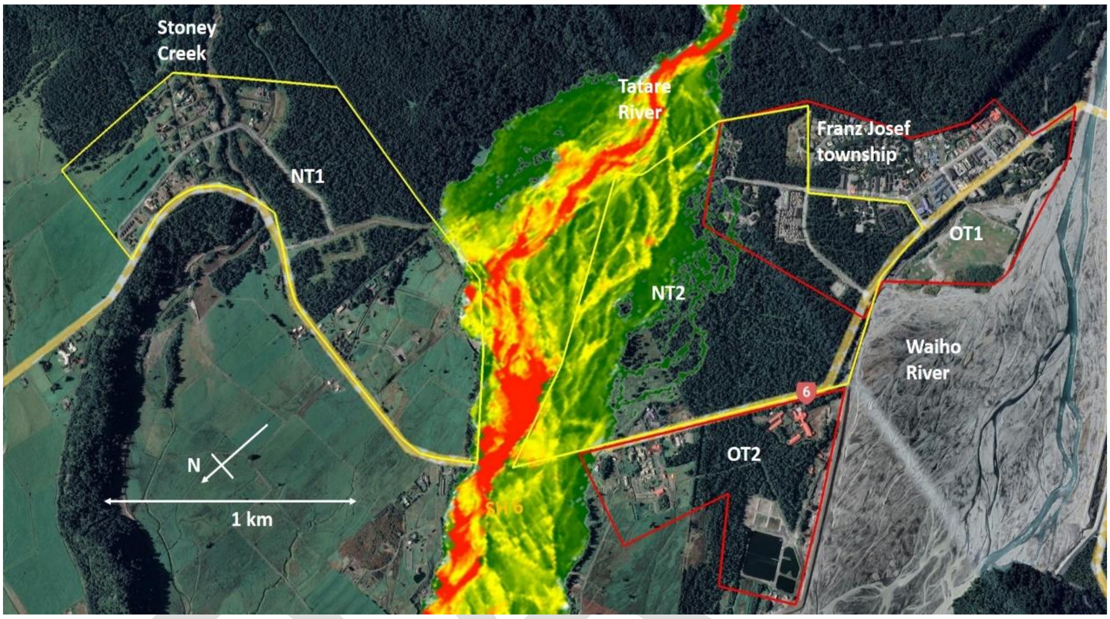


Fig. 8 Extent of ca 500-year return interval landslide dambreak flooding from the Tatare River ($5000\ m^3s^{-1}$). Modified Google Earth image.

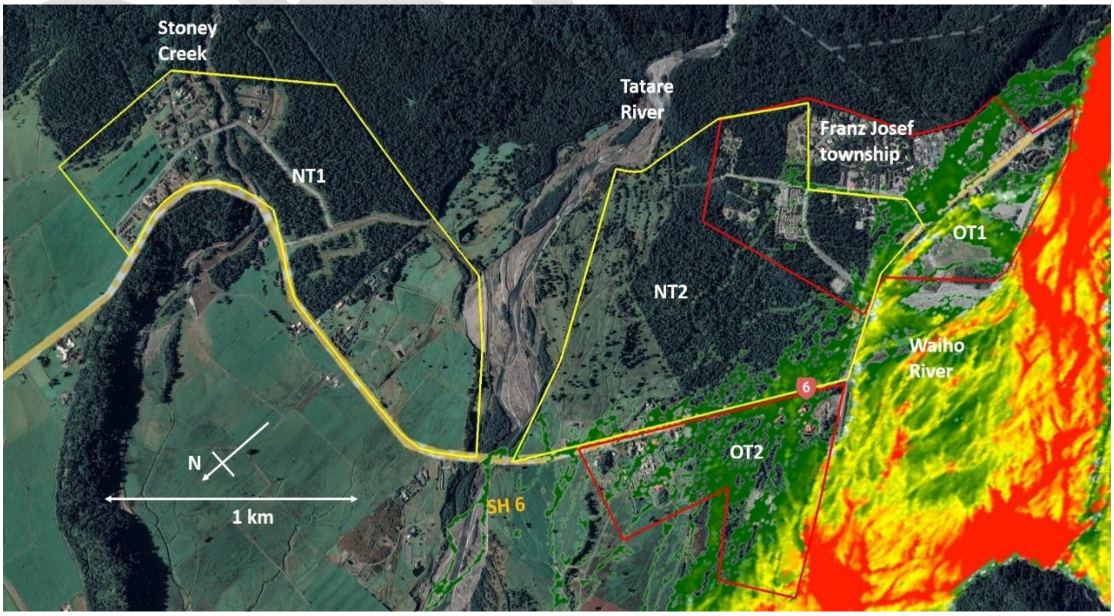


Fig. 9 Extent of ca 350-year return interval landslide dambreak flooding from the Callery River ($8600\ m^3s^{-1}$). Modified Google Earth image.

6.6 Debris flows

Debris flows are sudden, severe sediment-flood events that occur occasionally in small, steep catchments, and are capable of causing devastating damage to assets as demonstrated by the 2005 event at Matatā, Bay of Plenty; they also pose a serious threat to life. The catchment of Stoney Creek has been identified as prone to debris flows (Welsh and Davies, 2011), but no data are available to quantify the debris-flow magnitude-frequency relationship at this site. We have therefore adopted published international empirical relationships based on catchment area to assess the likely magnitudes and deposit areas of debris flows from Stoney Creek (Appendix A).

We also assume that such flows would result from rainfall-induced landslides in the Stoney Creek catchment, and that these would follow the magnitude-frequency relationship established for such events in the western Southern Alps by Hovius et al. (1997); see Table 5. It is acknowledged that this assumption ignores the potential for debris flows to mobilise streambed sediments in the catchment and on the fan, so estimates of volume are likely to be on the low side; however the catchment is short and very steep so this error is unlikely to be large. The areas affected by these flows are shown in Fig. 10. Note that this is the pre-earthquake debris-flow hazard, since the Hovius et al. (1997) data refer to non-seismic conditions. Following a major earthquake there is likely to be a large volume of available coseismic landslide sediment in the catchment, so the occurrence of debris flows in subsequent intense rainstorms will have a very high probability (Appendix C).

Table 5 Stoney Creek debris-flow magnitude-frequency

Debris flow volume m^3	Return period years
1000	500*
5000	100
10000	100
20000	150
50000	500
100000	1000
200000	2500

* Probability density rollover at low volume causes higher return period; see Hovius et al. (1997).

6.7. All hazards

Combining all the above hazards shows the hazardscape of the present and proposed town sites (Fig. 11). Note these are for various return periods: debris flows (blue) 500, 1000 and 2500 years; rock avalanche (brown) 100, 2500 and 100,000 years; landslide-dambreak flood (yellow) 300 years (Callery) and 500 years (Tatare); ground rupture (brown) and liquefaction (white), 50-100 years; and river flooding (light grey), 100 years. While the mix of return periods precludes detailed conclusions at this stage, some trends are clear:

- Much of the current township (OT1 and OT2) and most of the present NT2 site are hazard-affected, as is the Stoney Creek area in NT1
- About 80% of NT1 is free of known hazards except for ground shaking

A risk analysis allows these preliminary indications to be refined.

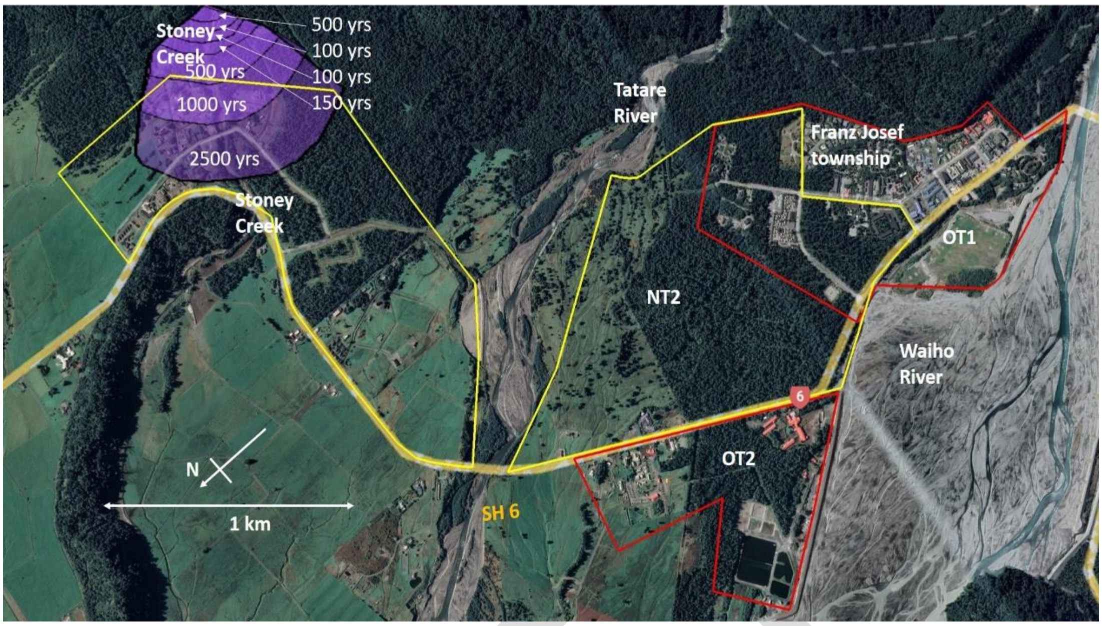


Fig. 10 Debris-flow hazards at Franz Josef. Modified Google Earth image.

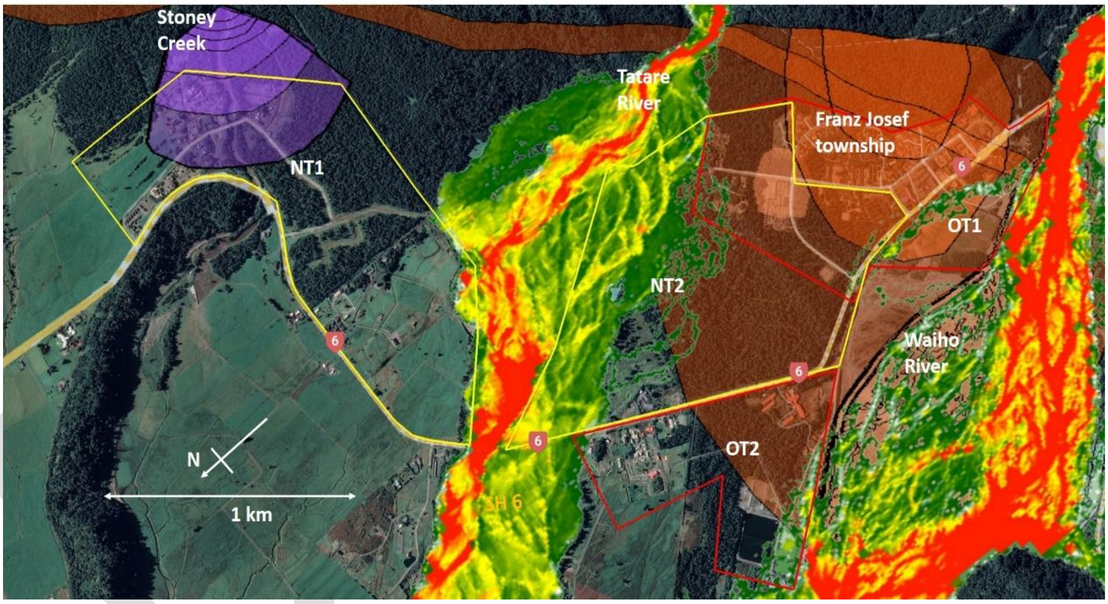


Fig. 11 All hazards affecting present and proposed town sites. Modified Google Earth image.

7. Risks

In order to quantify the risks to Franz Josef resulting from the hazards delineated above, it is necessary to quantify the assets and lives that could be damaged by hazard events. Since there is no information available about the spatial distribution of assets and population across the proposed relocation sites NT1 and NT2, we assume that both are uniformly distributed across the full area of NT1 and NT2. In order to compare the risks between the NT and OT sites, we therefore make the same assumption about the distribution of assets and population across existing town sites OT1 and OT2, rather than using the actual distributions.

7.1 Risks to assets

On the above basis, the risks to assets can be compared simply by comparing the proportion of each site exposed to specified hazards; thus the asset risks are directly proportional to asset exposures, assuming that the degree to which all assets are affected by all hazards is identical. Table 7.1 shows that the risks to assets in the present town sites OT1 and OT2 is about 30% greater than that in the proposed town sites NT1 and NT2. Considering the possible errors in the data and analysis, however, this not necessarily a significant difference.

Table 7.1 Risks to assets in present (OT1 & OT2) and proposed (NT1 & NT2) town sites

Hazard	Annual probability	Area of Intersection (OT1) (m^2)	Area of Intersection (OT2) (m^2)	Total Percentage of Intersection (OT1 + OT2)	Percent x probability OT	Area of Intersection (NT1) (m^2)	Area of Intersection (NT2) (m^2)	Total Percentage of Intersection (NT1 + NT2)	Percent x probability NT	Asset risk OT/NT
Alpine Fault Rupture	0.01	48530	0.00	3.92	.05	0.00	0.00	0.00	0.00	#DIV/0!
AF Liquefaction	0.01	56494	0.00	4.56	0.06	0.00	56494.00	2.49	0.03	1.83
AF Shaking	0.01			100.00	1.25			100.00	1.25	1.00
Total					1.36			0.01	1.28	1.06
Flooding - Waiho										
500 Cumecs	0.20	6795	0.00	0.55	0.11	0.00	0.00	0.00	0.00	#DIV/0!
1000 Cumecs	0.10	8559	0.00	0.69	0.07	0.00	0.00	0.00	0.00	#DIV/0!
1500 Cumecs	0.05	9947	0.00	0.80	0.04	0.00	0.00	0.00	0.00	#DIV/0!
2000 Cumecs	0.02	10836	0.00	0.87	0.02	0.00	0.00	0.00	0.00	#DIV/0!
2500 Cumecs	0.01	11477	0.00	0.93	0.00	0.00	0.00	0.00	0.00	#DIV/0!
3000 Cumecs	0.00	11957	0.00	0.97	0.00	0.00	0.00	0.00	0.00	#DIV/0!
3500 Cumecs	0.00	12576	0.00	1.02	0.00	0.00	0.00	0.00	0.00	#DIV/0!
Total					0.24				0.00	#DIV/0!
Flooding - Tatare										
570 cumecs	0.01	0.00	0.00	0.00	0.00	0.00	369793.00	16.29	0.16	0.00
Rock Avalanche										
10e4 m^3	0.64	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!
10e5 m^3	0.02	52207	0.00	4.21	0.07	0.00	0.00	0.00	0.00	#DIV/0!
10e6 m^3	0.00	438400	0.00	35.39	0.01	63155	0.00	2.78	0.00	12.72
10e7 m^3	0.00	813553	180409	80.25	0.00	813198	0.00	35.82	0.00	2.24
Total				119.86	0.08			38.60	0.00	56.02
Dambreak Flood - Callery										
1700 Cumecs	0.10	377	66	0.04	0.00	0.00	0.00	0.00	0.00	#DIV/0!
4200 Cumecs	0.02	4096	9246	1.08	0.02	10.95	0.00	0.00	0.00	2233
6000 Cumecs	0.01	9488	22983	2.62	0.03	13259	0.00	0.58	0.01	4.49
8600 Cumecs	0.00	21076	33485	4.40	0.00	16087	0.00	0.71	0.00	6.22
Total					0.06				0.01	8.50
Dambreak Flood - Tatare										
1000 Cumecs	0.03	0.00	0.00	0.00	0.00	3113	0.00	0.14	0.00	0.00
2500 Cumecs	0.01	0.00	0.00	0.00	0.00	46665	0.00	2.06	0.02	0.00
5000 Cumecs	0.00	0.00	0.00	0.00	0.00	208615	0.00	9.19	0.02	0.00
Total					0.00				0.04	0.00
Stoney Creek Debris Flow										
1000 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!
5000 m^3	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!
10000 m^3	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!
20000 m^3	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!
50000 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#DIV/0!
100000 m^3	0.00	0.00	0.00	0.00	0.00	0.00	101620	4.48	0.00	0.00
200000 m^3	0.00	0.00	0.00	0.00	0.00	0.00	405750	17.87	0.01	0.00
Total					0.00				0.01	0.00
TOTAL					**1.74**				**1.34**	**1.29**

7.2 Risks to life - Individual

The individual risk to life is the annual probability of being killed by a specific hazard event, related to the individual with the highest risk. Again we assume that the population is distributed equally across the areas of both the existing and the proposed town sites, so that the probability of an individual being in any specific location is equal everywhere. Then the risk of an individual being affected by a hazard event in any of the four sites is equal to the percentage of that site which is overlapped by the event multiplied by the probability of occurrence of that hazard.

However, not all hazards present an equal threat to life, and the probability of death requires the probability of impact to be multiplied by the probability that the impact will be fatal, which varies between hazards. Data on this factor are sparse, however; the factors used herein (Table 7.1) are explained in Appendix B, and Table 7.3 shows the resulting individual risks-to-life for the township sites. It is notable that individual risks-to-life are about 15 times higher in the present town sites than in the proposed town sites; even considering the potential errors in the analysis, this is a significant difference.

Table 7.2 Mortality rates (% of population exposed) for various hazards

Earthquake	0.3%
Flood	0.59%
Rock avalanche	100%
Dambreak flood	2%
Debris flow	27%

While these mortality rates are obviously very approximate, they are adequate for use to compare risks between the present and proposed sites.

The upper limit of acceptable individual risk-to-life in New Zealand is about 10^{-4} per year (Taig et al., 2012), so in Table 7.3 risks greater than 10^{-4} are highlighted in red while those between 10^{-5} and 10^{-4} are highlighted in yellow.

7.2 Risks to life – Societal

A further factor determining the societal acceptability of risk-to-life is the number of people at risk of death. Not surprisingly, society has less tolerance for events that cause many deaths than for those that cause few. Fig. 13 shows generally accepted tolerance limits for landslide deaths in Canada (Porter and Morgenstern, 2013), and similar diagrams have wide acceptance globally as indicators of orders of acceptable risk limits for a variety of hazards (Mona, 2014).

In order to estimate the societal risk-to-life at Franz Josef we need to know the population at risk. The permanent population is about 400; in addition, thousands of tourists visit the town in the season between about October and April, and these are serviced by a considerable number of temporary or itinerant workers. Hence to approximate the societal risk-to-life we assume a year-round population of 1000 as being of the correct order of magnitude. In this case Fig. 13 gives a bound on unacceptable risk as 10^{-6}; and Table 7.4 indicates that much of both the present and the proposed sites pose unacceptable societal risks-to-life. While the very approximate nature of the hazard mortality rates (Table 7.2) makes this deduction questionable, it indicates that even the relocated town site is by no means fully safe, even though it is about 15 times less risky than the present site.

Table 7.3 Individual risks-to-life for existing (OT1 and OT2) and proposed (NT1 and NT2) town sites. Red highlight indicates risk > 10^{-4} per year, yellow indicates risk > 10^{-5} per year.

Hazard	Annual Probability	Mortality Rate (%)	Total Percentage (%) of Intersection (OT1 +OT2)	Risk to Life OT1+OT2	Total Percentage (%) of Intersection (NT1 +NT2)	Risk to Life (NT1+NT2)	RTL Ratio OT/NT
Alpine Fault Rupture	0.0125	0.30	3.92	1.47E-06	0	0.00E+00	#DIV/0!
Flooding - Waiho							
500 Cumecs	0.2	0.59	0.55	6.49E-06	0.00	0.00E+00	#DIV/0!
1000 Cumecs	0.1	0.59	0.69	4.07E-06	0.00	0.00E+00	#DIV/0!
1500 Cumecs	0.05	0.59	0.80	2.36E-06	0.00	0.00E+00	#DIV/0!
2000 Cumecs	0.02	0.59	0.87	1.03E-06	0.00	0.00E+00	#DIV/0!
2500 Cumecs	0.005	0.59	0.93	2.74E-07	0.00	0.00E+00	#DIV/0!
3000 Cumecs	0.001	0.59	0.97	5.72E-08	0.00	0.00E+00	#DIV/0!
3500 Cumecs	0.0001	0.59	1.02	6.02E-09	0.00	0.00E+00	#DIV/0!
Total				1.43E-05		0.00E+00	#DIV/0!
Flooding - Tatare							
570 cumecs	0.01	0.59	0	0	10.1	5.96E-06	0
Rock Avalanche							
10^4 m^3	0.64	100.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
10^5 m^3	0.016	100.00	4.21	6.74E-04	0.00	0.00E+00	#DIV/0!
10^6 m^3	0.0004	100.00	31.24	1.25E-04	2.78	1.11E-05	11.24
10^7 m^3	0.00001	100.00	49.01	4.90E-06	35.82	3.58E-06	1.37
Total				8.03E-04		1.47E-05	54.65
Dambreak Flood - Callery							
1700 Cumecs	0.1	2.00	0.04	8.00E-07	0.00	0.00E+00	#DIV/0!
4200 Cumecs	0.02	2.00	1.08	4.32E-06	0.00	0.00E+00	#DIV/0!
6000 Cumecs	0.01	2.00	2.62	5.24E-06	0.58	1.16E-06	4.52
8600 Cumecs	0.001	2.00	4.40	8.80E-07	0.71	1.42E-07	6.20
Total				1.12E-05		1.30E-06	8.63
Dambreak Flood - Tatare							
1000 Cumecs	0.025	2.00	0.00	0.00E+00	0.14	7.00E-07	0
2500 Cumecs	0.01	2.00	0.00	0.00E+00	1.92	3.84E-06	0
5000 Cumecs	0.00217	2.00	0.00	0.00E+00	7.27	3.16E-06	0
Total				0.00E+00		7.70E-06	0
Stoney Creek Debris Flow							
1000 m^3	0.002	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
5000 m^3	0.01	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
10000 m^3	0.01	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
20000 m^3	0.067	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
50000 m^3	0.002	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
100000 m^3	0.001	27.00	0.00	0.00E+00	4.48	1.21E-05	0
200000 m^3	0.0004	27.00	0.00	0.00E+00	13.39	1.45E-05	0
Total				0.00E+00		2.66E-05	0
Total				**8.30E-04**		**5.62E-05**	**14.77**

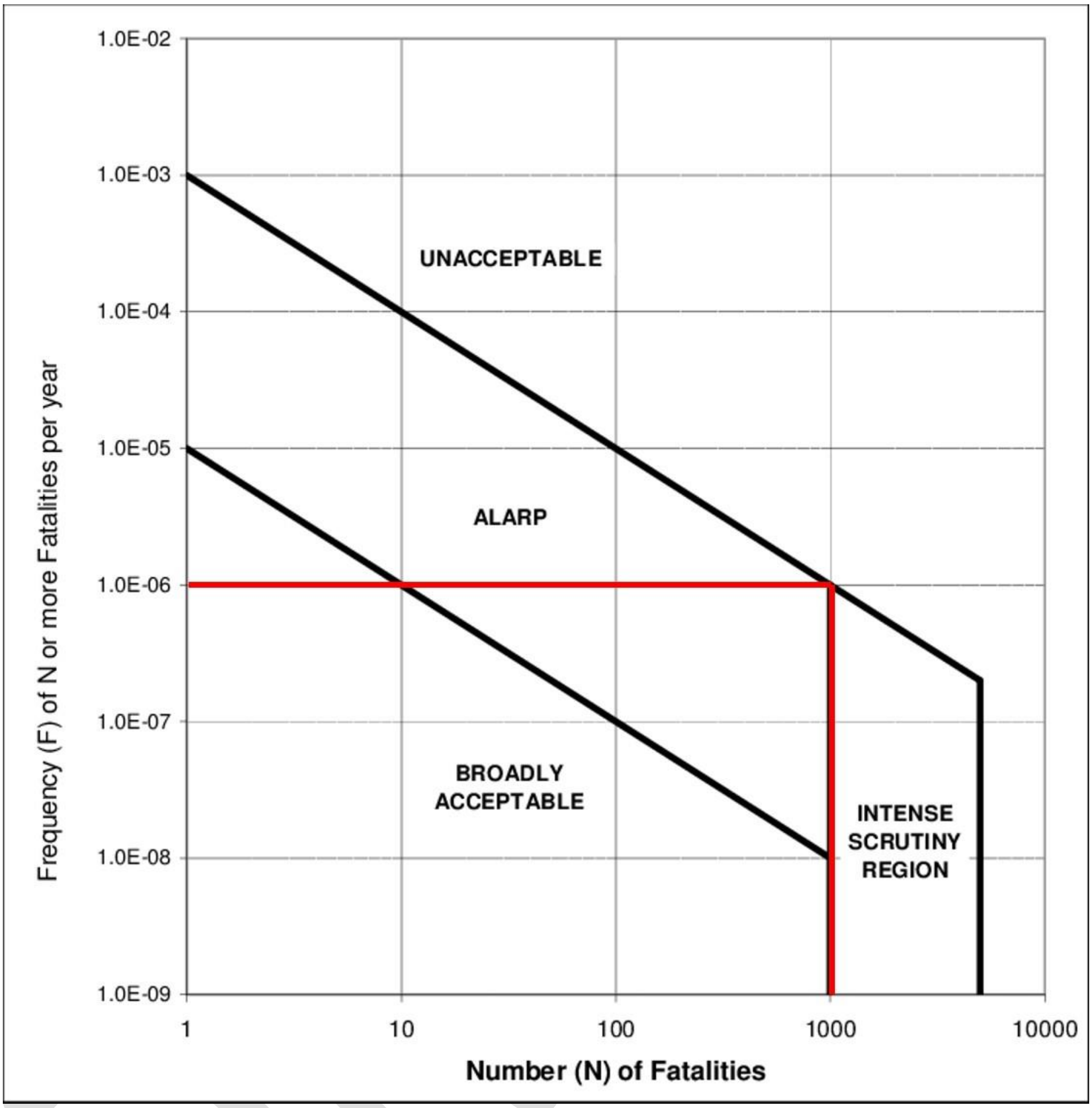


Fig. 13 Ranges of acceptable risks for multiple fatalities (Porter and Morgenstern, 2013). Red lines indicate that unacceptable risk for 1000 deaths is 10^{-6} per year.

Table 7.4 Societal risks-to-life for existing (OT1 and OT2) and proposed (NT1 and NT2) town sites. Red indicates risk > 10^{-6} per year

Hazard	Annual Probability	Mortality Rate (%)	Total Percentage (%) of Intersection (OT1 +OT2)	Risk to Life (OT1+OT2)	Total Percentage (%) of Intersection (NT1 +NT2)	Risk to Life (NT1+NT2)	RTL Ratio OT/NT
Alpine Fault Rupture	0.0125	0.30	3.92	1.47E-03	0	0.00E+00	#DIV/0!
Flooding - Waiho							
500 Cumecs	0.2	0.59	0.55	6.49E-03	0.00	0.00E+00	#DIV/0!
1000 Cumecs	0.1	0.59	0.69	4.07E-03	0.00	0.00E+00	#DIV/0!
1500 Cumecs	0.05	0.59	0.80	2.36E-03	0.00	0.00E+00	#DIV/0!
2000 Cumecs	0.02	0.59	0.87	1.03E-03	0.00	0.00E+00	#DIV/0!
2500 Cumecs	0.005	0.59	0.93	2.74E-04	0.00	0.00E+00	#DIV/0!
3000 Cumecs	0.001	0.59	0.97	5.72E-05	0.00	0.00E+00	#DIV/0!
3500 Cumecs	0.0001	0.59	1.02	6.02E-06	0.00	0.00E+00	#DIV/0!
Total				1.43E-02		0.00E+00	#DIV/0!
Flooding - Tatare							
570 cumecs	0.01	0.59	0	0	10.1	5.96E-03	0
Rock Avalanche							
10^4 m^3	0.64	100.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
10^5 m^3	0.016	100.00	4.21	6.74E-01	0.00	0.00E+00	#DIV/0!
10^6 m^3	0.0004	100.00	31.24	1.25E-01	2.78	1.11E-02	11.24
10^7 m^3	0.00001	100.00	49.01	4.90E-03	35.82	3.58E-03	1.37
Total				8.03E-01		1.47E-02	54.65
Dambreak Flood - Callery							
1700 Cumecs	0.1	2.00	0.04	8.00E-04	0.00	0.00E+00	#DIV/0!
4200 Cumecs	0.02	2.00	1.08	4.32E-03	0.00	0.00E+00	#DIV/0!
6000 Cumecs	0.01	2.00	2.62	5.24E-03	0.58	1.16E-03	4.52
8600 Cumecs	0.001	2.00	4.40	8.80E-04	0.71	1.42E-04	6.20
Total				1.12E-02		1.30E-03	8.63
Dambreak Flood - Tatare							
1000 Cumecs	0.025	2.00	0.00	0.00E+00	0.14	7.00E-04	0
2500 Cumecs	0.01	2.00	0.00	0.00E+00	1.92	3.84E-03	0
5000 Cumecs	0.00217	2.00	0.00	0.00E+00	7.27	3.16E-03	0
Total				0.00E+00		7.70E-03	0
Stoney Creek Debris Flow							
1000 m^3	0.002	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
5000 m^3	0.01	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
10000 m^3	0.01	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
20000 m^3	0.067	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
50000 m^3	0.002	27.00	0.00	0.00E+00	0.00	0.00E+00	#DIV/0!
100000 m^3	0.001	27.00	0.00	0.00E+00	4.48	1.21E-02	0
200000 m^3	0.0004	27.00	0.00	0.00E+00	13.39	1.45E-02	0
Total				0.00E+00		2.66E-02	0
Total				**8.30E-01**		**5.62E-02**	**14.77**

As expected, societal risk is directly proportional to individual risk using the assumptions herein, so the ratio of societal risk between the present and proposed town sites is again about 15; or, acknowledging the approximations involved, particularly in hazard mortality, about 10-20.

The contribution of the rock avalanche component to the total risk-to-life profiles is very high. If rock avalanche risk is assumed to be zero, the 10-20-fold reduction (14.77 in Tables 7.3 and 7.4) in risk-to-life achieved by relocating to the proposed sites NT1 and NT2 effectively disappears (becoming 0.65). Ignoring rock avalanche risk however has no significant effect on asset risk. This demonstrates the need for a geotechnical assessment of the reality of the rock avalanche hazard to assess the reality of the risk-to-life basis for relocation from the OT sites to the NT sites.

8. Risk reduction

8.1 Land use zoning

It is clear that the risks to assets and lives are lower – in the case of risks to life, much lower - if the township is relocated to the proposed new sites NT1 and NT2, and if the rock avalanche hazard is real. This assumes that assets and people are distributed uniformly across both present and proposed sites. While this assumption is necessary until information is available about asset and population distribution across relocated sites NT1 and NT2, it is clear from the hazard distributions outlined in section 5 above that risks to both lives and assets can be further reduced if assets and population across the relocated sites are distributed so as to avoid the high-hazard areas identified herein. In particular, the Stoney Creek fan area is exposed to debris-flow hazard in NT1, while eastern parts of NT2 are exposed to rock avalanche and to flood and dambreak flood hazard from the Tatare River (Fig. 12); western parts of NT2 are exposed to rock avalanche hazard. By contrast, all of NT1 except for the Stoney Creek fan appears to be hazard-free except for earthquake shaking.

8.2 Event warning and evacuation

The only hazard for which prior warning is readily feasible is rainstorm-generated flooding; weather forecasting and/or rain radar could conceivably provide perhaps hours of warning that might allow evacuation to save lives. However this hazard is the least intense of those affecting Franz Josef, and warning and evacuation have not been utilised hitherto for this common hazard on the West Coast.

When a landslide dam has formed, and does not fail immediately, the option exists to immediately evacuate areas that could be affected by a dambreak flood. However many landslide dams fail immediately on first overtopping, which can occur before the threatened populace is aware of the dam emplacement if this occurs during a severe storm (Davies, 2002), so this strategy cannot be completely reliable. Nevertheless it would be useful to install flow recorders at the Tatare and Callery valley mouths, so that the unusually low flows that accompany filling of a landslide dam could be detected even during severe floods.

Warning and evacuation are not feasible for earthquake, debris flow or rock avalanche hazard events.

8.3. Event modification

Risk can be reduced if the impact of hazard events on assets and people can be reduced by altering the behaviour of the hazard processes.

Flooding is commonly reduced by stopbanking, and this has been done extensively on the Waiho River at Franz Josef (Fig. 2). There is the possibility of using stopbanks to reduce the flood hazard from the Tatare River (Fig. 5) to the eastern part of NT2, but this may not be desirable because (i) there is evidence that stopbanking is not a permanent solution to flood hazards because it causes or exacerbates aggradation (Davies and McSaveney, 2006), as on the Waiho (Beagley et al., 2020); and (ii) it tends to increase flood hazard on the other side of the river.

Earthquake: there is no known way to modify the occurrence or severity of an earthquake. The impact of ground shaking on buildings can be reduced by strengthening the structure, but not to the extent that damage can be prevented in MM12 shaking. While strengthening may reduce the impact of ground rupture on a building there is no way to guarantee this.

Rock avalanche: A rock avalanche comprises a mass of rock debris from boulder- to dust-size, metres or tens of metres deep, moving across the land surface at some tens of metres per second. It is inconceivable that any structure could be designed to realistically resist or modify such an event, nor is it feasible to engineer the slope to reduce the probability that it will fail during an earthquake.

Landslide-dambreak flood: A landslide-dambreak flood usually has a much shorter and much higher peak than a rainstorm flood, and is also likely to be transporting much larger quantities of rock and tree debris. It is therefore much less feasible to attempt to modify a dambreak flood than a rainstorm flood; while stopbanks may retain part of the flow, overtopping and failure of stopbanks is much more likely during a dambreak flood, and design of stopbanks to contain a dambreak flood would be extremely difficult and unreliable.

Debris flow: While structural countermeasures for debris flows are common in Europe and Japan, they have only rarely been used in New Zealand. The data developed herein for the Stoney Creek risk analysis could be used to derive dimensions for debris-flow structures (detention basins, stopbanks or *Sabo* dams) but the reliability of the resultant design would be open to question, mainly because debris-flow behaviour is poorly known and models have large imprecisions (e.g. Davies, 1997; Farrell and Davies, 2019).

9 Comments

9.1. Precision and realism

This report provides a comparative analysis of the relative hazards and risks affecting the existing and proposed town sites at Franz Josef. In quantifying the hazards and risks a difficult balance has had to be struck between precision and realism, acknowledging that much of the data on which the analysis is based is of low reliability because of poor understanding of the hazard phenomena involved. Hence the hazard zones delineated, and the frequencies they are assigned, are both acknowledged approximations to the "truth".

While it would be possible, with considerably more effort, to develop more precise values for hazard magnitude-frequency relationships and for corresponding hazard zones, it is doubtful whether the effort would be worthwhile in terms of the usefulness of these outputs for decision-making. In my opinion it is not realistic to expect better than order-of-magnitude reliability for hazard frequency (recalling in any case that frequency cannot be measured accurately without data encompassing several tens of events; Davies and Davies, 2018). The same restriction therefore applies to quantification of risk, and this is made clear in the highlighting of the risk tables herein.

The work above, and the conclusions below, are aligned with the need for risk quantification to be explicit in land-use decision-making as a result of New Zealand becoming a signatory to the 2015 Sendai Framework for Disaster Risk Reduction. To this end the present work attempts to balance precision with realism in risk quantification.

9.2 Need for further research

The most serious hazard to the present town site, and to parts of the proposed relocated town site, is that of rock avalanche. However, Davies and Loew (2019) point out that, depending on the rock structure in the hillslope source of the event, it is possible that a coseismic slope failure might not result in a long-runout rock avalanche. If this were the case, and a rock avalanche were not a realistic prospect, the total risk-to-life across both existing and proposed relocated sites would be of the same order of magnitude. In order to settle what is therefore a crucial matter, detailed geotechnical investigation of the slope is required as outlined by Davies and Loew (2019).

Although the existence of rock avalanche deposits in similar locations elsewhere on the West Coast (Round Top, Dufresne et al., 2010; Wanganui, Chevalier et al., 2009; Cascade, Barth 2014) suggests that the hazard at Franz Josef is indeed real, the small chance that it is not, because of local geology, warrants investigation because of its dominant influence on risk-to-life.

As has been made clear, the ongoing aggradation of the Waiho River limits the conclusions herein to a time-frame from the present until about 2040, at which time the flood protection from proposed upgrading of the Waiho stopbanks is likely to be decreasing rapidly. In addition, the occurrence of a major earthquake in the region (whether on the Alpine fault or on a different fault within the mountains) is likely to significantly alter the hazard frequencies used herein; the probability of such an event before 2040 is about 20-40%. In order to plan the medium- to long-term future of Franz Josef, further information is needed on how stopbank failure and earthquake occurrence will affect subsequent hazards and risks at Franz Josef. In addition, because of the longer future time-scale, the likely impacts of climate change will be more significant and require deeper investigation.

10 Conclusions

Assuming that population and assets are uniformly and equally distributed among the present and proposed town sites at Franz Josef, then in the period up to about 2040, or until the occurrence of the next major West Coast earthquake, whichever is the sooner:

10.1 The total exposure of assets to all hazards is of similar order of magnitude in both existing and proposed relocated town sites.

10.2 The total risk-to-life, both individual and societal, from all hazards in the proposed relocated town site is about one order of magnitude (10-20 times) lower than that in the existing town site. This difference is caused mainly by the rock avalanche hazard to the latter.

10.3 While the individual risk-to-life appears to be close to acceptable across much of the proposed relocated sites, it is at unacceptable levels in much of the present town site due to rock avalanche hazard. However the societal risk-to-life appears to be distinctly unacceptable across parts of both town sites.

10.4 Judicious siting of assets and population across the proposed relocated town site could reduce the risks to both assets and life below the levels shown herein.

10.5 The most serious hazard to both present and proposed relocated town sites is from a major rock avalanche overrunning much of the OT sites and less of the NT sites. In effect, the rock avalanche hazard is the main risk-to-life justification for the proposed relocation. Because there is some doubt as to the reality of this threat, detailed geotechnical investigations are needed to confirm or deny its existence.

10.6 In order for the risks in the proposed relocated townsite to be known in the medium-to-long term (after a major earthquake or 2040, whichever comes sooner), more information is needed on the likely alteration of hazard distributions and frequencies that will result from aggradation-triggered Waiho River stopbank failures, and from an Alpine fault earthquake. Better information on climate-change impacts will also be needed for this longer time-frame.

11 Acknowledgements

Matthew Gardner of Land, River, Sea Consulting Ltd kindly provided flooding data for the Waiho River. Chris Massey of GNS Science Ltd carried out simulations and made available data for landslide dambreak flooding from the Waiho and Tatare rivers. Tom Robinson of University of Canterbury provided constructive comments throughout.

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APPENDIX A - HAZARD ANALYSES

A1 Flood hazard: Waiho River

Gardner (2021) carried out numerical modelling using MIKE 21 software and land surface elevation data from 2016 and 2019 Lidar together with 2021 satellite data. The modelling was used to develop designs for stopbank upgrading. Maps of water depths derived from this modelling were used to delineate flood extents for flows from 500 to 3500 m^3s^{-1} (Fig. A1)

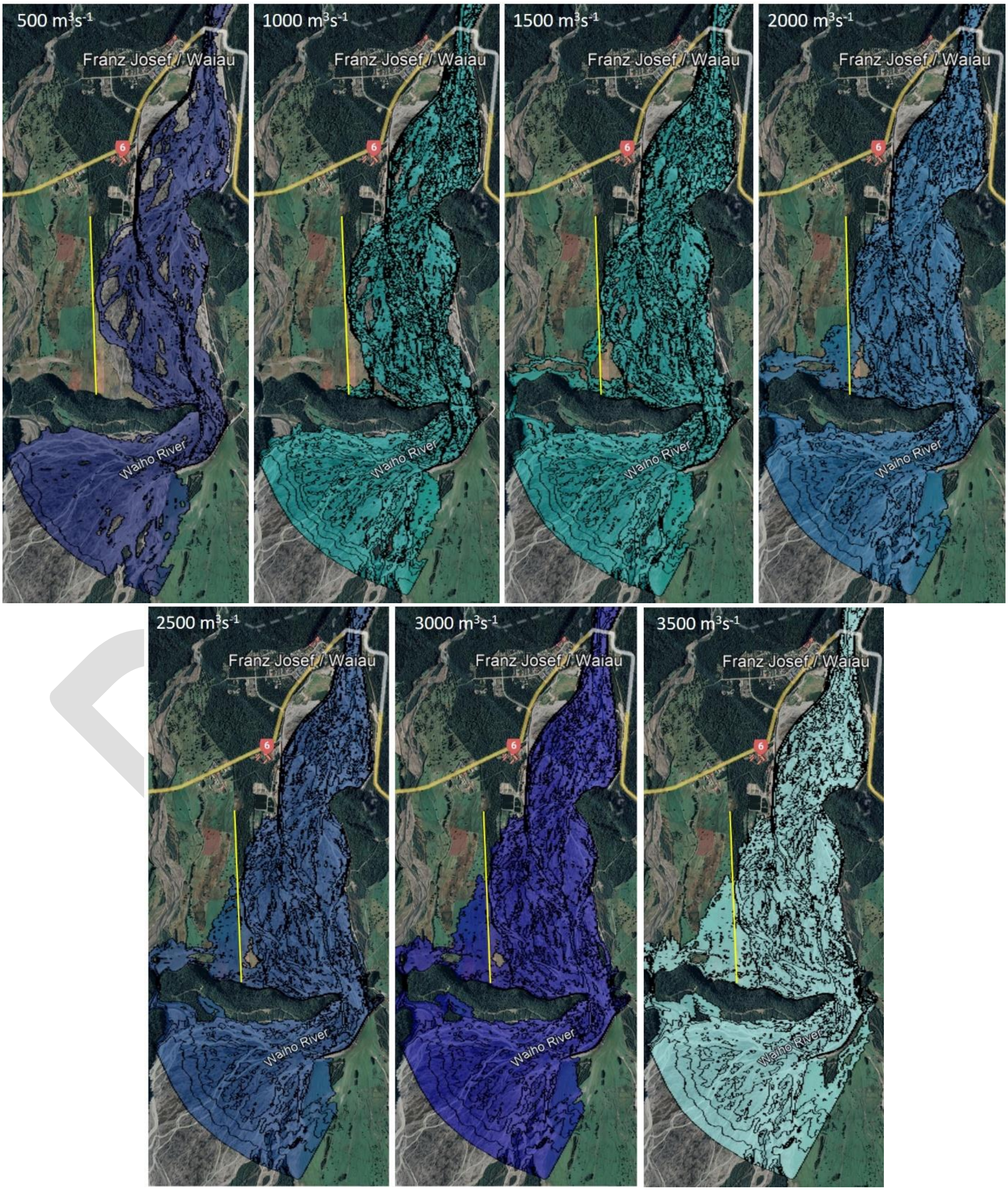

Fig. A1.1 Extents of Waiho River floods modelled by Gardner (2021). Yellow line is new stopbank effective up to 2500 m^3s^{-1}.

A2 Debris-flow hazard

The only known location in either town site potentially affected by debris flows is the settlement on Stoney Creek fan in NT1; this was first identified by Welsh and Davies (2010). The catchment area A_c of Stoney Creek is 2.1 km^2 and the catchment relief Δh above the fanhead is 1200 m, so

$$\text{Melton ratio } R = \Delta h / A_c^{0.5} = 1200/(2.1*10^6)^{0.5} = 0.82$$

It is well-known that catchments with R ≥ 0.5 are susceptible to debris-flow occurrence so it is reasonable to assume that this is the case with Stoney Creek. No records exist of debris flows in Stone Creek, but Welsh and Davies (2011) reported that large boulders were unearthed from below the fan surface during excavation of building platforms, confirming the occurrence of past debris-flow events. The Alpine fault also runs through the catchment, so the presence of fault-shattered rock will contribute to high sediment loads.

To establish a magnitude-frequency relationship for debris flows in Stoney Creek we first approximate debris-flow volume. ENGEO (2021) developed Fig. A2.1 from data in Bergmeister et al. (2009), Rickenmann & Zimmermann (1993) and d'Agostino and Marchi (2001); this suggests a debris-flow volume between 10 000 and 50 000 m^3 in a 2.1 km^2 catchment

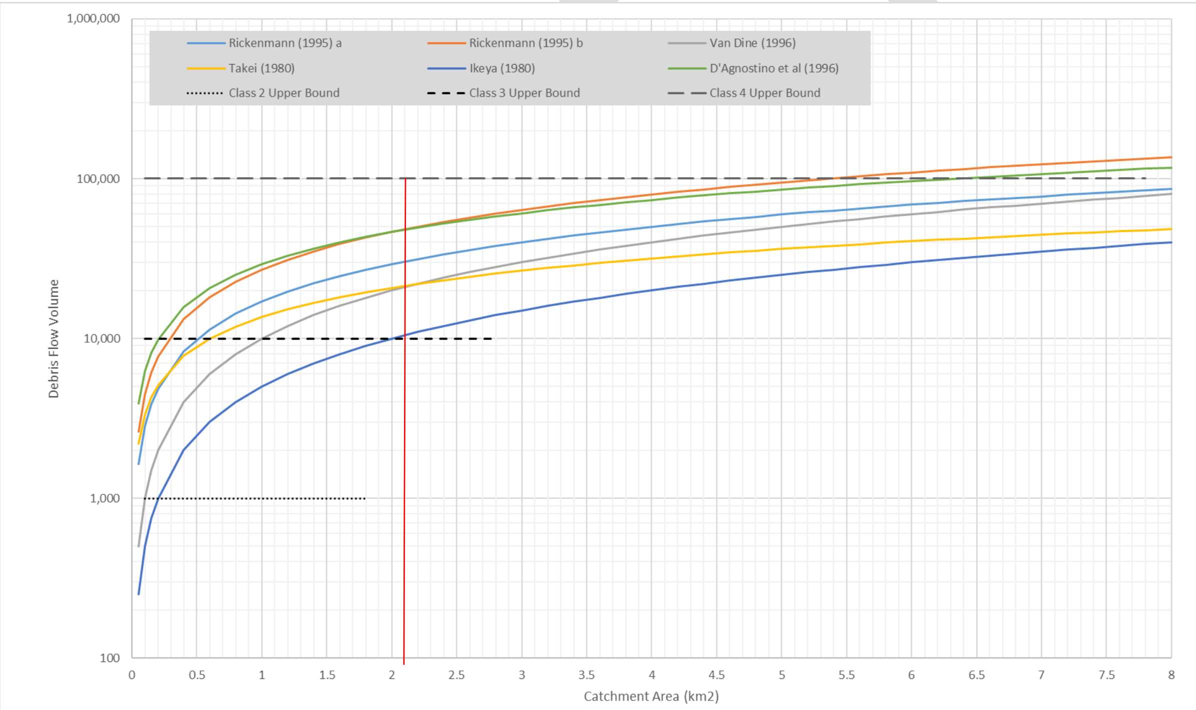

Fig. A2.1 Relationships between catchment area (km^2) and debris-flow volume (m^3) (ENGEO, 2021)

Alternatively, De Haas and Densmore (2019) and Marchi et al. (2019) show a maximum volume of 200,000 m^3 for a 2.1 km^2 catchment (Fig. A2.2).

Next we estimate the frequencies of debris flows of various volumes:

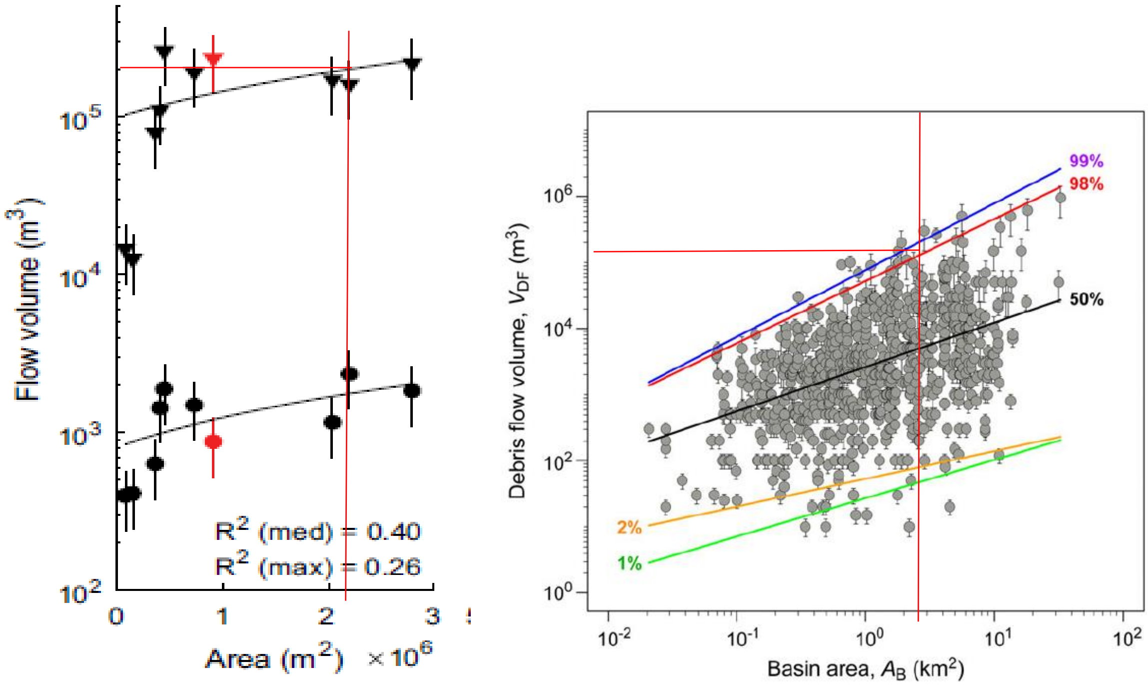

Fig. A2.2 Area-volume plots from De Haas and Densmore (2019) (left) and Marchi et al. (2019) (right)

If we use the higher of the volume estimates ($V = 2*10^5$ m^3), and assume that the debris-flow volume results from occurrence of a landslide of the same volume, then landslide surface area x mean depth = $2*10^5$. If we further assume that the landslide surface trace is an ellipse with eccentricity = 2 (i.e. length l = 2 x width w), then $lw = l^2/2$ and landslide surface area = $0.5\pi l^2$. Hovius et al. (1997, eq. 3), in their study of aseismic landslide frequency in Westland, use landslide depth d = 0.5l for aseismic landslides in Westland, which for a volume of $2*10^5$ m^2 gives a surface area of 40 000 m^2.

For the median debris-flow, Marchi et al. (2019) (Fig. A2.2) give a volume of 2000 m^3 which, using the same calculation as above, gives an area of 1800 m^2. Fig. A2.3 (Hovius et al., 1997) gives the

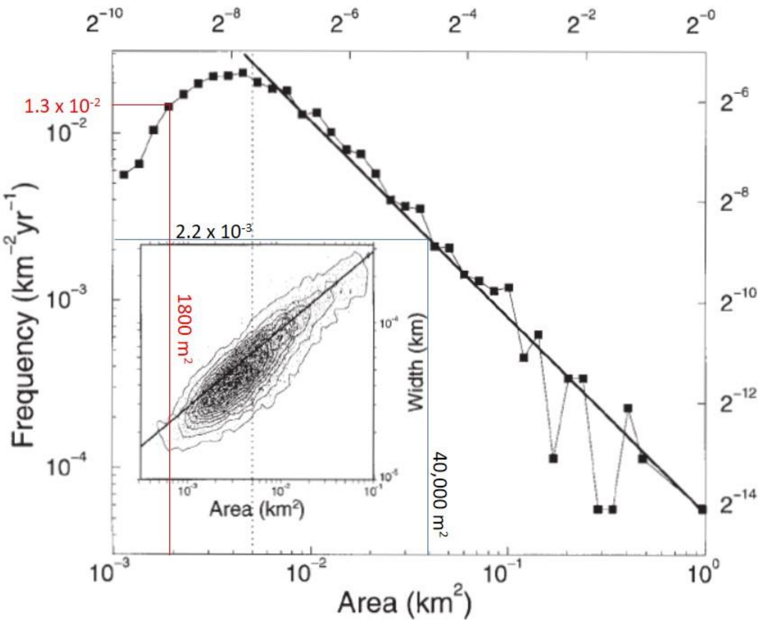

Fig. A2.3: frequency of maximum and median aseismic landslides in Westland (Hovius et al. (1997) Fig. 3); assumed to apply also to debris flows in Stoney Creek frequencies of these events as $2.2*10^{-3}$ and $1.3*10^{-2}$ respectively. Fig. A2.4 shows the frequency-magnitude relationship of Hovius et al. (1997) as the basis for debris flows at Stoney Creek.

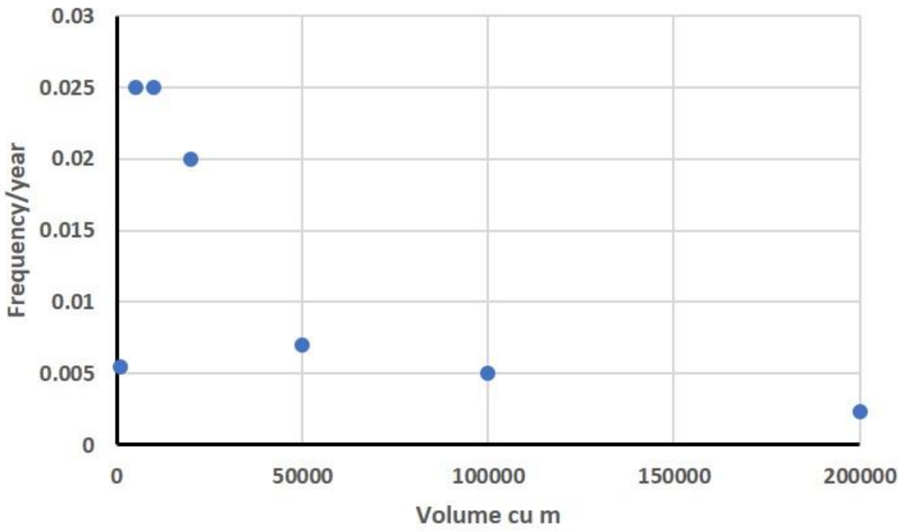

Fig. A2.4 Magnitude-frequency relationship for debris flows at Stoney Creek

The area inundated by a debris flow A_i, which is also the hazard area, is given by Jakob (2005) as $A_i = 20V^{2/3}$. No information is available to estimate the width and extent of a debris-flow deposit, so at Stoney creek the deposit areas were assumed to start at a point at the fan head, and to widen to approximately 100 m within 150 m downstream; thereafter the deposit areas were assumed to remain constant at ~ 100 m. Given the inundation areas this allowed the distance downstream extent of the deposit area to be estimated.

Since any given debris flow could run in a path anywhere on the fan, the probability of any particular fan location being impacted by a debris flow in any given year is equal to the annual frequency of a flow large enough to reach the location divided by the ratio of impacted area/whole fan area affected by that flow magnitude (Table A2.1), and the resultant hazard distribution is shown in Fig. A2.5.

Table A2.1: Volume-frequency data for Stoney Creek debris flows

Debris-flow volume cu m	**Event frequency /yr (Hovius)**	**Inundation area sq m**	**Total fan area vulnerable sq m**	**Whole-width impact frequency /yr**
1000	0.0055	2000	6000	0.0018
5000	0.025	5850	15000	0.0097
10000	0.025	9286	26000	0.0089
20000	0.02	14741	43000	0.0069
50000	0.007	27154	100000	0.0019
100000	0.005	43105	200000	0.0011
200000	0.0023	68427	400000	0.0004

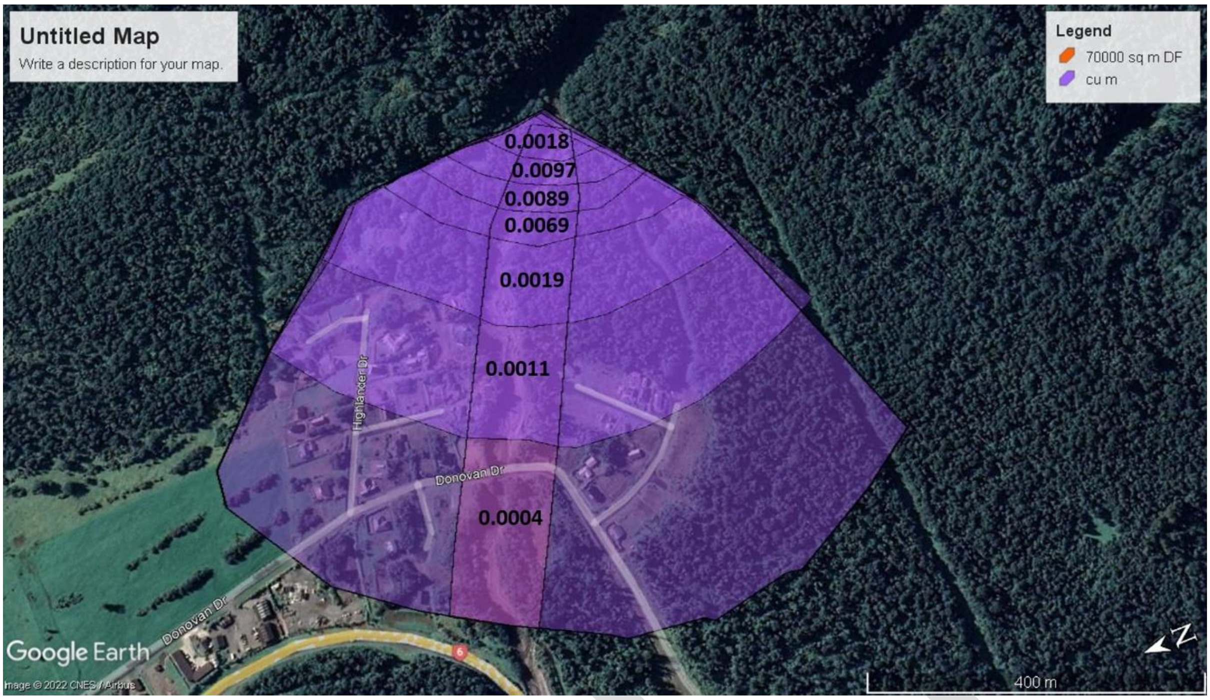

Fig. A2.5 Outlines of Stoney Creek debris-flow deposit areas with annual probabilities. Modified Google Earth image.

A3 Rock avalanche hazard (adapted from Davies & Moretti, 2021):

Immediately south-east of the present town site, a very steep hillslope rises about 750 m to a minor summit (Fig. A3.1). Davies and Loew (2019) and Davies and Moretti (2021) considered the morphology and likely origin of this slope, concluding that during successive earthquakes on the Alpine fault (which runs at its foot) it may be deforming in such a way that it could fail catastrophically in a future earthquake, causing rocky debris to run out across and bury the township.

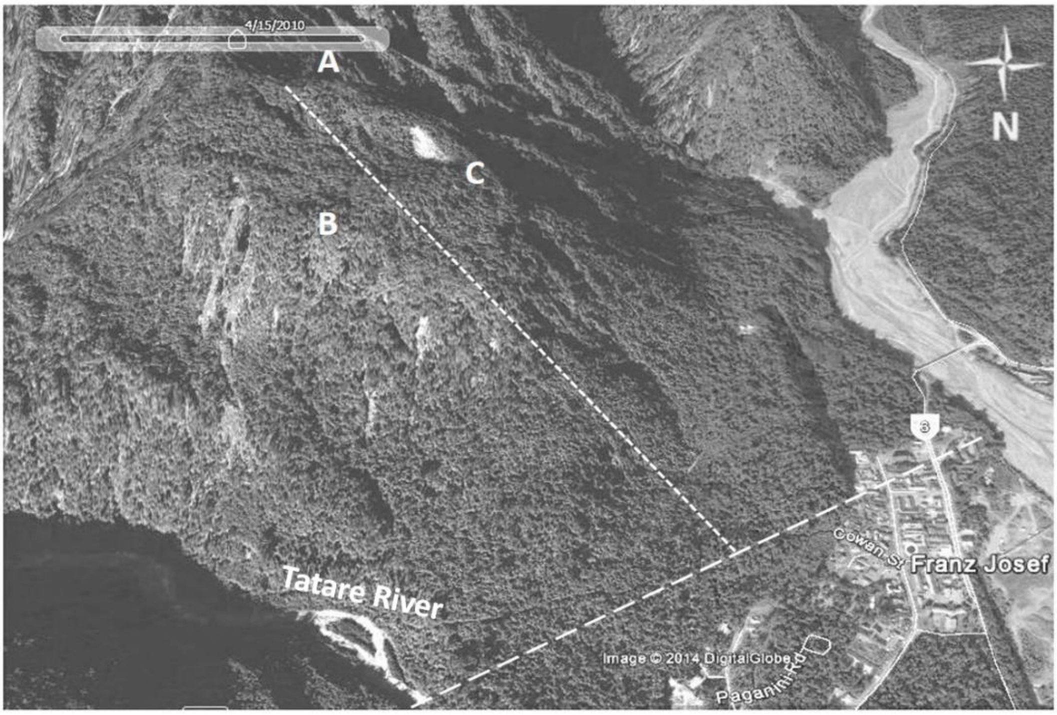

Fig. A3.1. Slope overlooking Franz Josef Glacier, Westland, New Zealand. BC indicates the outer edge of the slope-top bench; B to C is about 400 m. Dashed line indicates trace of the Alpine fault; dotted line is location of section (Fig. A3.3).

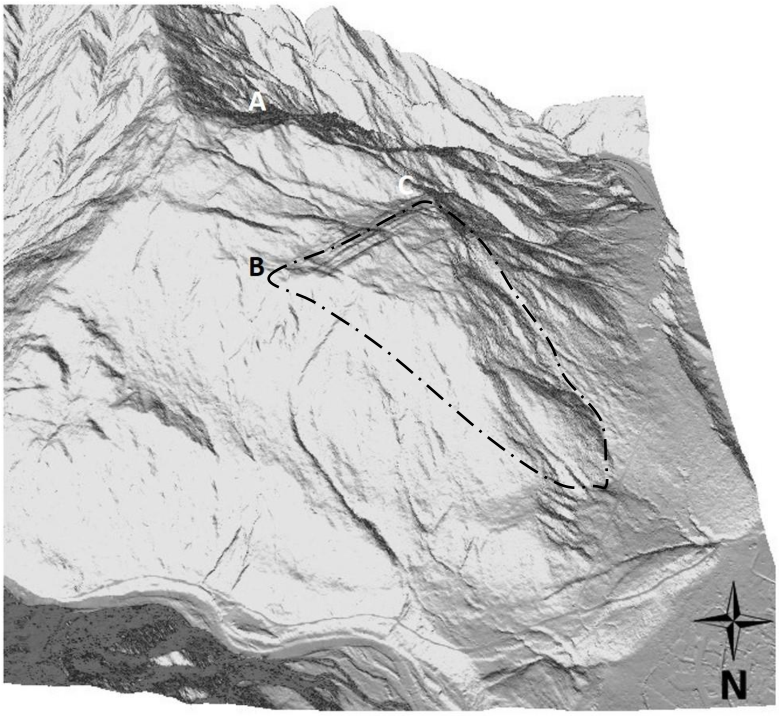

Fig. A3.2. Oblique LIDAR image of identical view to Fig. A3.1 with vegetation removed; A, B and C are corresponding locations. (Source: Danilo Moretti). Chain-dashed line indicated approximate potential failure area.

Fig. A3.2 is a Lidar image from which vegetation has been removed, showing the rock surface of the hillslope, in particular the prominent ridges that run across the slope-top bench, which Davies and Moretti (2021) show to be characteristic of slopes that are deforming prior to coseismic failure.

Volume: adapted from Davies & Moretti (2021):
"*If a potential failure surface is sketched on the Franz Josef slope profile (Fig. A3.3), the long-sectional area of the failure would be about 50 000 m^2. If the average width of the failure were say 200 m … then the failure volume would be of the order of 10^7 m^3.*

The conclusion is that the Franz Josef slope has characteristics that may indicate its potential for future large-volume catastrophic failure, and that, given the presence of a town at the foot of the slope, there is a need to consider the consequences of such a failure. It is also possible that the origin of the slope-top bench, and of the parallel ridges on the bench, do not imply current instability and failure potential of the slope. As we now demonstrate, however, the consequences of a large-scale failure of this slope would be extremely serious, therefore it is a matter of urgency that the origin of the Franz Josef hillslope morphology, and its current and future stability, are investigated as soon as possible.

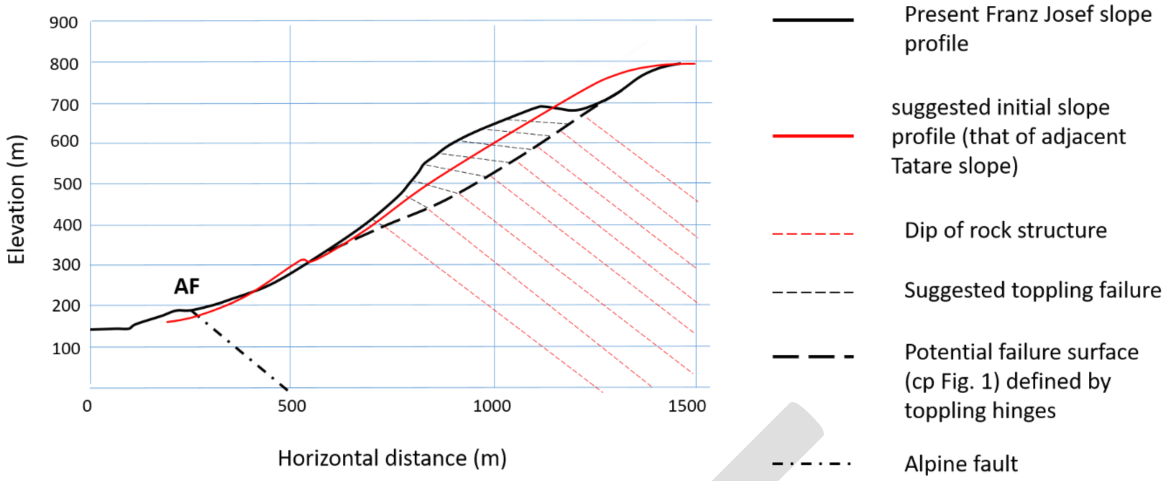

Fig. A3.3 Franz Josef slope profile (black full line) with suggested original profile (red full line, taken from adjacent Tatare slope to the north). Also sketched are Alpine fault (AF), and eastward dipping rock structure (light red dashed lines) with potential slip and toppling along failure surface defined by the toppling hinge envelope (light blue dashed lines).

A3.1 Rock avalanche

If a large-scale failure of the slope overlooking Franz Josef were to occur, debris comprising rocks of all sizes from powder up to boulders would slide and flow down the slope achieving velocities of many tens of metres per second and would run out across, and deposit on, the township. The forest and bush on the terrace at the base of the slope would offer little protection from a several-million-cubic-metre rock avalanche. The simple empirical relationship of Davies (1982):

$$L^* = 10\ V^{1/3}$$

where L is the end-to-end deposit length in m and V the volume in* m^3*, reasonably matches the deposit extents of the Cascade, Round Top and Toppenish Ridge landslides. It suggests that if the Franz Josef debris volume were* 10^7 m^3 *the debris deposit would be of the order of 2000 m long – thus extending over and then well beyond the township. If this were to occur buildings would be destroyed and many lives lost; the chances of survival in the runout zone, even if in a building, would be negligible. If the volume is only* 10^6 m^3 *the runout is ~ 1 km, and so still sufficient to cover the township.*

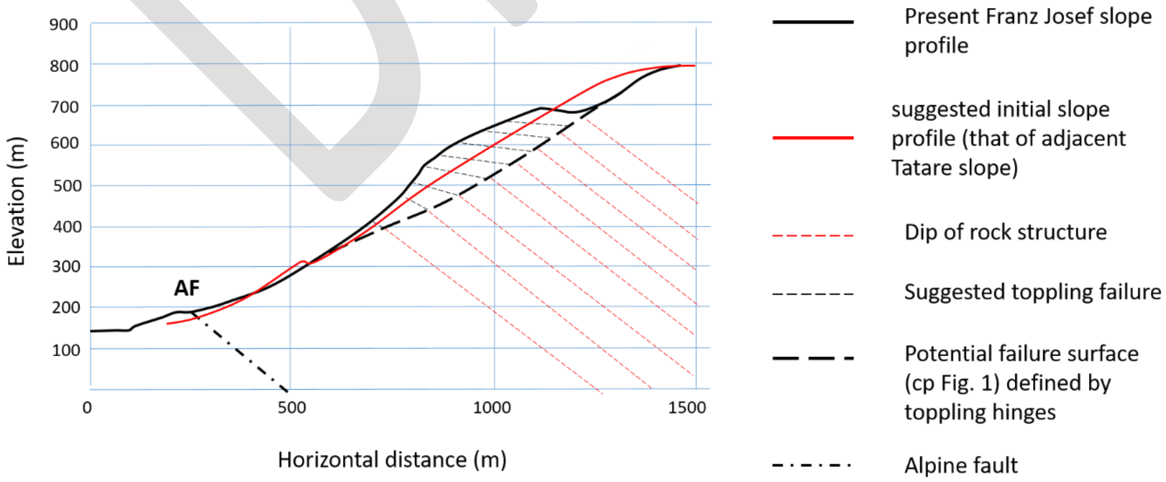

Fig. A3.4 Franz Josef slope profile (black full line) with suggested original profile (red full line, taken from adjacent Tatare slope to the north). Also sketched are Alpine fault (AF), and eastward *dipping rock structure (light red dashed lines) with potential slip and toppling along failure surface defined by the toppling hinge envelope (light blue dashed lines).*

The conclusion is that the Franz Josef slope has characteristics that may indicate its potential for future large-volume catastrophic failure, and that, given the presence of a town at the foot of the slope, there is a need to consider the consequences of such a failure. It is also possible that the origin of the slope-top bench, and of the parallel ridges on the bench, do not imply current instability and failure potential of the slope. As we now demonstrate, however, the consequences of a large-scale failure of this slope would be extremely serious, therefore it is a matter of urgency that the origin of the Franz Josef hillslope morphology, and its current and future stability, are investigated as soon as possible.

A3.2 Consequences

If a large-scale failure of the slope overlooking Franz Josef were to occur, debris comprising rocks of all sizes from powder up to boulders would slide and flow down the slope achieving velocities of many tens of metres per second and would run out across, and deposit on, the township. The forest and bush on the terrace at the base of the slope would offer little protection from a several-million-cubic-metre rock avalanche. The simple empirical relationship of Davies (1982):

$$L^* = 10\ V^{1/3}$$

where L^* is the end-to-end deposit length in m and V the volume in m^3, reasonably matches the deposit extents of the Cascade, Round Top and Toppenish Ridge landslides. It suggests that if the Franz Josef debris volume were 10^7 m^3 the debris deposit would be of the order of 2000 m long – thus extending over and then well beyond the township. If this were to occur buildings would be destroyed and many lives lost; the chances of survival in the runout zone, even if in a building, would be negligible. If the volume is only 10^6 m^3 the runout is ~ 1 km, and so still sufficient to cover the township.

A3.3 Failure Probability

Because there is no evidence that a major landslide has occurred previously from this slope, there are no local empirical data to estimate its future probability. Nevertheless, similar events have occurred elsewhere on the western range-front of the Southern Alps, at Round Top (4×10^7 m^3; ca 930 AD; Dufresne at al., 2010), Wanganui-Wilberg (4×10^7 m^3; ca 1300 AD; Chevalier et al., 2009) and Cascade (7×10^8 m^3; ca 660 AD; Barth, 2014). These have all occurred since about 660 A.D., giving a frequency of about 1 event every 500 years or 2×10^{-3} a^{-1} somewhere along the range-front. The length of the (Alpine fault-bounded) range-front is about 400 km; approximately half of this is occupied by valleys so the probability of a major slope failure per susceptible km is about 10^{-5} a^{-1}km^{-1}. Given that the hillslope at Franz Josef extends about 1 km along the range-front, the probability of large-scale failure of this specific hillslope is about 10^{-5} a^{-1}. It is important to note that because of the extremely dynamic geomorphology of the region (tectonic uplift ~ 5 mma^{-1}; annual rainfall ~ 10 000 mma^{-1}) deposits of even very large landslides can be rapidly removed by river erosion; for example Chevalier et al. (2009) estimated that 75% of the Wanganui-Wilberg deposit has been eroded by the Wanganui River in the 700 years since its emplacement. Thus the frequency of large landslides may be higher than the present estimate, but is unlikely to be lower.

There is no evidence of failure of the Franz Josef slope in the ca 18 000 years since it became ice-free, so the annual probability of its failure – if assumed unchanging with time - is likely to be less than 1 in 18 000, or about 5×10^{-5}. However, the morphological characteristics of the Franz Josef hillslope suggest that it is more likely to fail than the many hillslopes that do not exhibit these characteristics, so its failure probability, though unknown, is again likely to be greater than 10^{-5} a^{-1}." (Davies & Moretti, 2021)

Fig. A3.4 below shows probability trend of Southern Alps rock avalanches (Korup & Clague 2009). If the Franz Josef event has a volume of 10^7 m^3 and an annual probability of 10^{-5}, then the probabilities of landslides of greater and smaller volumes are as shown in Table A3.1, assuming the volume-probability line slope is that given by Korup & Clague (2009).

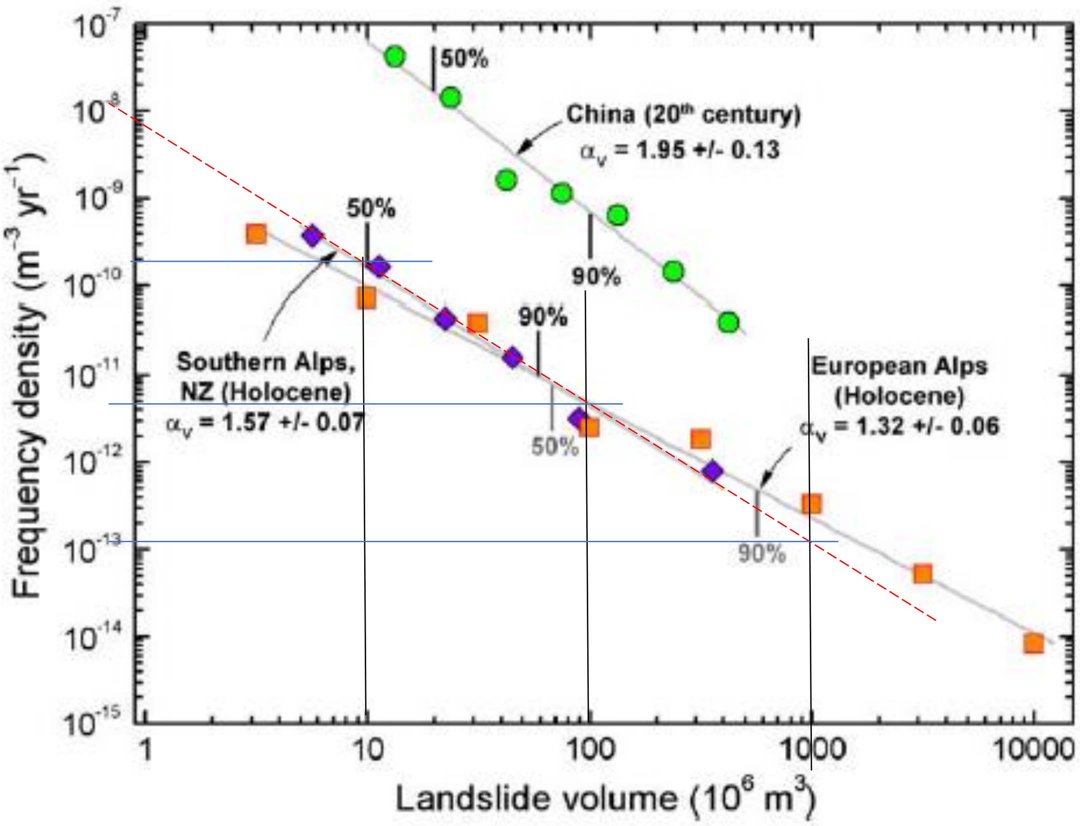

Fig. A3.4 Probability trend of Southern Alps rock avalanches (blue diamonds, red dashed line); after Korup and Clague, 2009.

Fig. A3.4 shows the approximate areas affected by the rock avalanches in Table A3.1.

Table A3.1 Rock avalanche volume, probability and runout distance

Volume, m^3	Probability, a^{-1}*	Runout, km**	Return period (yr)
10^8	2.4×10^{-7}	4.6	4,000,000
10^7	1×10^{-5}	2.1	100,000
10^6	4×10^{-4}	1.0	2,500
10^5	1.6×10^{-2}	0.5	60

*Korup and Clague, 2009 based on p(10^7 m^3) = 10^{-5} a^{-1}.
**Davies, 1982; runout = 10*(volume)$^{1/3}$.

Note that in reality the hillslope source of these rock avalanches can almost certainly not generate an event of 10^8 m^3 because it is not big enough. Hence this volume is not used in risk analyses.

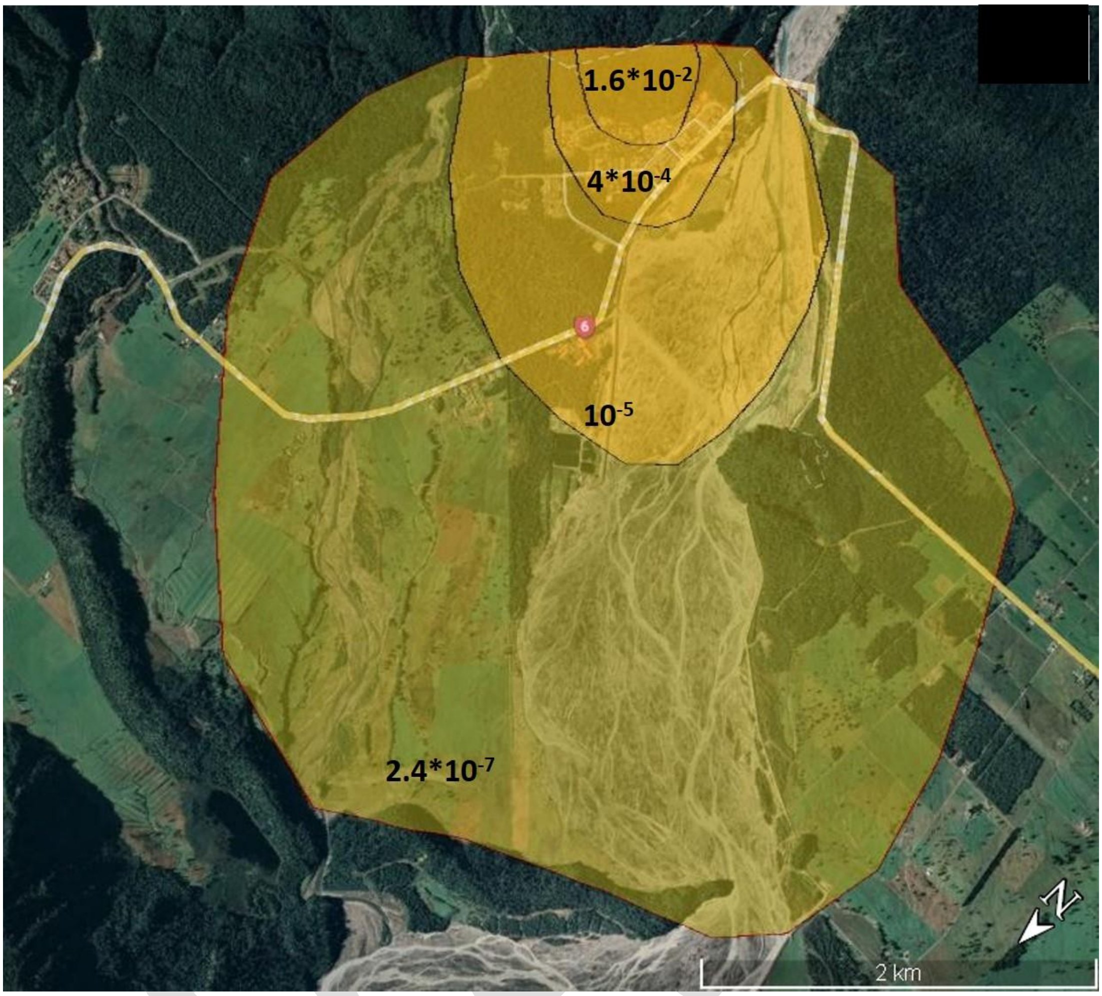

Fig. A3.5 Approximate areas covered by rock avalanche debris deposits of various annual frequencies. Modified Google Earth image.

A3.4 Can the slope in fact fail catastrophically?

Davies and Loew (2019) commented as follows on the question of whether the slope can fail in such a way as to cause a rock avalanche: “While this appears to be a possibility, it is also possible that the slope characteristics have arisen due to a geological process or slope deformation mechanism that does not lead to large-scale catastrophic failure of the slope. Whether or not this slope can fail catastrophically can only be determined by knowledge of the internal geological structure and activity of the slope. *In particular, if the slope has the potential to develop sliding along steeply dipping sliding planes (as indicated for the Cascade landslide in Fig. 9) then the situation is critical and calls for urgent mitigation measures.* The purpose of the present study is to point out the potential risk and to recommend investigations to resolve these fundamental questions.”

A4. Landslide dambreak floods: Tatare and Callery Rivers

The MDRR dissertation of R (2020) generated a magnitude-frequency relationship for landslide dambreak floods from the Tatare River, while Dunant (2019) derived a corresponding relationship for the Callery River (Fig. A4.1, upper and lower respectively).

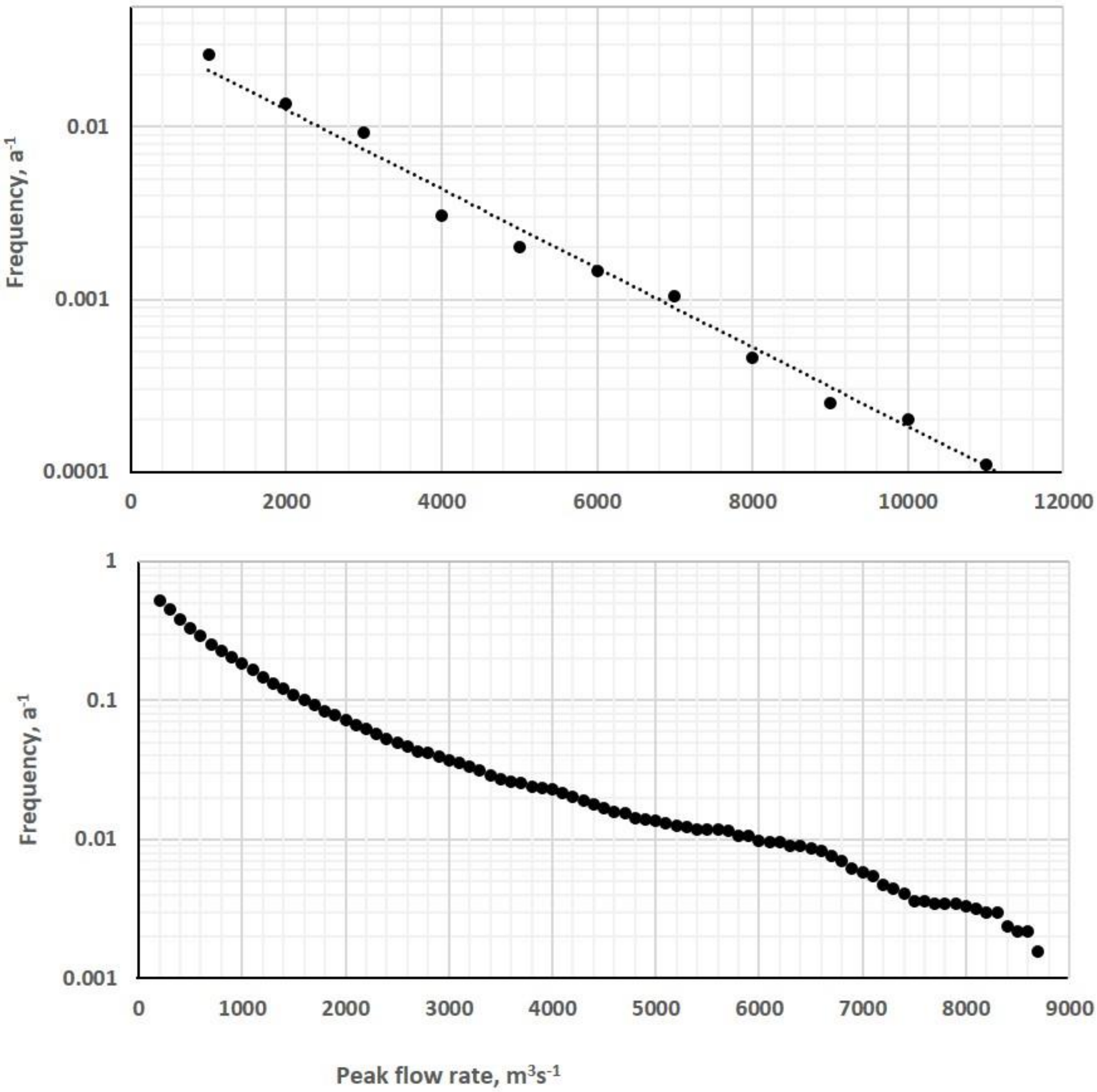

Fig. A4.1 Landslide-dambreak flood magnitude-frequency in the Tatare (upper; R, 2020) and Callery (lower; Dunant, 2019) Rivers.

In order to assess the land areas affected by landslide dambreak floods GNS Science Ltd (C.I. Massey, *pers. comm*. 2022) undertook numerical modelling using RAMMS software as outlined in Morgenstern et al. (2021) for selected flood peak flows as in Table A4.1 (this information was supplied as part of the Endeavour Research Programme "Kaikoura earthquake-induced landscape dynamics"):

Table A4.1 Peak flows and frequencies for modelled landslide dambreak floods

Tatare River				
Peak flow m^3s^{-1}	1000	2500	5000	
Frequency a^{-1}	0.03	0.009	0.002	
Callery River				
Peak flow m^3s^{-1}	1600	4200	6000	8600
Frequency a^{-1}	0.10	0.02	0.01	0.002

Note that these models were run with 2016 LIDAR data so do not account for planned stopbank improvements. However the ability of stopbanks to contain dambreak floods is significantly lower than their ability to contain normal floods because of the very large volumes of sediment associated with the former and the consequent severe bed aggradation.

Figs A4.2 – A4.4 below show the areas modelled as flooded by Tatare River landslide dambreak floods (modified Google Earth images).

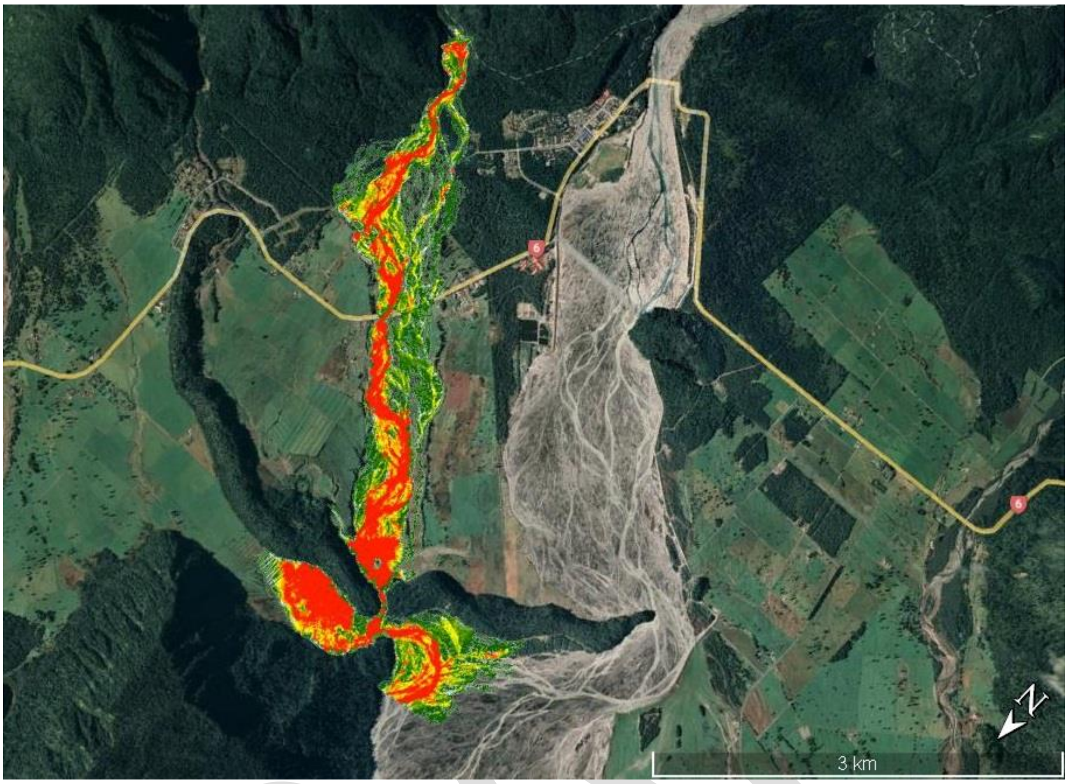

Fig. A4.2 Tatare River landslide dambreak flooding peak flow = 1000 m^3s^{-1}

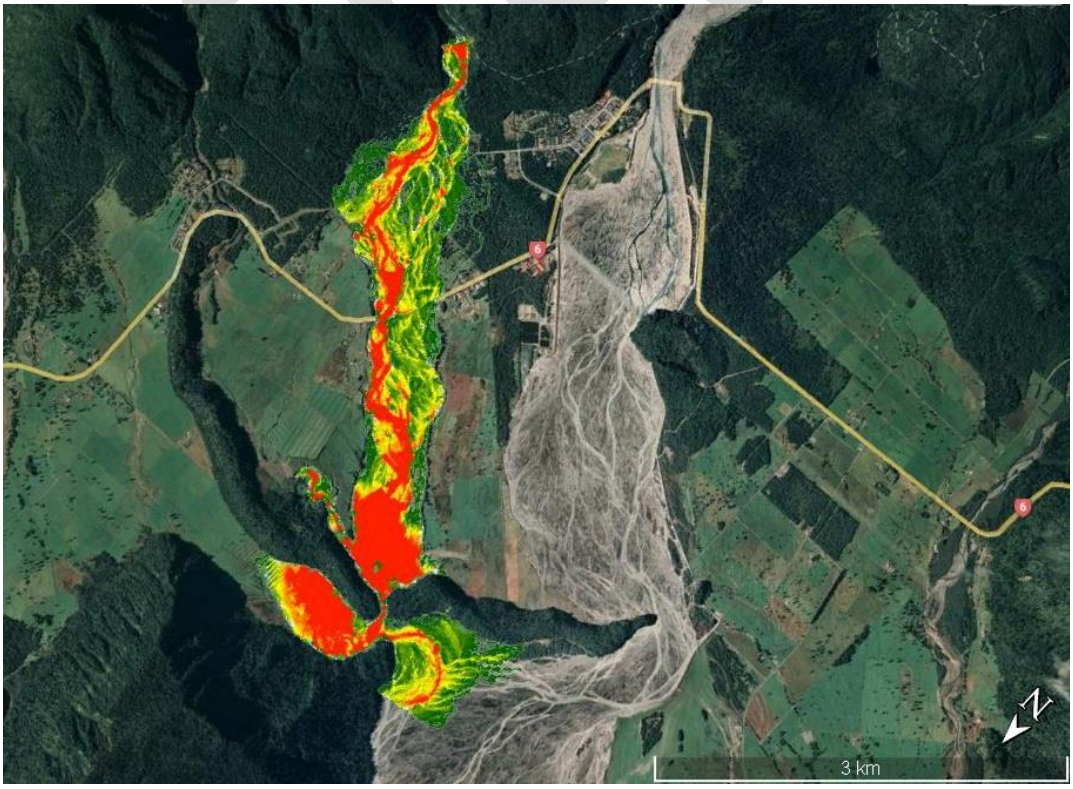

Fig. A4.3 Tatare River landslide dambreak flooding peak flow = 2500 m^3s^{-1}

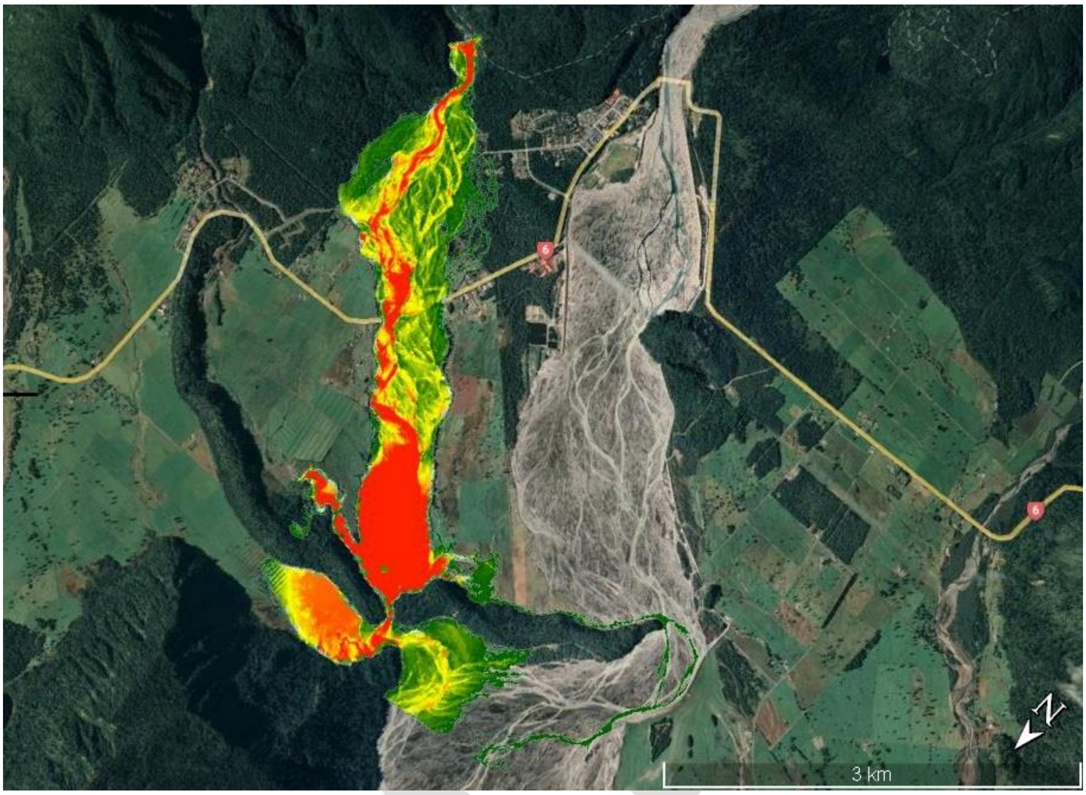

Fig. A4.4 Tatare River landslide dambreak flooding peak flow = 5000 m^3s^{-1}

Figs A4.5 – A4.8 below show the areas modelled as flooded by Callery landslide dambreak floods (modified Google Earth images).

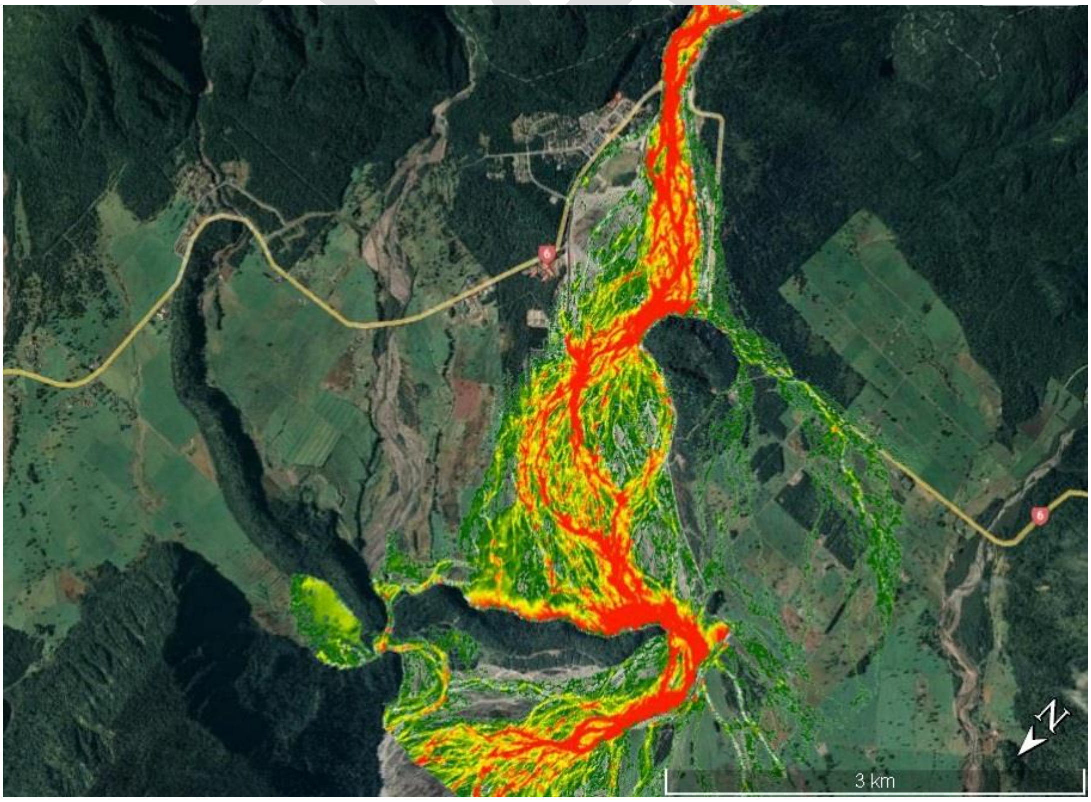

Fig. A4.5 Callery River landslide dambreak flooding peak flow = 1600 m^3s^{-1}

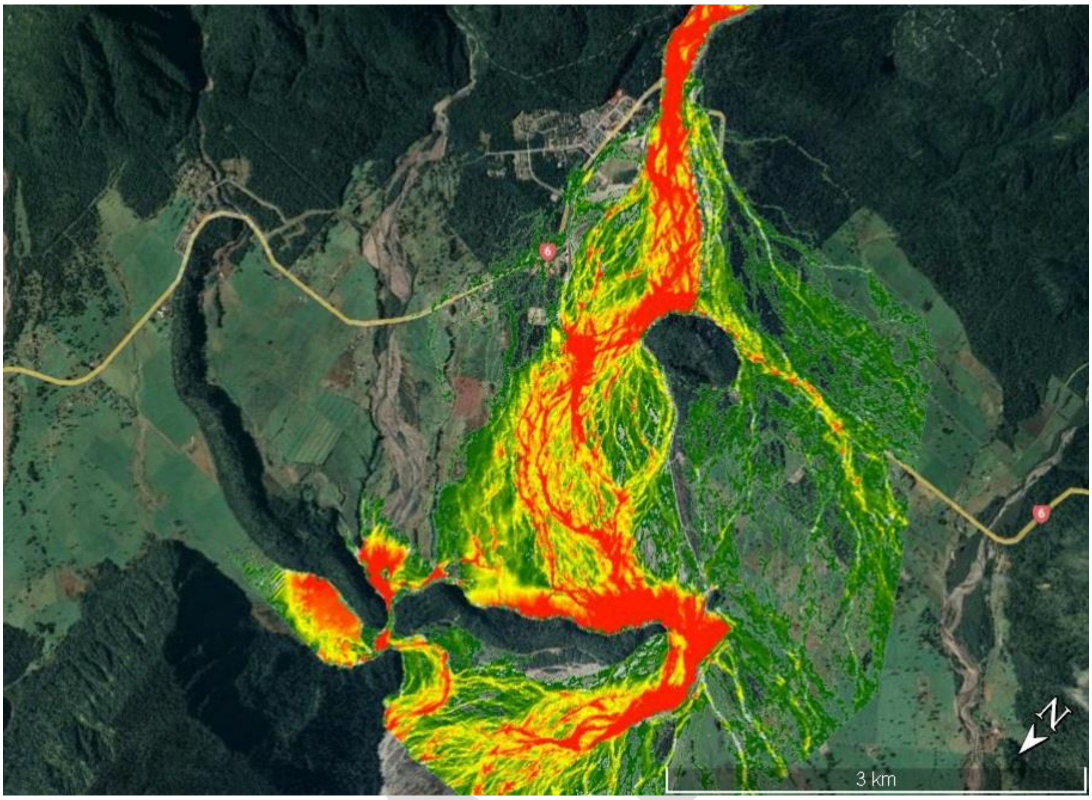

Fig. A4.6 Callery River landslide dambreak flooding peak flow = 4600 m^3s^{-1}

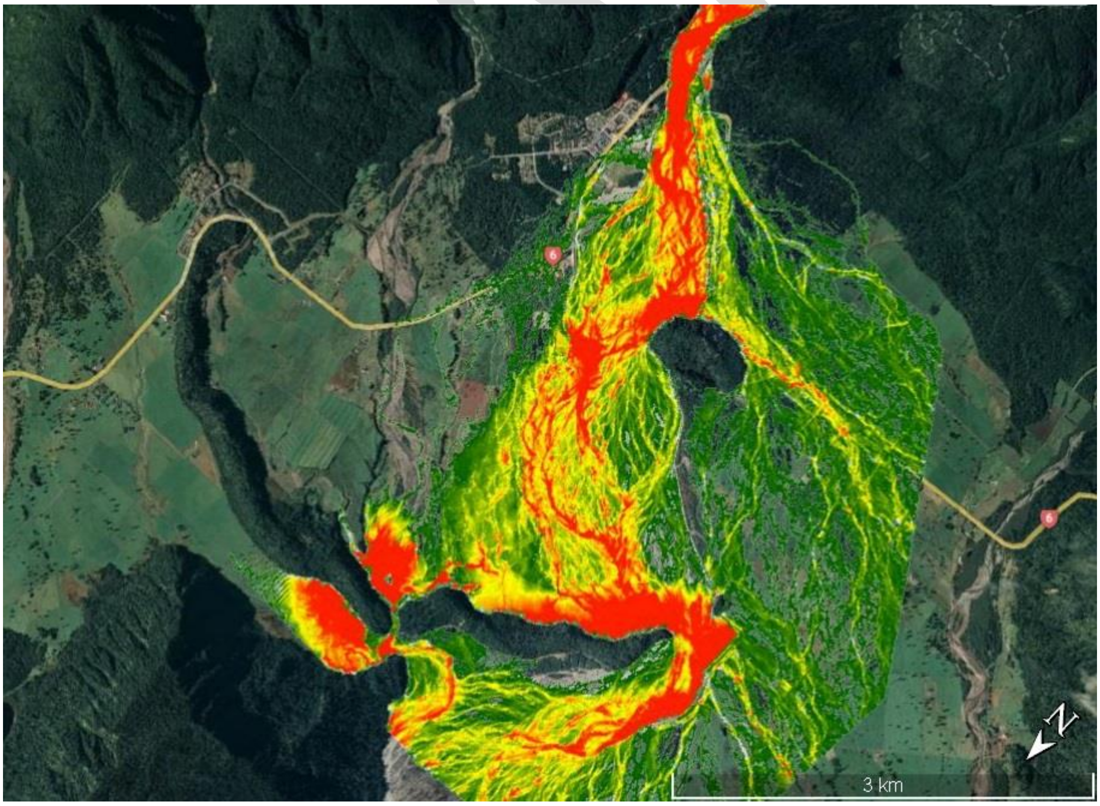

Fig. A4.7 Callery River landslide dambreak flooding peak flow = 6000 m^3s^{-1}

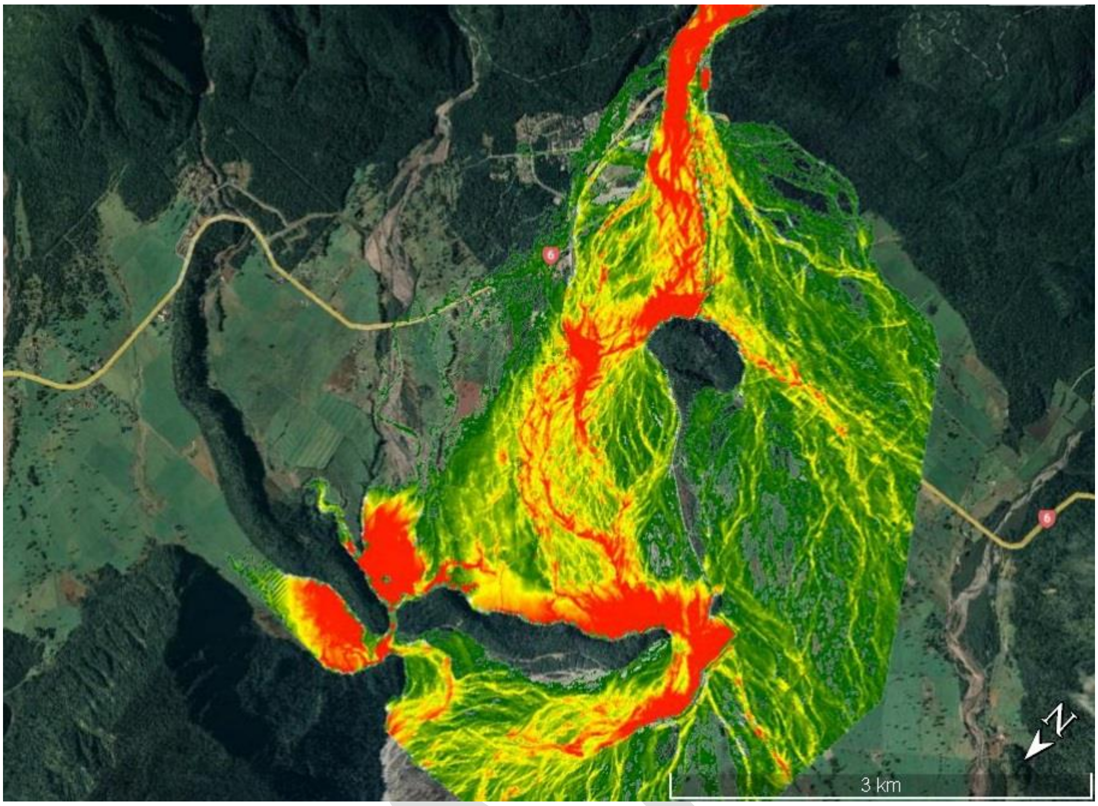

Fig. A4.8 Callery River landslide dambreak flooding peak flow = 8600 m^3s^{-1}

APPENDIX B - PROBABILITY OF DEATH RESULTING FROM IMPACT OF A HAZARD WITH A PERSON (MORTALITY RATES)

(Adapted from unpublished MSc thesis of R, 2022)

B1 Earthquake Mortality Rate

Casualty estimations or realistic fatality rates for earthquakes are generally complicated and hard to derive due to inconsistencies and lack of quality of data (So, 2016). When compared with other areas with similar seismicity, New Zealand has had a relatively low number of earthquake-related deaths (Nichols et al., 2000). There have been several methods and criteria used to calculate the mortality rates for earthquakes. For the purpose of this study, an earthquake-related death was defined as one that occurred directly or indirectly as a result of ground shaking and only considered earthquakes that have occurred in New Zealand. Abeling et al. (2017) examined patterns and mortality rates in New Zealand between the years 1840-2017, during which approximately 21 earthquakes with MMIs VII or greater occurred. The main factor of consideration for Franz Josef was the magnitude and intensity of any given earthquake. Fig. 3.9 by Abeling et al. (2017) illustrates the mortality rates by MMI.

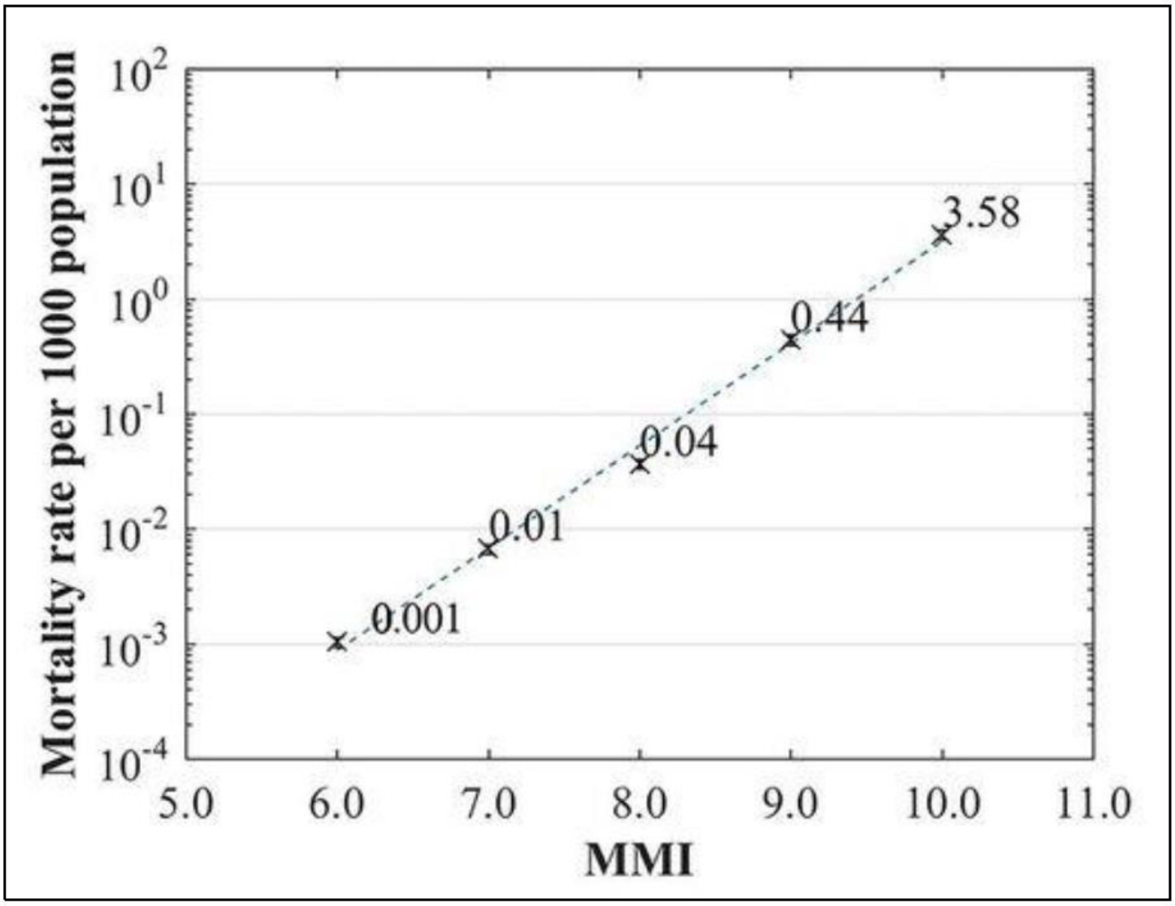

Figure B1.1: Mortality rate by MMI per 1000 population exposed to a severe New Zealand earthquake (Abeling et al., 2017)

Given that shaking from the Alpine fault earthquake is expected to be MM10 or greater across all of the town areas, an earthquake mortality rate of 3 per 1000 (0.3%) was used for the purposes of this study.

B2 Rock Avalanche Mortality Rate

Landslide vulnerability and the underlying causes of landslide fatality are widely understudied (Pollock & Wartman, 2020). There are several key factors that determine human vulnerability and probability of death during a landslide event. Of the various situational risk factors, distance from slope was deemed the most critical factor. According to Pollock and Wartman (2020), the odds of death increase with decreasing distance, whereby individuals closer to the slope (less than 100m) have 1.6x more likely to be killed. Due to the nature and fast velocity of a rock avalanche, the modelled runout distance, and the distance between buildings and individuals to the hillslope above the current townsite, a mortality rate of 100% was used.

B3 Flooding Mortality Rate

Flood-induced mortality rate was derived from (Hu et al., 2018), who calculated mortality rates for flood-induced deaths within different continents (Fig. B2). Given that past occurrence rates of floods, flood-affected population as well as other underlying factors such as GDP per unit area, income and other variabilities in New Zealand is comparable to that for the Australian continent, the flood mortality rate of 0.59% was used.

Continents	Occurrences	Total flood-induced deaths/event		Total flood-affected people/event		Mortality (%)	
		mean	SD	mean	SD	mean	SD
Africa	443	42.76	141.54	115,074.31	450,434.54	0.98	5.05
Asia	954	107.12	320.46	2,652,909.22	15,475,715.09	1.79	8.20
Australia	39	5.85	9.38	16,220.05	41,761.24	0.59	1.42
Europe	198	12.22	23.00	38,295.29	138,085.39	1.71	8.24
North America	240	31.23	183.55	96,056.15	730,162.66	0.95	4.47
South America	218	178.00	2,030.69	167,064.11	471,928.43	0.76	3.54

Figure B3.2: Flood induced mortality rate across the different continents (Hu et al., 2018).

B4 Landslide Dambreak Flood Mortality Rate

Flood-induced mortality rates for other flood disaster categories was also adopted from Hu et al. (2018). Figure B4.1 shows the mortality rates for different flood types. However, a category for

Flood type	Occurrence	Mortality rates (%)		Total Deaths/event		Total Affected People/event	
		Mean	SD	Mean	SD	Mean	SD
Coastal flood	41	2.050	11.990	60.439	138.790	499308.805	1283278.670
Flash flood	398	2.133	7.486	138.751	1508.927	420068.779	4172205.915
Riverine flood	1653	1.188	6.432	67.987	256.305	1489342.276	11657845.359

Figure B4.1: Mortality rates for the various flood types (Hu et al., 2018).

floods from a landslide-induced dambreak was not present. Therefore, the mortality rate for the most comparable flood type; flash flood (2.1%) was considered. The 1999 Mount Adams dambreak flood remained largely confined to the river channel and thus, caused no deaths and little damage (Becker et al., 2007). Given that floods caused by landslide dambreak events often occur quickly and carry more debris than normal floods, and are similarly detrimental to flash floods, a value of 2% mortality rate was used.

B5 Debris Flow Mortality Rate

The vulnerability values assigned by Wei et al. (2021) were used to calculate the mortality rate for a debris flow from Stoney Creek whereby vulnerability was defined as the "degree of loss of any given element exposed to a debris flow of a given magnitude". According to Wei et al. (2021), most injuries and deaths resulting from debris flows in China occur in buildings due to damage caused to the buildings. As such, only the risk to the lives of people in buildings was considered. Given that there are ongoing developments within the region next to Stoney Creek, it was safe to assume a similar scenario for a Stoney Creek debris flow, whereby only the risk to life of people within buildings was considered and the risk to life of people outside of buildings in the event of an occurrence was omitted. Therefore, the vulnerability of the people was calculated as vulnerability of person x building vulnerability. Wei et al. (2021), assigned the maximum vulnerability of people as 0.9 and the maximum building vulnerability as 0.315. Therefore, the mortality rate for debris flow was calculated to be 27%.

APPENDIX C – QUALITATIVE PICTURE OF RISK TRENDS POST-2040 AND/OR POST-EARTHQUAKE

It is worth exploring quantitatively the possible longer-term (post-2040/post-earthquake) changes in risks to the town sites, to provide a context for shorter-term decision-making. The main factors affecting longer-term risks are whether or not a major earthquake has occurred on the Alpine fault, and whether or not the Waiho River stopbanks on the true left (west) bank have been removed as suggested by Gardner (2021).

As noted in the Report, climate change will be a more significant factor in longer-term risk assessments. Collins (2021) has addressed this issue in preliminary fashion, suggesting for example that under the most extreme climate-change scenarios, winter river flows in Westland may exhibit detectable increases at multi-decadal time-scales. However, more useable inferences await further research. Debris-flow frequencies also seem likely to increase; for example, the 2005 debris flow at Matatā was triggered by a 200-500-year return interval rainstorm, but by the end of this century such an event would have a 40-50-year return interval under the RCP 8.5 climate change scenario.

We consider three longer-term scenarios:

1. Pre-earthquake, stopbanks still in place as per 2020 plan
2. Pre-earthquake, west bank Waiho stopbanks removed
3. Post-earthquake

C1 Pre-earthquake, stopbanks still in place as per 2020 plan

By 2040, assuming aggradation of the Waiho continues and no major earthquake has occurred, the river bed level will have risen so that the overtopping risk has become significantly higher. This will have the effect of increasing the flooding risk to much of the old town sites OT1 and OT2 and to part of NT2 (Fig. C1.1)

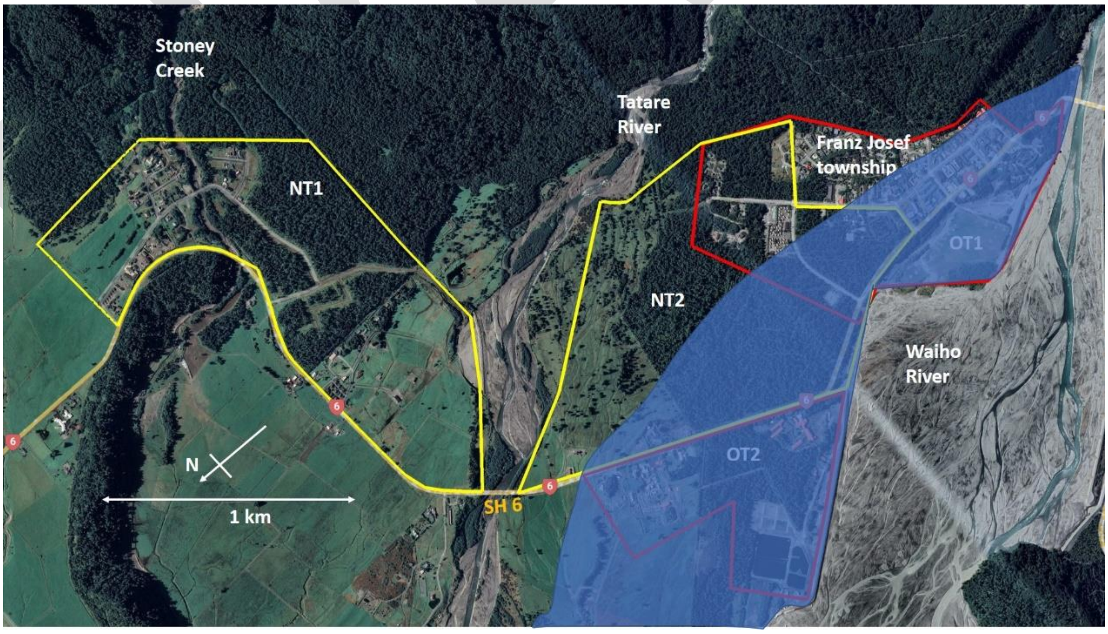

Fig. C1.1. Approximate higher-risk post-2040 and pre-earthquake Waiho River flood zone (blue).

C2 Pre-earthquake, west bank Waiho stopbanks removed

If the western stopbanks have been removed, the flood risk to the east side of the Waiho River will be very much reduced, effectively to zero as in the pre-2040 case (Fig. 5).

C3 Post-earthquake

The severe and widespread shaking accompanying a major earthquake will cause many slope failures in the mountains, some of them large. As noted in the Report, stopbanks will also be severely damaged and become ineffective. All river catchments may receive substantial quantities of landslide sediments during the mainshock and in some of the aftershocks, resulting in a major pulse of river-bed aggradation affecting the Waiho, Callery and Tatare Rivers. This pulse will begin during the first rainstorm following the earthquake, and will increase over several years or perhaps a decade to a peak depth of several or many metres at the range-front (aggradation following the 1999 Mt Adams landslide peaked at 5 m or so about 6 years after the event; Croissant et al., 2017); thereafter the aggradation wave will move down the river affecting floodplains over further decades, constraining land use over much of the West Coast (Blagen et al., 2022). Flood risks will also be increased adjacent to the Tatare River affecting township sites NT2 and possibly NT1 (Fig. 5)

During the seismic period of the mainshock and significant aftershocks (which is likely to last several years to a decade), landslide dambreak flood risks from the Callery and Tatare Rivers may increase significantly (Tables 3 and 4, Figs 8 and 9).

Debris flow risk on Stoney Creek fan (Fig. 10) will increase following the earthquake mainshock and large aftershocks, because of the increase in the volume of landslide sediment available in the catchment, through which the Alpine fault runs. The 1999 Chi Chi earthquake in Taiwan caused the number of rainfall-triggered landslides to increase fourfold during the two following years (Lin et al., 2004), while experience following the 2008 Wenchuan earthquake shows debris-flow occurrence in the affected area reducing fourfold from its post-earthquake peak by 2016 (Li et al., 2018), so debris-flow risk at Stoney Creek may follow a similar pattern of rapid increase and more gradual decrease.

C3(i) If an earthquake were to occur with the Waiho River western stopbanks still in place, the coseismic shaking would probably severely damage all the stopbanks, reducing their crest height greatly. This, together with the accelerated aggradation due to coseismic sediment input to the Callery and Waiho, means that flood risk will be greatly increased in the area shown in Fig. X, and probably even more widely.

C3(ii) However, if the western stopbanks are no longer in place when the earthquake occurs, much of the sedimentation may be expected to occur on the true left (western) side of the Waiho, with correspondingly less on the town side

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POTENTIAL LANDSLIDE RISK AT FRANZ JOSEF GLACIER TOWNSHIP, WESTLAND, NEW ZEALAND

Report to West Coast Regional Council

Tim Davies, Professor, Geological Sciences, University of Canterbury, New Zealand
Simon Löw, Professor, Chair of Engineering Geology, ETH-Zürich, Switzerland

7 February 2019

Summary

1. The steep hillslope that rises about 650 m immediately behind Franz Josef Glacier Township (Fig. 1) has a stepped profile with a flat bench near the top, above an oversteepened, bulging centre slope section. This profile is characteristic of some slopes prone to coseismic or rainfall-triggered failure, as demonstrated by the Round Top and Cascade rock avalanches (Westland), the Roche Pass slope failure (Canterbury), the Toppenish Ridge landslide (Washington, USA), and ten slopes in Japan that failed during intense rain in 2011 (Chigira et al., 2013). This slope morphology can be the result of deformation of the slope prior to catastrophic failure.
2. The flat bench on the Franz Josef slope shows a prominent set of slope-parallel ridges. Such ridges are found also on the Toppenish Ridge bench and on a bench that failed in the Shimuzu landslide, Japan during the 2011 typhoon. These slope-parallel ridges may result from deformation of the rock forming the bench prior to failure.
3. The morphology of the Franz Josef slope thus suggests the possibility that it could suffer large-scale failure in the future. Any such failure would constitute a serious hazard to the township; it would severely damage the township with many casualties.
4. An order-of-magnitude analysis indicates that, if large-scale failure of the slope is indeed possible, the current risk-to-life posed by this situation is about 10^{-2} per year, which is about 1000 times higher than the upper limit of acceptable risk for a hazard of this type. This estimate needs to be refined by further research.
5. It is therefore a matter of urgency that geotechnical investigations are undertaken to establish (i) the geological structure of the hillslope, i.e. whether landslide displacements have occurred in the geological past; (ii) the current slope activity, i.e. whether or not the slope is currently deforming; (iii) the stability of the slope, i.e. whether or not realistic intensities of seismic shaking and/or rainfall could cause failure of the slope; and (iv) the volume and velocity of a potential failure and the extent of its deposit.

Fig. 1 Hillslope above Franz Josef Township (lower right) with dashed profile line (Google Earth image 2013)

1. Introduction

Franz Josef Glacier township, Westland, New Zealand is a tourism centre whose 450 residents host over 3000 overnight visitors and support about 6000 daily visitors to the glacier. Visitor numbers are increasing by about 9% annually, and the township is developing correspondingly.

It is well-known that Franz Josef is vulnerable to earthquake and flood hazards, but the hazard due to landsliding from the steep hillslope that rises about 650 m immediately east of the township (Fig. 1) is less obvious. This possibility was mentioned by McSaveney and Davies (1998) but dismissed because there were no obvious signs of instability of the slope; Barth (2014) suggested a similarity between the Franz Josef slope and that adjacent to the Cascade rock avalanche; and a more recent hazard assessment (Langridge et al., 2016) discussed the issue in more depth and recommended further work, based on the possibility that the slope could fail in the next major earthquake. The present report shows that the benched profile of this slope, and prominent parallel ridges on the bench, are generally similar to those of slopes elsewhere (in Westland, Canterbury and overseas) that have failed and generated rock avalanches whose deposits cover large areas with rocky debris.

This association of the bench-and-parallel-ridge morphology with slope failure suggests that the Franz Josef slope may be vulnerable to failure; however, it is also possible that this is not the case. If the bench and ridges reflect significant prior deformation of the slope, then future failure becomes a possibility; this possibility, however, depends in turn on the actual rock structure and mechanical properties, the nature of the past displacements (i.e. the landslide kinematics) and the geometry of failure surfaces, all of which are presently unknown.

Herein we present arguments suggesting that if a major slope failure is indeed possible, then there is an unacceptable risk-to-life from this slope, and we recommend measures to establish whether such a landslide is possible, in order to form the basis for risk reduction strategies. The potentially large number of deaths that could result from slope failure makes this work urgent. We recommend that detailed geotechnical investigations of the slope be carried out to determine the origin of its morphology and the probability of a future major failure.

2. Slope profiles

Here we compare the Franz Josef slope profile with two other slopes that have failed in similar geological environments (i.e. on the hanging wall of the Alpine fault) - the Round Top and Cascade slopes; and with the Roche Pass slope in Canterbury which partly failed in the 1929 Arthur's Pass earthquake. We then extend the comparison to the Toppenish Ridge (USA) and Shimuzu (Japan) slopes, both of which show, in addition to the benched profile, prominent slope-parallel ridges on the bench; both of these slopes have failed generating large-volume landslides.

*2.1 **Franz Josef slope***

This slope, with a profile line (dashed), is shown in Figure 1. The proximity to Franz Josef Township is evident, and the profile shows the bench on the upper slope and the steep section below the bench. Without this profile, however, the bench is not prominent, and is indeed invisible from below. The trace of the 400 km-long Alpine fault at the base of the slope is also indicated; this fault is known to generate M_w8 earthquakes several times per millennium (Cochran et al., 2017).

Figure 2 shows a profile of the Franz Josef slope, derived from Google Earth. This clearly shows the upper bench and the oversteepened slope beneath it, compared with a profile of the adjacent slope on the northern side of the Tatare River.

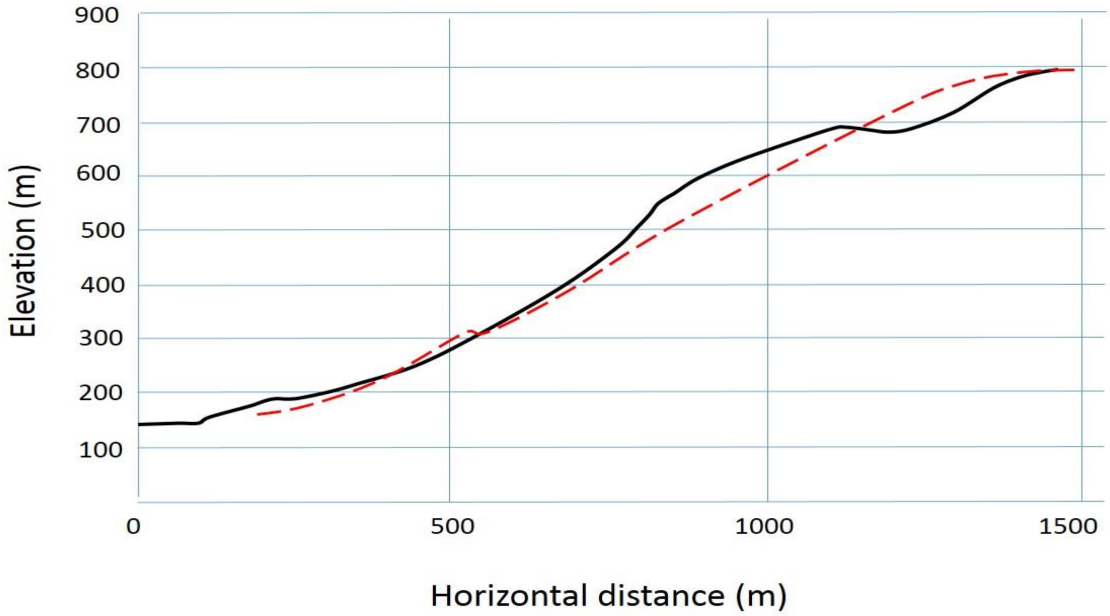

Fig. 2 Profile of Franz Josef slope. Red dotted line is profile of adjacent slope (north of the Tatare River) for comparison. (Source: Danilo Moretti)

Figure 3 shows the conspicuous rock structures on the bench, which are not visible until post-processing of Lidar data enables the obscuring effect of vegetation to be removed. The structures are slope-parallel ridges with a length of about 350 m and an amplitude of about 4 m (Fig 4).

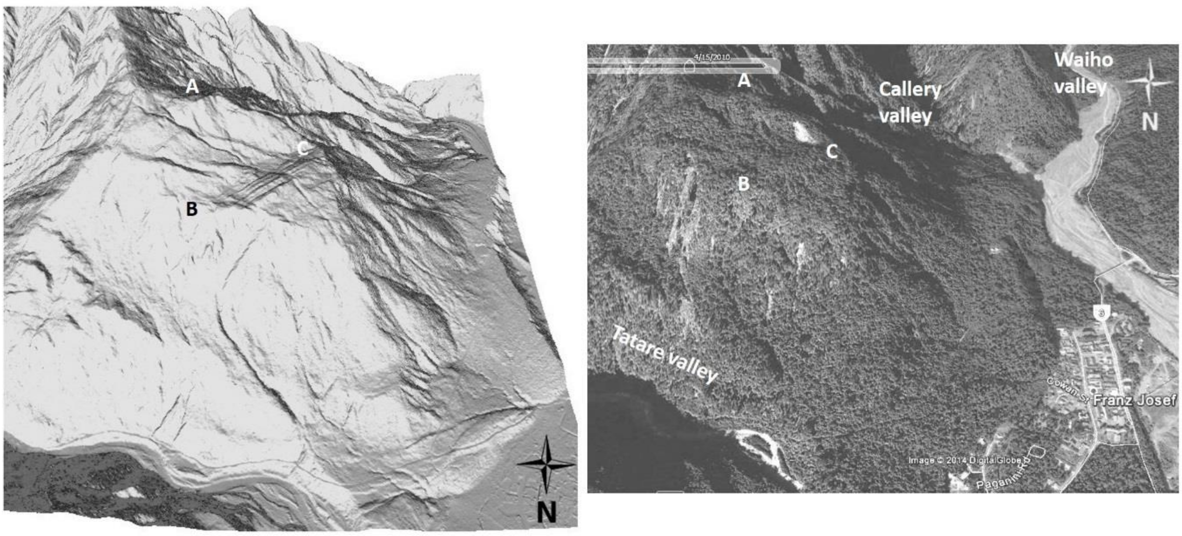

Fig. 3 Slope overlooking Franz Josef, showing Lidar image with vegetation removed (left) compared to normal view (right). A, B and C are corresponding locations in both images. The distance BC is about 350 m. (Source: Danilo Moretti)

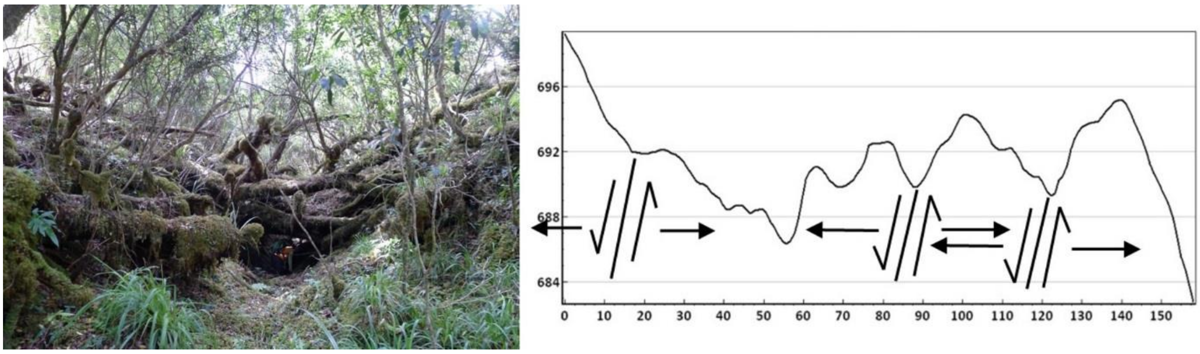

Fig. 4 Slope-parallel ridges on the Franz Josef slope bench. Left: Field view; Right: Lidar-based cross-section showing amplitude and wavelength (vertical exaggeration is about 10:1). Source: Danilo Moretti.

The geology and rock structures of the Franz Josef slope have not been mapped; however rock exposures in the vicinity (Fig. 5) indicate that foliation dips south-eastwards into the slope. This corresponds with the regional geology on the hanging wall of the Alpine fault (Fig 6), and has also been inferred for the Cascade and Round Top sites described below.

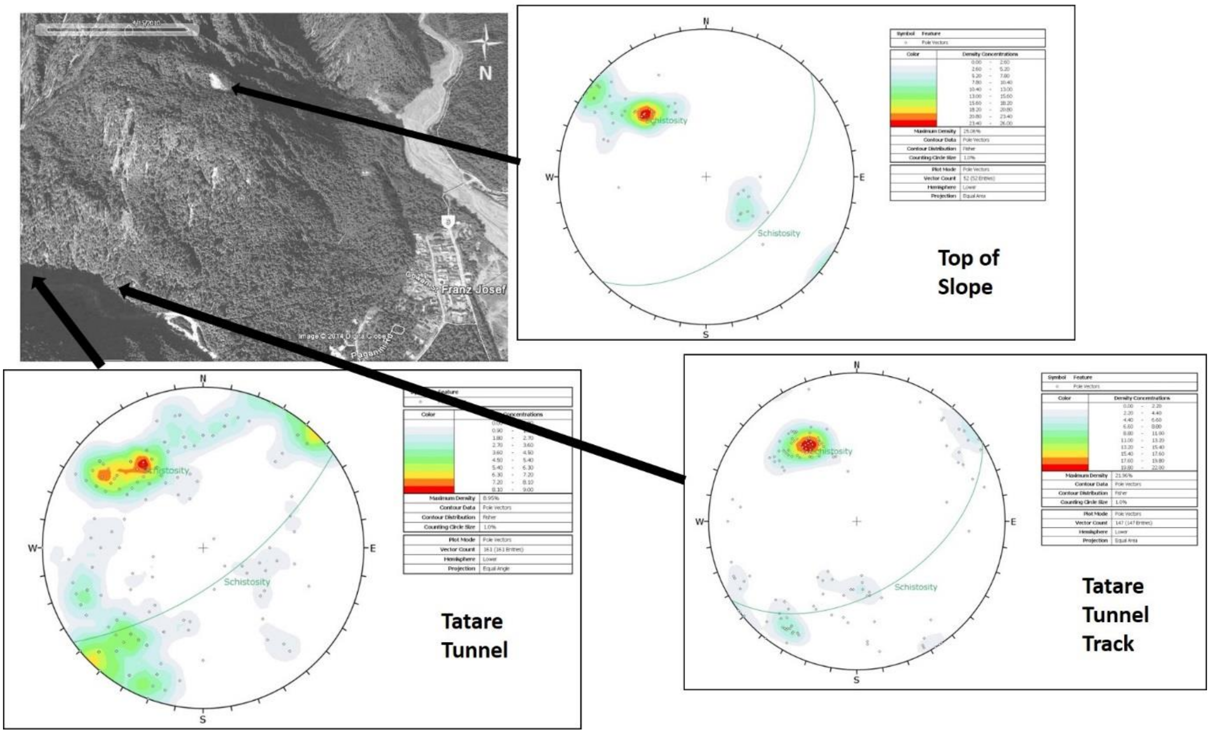

Fig. 5 Stereo plots of rock structure near Franz Josef hillslope. Source: Danilo Moretti.

The Franz Josef slope was under ice during the most recent glaciation, and would have become ice-free about 18 000 years ago. While the bench could thus be a result of glacial erosion, its orientation with respect to ice-flow out of the adjacent Waiho, Callery and Tatare valleys (Fig. 3) makes this unlikely. Similarly, a glacial-meltwater-erosion origin for the parallel ridges appears unlikely. The orientation of foliation dipping into the slope suggests that toppling is the main potential instability mechanism at Franz Josef. The bench could represent the transition between stable bedrock and the toppling landslide mass, whereas the parallel ridges could have been created as uphill facing toppling scarps.

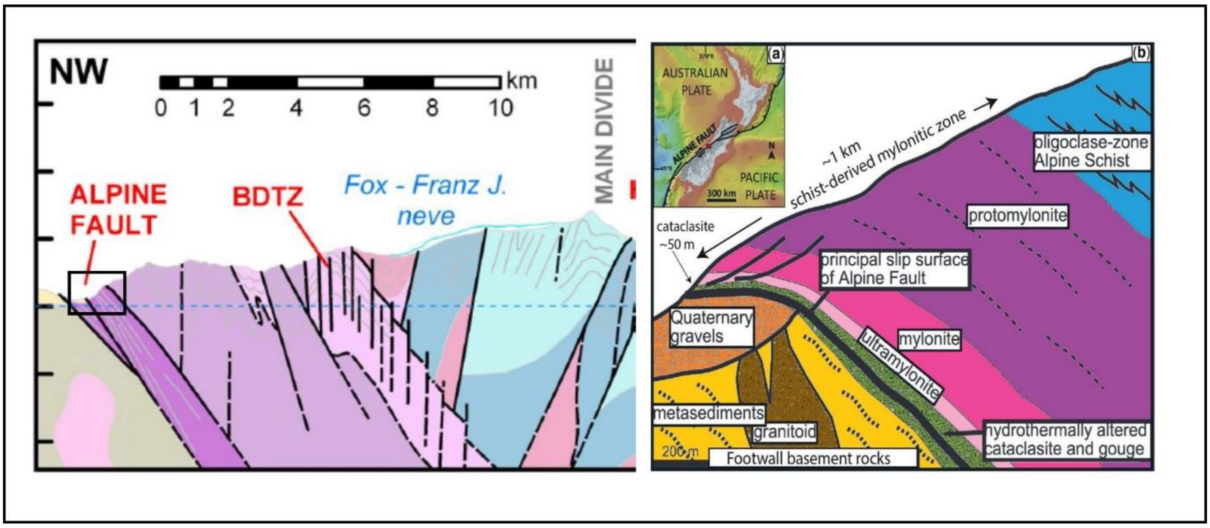

Fig. 6 Left: Geological setting of the Southern Alps western rangefront (Cox et al., 2012); Black square shows location of right-hand diagram. Right: detail of characteristic geology adjacent to the surface trace of the Alpine fault (Kirilova et al., 2018). Note that the Franz Josef slope is steeper than that shown.

Down-slope dipping fractures, which would be required for rapid sliding, have not been mapped by Moretti, but they might occur in the deeper subsurface (for example along toppling hinge lines).

2.2 *Cascade slope*

The Cascade rock avalanche deposit (Fig. 7: Barth, 2013), about 160 km SW of Franz Josef, has been dated to about 660 AD. It has a volume of about 0.75 km^3 and a runout distance of at least 4.5 km. The presence of a prominent bench on the upper part of the unfailed slope immediately south of the failure scarp suggests that the failed part of the slope also had such a bench prior to failure. A profile of the slope is shown in Fig. 8, and a geological section in Fig. 9.

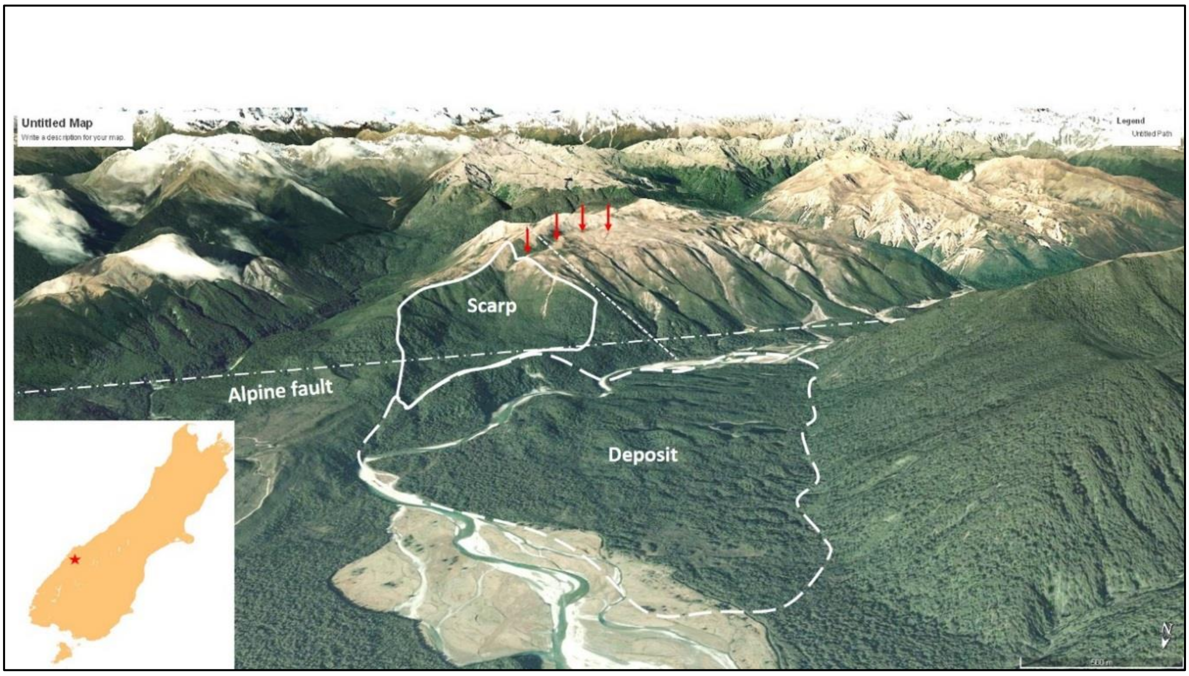

Fig. 7 Cascade rock avalanche, Westland. Red arrows indicate bench which is about 100 m high and 1.8 km long. Dotted line is location of section Fig. 8

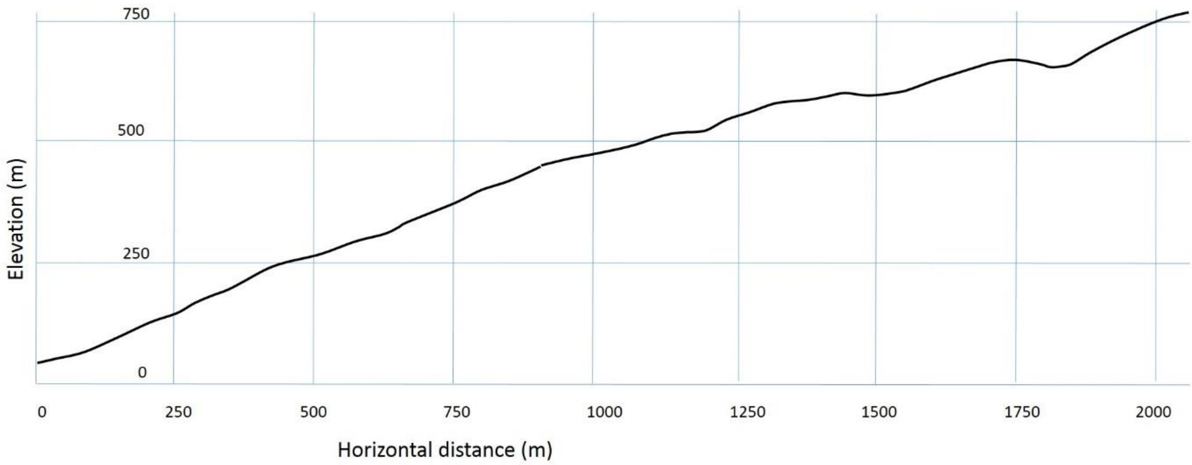

Fig. 8 Profile of slope adjacent to headscarp of Cascade rock avalanche

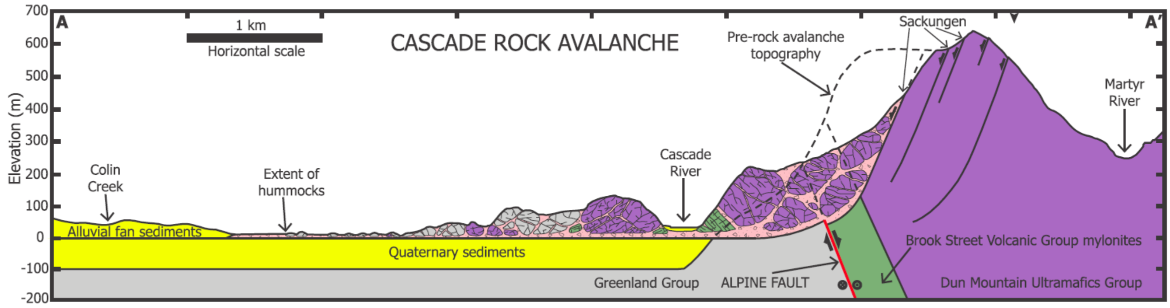

Fig. 9 Geological section of Cascade rock avalanche and source area (Barth, 2013). Vertical exaggeration 2.5:1.

The general tectonic situation and the dip of bedding and foliation of the Cascade failure is similar to that of the Franz Josef and Round Top slopes (Fig. 6). On the other hand Barth (2013) interprets the benches at Cascade and Round Top (next section) as "Sackungen" indicating the presence of deep-seated and downslope dipping rock fractures, which led to a sliding type slope failure, and suggests that the same may apply at Franz Josef. The presence of the Alpine fault at the base of the failure scarp strongly suggests that the failure was earthquake-triggered.

2.3 Round Top slope

The Round Top rock avalanche deposit (Fig. 10), about 90 km NE of Franz Josef, was emplaced in about 930 AD (Wright 1998). It has a volume of about 45 x 10^6 m^3 and a runout of about 3.5 km. Again there is a bench in the upper slope adjacent to the headscarp. The slope profile is shown in Fig. 10. The general tectonic situation is generally similar to that at Franz Josef and Cascade. The presence of the Alpine fault at the base of the failure scarp strongly suggests that the failure was earthquake-triggered.

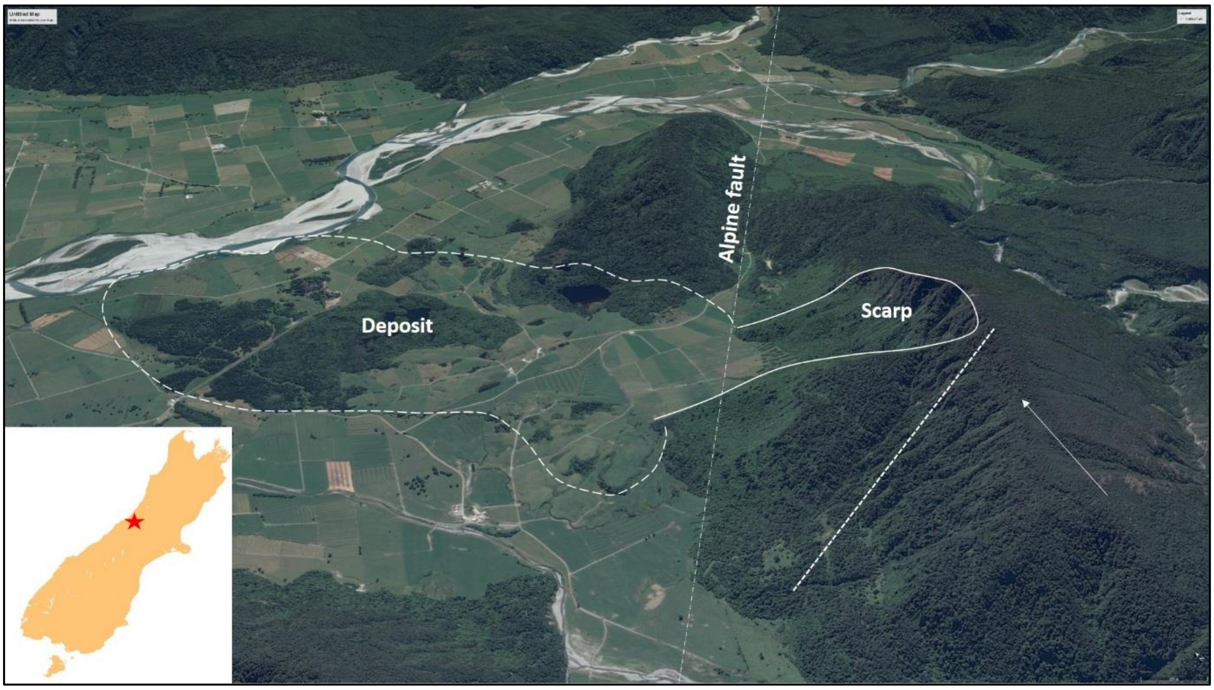

Fig. 10 Round Top rock avalanche. Arrow indicates bench (or double ridge) on upper part of slope adjacent to headscarp; dotted line is approximate location of section (Fig. 11)

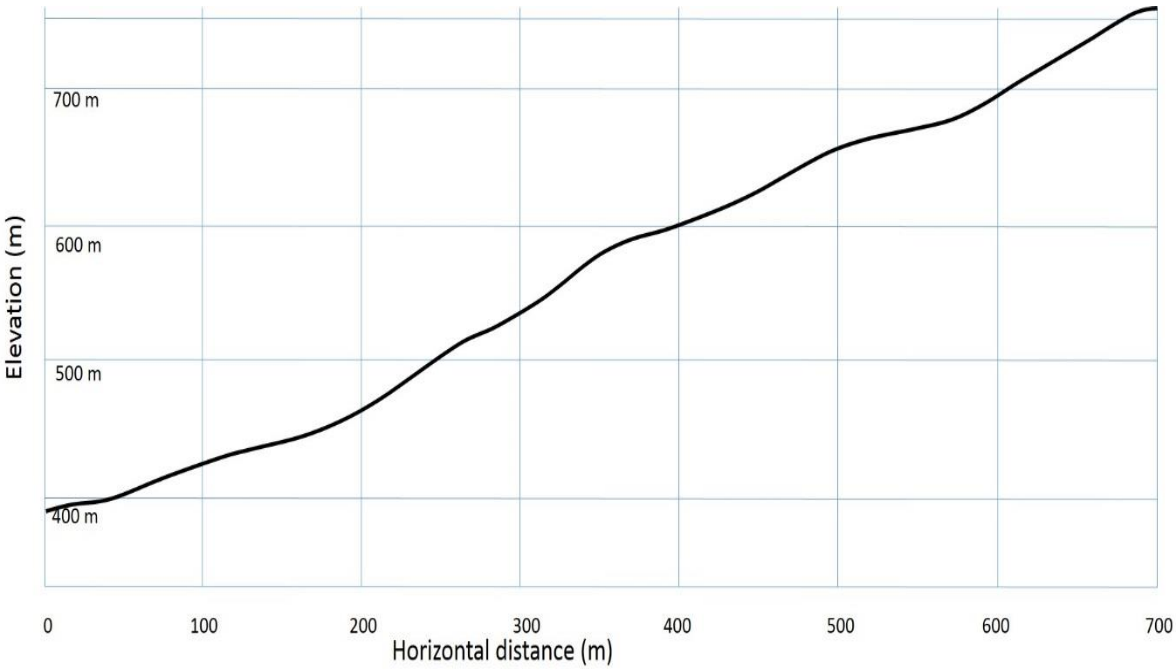

Fig. 11 Profile of slope adjacent to Round Top headscarp.

2.4 Roche Pass slope

In the 1929 M_W7.1 Arthur's Pass earthquake, Canterbury, New Zealand, a slope about 35 km to the east of the epicentre partly failed (Fig. 12). About 2 x 10^6 m^3 of greywacke were displaced and partly disaggregated, but were not evacuated completely. The bedding or foliation orientation is oblique to the main slope and the failure mechanism and displacement are 3-dimensional. Fig. 12 shows the bench formed in this event, and the sets of parallel and oblique ridges that developed during the deformation. The profile of the benched slope is shown in Fig. 13. Here the motion of the landslide is complex, so interpretation of the lineations on the bench is difficult. The primary landslide motion triggered by the Arthur's Pass earthquake was not in the direction of the main valley, and the rotational sliding plane arrested the landslide displacements.

Fig. 12 Roche Pass coseismic failure, Canterbury, New Zealand. Dotted line is location of section (Fig. 13)

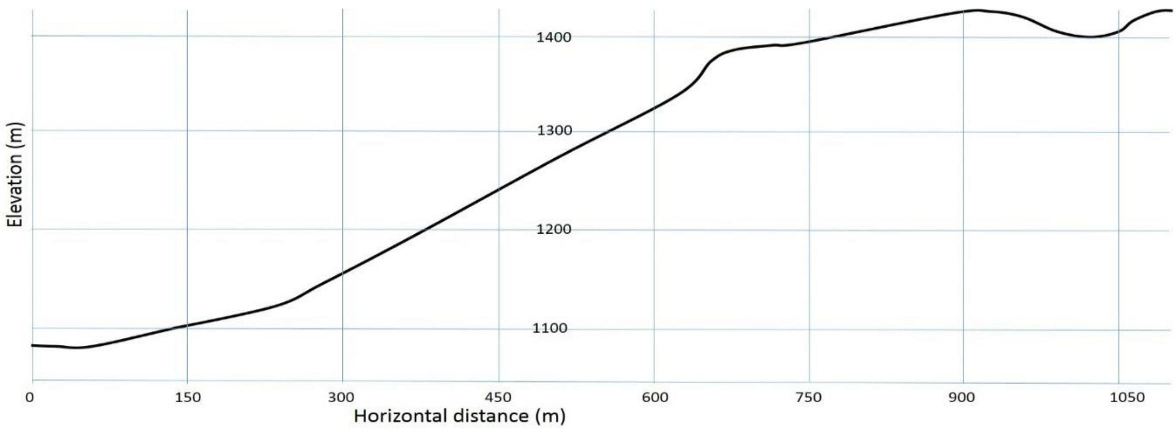

Fig. 13 Roche Pass slope profile

2.5 Toppenish slope

At Toppenish Ridge, Washington, USA a landslide comprising Quaternary sedimentary rocks and Miocene basalts failed several thousand years ago forming a debris deposit of about 3 x 10^6 m^3, about 700 m long (Fig. 14). However part of the slope failed only partially, and remains *in situ* forming a slope-top bench; this bench has prominent slope-parallel ridges. Moreover, a lineation across the upper part of the failed slope (dashed arrows in Fig. 14) suggests that prior to final failure the right-hand part of the slope had a surface continuous with the present bench, suggesting that the whole slope experienced pre-failure deformation to a state represented by the bench present on the left of the failed slope. This implies that the parallel ridges on the bench reflect rock deformation during downward motion of the rock mass prior to failure. Fig. 15 shows the slope profile through the bench.

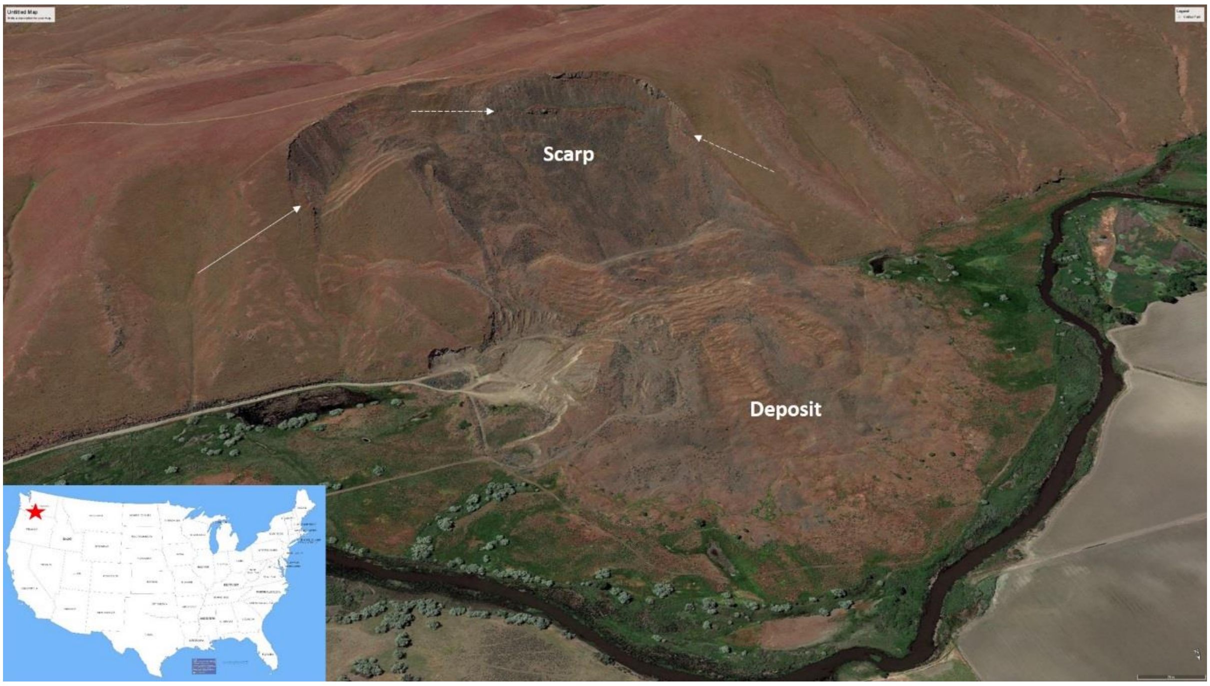

Fig. 14 Toppenish ridge landslide, Washington, USA. Solid arrow indicates slope-top bench with prominent slope-parallel ridges. Dashed arrows indicate lineation in deposit headscarp.

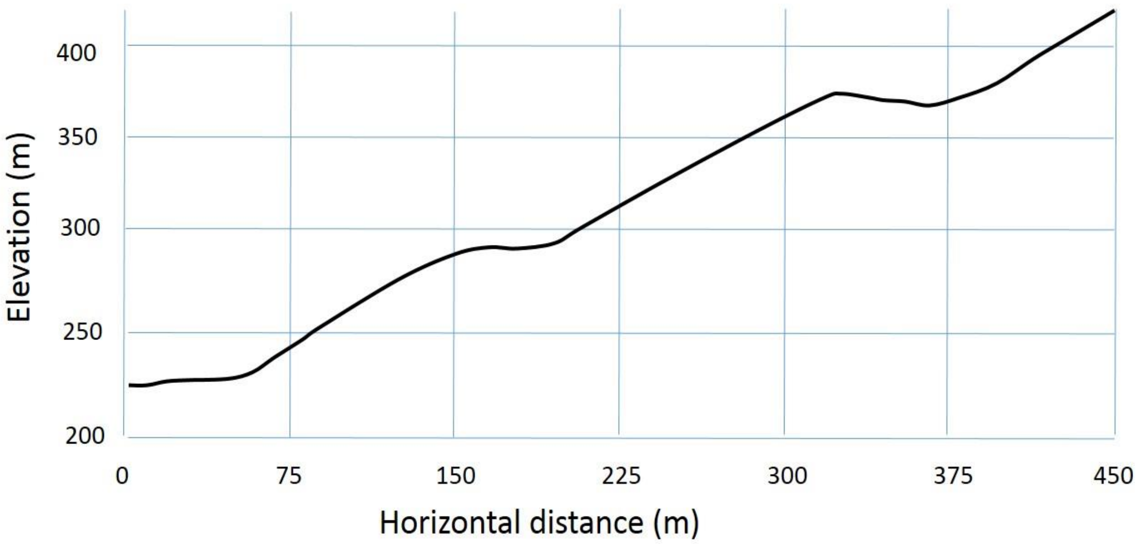

Fig. 15 Profile through bench of Toppenish Ridge landslide.

The significance of this landslide is the clear association of the slope bench and longitudinal ridges with the complete failure of the adjacent part of the slope. The cause of the failure is unknown, but the region is seismic.

2.6 Shimizu landslide

Typhoon Talas in 2011 caused number of large landslides in Japan (Chigira et al., 2013). Ten of these occurred on slopes that had slope-top benches prior to the event; in addition, one of these, the Shimizu landslide, had prominent parallel ridges on its bench (Fig. 16). The volume of this landslide

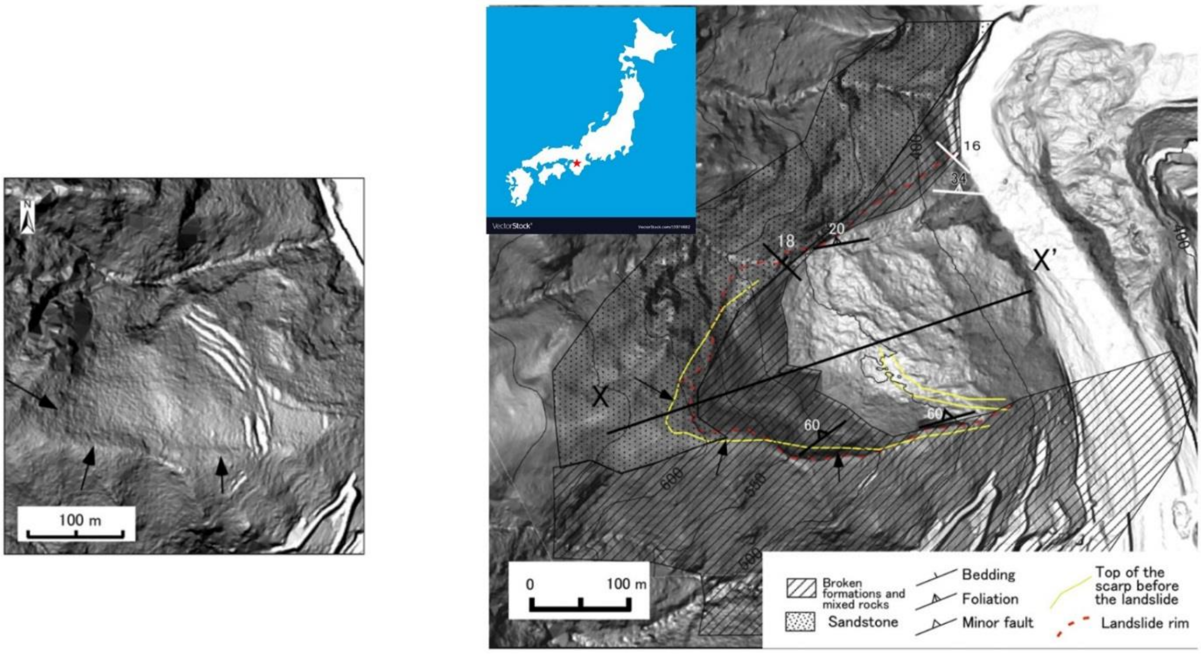

Fig. 16 Shimizu landslide, Japan. Lidar images before (left) and after (right) rainstorm-triggered failure (Chigira et al., 2013)

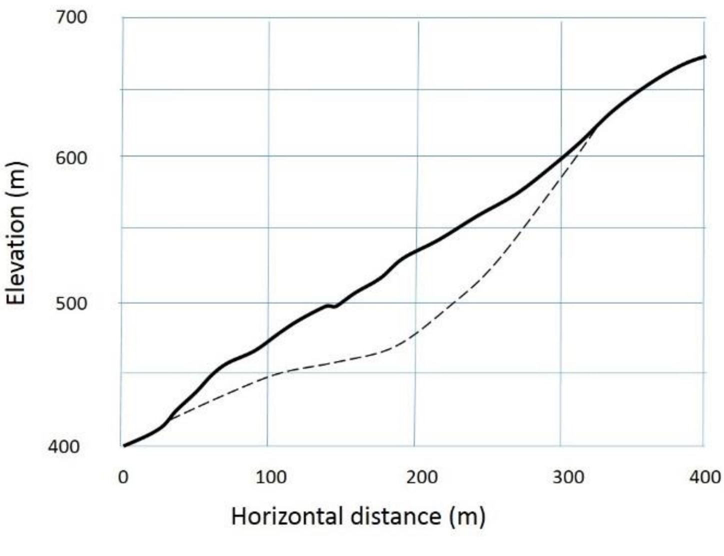

Fig. 16 Shimizu slope profile prior to (solid line) and after (dashed line) failure

was about 10^6 m^3 of sandstone and mudstone; the deposit temporarily blocked the river at the slope toe before it was overtopped and eroded away. This is the only failure considered herein that is unequivocally known to be caused by intense rain.

3. Implications

The examples 2.2-2.5 above show that presence of slope-top bench, double ridges and slope parallel depressions can often be associated with large landslides with the potential for catastrophic failures involving millions of cubic metres of debris. Slope-top benches in general may also be caused by e.g. glacial or fluvial erosion in the distant past, but the collapse of the immediately adjacent slope (2.2, 2.3) or of the slope itself (2.5), unequivocally associates these examples with slope collapse following earlier slow deformation of the slope or co-seismic displacements as in the case of the "bench" at Roche Pass.

Therefore the presence of a slope-top bench with slope-parallel ridges on the Franz Josef slope (2.1) implies that it too *may* have the potential for large-scale failure, triggered by either earthquake or rainfall. It should be noted also that since 1991 six large-scale slope failures have occurred in the Southern Alps, which were not triggered by earthquake or rainfall, so a similar failure of the Franz Josef slope with neither earthquake nor heavy rain cannot be ruled out.

If a potential failure surface is sketched on the Franz Josef slope profile (Fig. 17), the long-sectional area of the failure is about 50 000 m^2. If the average width of the failure is say 200 m (assuming a triangular planform with the bench width BC = 400 m as a base; Fig 3) then the failure volume is of the order of 10^7 m^3.

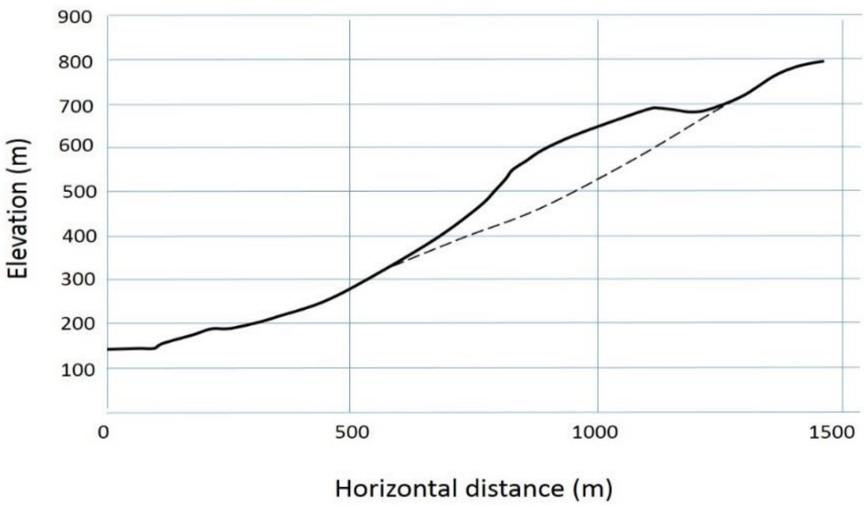

Fig 17 Franz Josef slope profile with possible failure surface (dashed line)

Our objective herein is to point out that the Franz Josef slope has characteristics that *may* indicate its potential for future failure, and to consider the consequences of such a failure. It is also possible that the origin of the slope-top bench, and of the parallel ridges on the bench, do not imply current instability and failure potential of the slope. As we now demonstrate, however, the consequences and risks of a failure of this slope would be extremely serious, therefore it is a matter of urgency that the origin of the Franz Josef hillslope morphology, and its current and future stability, are investigated as soon as possible.

4. Consequences

If a large-scale failure of the slope overlooking Franz Josef were to occur, debris comprising rocks of all sizes from powder up to boulders would slide and flow down the slope achieving velocities of many tens of metres per second and would run out across, and deposit on, the township. The forest and bush on the terrace at the base of the slope would not significantly retard the rock avalanche motion. The simple empirical relationship of Davies (1982):

$$L^* = 10(V)^{1/3}$$

where L* is the end-to-end deposit length in m and V the volume in m^3, correctly estimates the deposit extents of the Cascade, Round Top and Toppenish Ridge landslides. It suggests that if the Franz Josef debris volume were 10^7 m^3 the debris deposit would be of the order of 2000 m long – thus extending well beyond the township. Buildings would be destroyed and many lives lost; the chances of survival in the runout zone, even if in a building, would be negligible. If the volume is only 10^6 m^3 the runout is ~ 1 km, still sufficient to devastate the township.

If such a collapse were to occur at night during the tourist season, it is reasonable to assume that at least 1000 tourists (and up to 3000) would be in accommodation in the runout zone, and that a high proportion of them would be killed.

5. Failure Probability

Because there is no evidence that a major landslide has occurred previously from this slope, there are no immediately applicable empirical data to estimate its future probability. Nevertheless, similar events have occurred elsewhere on the western range front of the Southern Alps, at Round Top (4 x 10^7 m^3; ca 930 AD; Dufresne at al., 2008), Wanganui-Wilberg (4 x 10^7 m^3; ca 1300 AD; Chevalier et al., 2010) and Cascade (7 x 10^8 m^3; ca 660 AD; Barth, 2014). These have all occurred since about 660 A.D., giving a range-front probability of about 1 event every 500 years or 2 x 10^{-3} a^{-1}. The length of the range-front is about 400 km; approximately half of this is occupied by valleys so the probability of a major slope failure per susceptible km is about 10^{-5} $a^{-1}km^{-1}$. Given that the hillslope at Franz Josef extends about 1 km along the range-front, the probability of large-scale failure of this specific hillslope is about 10^{-5} a^{-1}.

There has been no failure of this slope in the ca 18 000 years since it became ice-free, so the annual probability of failure – if assumed unchanging with time - is less than 1 in 18 000, or about 5 x 10^{-5}.

However, the morphological characteristics of the Franz Josef hillslope suggest that it is more likely to fail than the many hillslopes that do not exhibit these characteristics, so its failure probability, though unknown, is likely to be greater than 10^{-5} a^{-1}.

6. Risk to life

Assuming, conservatively, that 1000 deaths would be caused by a large-scale failure of the Franz Josef slope, the annual risk-to-life from this event is greater than 1000 x 10^{-5} = 10^{-2} a^{-1}. Fig. 18 indicates that for 1000 deaths due to an industrial accident the upper limit of acceptable probability is about 10^{-5} a^{-1}; we suggest that the same should apply to a specific landslide which has been identified as possible. On this basis the risk to life at Franz Josef is at least three orders of magnitude higher than acceptable.

7. Risk management

At the current state of knowledge and technology, there is no way of either predicting the occurrence, or modifying the behaviour, of a coseismic landslide. Thus the only realistic strategy for reducing the coseismic landslide risk at Franz Josef to an acceptable level is to reduce the number of people in the risk-to-life area by a factor of at least 1000, which effectively means relocation of the township beyond the reach of the event.

If it turns out that rainfall is the most important trigger for landsliding then other strategies (e.g. drainage) may become feasible.

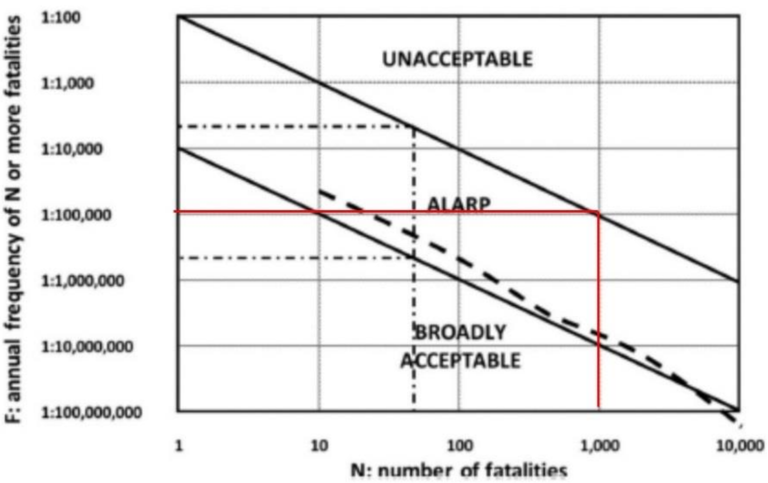

Fig 18 Risk acceptability of multiple deaths due to industrial accidents (Hungr et al., 2016)

8. Status of this report

The preceding risk calculations are based on the presumption that the morphological characteristics of the Franz Josef hillslope indicate large gravitational slope deformations increasing its sensitivity to co-seismic failure. While this appears to be a possibility, it is also possible that the slope characteristics have arisen due to a geological process or slope deformation mechanism that does not lead to large-scale catastrophic failure of the slope. Whether or not this slope can fail catastrophically can only be determined by knowledge of the internal geological structure and activity of the slope. *In particular, if the slope has the potential to develop sliding along steeply dipping sliding planes (as indicated for the Cascade landslide in Fig. 9) then the situation is critical and calls for urgent mitigation measures.* The purpose of the present study is to point out the potential risk and to recommend investigations to resolve these fundamental questions.

9. Conclusion and recommendations

9.1 The morphological characteristics of the Franz Josef hillslope suggest that at some time in the future it may fail as a large-scale rock avalanche. Substantial loss of life would be unavoidable if Franz Josef township were in the runout zone of such an event.

9.2 Preliminary estimates of event probability and loss of life indicate that if a catastrophic slope failure is possible, the risk to life exceeds internationally-acceptable levels by more than three orders of magnitude.

9.3 Reducing the risk of an earthquake-triggered landslide by predicting or modifying the hazard is not feasible; thus the only feasible risk reduction strategy for such an event is to reduce the exposure of people to the event, by relocation of the township outside the impact area. If it turns out that heavy rain is the most important trigger for failure, then drainage of the slope using a gallery may be a feasible hazard and risk management strategy.

9.4 The possibility or otherwise of failure of the Franz Josef slope can be assessed if further data are acquired on

(a) Rock slope structure and possible previous gravitational slope deformations compatible with the observed slope morphology
(b) The current activity of slope movements (if any) and temporal relationships with environmental factors (temperature, precipitation, earthquake shaking)
(c) the influence of rainfall (pore pressure) and earthquakes on slope stability and the potential for catastrophic failure
(d) the relationship between failure volume (which determines deposit extent) and failure probability

9.5 Acquisition of these data will require field work and borehole drilling/monitoring to develop a detailed geological and kinematic model of the hillslope and an investigation of causative factors. In the case of a hazardous geological situation, these data can then be used as inputs to numerical simulations of slope behaviour in response to a range of intensities of both seismic and rainfall trigger events; and to no trigger at all. The value of a drainage gallery could also be studied.

9.6 This investigation will require significant resource, but is feasible, and is justified by the potential risk to life if a slope failure is indeed possible.

10. Acknowledgements

We are grateful to Danilo Moretti, Opus International Consultants, Wellington, New Zealand for use of data acquired during a research study of the Franz Josef hillslope. TD's contribution to this work was supported by the New Zealand National Science Challenge "Resilience to Nature's Challenges" under contract no GNS-RNC011.

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