

Committee Members

Chair: Cr Chris Coll
Cr Allan Birchfield
Cr Andy Campbell
Cr Ashley Cassin

Cr Peter Ewen
Cr Mark McIntyre
Cr Colin Smith

Iwi Representatives

Representative Te Rūnanga o
Ngāti Waewae
Representative Te Rūnanga o
Makaawhio



WEST COAST
REGIONAL COUNCIL

PUBLIC COPY

West Coast Regional Council

AGENDA

Environmental Management Committee Meeting

Date: Tuesday 2 December 2025

Time: Following the completion of the Council Meeting.

Venue: West Coast Regional Council Chambers,
388 Main South Road, Greymouth

This meeting will also be live streamed via West Coast Regional Council's YouTube Channel: @westcoastregionalcouncil5171

Order of business

1.	Welcome (<i>Haere mai</i>)	
2.	Apologies (<i>Ngā Pa Pouri</i>)	
3.	Declarations of Interest	
4.	Public Forum, Petitions and Deputations (<i>He Huīnga tuku kōrero</i>)	
5.	Confirmation of Minutes (<i>Whakau kōrero</i>)	1
5.1	Environmental Management Committee Meeting Minutes – 13 November 2025	2
6.	Actions List	8
6.1	Actions List Public Items – Update	9
7.	Chairs Report (verbal update)	
8.	Reports	
8.1	Regional Landslide Model Report	10
8.1.1	Regional landslide-debris-inundation analysis for West Coast Emergency Management. GNS Science consultancy Report 2025/28	18
8.2	West Coast Regional Council – Hydrology Telemetry Improvement Project	183
8.3	Options Assessment Report: Re-installation of Sofar Spotter Wave Buoy – Westport Coast	187
8.4	October Flood Reports	195
8.4.1	Hydro Event Report 10–12 October 2025	199
8.4.2	Hydro Event Report 20–25 October 2025	228
8.5	West Coast Region Waterway Health and Quality State Report	283
8.5.1	WCRC State of the Environment Monitoring Waterway Health and Quality State Report	288
8.6	Planning and TTPP Report	342
8.6.1	Te Uru Kahika submission on Fast-Track Approvals Amendment Bill	346

8.7 Proposed Policy on Dangerous Dams, Earthquake-Prone Dams and Flood-Prone Dams 2025 – Hearing and Deliberations.....	355
8.7.1 Proposed Policy on dangerous dams, earthquake-prone dams and flood-prone dams 2025.....	359
8.7.2 Public Submissions.....	367
8.7.3 Staff analysis of submissions.....	370

9. General Business

There are no Public Excluded items on this agenda.

D. Lew
Chief Executive

Purpose of Local Government

The reports contained in this agenda address the requirements of the Local Government Act 2002 in relation to decision making. Unless otherwise stated, the recommended option promotes the social, economic, environmental, and cultural well-being of communities in the present and for the future.

Health and Safety Emergency Procedure

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5 Minutes of Environmental Management Committee Meeting 13 November 2025

Author Meryl Wilde, Governance Support Officer

Public Excluded No

Report Purpose

The purpose of this report is to receive the minutes of the Environmental Management Committee meeting of 13 November 2025.

Recommendation

It is recommended that the Committee resolves to:

- 1. Confirm that the minutes of the Environmental Management Committee meeting held on 13 November 2025 are a true and correct record.*

Attachments

Attachment 1: Minutes of the Environmental Management Committee meeting held on 13 November 2025.

WEST COAST REGIONAL COUNCIL

MINUTES OF THE ENVIRONMENTAL MANAGEMENT COMMITTEE MEETING HELD ON THURSDAY 13 NOVEMBER 2025 AT THE OFFICES OF THE WEST COAST REGIONAL COUNCIL, 388 MAIN SOUTH ROAD, GREYMOUTH, COMMENCING AT 10AM.

- PRESENT:**
- C. Coll (Chair)
 - A. Birchfield
 - A. Campbell
 - A. Cassin
 - C. Smith
 - P. Ewen
 - M. McIntyre
 - J. Douglas (Te Rūnanga o Makaawhio)
- IN ATTENDANCE:**
- D. Lew (Chief Executive)
 - S. Morgan (Group Manager Environmental Science)
 - M. Smith (Acting Group Manager Regulatory and Policy)
 - J. Field (Group Manager Office of the CE)
 - M. Beagle (Group Manager Catchment Management)
 - C. Weeks (Group Manager Corporate Services)
 - T. Wyndham-Smith (Principal Communications and Engagement Advisor)
 - C. Cameron (Principal Natural Hazards Analyst – via Zoom)
 - S. Gibson (Team Lead Catchment Co-Ordination)
 - D. Thompson (Principal Governance Advisor – via Zoom)
 - M. Wilde (Governance Support Officer)
 - R. Barrow (Executive Assistant)

1. Welcome

The Chair welcomed those attending and started the meeting.

2. Apologies

There were no apologies.

3. Declarations of Interest

The Chair called for declarations of interest. There were none.

4. Public Forum, Petitions and Deputations

No public forums or deputations.

5. Actions List

The actions list was reviewed, and the following updates were noted.

- Item 1 (ACT0004) – Ongoing.
- Item 2 (ACT0008) – Ongoing.
- Item 3 (ACT0046) – Ongoing. M Smith to reach out to P. Phelps from Minerals West Coast to arrange a working group of miners and consultants to work through consent concerns.

Moved (McIntyre / Smith) *that the Committee:*

1. *Note the actions outstanding from the previous triennium that are ongoing and remain relevant.*
2. *Receive the actions list and the information noted.*

Carried

6. Chairs Report (verbal update)

Chair Coll highlighted the approaching summer recreation period and the importance of boat owners and other lake users to do their part in protecting lake ecosystems by cleaning their boats and equipment between use.

The Chair also noted the information available from Land Air Water Aotearoa (LAWA) which provides the public with details on water quality in popular swimming areas on the West Coast.

Moved (Cassin / Douglas) *that the Committee receives the Chair's report.*

Carried

7. Reports

7.1 Quarter One Biosecurity Report

S. Morgan presented the report, noting:

- All 50 KPIs are currently on track (green status).
- The Clean Check Dry advocacy programme will be implemented over summer.
- Significant findings of woolly nightshade in the Buller region, which has economic impacts on farming and livestock.

- Successful control of parrot's feather in some Karamaea waterways, which can cause flooding when left unchecked.
- Ongoing work to contain Japanese knotweed, which is spreading across the coast.

D. Lew highlighted that biosecurity work originated to protect primary agriculture but has broadened to include ecological and environmental threats. He noted that a full review of the Regional Pest Management Plan is upcoming, which will require engagement with the primary sector.

Discussion occurred regarding the potential inclusion of animal pest control in the plan, with the Committee agreeing on the importance of the work but expressing concern about ratepayers funding control of pest animals coming from conservation land.

Moved (McIntyre / Ewen) *that the Committee:*

1. *Receive the report.*
2. *Notes the progress on the annual Biosecurity operational plan.*

Carried

7.2 Catchment Coordination Program Quarterly Report

S. Morgan presented the report with support from S. Gibson, noting:

- The programme employs five staff who support landowners and industry with environmental management through a non-regulatory approach.
- The programme is funded by the Ministry for the Environment, but funding will expire in March 2026.
- The team has engaged with over 500 ratepayers in the last quarter.
- Successful initiatives include Rural Women's Resilience Road Shows and planting programmes in areas with poor water quality.

D. Lew noted that continuing this programme would require ratepayer funding, which will be discussed during Annual Plan deliberations. He emphasised the value of having staff who can advise and collaborate with communities rather than relying solely on compliance measures.

S. Gibson mentioned potential future funding for catchment collectives from June next year, which could provide an opportunity for continued support.

Moved (Ewen / McIntyre) *that the Committee:*

1. *Receive the report.*

2. *Notes the progress and growing regional impact of the Catchment Coordination Programme.*

Carried

7.3 Quarterly Natural Hazards Update

S. Morgan provided an update on natural hazards work, including:

- Meeting LGOIMA regulations around provision of natural hazard information.
- Improving accessibility of information through website summaries and GIS portals.
- Development of a Regional Landslide Hazard Model, which will be presented to the committee on 2 December 2025.

It was noted that landslide risk on the West Coast is higher than most regions in New Zealand.

D. Lew emphasised the importance of providing plain English interpretations of hazard information to help property buyers make informed decisions, particularly following recent flooding events in other parts of New Zealand.

Moved (Cassin / McIntyre) *that the Committee:*

1. *Receive the report.*
2. *Note the Government release of a National Adaptation Framework and its potential implications to Council.*

Carried

[11.01am – Cr Smith left the room]

11.03am – Cr Smith returned to the room]

7.4 Consents Quarterly Report

M. Smith presented the Consents Quarterly Report.

Committee members expressed concern about delays in processing mining consents.

D. Lew clarified that while the Council has a good record of meeting statutory timeframes (which exclude time when applications are on hold), applicants often measure the total elapsed time from submission to approval. He noted that staff are working to clean up a backlog of applications.

Moved (Douglas / McIntyre) *that the Committee:*

1. *Receive the report.*

Carried

7.5 Compliance Monitoring Quarterly Report

M. Smith presented the Report noting:

- 94 site visits were undertaken during the period.
- 28 complaints were received.
- 6 bonds were received for mining activities.

Committee members queried some of the details around compliance issues, M. Smith offered to provide further information on these queries to Councillors.

Moved (Ewen / Campbell) *that the Committee:*

1. *Receive the 1 July 2025 to 30 September 2025 report of the Compliance Group.*

Carried

7.6 Planning and TTPP Report

M. Smith presented the report, noting:

- The government is drafting bills that will require a combined regional plan for each region. The TTPP will cover most of the required framework, putting the West Coast in a good position compared to other regions.
- The bills are expected to be released in late November 2025.
- The TTPP decision version was notified in October 2025 with appeals closing on 21 November 2025 (though a two-week extension has been requested by Federated Farmers). Mediation on appeals is likely to occur in March-April 2026.

The Draft Dangerous Dams Policy was presented, with two submissions received, one of which will be heard in December 2025.

Moved (McIntyre / Douglas) *that the Committee:*

1. *Receive the report.*

Carried

8. General Business

Discussion occurred regarding the government's consideration of establishing a national compliance and enforcement regulator that would take over RMA compliance functions from Regional Councils.

D. Lew expressed concern about this proposal, noting that many Councillors and the former Chair were opposed to a centralised model that might not understand local situations. He indicated that the regional sector is generally preparing to oppose this initiative when the new acts are released for submission in December 2025.

There being no further business, the meeting concluded at 11.46am.

.....
Chair

.....
Date

6 Actions List**Author** Meryl Wilde, Governance Support Officer**Public Excluded** No

Report Purpose

This report is a summary of items that require actions.

The responsible managers have updated the list and will address their respective action items.

Recommendation

It is recommended that the Committee resolves to:

- 1. Receive the actions list and the information noted.*

Attachments

Attachment 1: Actions List Public – Updated

ACTIONS LIST – Public

Item No.	Reference	Date of Meeting	Item	Officer	Update
1.	ACT0004	10 Sep 24	To determine the timelines for the review and update of the Flood Protection Bylaw	Group Manager – Regulatory and Policy	Ongoing. Set back calculations to be supplied by river engineering. Meeting set down for December 2025.
2.	ACT0008	9 Apr 24	To investigate the delegation and/or deeds with WDC regarding the mining operations and noise issues/consents and update the Councillors.	Group Manager – Regulatory and Policy	Ongoing. Staff have followed up with WDC and this is sitting with WDC and is out of our control. Suggest removing this action point.
3.	ACT0046	6 May 25	Staff to contact P. Phelps from Minerals West Coast to arrange a workshop with interested parties and the consents/compliance team to collaborate on an agreed set of conditions for processing of alluvial gold mine consents.	Group Manager – Regulatory and Policy	Ongoing. Patrick has been contacted and options for socialisation being discussed

REPORTS

8.1

Regional Landslide Model Report

Author

Dr Sharon Hornblow, Senior Natural Hazards Analyst

Authoriser

Shanti Morgan, Group Manager Environmental Science

Public Excluded

No

Report Purpose

The purpose of this report is to inform the Environmental Management Committee of the region-wide landslide debris inundation model data and report received last month, and outline how this will enhance planning and emergency management decision-making.

This work was commissioned by West Coast Emergency Management (WCEM) to inform lifelines decision-making and provide a basis from which to create a future land instability or landslide inundation risk-based overlay for the Te Tai o Poutini Plan.

Report Summary

The new regional Landslide Debris Inundation (LDI) Report provides a comprehensive, quantitative assessment of landslide hazards and property risks across the West Coast, covering both earthquake- and rainfall-induced events. It represents a major step forward in quantifying and spatially resolving LDI risk across the West Coast, providing critical data to enhance both emergency response and long-term land-use planning decisions.

The report introduces geomorphic modelling methods which efficiently estimate Annual Property Loss Risk (APLR) and debris flux over time for any given area, at a regional scale. The model incorporates multiple climate change, rainfall, and earthquake scenarios, enabling assessment of future hazard variability. The report also highlights key uncertainties, particularly the trade-off between achieving consistent, region-wide coverage, with the resource and expense required to model at high resolution, such as on the regional Light Detection and Ranging digital elevation model (LiDAR DEM). The work was externally peer-reviewed by leading landslide specialists at Manaaki Whenua (Landcare Research) who found that the methodology underlying the model were sound and well-executed and commended the work overall, which brings the latest in landslide modelling research to a region where no previous comprehensive model has been done and existing landslide mapping data were limited.

Recommendations in the report and discussion between staff and landslide experts at Earth Sciences New Zealand (ESNZ) resulted in the development of an internal work programme for making the data and findings accessible to the public and Territorial Authority (TA) partners, including for capturing on LIMs. Options and costs are also being outlined for a recommended next stage of ensuring the model outputs have the lowest possible uncertainty by running the model on the regional LiDAR DEM, and at higher resolution where APLR is greatest and/or population growth is likely (e.g., Greymouth hillside areas, coastal Buller). There is a chapter of the report detailing the recommended use of results and process to applying the datasets for planning purposes, such as via a Plan Change to the TTPP, which Natural Hazards staff support.

Recommendation

It is recommended that the Committee resolve to:

- 1. Receive the report.*
- 2. Note the Regional landslide-debris-inundation analysis report (attachment one).*
- 3. Endorse using the new Regional LiDAR data to update and improve the landslide hazard mapping for the West Coast.*
- 4. Support staff working with Te Tai o Poutini Plan staff and the territorial authorities to use the updated hazard information in planning and climate adaptation work.*

Issues and Discussion

Background

The West Coast region faces significant exposure to landslide debris inundation, primarily near steep slopes, within channels and gullies, and on debris fans where rates of sediment and debris production are rapid. Although rainfall-induced landslides dominate the hazardscape along range-front areas, earthquake-induced landslides are the main contributor to risk northeast of Greymouth. Critically, the regional risk is highly concentrated: 95% of the total APLR is attributed to approximately 2% of existing residential buildings in the region. Furthermore, under the RCP 6 climate-change scenario in the coming century this is expected to increase by at least 50%. Existing structures are chiefly exposed to highly mobile and destructive debris-flow processes, due to their greater runout reach, compared to less mobile landslides.

This report significantly progresses understanding of the hazard posed by landslides on the West Coast through employing a novel “process-based” methodology for regional LDI hazard assessment, which moves beyond previous conventional modelling. Traditional approaches rely on defining a finite number of hypothetical,

discrete landslide sources and simulating their runout paths. This method, in contrast, calculates hazard by modelling the continuous production of landslide debris through time and simulating the movement of this debris as a "flux" (volume per unit area per year) through the landscape.

This quantitative process-based approach is fundamentally linked to long-term geomorphological processes, such as the rate of tectonic uplift and erosion, ensuring that the modelled volume and probability of inundation by debris is constrained by the likely rates of sediment generation across the landscape. A significant technical advantage of this method is the ability to simulate runout from all potential source locations across wide areas, including those sources nominally smaller than the modelled grid resolution, resulting in a spatially comprehensive assessment. The spatial data outputs delivered with the report include three key metrics: landslide-debris flux, the probability of inundation, and APLR, which collectively provide detailed insight into the frequency and magnitude of potential debris impact.

The data provided can substantially improve emergency management and response outcomes, especially concerning event-specific planning, e.g., AF8 preparedness exercises. Scenario-specific outputs for landslide-debris flux quantify the volume of material expected to move across the landscape in response to defined triggers, such as various annual return interval (ARI) rainfall totals or an Alpine Fault earthquake event. This information is valuable for estimating the probable debris volumes that could obstruct highways, damage infrastructure, or enter river networks, allowing WCEM to use the outputs to inform future response and recovery plans for major events and cascading hazards.

For land-use planning, the results lay groundwork for incorporating LDI risk into future planning processes, such as the Te Tai o Poutini Plan (One Plan). While the outputs are primarily suitable for region-wide risk screening and planning purposes due to uncertainties, (Level A-B, suitable for screening and risk mapping under *Landslide Planning Guidance*¹) they effectively identify high-risk areas where further constraint may be necessary. Suggestions for how Plan rules can use the data to follow a risk-based approach to reducing property damage and life risk from landslide hazards in a West Coast context are given in the final report chapter, along with recommendations for further work to refine the model for these purposes.

DeVilder SJ, Kelly SD, Buxton RB, Allan S, Glassey PJ. 2024. Landslide planning guidance: reducing landslide risk through land-use planning. Lower Hutt (NZ): GNS Science. 77 p.

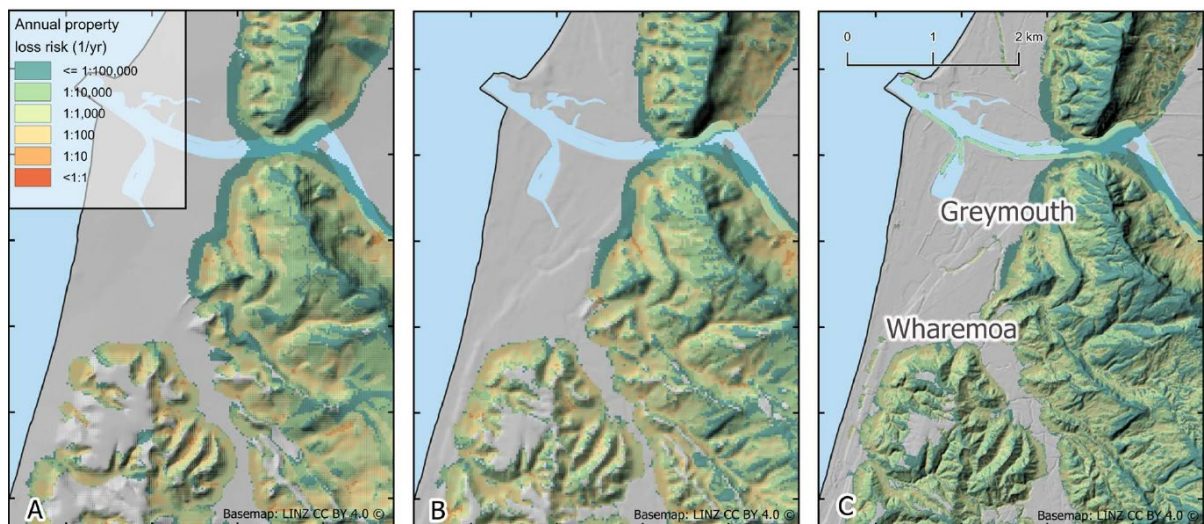


Figure 1. Comparison of annual property loss risk in the Greymouth region calculated on (a) the 25 m regional digital elevation model (DEM) employed in Leith et al. (2025), (b) the 2020–2024 LiDAR-derived DEM down-sampled to 25 m resolution and (c) the 2020–2024 LiDAR-derived DEM down-sampled to 8 m resolution.

Next steps

Model on Regional LiDAR

As recommended within the technical report council staff are planning to rerun the existing landslide model using the new Regional LiDAR Digital Elevation Model (DEM) at 25 m resolution. This will give a more accurate picture of landslide source areas and inundation extents across the region.

In higher-risk and urban areas (e.g. Greymouth), the model will then be refined to 8 m resolution. This is expected to show that fewer properties are exposed to landslide risk than the current, coarser modelling suggests.

These refinements will:

- Reduce the number of properties captured in hazard layers overall.
- Reduce uncertainty and improve confidence in the hazard mapping.
- Increase the usefulness of the outputs for land-use planning and emergency management.

Using the new LiDAR DEM would reduce APLR uncertainty from ± 1.25 orders of magnitude to about ± 0.75 at 25 m resolution, and to less than ± 0.75 at 8 m resolution. This improvement is sufficient for higher-level planning under the national Landslide Planning Guidance (Levels B–C), supporting more proactive risk management and reducing the likelihood of poorly informed planning decisions and future liability.

Engagement and Te Tai o Poutini Plan

WCRC will first work with TA staff to ensure the updated dataset is:

- Clearly reflected on LIM reports, and
- Available online in easily understood map formats.

The data is also being provided to TTPP staff. This may lead to a plan change so the new information is built into natural hazard overlays and a risk-based approach to landslide hazards is consistently applied across the West Coast.

Natural Hazards and Planning staff will work together, and with TAs, on any agreed plan change. This will include:

- Setting appropriate risk-tolerance thresholds
- Agreeing suitable confidence levels based on the type and criticality of activities (e.g. different building types)

There is an option to contract ESNZ in 2026/27 to support this work, which would be provided for in the 2026/27 Annual Plan.

This engagement is particularly important for climate adaptation planning. The study indicates that average annual probability of landslide risk (APLR) for rainfall-induced landslides is projected to increase by at least 50% for existing residential buildings under the RCP6 2081–2100 climate scenario.

Considerations**Implications/Risks****1. Technical and Data Limitations**

- **Risk of misinterpretation or inappropriate use**

The LDI outputs are most appropriate for regional-scale screening and strategic planning (Level A–B under the Landslide Planning Guidance). There is a risk that users (internal or external) might treat the data as site-specific or definitive, leading to over-reliance on the maps without further investigation, or inappropriate expectations of accuracy for consenting or detailed design. Clear communication via the natural hazards data portal, and community and TA engagement are planned to mitigate this risk.

- **Need for ongoing updates and maintenance**

New LiDAR and climate data are examples of ongoing inputs which could date the current model outputs. Decisions made on outdated information could undermine confidence in Council's hazard information and potentially increase long-term liability.

To mitigate this, Council staff have a plan in place to work the new regional LiDAR into the model to ensure data are using best available DEMs. Periodic review of the model using the latest climate and rainfall datasets will be incorporated into future Long-term Plan project timelines.

2. Planning and Regulatory Implications

- **Increased pressure for plan changes and overlays**

The LDI report provides a clear evidence base for risk-based plan provisions in the Te Tai o Poutini Plan. There is a risk that, if Council does not act on this information in a timely way, it may be criticised for failing to give effect to its natural hazard management responsibilities and for allowing further development in high-risk areas.

Natural Hazards staff are recommending the new data are used as the basis for a natural hazards landslide overlay-based Plan Change, once the decisions version of the Plan is adopted in the next 18 months, and are working with TTPP staff and TAs to socialise the data with communities in preparation for this.

3. Property, Community, and Socio-Economic Implications

- **Impact on property values and insurability**

Identifying high LDI risk areas and including them on LIMs and planning maps may affect property values, insurability, and mortgage availability for some landowners. This could lead to heightened concern, complaints, or political pressure on Council, especially in communities where a small number of properties carry a large share of the regional risk.

Given the regulations which require Council to share natural hazard information with landowners and the public as requested, Council staff are working to ensure the full dataset and plain-language summaries are available so that homeowners can make informed decisions.

4. Organisational, Financial, and Resourcing Risks

- **Cross-agency coordination risk**

Effective use of the data relies on close coordination between WCRC, WCEM, Territorial Authorities, and lifeline utilities. If roles and responsibilities are unclear, or engagement is limited, the region may not fully realise the benefits of the modelling and may miss opportunities to integrate LDI risk into infrastructure and land-use decisions.

5. Reputational Risks

- **Risk of inconsistent messaging**

If different parts of Council, or Council and TAs, communicate differently about the meaning and use of the LDI data, this may create confusion and undermine confidence in the hazard information. This inconsistency could be particularly problematic during and after major events, when clear, concise messaging is critical.

Council staff are working to ensure the full dataset and plain-language summaries are available in an accessible format online, and via in-person workshops and roadshows attended by Council staff around the Region.

6. Emergency Management Implications

- **Improved planning with higher expectations**

The availability of scenario-specific LDI outputs for major rainfall events and Alpine Fault scenarios will significantly enhance WCEM's ability to plan for debris impacts on lifelines and communities. However, this also raises expectations that evacuation planning, response priorities, and recovery planning will be updated promptly. Natural Hazards staff are working with Emergency Management staff to ensure they are aware of the new data and confident in its potential uses, so it may be incorporated into lifelines and community emergency planning in a reasonable timeframe.

- **Cascading hazard and residual risk**

While the model improves understanding of debris inundation, it cannot remove the hazard. There remains a residual risk that extreme or compounding events exceed modelled scenarios. Over-confidence in the modelling could result in under-preparation for rare but high-consequence events. The recommended next step of modelling, using the LiDAR DEM, will increase the confidence in the data and that the modelled scenarios are reasonably representative of credible scenarios.

Significance and Engagement Policy Assessment

There are no issues within this report which trigger matters in this policy.

Tangata whenua views

While the study does not specifically detail an analysis of risks to unique tangata whenua assets or cultural sites, the main impact of the analysis will be in integrating the data into planning and emergency management processes, which will affect all communities on the West Coast.

Financial implications

This work was completed within provisioned budget. It is highly likely that the recommended next stage of work, such as the LiDAR re-run of the model, could be completed within the Natural Hazards budget for 2025–26 year.

Legal implications

The LDI report directly supports the West Coast Regional Council's obligations under the RMA by providing a scientifically robust basis for identifying, assessing, and managing natural hazard risks across the region. The model's outputs enable the Council to meet its duties under sections 30 and 31, which require the control of land use to avoid or mitigate natural hazards, and to inform regional policy and plan development—particularly through the Te Tai o Poutini Plan.

Having robust regional LDI information increases expectations that Council will use it to inform planning, consenting, and emergency management. If this information is not adequately incorporated into decision-making, or if it is withheld from LIMs or public access, there is a risk of legal challenge and reputational damage following future events.

This report summarises natural hazard information which must be disclosed to the relevant territorial authorities under section 44C of the RMA regarding Regional Councils' responsibilities around the provision of Natural Hazard Information.

Local Government (Natural Hazard Information in Land Information Memoranda) Regulations 2025 clarify what natural hazard information must be provided by Regional Councils to the Territorial Authority – this report and the associated datasets will be shared with the TAs.

Attachments

Attachment 1: Regional landslide–debris–inundation analysis for West Coast Emergency Management. GNS Science consultancy Report 2025/28 (Leith et al., 2025)



Regional landslide-debris-inundation analysis for West Coast Emergency Management

KJ Leith
CI Massey

SJ de Vilder
B Lukovic

**GNS Science Consultancy Report 2025/28
October 2025**

DISCLAIMER

This report has been prepared by the New Zealand Institute for Earth Science Limited (Earth Sciences New Zealand) exclusively for West Coast Regional Council for and on behalf of West Coast Emergency Management Group (formerly known as West Coast Civil Defence & Emergency Management Group). It is based on available information and professional judgment at the time of preparation, and is subject to any limitations or assumptions set out in the report. Unless otherwise agreed in writing by Earth Sciences New Zealand, Earth Sciences New Zealand provides no warranty as to the use of the report other than by West Coast Emergency Management for the Purpose and Earth Sciences New Zealand will not be liable for any loss, damage or expense (whether direct, indirect or consequential) arising from use of or reliance on this report or its contents by any person other than to West Coast Emergency Management.

Use of Data:

Date that Earth Sciences New Zealand can use associated data:
October 2025

BIBLIOGRAPHIC REFERENCE

Leith KJ, de Vilder SJ, Massey CI, Lukovic B. 2025. Regional landslide-debris-inundation analysis for West Coast Emergency Management. Lower Hutt (NZ): Earth Sciences New Zealand. 152 p. GNS Science Consultancy Report 2025/28. Prepared for West Coast Emergency Management.

CONTENTS

Executive Summary	viii
1.0 Introduction.....	1
1.1 Methodology Overview	1
1.2 Report Structure	4
1.3 Personnel	5
1.4 Landslide Hazards	5
1.4.1 Terminology	5
1.4.2 Landslide Types Assessed and Associated Definitions	6
2.0 Landslide-Debris-Inundation Modelling.....	10
2.1 Landslide Source to Inundation Process Model Overview	10
2.1.1 Consideration of Hazard and Risk	12
2.1.2 Quantification of Regional Landslide-Debris-Inundation Hazards	12
2.1.3 Derivation of Debris-Inundation Probability and Annual Property Loss Risk	14
2.1.4 Climate-Change Scenarios and Event-Specific Hazard Assessment	15
2.1.5 Quantification of Results and Uncertainties	16
2.2 Landslide Source-Susceptibility Model	17
2.2.1 Overview.....	17
2.2.2 Results and Uncertainties	17
2.3 Landslide Sediment-Production Model	19
2.3.1 Overview.....	19
2.4 Landslide Sediment-Distribution Model	28
2.4.1 Overview.....	28
2.4.2 Results and Uncertainties	29
2.5 Landslide Debris-Inundation-Risk Model.....	31
2.5.1 Overview.....	31
2.5.2 Results and Uncertainties	32
2.6 RCP6 2081–2100 Climate-Change Scenario	34
2.7 Field Reconnaissance	36
3.0 Discussion.....	38
3.1 Consistency with Actual Experience	38
3.1.1 Alpine Fault Scenario Impacts	38
3.1.2 Rainfall-Induced Landslide Damage	38
3.1.3 Insights into an Alpine Fault Magnitude 8 Scenario	39
3.1.4 Insights into Overall Landslide Debris-Inundation Risk	40
3.2 Landslide Source to Inundation Process Model Sensitivity to Key Uncertainties.....	41
4.0 Project Deliverables	43
4.1 Deliverables for Landslide-Debris Flux	43
4.1.1 Mean Annual Hazard Maps	43
4.1.2 Hazard Maps for Scenarios 1–4.....	44
4.2 Deliverables for Probability of Inundation.....	44
4.2.1 Mean Annual Probability Maps.....	44
4.2.2 Scenario-Specific Maps.....	44

4.3	Deliverables for Annual Property Loss Risk.....	44
4.3.1	Mean Annual Risk Maps.....	44
4.3.2	Scenario-Specific Risk Maps	44
5.0	Applying these Results	45
5.1	Overview.....	45
5.2	Landslide-Debris-Flux Summary.....	47
5.3	Summary of Annual Property Loss Risk	48
5.3.1	Present-Day Climate Conditions.....	48
5.3.2	RCP6 2081–2100 Climate-Change Scenario.....	48
5.3.3	Applying Risk Metrics	49
5.4	Recommended Next Steps	51
5.5	Re-Evaluation of Hazard and Risk and Re-Classification of Sites	53
6.0	Summary and Conclusions	55
7.0	Acknowledgements.....	57
8.0	References	57

FIGURES

Figure 1.1	Overview of the project area.	4
Figure 1.2	Schematic representation of the source and debris-inundation areas (source, transport and deposit zones) of a landslide.....	6
Figure 1.3	Debris flows generated by rain in Eastbourne, Wellington, in November 2006.....	7
Figure 1.4	Debris avalanches on Whataroa Highway generated by the 2019 West Coast storm.....	8
Figure 1.5	Hapuku rock avalanche generated by the 2016 Kaikōura earthquake	9
Figure 2.1	Geomorphological model of a hill-slope system.....	13
Figure 2.2	Selection of landslide source-susceptibility model outputs	18
Figure 2.3	Selection of landslide sediment-production model outputs.....	21
Figure 2.4	Calculated maximum landslide depths based on kinematic models and depth-limiting criteria employed in the kinematic model.....	23
Figure 2.5	Depth to the kinematically feasible failure surface and volume classes used to determine the maximum feasible volumes for the landslide sediment-production model	24
Figure 2.6	Landslide sediment-production frequency-magnitude relationships derived for the vicinity of Kokiraki using the landslide sediment-production model.....	26
Figure 2.7	Present-day mean annual landslide-debris flux in the vicinity of Kokiraki	30
Figure 2.8	Annual probability of landslide-debris inundation in the vicinity of Kokiraki	32
Figure 2.9	Calculated annual property loss risk in the vicinity of Kokiraki.....	33
Figure 2.10	Landslides and debris flows generated by the December 2019 West Coast storm.....	34
Figure 2.11	Selection of landslide source-susceptibility model outputs for the RCP6 2081– 2100 climate scenario	35
Figure 2.12	Present-day mean annual landslide debris flux and RCP6 2081–2100 mean annual debris flux derived from the ensemble of landslide sediment-distribution model results.	36
Figure 2.13	Overview of field data collection during 10–12 August 2023	37
Figure 3.1	Annual property loss risk sampled at residential-building locations throughout the region overseen by West Coast Emergency Management	39
Figure 3.2	Expected annual property loss risk for residential buildings in the region overseen by West Coast Emergency Management.	40

Figure 3.3	Hypothetical annual property loss risk sampled at random locations throughout the region overseen by West Coast Emergency Management.	41
Figure 5.1	Standard normal distribution displaying the relationship between statistical confidence intervals described as standard deviations, cumulative percentage and central coverage probabilities.	46
Figure 5.2	A framework for considering predicted risk and associated uncertainty when planning for existing and new activities	49

TABLES

Table 2.1	Key attributes of volume-class ranges used for the landslide sediment-production, sediment-distribution and debris-inundation-risk models.....	25
Table 5.1	Five levels of susceptibility, hazard and risk analysis, with recommended applications.....	47
Table 5.2	Indicative order-of-magnitude uncertainty thresholds and associated confidence levels that may be applied to determine the utility of Annual Property Loss Risk datasets for a range of planning purpose levels.....	52

APPENDICES

APPENDIX 1	Datasets	67
APPENDIX 2	List of Landslide-Debris-Inundation Model Variables	68
APPENDIX 3	Landslide Source-Susceptibility Model	70
A3.1	Statistical-Modelling Methodology.....	70
A3.1.1	Model Training.....	70
A3.1.2	List of Landslide Source-Susceptibility Model Predictors	71
A3.1.3	Model Standardisation and Bootstrapping	73
A3.1.4	Logistic Lasso Regression.....	74
A3.2	Earthquake-Induced Landslide Forecast Model.....	74
A3.3	Western South Island Rainfall-Induced-Landslide Model.....	76
A3.3.1	Area of Interest Definition	76
A3.3.2	Variable Selection	77
A3.3.3	Model Results	77
A3.4	Calculation of Slope Failure Probability.....	79
A3.5	Landslide Source-Susceptibility Model Adjustment for the RCP6 2081–2100 Climate-Change Scenario.....	79
A3.6	Key Landslide Source-Susceptibility Model Uncertainties and Assumptions	80
APPENDIX 4	Landslide Sediment-Production Model	82
A4.1	Determination of Landslide-Erosion Rates	82
A4.1.1	Determination of Landslide-Sediment Production	82
A4.1.2	Comparison between Adopted Denudation Rates and Global Erosion Datasets	85
A4.1.3	Estimation of Landslide Sediment-Production Rates	86
A4.2	Kinematic Landslide Source Model.....	86
A4.3	Characteristic Landslide-Volume Distributions	88
A4.4	Landslide-Volume Classes	91

A4.5	Mean Annual Landslide-Debris-Production Rates	92
A4.6	Scenario-Specific Landslide-Sediment Production.....	95
A4.7	Landslide Sediment-Production Adjustment for the RCP6 2081–2100 Climate-Change Scenario	96
A4.8	Key Landslide Sediment-Production Model Assumptions and Uncertainties	96
APPENDIX 5	Landslide Sediment-Distribution Model	99
A5.1	Landslide-Source-Material Thickness	99
A5.2	Probability of ‘Avalanche’ versus ‘Flow’ Movement Types	99
A5.3	Landslide-Runout Simulation	100
A5.3.1	Landslide-Runout Modelling	100
A5.3.2	Gravitational Path Process Model	100
A5.4	‘Avalanche’ Movement Types	102
A5.4.1	Empirical ‘Fahrböschung’ (or ‘Energy Line’) Principle	102
A5.4.2	Fahrböschung Data	103
A5.4.3	Gravitational Path Process Avalanche-Type Model Implementation	104
A5.4.4	Model Validation	105
A5.5	‘Flow’ Movement Types	106
A5.5.1	PCM Model Principle	106
A5.5.2	Gravitational Path Process Flow-Type Model Implementation	107
A5.5.3	Model Validation	108
A5.6	Deposition Model.....	108
A5.7	Mean Annual Landslide-Debris Flux.....	109
A5.8	Scenario-Specific Landslide-Sediment Distribution.....	110
A5.9	Key Landslide Sediment-Distribution Model Uncertainties and Assumptions	110
APPENDIX 6	Landslide Debris-Inundation-Risk Model.....	112
A6.1	List of Landslide Debris-Inundation-Risk Model Variables.....	112
A6.2	Landslide Debris-Inundation-Event Frequency and Magnitude.....	112
A6.2.1	Validation of Landslide Debris-Inundation-Event Frequency Model	115
A6.3	Probability of Loss (Vulnerability).....	116
A6.4	Mean Annual Property Loss Risk	118
A6.5	Key Landslide Debris-Inundation-Risk Model Uncertainties and Assumptions	118
APPENDIX 7	Landslide Source to Inundation Process Model Uncertainties and Sensitivity Analysis	120
A7.1	Sensitivity Analysis.....	120
A7.2	Landslide Source-Susceptibility Model Uncertainties	124
A7.3	Landslide Sediment-Production Model Uncertainties	124
A7.4	Landslide Sediment-Distribution Model Uncertainties	125
A7.5	Landslide Debris-Inundation-Risk Model Uncertainties	126
A7.6	Total Uncertainty.....	126
A7.6.1	Parametric Uncertainties Resulting from Model Assumptions and Inputs ..	126
A7.6.2	Spatial Uncertainties Relating to Digital Elevation Model Accuracy and Resolution.....	129
A7.6.3	Combined Parametric and Spatial Uncertainties	131
A7.7	Summary of Uncertainties and Recommendations.....	133
A7.7.1	Parametric Uncertainty.....	133

A7.7.2	Uncertainties due to Digital Elevation Model Inaccuracies	134
A7.7.3	Uncertainties due to Digital Elevation Model and Model Resolution	134
A7.7.4	Present-Day Model Uncertainties	134
A7.7.5	RCP6 2021–2100 Model Uncertainties	134
A7.7.6	Reducing Uncertainties	135
APPENDIX 8	Alignment with Australian Geomechanics Society Landslide Risk Management Guidelines	136
A8.1	Introduction	136
A8.2	Hazard Analysis	136
A8.2.1	Data Gathering / Desk Study	136
A8.2.2	Field Investigation Requirements	136
A8.3	Landslide Characterisation	137
A8.4	Frequency Analysis	138
A8.4.1	Techniques for Frequency Analysis	138
A8.4.2	Estimation of Annual Probability (Frequency) of Each Landslide	139
A8.4.3	Assess the Travel Distance and Probability of Spatial Impact of the Elements at Risk	139
A8.5	Consequence Analysis	140
A8.5.1	Elements at Risk	140
A8.5.2	Temporal Spatial Probability	140
A8.5.3	Evaluation of Consequence to Property	141
A8.5.4	Evaluation of Consequence to Persons	141
A8.6	Risk Estimation	141
A8.6.1	Quantitative Risk Estimation	141
A8.6.2	Semi-Quantitative and Qualitative Risk Estimation for Risk to Property	141
A8.6.3	Risk Matrix for Property Loss	141
A8.6.4	Estimation of Risk of Loss of Life	141
APPENDIX 9	External Review and Responses	142

APPENDIX FIGURES

Figure A4.1	Compilation of various indicators of sediment production and erosion compared against mean rates	84
Figure A4.2	A global compilation of ¹⁰ Be-derived long-term erosion rates compared against the mean gradient in the contributing drainage basin	85
Figure A4.3	Example of the maximum depth surface derived from the kinematic landslide source model ..	88
Figure A4.4	Probability-density distributions derived from the log of calculated landslide volumes from a compilation of 19 mapped landslide catalogues from around the globe, as well as planetary observations	89
Figure A4.5	Landslide frequency-volume plots for all landslide sources in the rainfall- and earthquake-induced landslide datasets employed in this study	91
Figure A4.6	Comparison of combined annual landslide-debris-flux outputs from preliminary landslide sediment-distribution model runs incorporating 33% and full decadal class intervals	92
Figure A4.7	Calculated maximum landslide depths based on kinematic models and maximum volume-class ranges based on the mean depth within each kinematically feasible region	93
Figure A4.8	Calculated mean annual landslide-debris-production rates for the present-day and a future RCP6 2081–2100 climate-change scenario	94

Figure A4.9	Landslide sediment-production model output describing cumulative annual sediment production for a given grid cell	95
Figure A5.1	Flowchart of the fully featured Gravitation Path Process model used in this analysis	102
Figure A5.2	Schematic representation of the fall height (ΔH) and runout distance (L) parameters for a landslide and the conceptual relationship between $\Delta H/L$ and the landslide volume	103
Figure A5.3	Empirical relationship between $\Delta H/L$ ratio and volume in open-slope dry-debris avalanches and rock avalanches	104
Figure A5.4	Mapped landslide outlines resulting from the 1968 Inangahua earthquake	106
Figure A5.5	Mean annual material flux derived from Gravitational Path Process runout models for selected volume class sizes, triggers and movement types.	110
Figure A6.1	Example of model inputs to calculate mean annual landslide debris-inundation frequency from two representative landslide sources.	115
Figure A6.2	Building vulnerability to falling debris and debris flows over a range of common landslide inundation depths	117
Figure A7.1	Example 1D topographic profiles employed to quantify model uncertainties	120
Figure A7.2	Landslide debris-inundation-risk model sensitivity to uncertainties in model variables	123
Figure A7.3	Calculated variation in annual property loss risk as a result of Monte Carlo simulation of landslide source-susceptibility, landslide sediment-production, landslide sediment-distribution and landslide debris-inundation-risk model inputs.....	127
Figure A7.4	Comparison of annual property loss risk in the Greymouth region	130
Figure A7.5	Cumulative density function demonstrating the change in predicted annual property loss risk in the Greymouth area from LiDAR-derived results to the regional analysis presented in this study	131

APPENDIX TABLES

Table A1.1	Digital elevation models.	67
Table A1.2	Landslide catalogues.	67
Table A1.3	Landslide triggers.....	67
Table A2.1	List of landslide-debris-inundation model variables.	68
Table A3.1	Predictor variables used in the logistic regression model.....	71
Table A3.2	GeolCode1: logistic regression coefficients.....	75
Table A3.3	GeolCode2: logistic regression coefficients.....	75
Table A3.4	GeolCode3: logistic regression coefficients.....	75
Table A3.5	GeolCode4: logistic regression coefficients.....	76
Table A3.6	GeolCode5: logistic regression coefficients.....	76
Table A3.7	Results from the model fitting: calculated as the Nagelkerke and area under the random operator characteristic curve.....	76
Table A3.8	Results from the best-fitting logistic-regression models, their variables and mean coefficients and the model pseudo R^2 and area under the receiver operating characteristic curve.....	78
Table A3.9	Percentage-change factors to project rainfall depths derived from the current climate to a future climate that is one degree warmer.....	79
Table A3.10	New Zealand land-average temperature increase relative to 1986–2005 for four future emissions scenarios	80
Table A4.1	Summary of polygons used for volume estimation and model validation	90
Table A4.2	Summary landslide frequency-volume statistics for rainfall- and earthquake-induced landslides in the study region.	91
Table A5.1	Summary of fahrböschung and $\Delta H/L$ values for each volume class of avalanche-type movements used in this project	104

Table A5.2	List of input parameters for the Gravitational Path Process avalanche-type model.....	105
Table A5.3	List of input parameters for the Gravitational Path Process flow-type model.....	107
Table A6.1	Landslide debris-inundation-risk model variables.	112
Table A7.1	List of variables, assumed baseline values and ranges employed in the sensitivity calculation	121
Table A7.2	Summary statistics for annual property loss risk variability based on 1D Monte Carlo simulation results.	129
Table A7.3	Summary statistics for change in relative annual property loss risk in the Greymouth area to the regional analysis presented in this study.....	131
Table A7.4	Calculation of total annual property loss risk uncertainties.....	133

EXECUTIVE SUMMARY

West Coast Regional Council (on behalf of West Coast Emergency Management Group [WCEM], formerly known as West Coast Civil Defence & Emergency Management Group) commissioned GNS Science – now a business unit of Earth Sciences New Zealand – to identify areas overseen by WCEM that could potentially be affected by landslides generated by earthquakes and/or rainfall and so potentially present a risk to property and life.

Earth Sciences New Zealand has carried out a regional-scale basic quantitative landslide-debris-inundation hazard and risk analysis for the region overseen by WCEM. The project has been undertaken in two phases, as outlined in GNS Science Proposal Q31872684 (2 March 2022). Stage 1 of this project identified landslide-debris-inundation hazard-footprint areas (outlined in Leith and de Vilder [2022]), while Stage 2 integrated the models developed in Stage 1 with probabilistic models of landslide initiation and runout in order to evaluate annual building loss risks associated with earthquake- and rainfall-induced landslide-debris-inundation events. This study has benefitted from model development and data derived from the Ministry of Business, Innovation & Employment (MBIE)-funded GNS Science Extreme Weather Strategic Science Investment Fund (SSIF) uplift following the impacts of Cyclone Gabrielle (Leith et al., in prep.).

The landslide hazard metrics adopted in this study are landslide-debris flux and probability of inundation (P_i).

- **Landslide-debris flux** quantifies the average volume of landslide debris that can be expected to pass a given location either in a given year or, alternatively, in response to a given earthquake or rainfall scenario. A value of 1 indicates that an average of 1 m³ of landslide debris can be expected to pass through ('inundate') each square metre of land either per year or in response to a given scenario.
- P_i quantifies the probability of debris from any size of landslide passing a given location in a given year. A value of 1 indicates that an unspecified volume of landslide debris can be expected to pass through ('inundate') a given location on an annual basis.

We use Annual Property Loss Risk (APLR), derived from the landslide-debris-flux hazard, to demonstrate present-day risk from landslide-debris inundation and how this may change under a future climate scenario.

- **APLR** represents the annual probability that landslide debris will damage a generic ('undifferentiated') building beyond economic repair. A value of 1 indicates that landslide debris can be expected to cause total damage to a hypothetical building at a given location on an annual basis.

The methods used to estimate landslide-debris flux, P_i and APLR are based on assessing both the probability of debris being generated at a given location and its potential to inundate downslope areas when transported as part of a landslide. This represents a new methodology in which the landslide hazard calculation is based on an assessment of the processes that generate landslide debris and transport it through the landscape. This differs from more traditional scenario-based landslide-hazard modelling approaches in which the probability of inundation is most commonly assessed with respect to a given number of discrete hypothetical landslide sources and runout paths.

This new hazard assessment method provides a more spatially comprehensive quantitative analysis of regional landslide-debris-inundation hazard and ensures that calculated volume and probability of inundation is constrained by probable rates of geomorphological and geological processes. The methodology, where appropriate, follows applicable parts of the Landslide Risk Management Guidelines (AGS 2007).

The level of detail of the analysis is similar to a ‘Level D’ basic quantitative hazard and risk analysis, as outlined in Table 4.2 of the Landslide Planning Guidance (de Vilder et al. 2024), although we employ a novel method to calculate hazard. Due to uncertainties in input data, as well as the adopted resolution of the analysis, the outputs are primarily suitable for screening purposes (equivalent to the ‘Level A’ or ‘Level B’ analyses described in de Vilder et al. [2024]). In order to ensure homogeneity in the outputs, this regional-scale analysis employs spatially consistent datasets and has been undertaken at a nominal resolution of 25 m. Residual uncertainties vary spatially, and we recommend adopting an uncertainty level of at least ± 1.25 orders of magnitude when evaluating hazard and risk outputs under present-day climate conditions and of ± 2.75 orders of magnitude for future Representative Concentration Pathway (RCP) 6 (2018–2100) climate conditions.

In areas where the level of hazard or risk exceeds tolerance thresholds determined for given activities, more detailed analysis may be necessary to provide sufficient certainty for decision-making.

The conclusions of this study are that:

1. Landslide-debris-inundation hazard and risk are highest close to steeper slopes, within channels and gullies and on debris fans. Regionally, hazards are greatest in areas where rates of annual landslide-debris production are most rapid.
2. The main contributor to landslide hazard is rainfall-induced landsliding along range-front areas and earthquake-induced landsliding in areas to the northeast of Greymouth. This reflects the main triggering factor of landsliding in each setting.
3. APLR at the location of existing buildings is greatest for debris flows, debris avalanches and rock avalanches (considered here as ‘flow’-type landslide movements), while relatively few buildings are exposed to inundation by debris slides (‘avalanche’-type movements). This reflects the greater reach of debris resulting from flow-type movements, as well as historical urban planning that may have limited development in areas prone to less mobile landslides.
4. 95% of APLR is carried by approximately 2% of existing residential buildings in the region overseen by WCEM.
5. The susceptibility of hill slopes to landsliding in response to RCP6 2081–2100 climate-change conditions is expected to increase APLR to existing residential buildings by at least 50%.
6. Residual uncertainties are spatially variable and increase with increasing distance from landslide sources. These are particularly large in areas adjacent to small-scale topography with spatial extents less than 100,000 m², which is poorly represented in the national digital elevation model (DEM).
7. In order of impact on calculated APLR, the largest uncertainties in this analysis result from constraints on:
 - a. The accuracy of the national DEM (LINZ 2014) employed in this study.
 - b. The relatively low resolution (25 m) of the landslide-debris-inundation analysis.
 - c. The volume of sediment available to develop into landslides each year. This is particularly poorly understood in the future climate-scenario models.
8. Replacing the national DEM with a Light Detecting and Ranging (LiDAR)-derived DEM (LINZ 2022) can reduce residual uncertainties to ± 0.75 orders of magnitude.

A guide to applying these results, including references to relevant previous examples and a list of recommended next steps, is provided in Section 5. We recommend that further engineering geological / geotechnical engineer, risk and land-use planning advice is sought in relation to specific applications of the analysis presented in this report.

We suggest that land-use planning documents referring to the results of this study should include provisions whereby site-specific information for a site/dwelling could be used to re-evaluate the landslide risk, thus allowing the given site to be re-classified. This may include the utilisation of more accurate, or higher-resolution, topographic data; collection of site-specific hazard information; incorporation of more detailed landslide-debris-inundation models; and/or re-evaluation of the vulnerability of affected structures.

Application of Results for Planning Purposes
Key Metrics • Landslide-debris flux ($\text{m}^3/\text{m}^2/\text{year}$): Volume of debris expected to pass through a location annually. • Probability of inundation (P_i) (1/year): Likelihood that debris reaches a location in a given year. • Annual Property Loss Risk (APLR) (loss/year): Probability that a generic building at a location will be damaged beyond economic repair annually.
Risk-Tolerance Thresholds • A risk-tolerance threshold for acceptability of APLR = $1 \times 10^{-5}/\text{year}$ (1 in 100,000) is recommended as a starting point for existing risks. • Thresholds may vary depending on activity type, societal norms and planning level.
Uncertainty Interpretation • Adopt uncertainties consistent with the 1-sigma (standard deviation) (84th percentile) confidence interval. • Present-day climate: APLR uncertainty at 1-sigma is ± 1.25 orders of magnitude. • RCP6 2081–2100 climate scenario: APLR uncertainty at 1-sigma is ± 2.75 orders of magnitude.
Practical Implication • When applying a risk tolerance threshold, uncertainty must be included. For example, if the threshold is $1 \times 10^{-5}/\text{year}$ and uncertainty is ± 1.25 orders of magnitude, then any location with APLR less than $5.6 \times 10^{-7}/\text{year}$ is statistically unlikely to exceed the threshold. • This means that locations with APLR values below the threshold adjusted for uncertainty can be considered as having Acceptable Risk under the current planning framework.
Use of Results for Planning Purposes (refer to Table 5.1). • Residual uncertainties limit the application of outputs for specific planning activities (see Table 5.2). • Raster datasets should be presented at a maximum zoom of 1:500,000 for publicly facing GIS applications and/or down-sampled to a minimum pixel size of 150 m. • Current outputs are suitable for Level A screening and possibly Level B planning purposes. • Reducing uncertainty by using new LiDAR data may make outputs suitable for Level B–C applications. • Outputs are not suitable for planning applications considered for Level D assessments without site-specific refinement. • Where risk exceeds thresholds or uncertainty is high, further analysis should: – Re-evaluate using higher-resolution data (e.g. 8 m LiDAR). – Incorporate local geotechnical and hazard information. – Re-classify sites based on refined risk metrics.
Refer to Section 5.3.3.2 for the decision-making framework and Sections 5.4 and 5.5 for recommended next steps and re-evaluation procedures.

1.0 Introduction

West Coast Regional Council (on behalf of West Coast Emergency Management Group [WCEM], formerly known as West Coast Civil Defence & Emergency Management) commissioned GNS Science – now a business unit of Earth Sciences New Zealand – to identify areas overseen by WCEM (Figure 1.1) that could potentially be affected by landslides generated by earthquakes and/or rainfall and so potentially present a risk to property and life. This report accompanies data deliverables resulting from completion of the West Coast landslide-debris-Inundation assessment (contract no. Q31872684). This provides a probabilistic assessment of ‘debris flow’, ‘debris slide’, ‘debris avalanche’ and ‘rock avalanche’ hazards, as well as associated landslide-debris-inundation risk to buildings. This report describes the modelling and hazard assessment methodologies, an overview of the results and a discussion of these in the context of regional landslide-debris-inundation risk to buildings. In addition, we provide guidance with respect to the application of hazard- and risk-model results for regional land-use planning applications. This study has benefitted from model development and data derived from the Ministry of Business, Innovation & Employment (MBIE)-funded GNS Science Extreme Weather Strategic Science Investment Fund (SSIF) uplift following the impacts of Cyclone Gabrielle (Leith et al., in prep.).

It is our understanding that the results from this project may inform future Te Tai o Poutini Plan (One Plan) Change processes, as well as response and recovery plans for future severe weather events, major earthquakes and cascading hazard events. These outputs will provide a basis for determining critical, or high-risk, areas that may require further local or site-specific analysis.

The scope of work and study area were outlined in GNS Science proposal Q31872684, which was approved by WCEM on 31 March 2022.

It was agreed that this work be carried out in two stages:

- **Stage 1:** Generate models of landslide susceptibility and associated debris runout in order to identify the potential footprint of landslide-debris-inundation hazards across the region. These were essential inputs for Stage 2, although high uncertainties mean that these are not suitable for planning purposes. Outcomes of Stage 1 are outlined in Leith and de Vilder (2022).
- **Stage 2:** Integrate models generated in Stage 1 with probabilistic models of landslide initiation and debris runout in order to describe the probability of landslide debris inundation and associated risks across the region (preliminary outputs were provided to WCEM in a letter report [Leith 2024]).

Earth Sciences New Zealand has carried out a regional-scale basic quantitative landslide-debris-inundation hazard and risk analysis for the region overseen by WCEM, as shown in Figure 1.1.

The object of this study is to inform WCEM of the spatial distribution of potential landslide-debris-inundation hazards and associated risk to buildings across the region.

1.1 Methodology Overview

Assessing landslide-debris-inundation hazards over the vast expanse of the region overseen by WCEM (approximately 25,000 km²) requires innovative approaches due to the computational demands of modelling such events at a regional scale. This regional-scale analysis utilises the relevant datasets that are consistently available across the entire West Coast region.

To address this, Earth Sciences New Zealand has developed a new ‘process-based’ methodology that combines geomorphological process rates with established hazard- and risk-estimation techniques.

Within the framework of a traditional event-based quantitative landslide hazard and risk analysis, landslide hazard and risk are typically assessed using a scenario-based methodology. In this approach, a finite number of hypothetical landslides are defined with specific source areas and volumes, and runout models are applied to simulate the resulting inundation footprints. These scenario footprints are then linked to the estimated frequency of landslides of corresponding size in order to calculate the probability of impact at a given location (e.g. Massey et al. 2021b).

In contrast, the process-based methodology developed here derives the probability of inundation events without relying on a limited set of scenarios. Instead, it models the continuous production of landslide debris through time, then simulates the movement of debris downslope (the 'flux') by assigning rules consistent with a range of different landslide types. Hazard is expressed in terms of debris flux (volume per unit area per year) and probability of inundation, providing a spatially comprehensive assessment without the requirement to consider discrete landslide footprints.

In the process-based methodology, the magnitude and frequency of landslide hazards are regulated by debris-production rates, informed by the rate of geomorphic processes (e.g. tectonic uplift, erosion), landslide inventories and a geotechnical landslide source model. Spatial impact is calculated with empirical and physically based debris-transport models, using conventional approaches to derive model inputs from international datasets and landslide behaviours in the study area. We employ a deterministic model of characteristic landslide-debris flux to convert the spatial hazard output to a magnitude-frequency relationship for landslide-debris inundation. When, for example, the annual debris flux at a location equals the characteristic debris flux, we expect to observe landslide events passing that location on an annual basis.

For example, if landslide-debris flux indicates that landsliding from hill slopes will result in an average of 0.3 m^3 of debris passing a given downslope location annually, and the characteristic inundation volume at that location is 30 m^3 , the annual probability of debris inundation would be 0.01, or 1%. This approach shifts the focus from assigning uniform probabilities to discrete landslide runout paths and allows a regionally consistent assessment of spatially variable landslide-debris-inundation hazard and risk throughout the study region.

Although the new approach employed here sacrifices a degree of accuracy in terms of reproducing dynamic aspects of individual runout events, it has several advantages over standard methods to estimate landslide risk:

- Landslide runout is simulated from every potential source location over a wide spatial area.
- Minimum landslide size can be smaller than the modelled grid resolution.
- Landslide-debris-inundation hazard and risk scales directly with the potential number of landslides passing a given location.
- Calculation of potential hazard and risk incorporates a combination of short-term observational data and long-term geological data, reducing reliance on invariably incomplete landslide records.
- Algorithms are computationally efficient, allowing for large areas to be modelled at one time.

The following tasks were undertaken during this project:

1. Collate reference datasets required to undertake a regional landslide-susceptibility assessment (Stage 1.1), regional debris-runout assessment (Stage 1.2), regional assessment of landslide probability (Stage 2.1) and regional assessment of debris-inundation probability (Stage 2.2).
2. Develop earthquake- and rainfall-induced landslide susceptibility models based on the methods presented in Massey et al. (2021a) and Rosser et al. (2021).
3. Derive landslide frequency-volume relationships for earthquake- and rainfall-induced landslide catalogues in the study region.

4. Determine an appropriate landslide-debris-production model for the study region.
5. Develop geospatial landslide-hazard models based on local susceptibility, frequency-volume and debris-production estimates.
6. Develop geospatial landslide-risk models based on landslide-hazard model results and appropriate vulnerability datasets.
7. Carry out field validation of the regional hazard- and risk-analysis results.
8. Provide guidance on the adoption of hazard- and risk-analysis results for regional land-use planning purposes.

Where applicable, the methods employed here follow appropriate parts of the Australian Geomechanics Society framework for landslide risk management (AGS 2007); see Appendix 8.

Three primary metrics are employed to describe landslide-debris-inundation hazard and risk:

- **Hazard magnitudes** are described using the metric of landslide debris flux. This is expressed as the average volume of debris that can be expected to pass through one square metre of land, either on an annual basis (considering a full year) or for a specific trigger scenario (such as heavy rainfall or an earthquake). Landslide-debris-inundation hazard magnitudes are measured in $\text{m}^3/\text{m}^2/\text{year}$ for annualised outputs or $\text{m}^3/\text{m}^2/\text{event}$ for scenario-based outputs.
- **Hazard frequencies** are described using the metric of probability of inundation (P). This is expressed as the probability that any volume of landslide debris will pass through a location, either on an annual basis (considering a full year) or for a specific trigger scenario (such as heavy rainfall or an earthquake). Landslide-debris-inundation hazard frequencies are measured by 1/year for annualised outputs or 1/event for scenario-based outputs.
- **Risks** are described using the metric of Annual Property Loss Risk (APLR), which is expressed as the probability that a generic hypothetical building present at a particular location will sustain damage such that the re-instatement cost exceeds the replacement value (Massey et al. 2019). Landslide-debris-inundation risks are measured by loss/year for annualised outputs or loss/event for scenario-based outputs, where 100% loss indicates that the re-instatement cost of a building footprint within the cell exceeds its replacement value.

This study does not include any assessment of hazards associated with river-related (fluvial) erosion or flooding, tsunami, rockfall, ground deformation as a result of slow-moving landslides or slippage, or earthquake rupture.

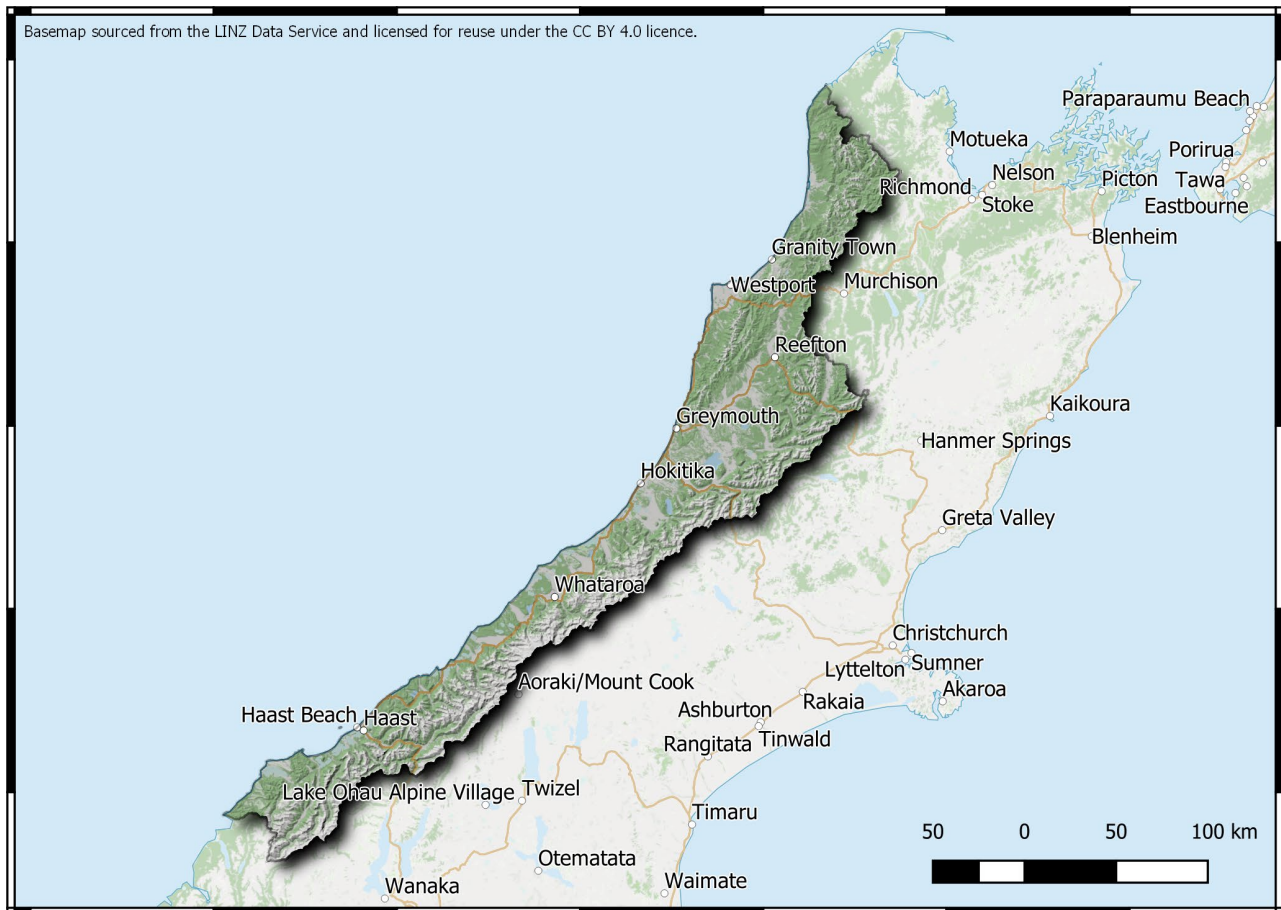


Figure 1.1 Overview of the project area.

1.2 Report Structure

This report has been structured into six sections:

1. Introduction:
 - Project background
 - Overview of landslide hazards
2. Landslide-debris-inundation modelling methodology:
 - Conceptual overview of the modelling method
 - Determination of landslide source susceptibility
 - Calculation of landslide sediment production
 - Landslide-debris-runout modelling
 - Calculation of risk to buildings
3. Discussion:
 - Consistency with actual experience
 - Sensitivity to key uncertainties
4. Description of project deliverables:
 - Landslide-hazard deliverables
 - Landslide-risk deliverables.
5. Applying these results:

- Applications for landslide-hazard data
- Applications for landslide-risk data
- Recommended next steps

6. Summary and conclusions.

Sections 1–5 of the report provide a high-level overview of the landslide-debris-inundation hazard methodology. Detailed descriptions of input data and the methodology employed can be found in Appendices 1–7.

1.3 Personnel

This report has been prepared by Kerry Leith, Saskia de Vilder, Chris Massey and Biljana Lukovic (Earth Sciences New Zealand). The risk calculations and calculation route were reviewed by Sally Dellow (Earth Sciences New Zealand). This report was independently reviewed by Dr Feiko van Zadelhoff and Dr Andrew Neverman (Manaaki Whenua – Landcare Research; see Appendix 9 for review and responses). Kerry Leith and Sam McColl visited study areas during 10–12 August 2023 to carry out field-validation surveys of the risk models and input data and to meet with West Coast Regional Council staff to discuss the results and input variables to be used in the hazard and risk model.

1.4 Landslide Hazards

1.4.1 Terminology

Landslides are defined as the movement of rock, soil or debris downslope (Evans 2001). A landslide hazard is defined as a landslide that has the potential to cause an undesirable outcome. A landslide-hazard assessment provides a quantitative measure of the probability of a hazardous landslide occurring within a defined time period and area (Corominas et al. 2023). Landslide hazards (as defined in the Building Act 2004) can be divided into two broad categories:

1. ‘Slippage’, which includes the movement or loss (including partial loss) of land from a slope when this occurs beneath a structure (e.g. dwelling, garage, road, shed).
2. ‘Falling debris’, which includes soil, rock, vegetation, snow or ice that may fall and ‘runout’ onto a property (e.g. dwelling, garage, shed and/or land) from up-slope (the landslide source area), inundating the property.

In this project, we assess landslide hazards associated with falling debris, as defined in the Building Act 2004. The ‘landslide-debris-inundation area’ refers to the runout path that is inundated by soil and/or rock, which includes the debris source, transport and deposit zones (Figure 1.2).

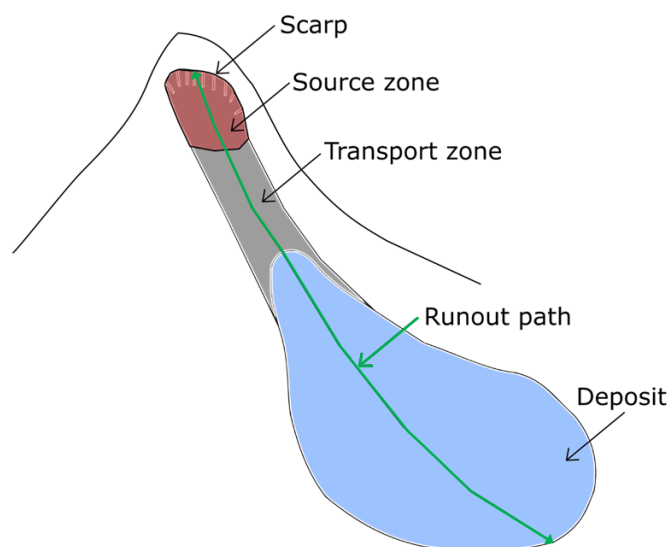


Figure 1.2 Schematic representation of the source and debris-inundation areas (source, transport and deposit zones) of a landslide. Illustration modified from Mitchell et al. (2020).

1.4.2 Landslide Types Assessed and Associated Definitions

Evaluating the hazards associated with landslide debris inundation requires an understanding of the types of landslide that may occur at a given location. The typical behaviour of each type of landslide (e.g. velocity of displacement, re-occurrence, travel distance) will affect both the extent of areas impacted and the nature of that impact. Based on the classification by Hungr et al. (2014), the rapidly moving landslide types to be assessed in this project are: (1) debris flows, (2) debris avalanches and (3) rock avalanches. These rapidly moving landslides present a threat to life and property, with the speed of movement of the landslide limiting the ability for evasion and evacuation to occur. Inundation by slow-moving landslides or rockfall events is not assessed as part of this study.

1.4.2.1 Debris Flows

Debris flows can be defined as a “very rapid to extremely rapid surging flow of saturated debris in a steep channel” (Hungr et al. 2014). Entrainment of material and water from the flow path can occur along the runout path. Debris flows often occur simultaneously with floods. The debris flow may be initiated by a debris slide, debris avalanche or rockfall from a steep bank, or by spontaneous instability of the steep stream bed. The sediment concentration of debris flows exceeds 40% (typically 50–70%), and their volume can be up to 1,000,000,000 m³ (Iverson et al. 2011). Figure 1.3 shows the result of a mobile channelised debris flow.

Once saturated material begins to move in a steep channel, the volume of a debris flow can change due to entrainment (Iverson et al. 2011). Entrainment results from scour of channel-bed sediment or collapse of stream banks. The bulk of the material involved in a debris-flow event can sometimes originate from entrainment within the runout path. Changes in debris-flow volume and momentum due to entrainment have the potential to influence the debris-flow velocity and travel distance (Iverson et al. 2011).

Following Hungr et al. (2014), ‘debris flow’ refers exclusively to a channelised landslide, whereas a landslide consisting of flowing debris on an open slope is referred to as a ‘debris avalanche’. It is possible that debris flows become debris avalanches (Section 1.4.2.4) if the channel these flow down becomes less confined, and, conversely, a debris avalanche may become debris flows if the debris enters a channel. Where the long-term rate of debris-flow sediment deposition outpaces the rate of long-term sediment transport, the deposits from multiple debris flows form debris fans. Debris fans provide geomorphic evidence of the extent of debris-flow hazards.



Figure 1.3 Debris flows generated by rain in Eastbourne, Wellington, in November 2006. The source areas of the debris flows are in the left of the photograph. The debris travelled down-slope several hundreds of metres, where it impacted the dwellings shown in the right of the photograph. Photograph by G Hancox, GNS Science.

1.4.2.2 Fan

Fans are cone-shaped landforms that are generated when confined watercourses (e.g. gullies, creeks, rivers) become wider and the water-course less confined, for example, when water-courses enter valleys, plains or lakes. The resulting decrease in flow velocity promotes sediment deposition. The dynamic nature of such landforms poses a hazard to people and infrastructure located on these, as areas that were inactive (and have since been built on) can re-activate and start actively eroding or receiving sediments. Davies and McSaveney (2008) have discussed some of the considerations for sustainable development on fans. They also discussed that fans can be divided into two end-members: (1) alluvial fan – dominated by deposition of sediment from fluvial processes; and (2) debris-flow fan – dominated by deposition of sediment from debris flows and debris floods.

1.4.2.3 Debris Slides

A debris slide is defined by Hungr et al. (2014) as:

“sliding of a mass of granular material on a shallow, planar surface parallel with the ground. Usually, the sliding mass is a veneer of colluvium, weathered soil, or pyroclastic deposits sliding over a stronger substrate. Many debris slides become flow-like after moving a short distance and transform into extremely rapid debris avalanches.”

Debris slides are not analysed separately in this project, and this definition is only provided to describe the initial stage of a debris avalanche (Section 1.4.2.4).

1.4.2.4 Debris Avalanches

A debris avalanche is defined by Hungr et al. (2014) as a “very rapid to extremely rapid shallow flow of partially or fully saturated debris on a steep slope, without confinement in an established channel”. Hungr et al. (2014) also describe debris avalanches as initiating as debris slides (Section 1.4.2.3) and are associated with failures of residual soil, colluvial, pyroclastic or organic veneer.

The important distinction between debris avalanches and rockfalls is that the latter comprise individual fragments, which move as independent rigid bodies interacting with the substrate by means of episodic impacts. By contrast, debris avalanches move in a flow-like manner as masses of interacting fragments and water. Figure 1.4 provides examples of debris avalanches from the West Coast region.



Figure 1.4 Debris avalanches on Whataroa Highway generated by the 2019 West Coast storm. Photograph by D Townsend, Earth Sciences New Zealand.

1.4.2.5 Rock Avalanches

A rock avalanche is defined by Hungr et al. (2014) as:

“an extremely rapid (>5 m/s), massive, flow-like motion of fragmented rock from a large rock slide or rock fall. Large rock avalanches have a degree of mobility that exceeds the behaviour of a smaller-volume frictional flow of dry, angular, broken rock.”

The mobility of rock avalanches, which affects the runout distance, increases systematically with the volume of the event. To capture the increase of mobility as a function of volume, the current project restricted the use of rock avalanches to landslides having a volume greater than 100,000 m³. Figure 1.5 provides examples of a rock avalanche from the Kaikōura district.

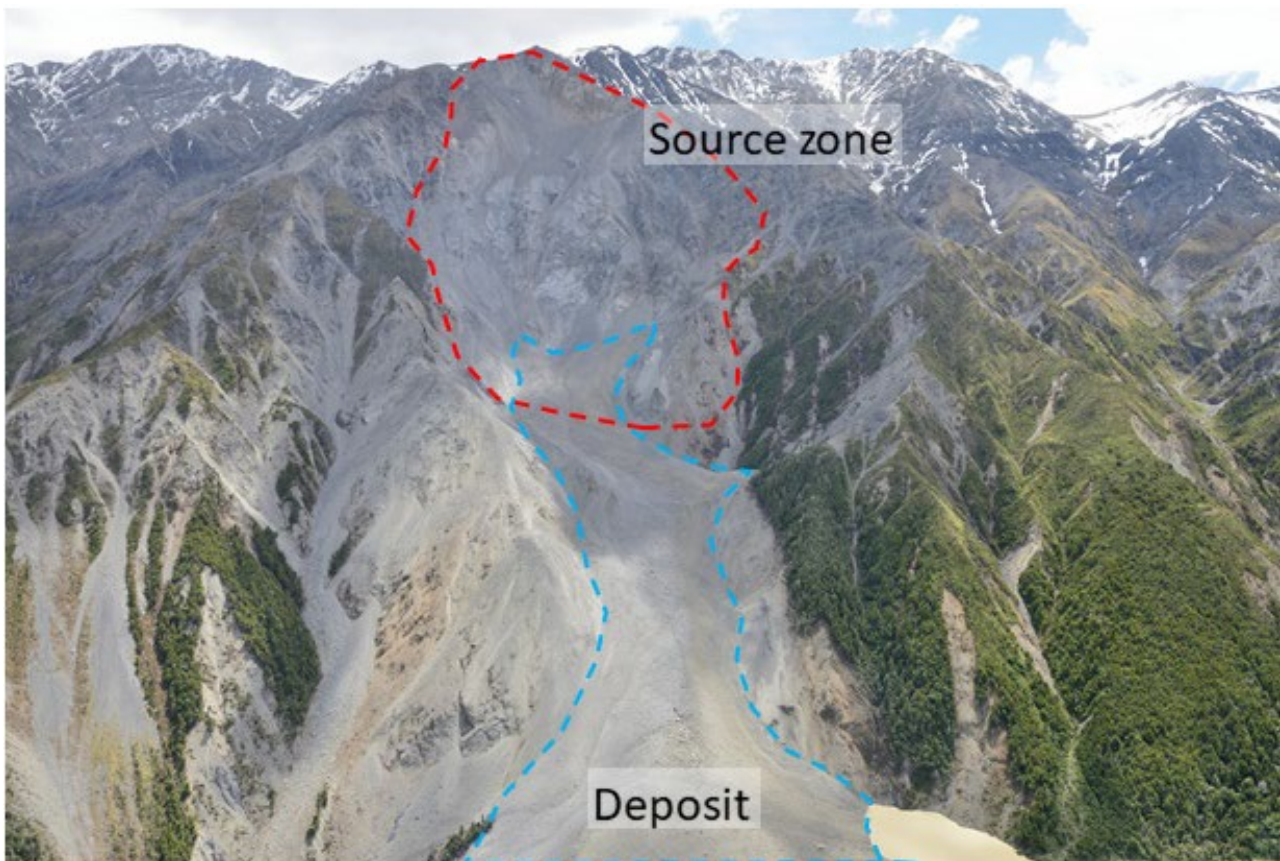


Figure 1.5 Hapuku rock avalanche generated by the 2016 Kaikōura earthquake. The deposit extends outside the current field of view. Photograph by D Townsend, Earth Sciences New Zealand.

2.0 Landslide-Debris-Inundation Modelling

Landslides directly impact both the natural and built environment by mobilising soil and rock on steep hill slopes and efficiently moving it downslope. A landslide-hazard assessment includes evaluation of the spatial and temporal contributors to landslide processes that pose a risk to people or property. This assessment involves determining the likelihood of landslide initiation, the extent of potential debris movement and the frequency and magnitude of debris inundation at a specific site. In this context, a landslide-debris-inundation risk analysis builds on hazard assessment by considering the vulnerability of structures in the area in order to quantify the potential impacts from landslide events.

Developing a full probabilistic workflow capturing landslide hazard and building risk requires an understanding of (1) the probability of a given type of slope failure in a given event, (2) the probability of debris originating from a landslide source reaching a given location and (3) the probability of damage due to inundation by landslide debris.

In this section, we provide a brief overview of the methods adopted in this study, describe the components of the hazard and risk assessment alongside examples of results and key uncertainties, outline the process employed to undertake calculations for Representative Concentration Pathway (RCP) 6 2081–2100 future climate scenarios and describe field-reconnaissance activities.

2.1 Landslide Source to Inundation Process Model Overview

Given the large spatial scale of the West Coast, and the associated computational cost of running multiple landslide runout models over such a wide area, we employ a new Landslide Source to Inundation Process Model (LS-IPM) methodology developed by Earth Sciences New Zealand for regional-scale analysis of landslide-debris-inundation hazards, incorporating a consideration of geomorphological process rates.

We assume that the past is a guide for the future, and the calculation of landslide hazard and risk is then based on the limit of the number of landslide-debris-inundation events of a given volume occurring in a given area over a given period of time. We assume that the rate of landslide-debris production is a limiting factor and that, as such, the frequency of occurrence is directly related to the source volume of contributing landslides – the greater the expected proportion of large landslides, the less frequent landsliding will need to be in order to maintain the rate of debris production. We account for future climate scenarios by adjusting the limiting rate of landslide-debris production in concert with expected changes in landslide-event frequency. This differs from a traditional frequentist interpretation of landslide probability, which would typically use observations of previous landslide frequencies to determine the limit of the number of discrete landslide events expected to occur in a given area over a given period of time. Although traditional frequentist approaches may include a consideration of landslide-event size, the debris production rate is rarely, if ever, considered a limiting factor. The approach used here allows the integration of geological, geomorphological and geophysical data to account for processes that influence landslides, providing constraint on landslide occurrence beyond the limited historical record of landslide events, as employed in frequentist approaches. This helps to provide a more accurate and detailed understanding of regional landslide hazard and risk.

We explicitly tie inundation hazard to a combination of (1) the production of debris by landslides of given size ranges and (2) the manner in which the debris is distributed as it travels to the inundation location. As our hazard metrics describe the probability of a volume of landslide debris passing a given location (rather than the number of discrete landslides that could potentially inundate that location), we calculate the annual probability of inundation by landslides of a given size (irrespective of trigger) as:

$$\text{annual probability (landslide inundation)} = \frac{\text{mean annual landslide debris flux}}{\text{characteristic landslide inundation volume}}$$

where the mean annual landslide-debris flux for a given landslide volume range is based on the amount of landslide debris that we expect can be generated up-slope of a given location, as well as the proportion of that debris that can be expected to travel down-slope past the given location (allowing for potential deposition, spreading or channelisation along the route). The characteristic landslide-inundation volume is derived from a combination of the initial landslide geometry and assumed spreading characteristics as material travels down-slope to the given location. For example, if modelled runout of house-sized (up to 1000 m³) landslides from all possible contributing hill slopes results in an average of 0.3 m³ of debris passing a given location each year, and the actual expected volume of debris from a single house-sized landslide passing that location is just 30 m³ (i.e. a fraction of the initial source volume), then:

$$\begin{aligned} \text{annual probability (landslide inundation)} &= \frac{0.3 \text{ m}^3/\text{yr}}{30 \text{ m}^3} \\ &= 0.01, \text{ or } 1\% \text{ per year} \end{aligned}$$

When assessing the chance of an event happening each year, it is important to understand what ‘annual probability’ really means. For example:

1. A 1% chance of occurrence similarly means a 99% chance that an event will not occur.
 - If an event has a 1% (0.01) chance of occurring in a given year, there is also a 99% chance that it will not occur that year.
 - This probability resets each year and does not carry over from one year to the next.
2. ‘1% per year’ does not mean ‘once every 100 years’.
 - Having a 1% annual probability does not guarantee that the event will happen exactly once in 100 years. It simply means that there is a 1% chance of it happening in any given year. Alternatively, this means that there is a 63% chance that it will occur **at least once** in that 100-year period.
3. Events with very low probabilities can be expected to occur in the region every year.
 - For example, if 100,000 locations each have an annual probability of 10⁻⁵ (0.001%), then:

$$100,000 \times 10^{-5} = 1$$
 - On average, you would expect about one event each year across those 100,000 locations.

The assumptions we require to determine the rate of landslide-debris production constitute a ‘degree of belief’ interpretation and, although constrained by regional datasets, are subject to engineering geological/geomorphological judgement. For example, we assume that all primary erosion that occurs on hill slopes capable of generating landslides occurs as a result of landsliding (see Section 2.3.1.1). This is supported by evidence from regional landslide studies (see Section A4.1.1); however, both the rate of debris production and proportion of debris eroded through landsliding are not well constrained in the study region. We therefore evaluate the uncertainty associated with this, as well as other input parameters, by calculating the change in landslide-debris-inundation risk from our favoured (or ‘most likely’) solution by testing a range of values for variables controlling both erosion rates and the proportion of erosion that contributes to landslide-debris production (see Section 2.3.1). Uncertainties associated with all key assumptions are evaluated in a similar manner (see Sections A7.1–A7.5), and we employ a Monte Carlo approach to evaluate the combined impact of all input uncertainties and assumptions on calculated APLR at various distances from potential landslide sources (see Section A7.6.1). Finally, we estimate uncertainties associated with the accuracy of the topographic model and analysis resolution by comparing the calculated risk from the 25 m regional digital elevation model (DEM) against risks calculated using a recent Light and Detecting Ranging (LiDAR)-derived DEM at both 25 m and 8 m resolutions (see Section A7.6.2).

2.1.1 Consideration of Hazard and Risk

This LS-IPM is based on a combined workflow that provides quantitative forecasts of landslide sediment distribution from hillslopes to populated regions. The workflow incorporates four sub-model components, namely the:

1. Landslide source-susceptibility model (LSS).
2. Landslide sediment-production model (LSP).
3. Landslide sediment-distribution model (LSD).
4. Landslide debris-inundation-risk model (LDIR).

The LSS model describes the probability of slope failure for a range of triggering scenarios and combines outputs from the Rainfall-Induced Landslide (RIL) Tool (Rosser et al. 2021) and Earthquake-Induced Landslide (EIL) Tool (Massey et al. 2021a) to generate both mean annual and scenario-based probabilities of failure for a range of landslide volume classes. The LSP forecast model provides estimates of the volume of debris generated from all feasible landslides and incorporates data describing assumed landslide erosion rates, as well as observed landslide-size characteristics derived from mapped landslides in the study region. The LSD model simulates the movement of landslide debris downslope and can be used to quantify the landslide-debris-inundation probability throughout the study region. The LDIR model incorporates an estimate of building vulnerability in order to derive APLR estimates.

This workflow is briefly described in the following sections. For a detailed description of the model components and assumptions, see Appendices 3–6. Model uncertainties are discussed in detail in Appendix 7.

2.1.2 Quantification of Regional Landslide-Debris-Inundation Hazards

The hazard equation provides a means of describing hazard events, such as landslides, floods or earthquakes, based on factors related to the event's probability and potential intensity or magnitude. In general, the hazard equation can be expressed as:

$$\text{Hazard} = \text{Probability of Occurrence} \times \text{Intensity or Magnitude}$$

We can break down the relative components as:

- **Probability of Occurrence:** The likelihood that a specific hazard event will occur in a given area within a specified time period.
- **Intensity or Magnitude:** The severity or strength of the hazard event (e.g. earthquake magnitude, flood depth, landslide volume).

This equation provides a way to quantify the level of hazard by combining how likely the event is to occur with how severe it could be. For probabilistic models, hazard is often represented through recurrence intervals (e.g. a '100-year flood') or exceedance probabilities (e.g. a 1% chance of occurrence per year). In this section, we briefly introduce the key elements of the hazard-modelling approach.

The landslide-debris-inundation hazard assessment is based on a geomorphologically consistent evaluation of landslide-sediment production and distribution across the region by landslide processes. We consider the volume and rate of landslide initiation to be limited by the rate of debris production on hill slopes (Figure 2.1). Once initiated, landslide debris then travels through the hill-slope system as primary 'runout' (i.e. as debris flows or debris avalanches from the landslide source) and is either directly deposited in river channels, which then flush the sediment from the landscape, or deposited on hill slopes before being moved to river channels by secondary debris-transport processes such as sheet wash, rilling, gullying and other fluvial or glacial mechanisms. These secondary processes are not

considered in the current study; however, these play an important role in the geomorphological system, as they act as a buffer between landslide deposits and the river system. As secondary transport processes operate at a more or less constant rate through time (e.g. Croissant et al. 2019), we can expect average rates of sediment transport in rivers, for example, to reflect long-term rates of landslide-debris production in the contributing landscape.

We assume that hill-slope debris inputs (through weathering and strength degradation) and outputs (through delivery to glaciers, rivers or coastlines) are balanced over millennial timescales and therefore employ a sediment-production (or erosion-rate) model developed from a combination of uplift, erosion and fluvial sediment-load data to constrain the maximum rate of landslide-source debris production in the landscape. This approach draws parallels to that of Neverman et al. (2023), in which a derivative of the same specific-fluvial-sediment-yield dataset was employed to help constrain rates of shallow rainfall-induced landslide sediment delivery to fluvial networks across New Zealand.

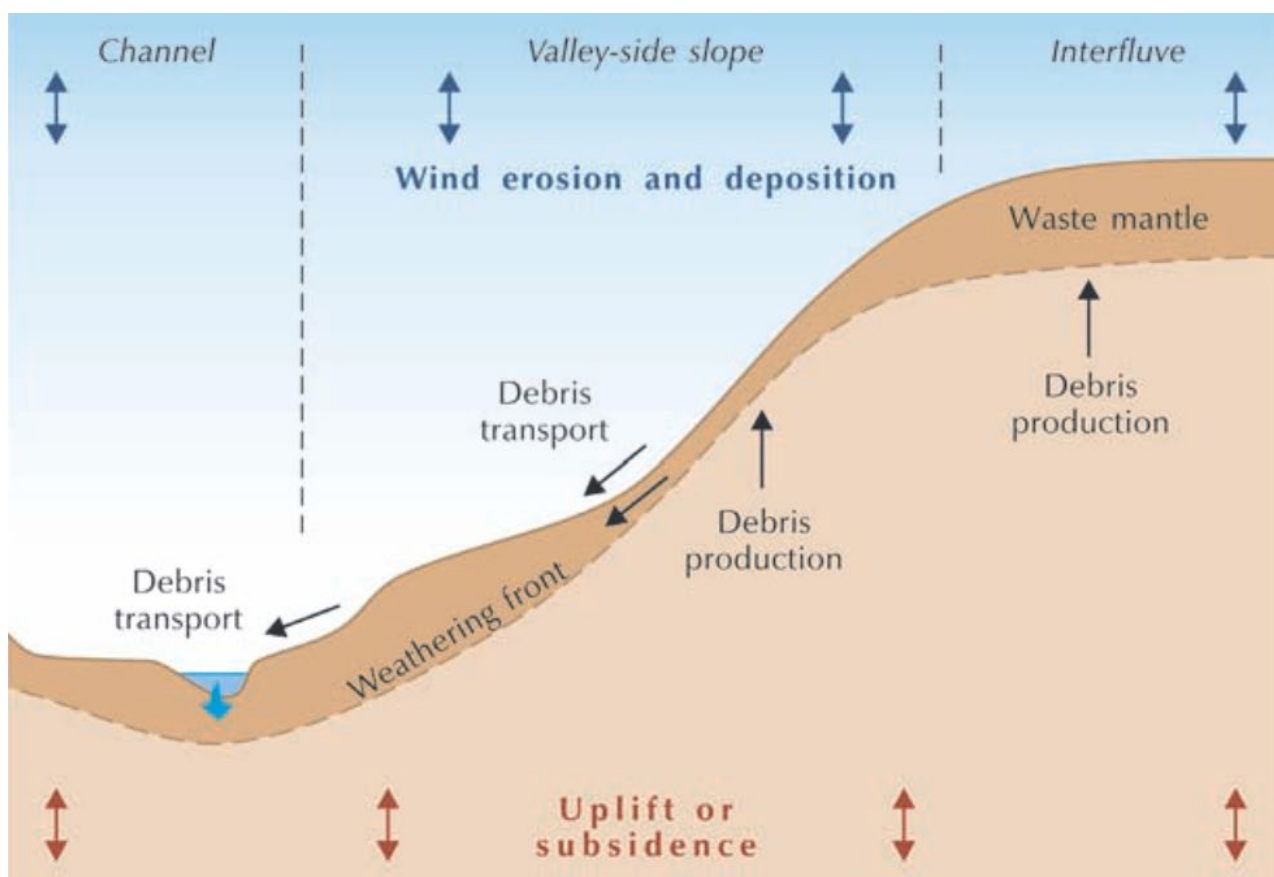


Figure 2.1 Geomorphological model of a hill-slope system. The model includes inputs (e.g. debris production through fracturing and weathering, as well as deposition by wind), storage (e.g. the waste mantle), throughputs (e.g. debris transport by hill-slope processes) and outputs (e.g. evacuation of debris by the fluvial system). Modified after Huggett and Shuttleworth (2012).

Rates of landslide-sediment production, transport and deposition in active landscapes are ultimately limited by the rate at which unstable sediment becomes available. On geomorphologically active hill slopes, the generation of unstable sediment is regulated by the rate of relief production (through a combination of tectonic uplift and fluvial or glacial erosion) and rock-strength degradation (through weathering and fracturing), while landslide-sediment transport is regulated by the frequency of landslide-inducing events and the mobility of the resulting landslides.

We quantify landslide hazard at a given location in terms of both mean annual and scenario-based landslide-debris flux, a measure of the volume of landslide debris that can be expected to pass a given location as a result of all possible triggers, source volumes and movement modes. Fundamentally, the landslide-debris flux at a given location is a function of the landslide-sediment production up-slope of the site, as well as the potential for that sediment to travel down-slope past the location. While the location and potential volume of landslides is derived from the LSS and LSP models, the travel distance needs to be calculated using an LSD model. The distance that a landslide travels (and therefore the potential for it to pass a given location) depends on (1) the initial gravitational potential energy of material in the landslide source and (2) the rate at which energy is gained and lost as the debris moves through the landscape. The initial energy of the landslide is a function of its initial volume and release elevation, while energy may be gained by entraining debris along the travel path. The rate of energy loss is a function of (among other factors) the materials that the landslide is composed of, the material along the travel path, the mode of movement and the topography along the runout path. As it is currently impractical to model these complex physical relationships at a regional scale, inputs to the LSD model employed here adopt empirical statistical relationships to account for key physical parameters controlling runout processes. We account for different modes of movement by adopting modelling methods suited for both ‘avalanche’- and ‘flow’-type movements.

The landslide-debris flux metric derived from the LSD model provides an integrated measure of both mean annual and scenario-based hazard intensity by combining the calculated frequency and magnitude of all potential landslides capable of inundating a site. As such, landslide-debris flux does not provide a measure of landslide-debris-inundation risk (which requires intensity and frequency to be separated). Intermediate outputs of the LSD model (representing individual triggers, return intervals and volume classes) are used to calculate the probability of inundation (P_i) and APLR in the LDIR model. This is described in the following section.

2.1.3 Derivation of Debris-Inundation Probability and Annual Property Loss Risk

The frequency and magnitude of landslide-source events can be determined by evaluating a combination of susceptibility to failure, sediment-production rates and probable landslide-size characteristics. However, deriving the frequency and magnitude of inundation events at a given down-slope location is more complicated. The amount of debris that travels to a site is closely tied to the geographic position of the site, the initial volume of the landslide and the characteristics of the travel path between the source and inundation location. A site on a debris-flow fan far from a landslide source may, for example, only experience inundation events when channelisation on the fan coincides with the location of the site – at which point the magnitude of landslide debris passing the location (the debris flux) may equal the full volume of the landslide source (or more, if debris is entrained during runout). In contrast, a site on an open hill slope close to a landslide source may experience inundation events every time a landslide occurs, although the inundation volume is likely less than the total landslide source volume, as only a portion of the original failure may intersect the site. In order to calculate the frequency of inundation by representative landslide volumes at a given location, we employ a probabilistic approach to compare the mean annual landslide-debris flux to an estimated characteristic flux from contributing landslide sources. This method is described in detail in Appendix A6.2.

APLR is a function of the frequency of various magnitudes of landslide inundation events occurring and the vulnerability of buildings to those inundation hazards. The level of detail in the LS-IPM analysis is similar to a ‘Level D’ basic quantitative hazard and risk analysis, as outlined in Table 4.2 of the Landslide Planning Guidance (de Vilder et al. 2024), including regional analysis of the size and frequency of landslides that could occur for given scenarios, regional modelling of the runout for the full range of landslide sizes and basic analysis of the vulnerability of buildings to inundation by different landslide sizes. A novel approach has been employed to calculate landslide debris-inundation hazard. We note that the input datasets for the LSS and LSP models have been selected to maintain regional consistency and, as such, the residual uncertainties exclude the application of outputs for ‘Level D’ planning and consenting purposes (see Section 5.4 for further discussion on uncertainties and application of these results). The LS-IPM workflow incorporates physically constrained statistical methods appropriate for regional hazard and risk analysis, although this should not be considered a substitute for local hazard and risk analysis.

The general equation for risk in the context of natural hazards can be expressed as:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Exposure}$$

We can break down the relative components as:

- **Hazard:** The probability or likelihood of a natural or man-made event of a given magnitude occurring (e.g. landslide, flood, earthquake).
- **Vulnerability:** The degree to which people, infrastructure or assets are susceptible to damage from the hazard. This includes factors such as structural resilience, preparedness and capacity to respond.
- **Exposure:** The presence of people, assets, infrastructure or resources in areas where these could be affected by the hazard.

Thus, risk quantifies the potential impact of a hazard, taking into account the likelihood of the event, the vulnerability of affected entities and the extent to which these are exposed. In this section, we briefly introduce the key elements of the LDIR model as these relate to the general risk equation presented above. Section 2.5 provides further details on the LDIR model, associated outputs and key uncertainties.

The vulnerability of buildings to landslide inundation depends on the magnitude or intensity of an inundation event, the type of structure and the nature of the impact (e.g. falling debris through a roof or gradual burial by debris flows) and the consequence to the element(s) being impacted. As vulnerability is a key element of the general risk equation above, calculated landslide-debris-inundation risk is only relevant for the type of element considered in the risk calculation. Here, we adopt an economic approach to quantify the vulnerability of buildings in terms of a ‘damage ratio’, describing the ratio between the cost to repair damage and the cost to replace the damaged structure. This approach is supported by an empirical damage function derived by Massey et al. (2019) from a New Zealand and international dataset of undifferentiated building types, which relates the landslide-debris height observed following inundation events to the assessed damage ratio at each site.

2.1.4 Climate-Change Scenarios and Event-Specific Hazard Assessment

As well as considering mean annual hazard and risk, we also evaluate landslide-debris-inundation hazard and risk associated with four credible landslide-inducing scenarios. These include:

- **Scenario 1:** Present-day precipitation triggers based on 50-, 100- and 250-year annual return interval (ARI) 24-hour precipitation totals derived from the National Institute of Water & Atmospheric Research (NIWA)’s High Intensity Rainfall Design System (HIRDS) V4¹ model.

¹ <https://hirds.niwa.co.nz/>

- **Scenario 2:** Future precipitation triggers based on 50-, 100- and 250-year ARI 24-hour precipitation totals derived from the HIRDS V4 model rainfall projections for a future RCP6 scenario (Carey-Smith et al. 2018).
- **Scenario 3:** A regional earthquake trigger based on 100-, 250-, 500- and 1000-year ARI peak ground accelerations (PGA) derived from the New Zealand National Seismic Hazard Model (NSHM) 2022 (Gerstenberger et al. 2022).
- **Scenario 4:** An Alpine Fault earthquake event (e.g. based on PGA derived from the AlpineF2K rupture model [Bradley et al. 2017]).

We note that, aside from the Alpine Fault earthquake event, these scenarios do not reflect the landslide inundation associated with a specific triggering event but rather the probable debris production and inundation hazard associated with the precipitation or ground accelerations representing various return intervals throughout the region.

2.1.5 Quantification of Results and Uncertainties

In order to demonstrate the spatial variability of some model outputs, we adopt a representative study region in the vicinity of The Doughboy/Kokiraki (-42.92, 171.06). The Kokiraki study region encompasses a catchment of approximately 4500 km², incorporating a range of topographic settings representative of the wider region overseen by WCEM. By focusing on this area, we can illustrate how factors such as terrain steepness, geology and land cover influence both the estimated landslide probabilities and associated uncertainties. Unless a result specifically refers to the vicinity of Kokiraki, all results can be assumed to apply to the entire region overseen by WCEM.

Uncertainties relating to the assumptions and input parameters in this study are quantified by assessing the effects of model-input variations and assumptions on calculated landslide-debris-inundation results using a simple 1D model. Specifically, changes in key inputs to the LSS, LSP, LSD and LDIR models are evaluated in relation to the calculated APLR at multiple locations down-slope of a theoretical landslide source. Electing to use a 1D, instead of 2D, model enables a broad exploration of the parameter space while minimising computational costs. While the model is conceptual and simplifies geographic complexities, it effectively captures the magnitudes and trends of impact. This model is described in detail in Sections A7.1–A7.5.

Employing this 1D model, we systematically adjust key variables (e.g. landslide size, probability, debris characteristics and runout parameters) and evaluate how this changes the APLR from its ‘most likely’ value at several locations down-slope of a hypothetical landslide source. The ‘most likely’ APLR at each location represents the calculated risk assuming ‘best estimate’ input parameters selected for this study. Although this framework does not replicate specific real-world conditions, it captures both the magnitude and trends of potential impacts. By identifying which parameters most strongly affect the results, as well as evaluating the total uncertainty at each down-slope location, the study provides guidance on interpreting the hazard estimates in the context of data limitations and potential under- or over-estimates at local scales. This model is described in detail in Section A7.6.1.

Uncertainties relating to the accuracy of the DEM employed in the LSP and LSD models are quantified by comparing 2D APLR results from the area around Greymouth against results generated using a LiDAR-derived DEM. We select an area in the vicinity of Greymouth, rather than in the Kokiraki region, due to the full LiDAR data coverage in this area. We assume that this DEM provides an accurate representation of present-day topography and are therefore able to isolate the impacts of inaccuracies in the national DEM (LINZ 2014), as well as the effect of down-sampling the DEM to a lower resolution prior to running the LSP and LSD models. Although this analysis is undertaken in a limited area, and we do not test the impact of changing model assumptions and parameters, we expect that the analysis effectively captures the magnitude and trends of impacts associated with spatial accuracy of the model. This model is described in detail in Section A7.6.2.

Further details regarding uncertainties relating to each model component are presented in Sections 2.3–2.5 and summarised in Section 3.2.

2.2 Landslide Source-Susceptibility Model

2.2.1 Overview

The LSS model is used to evaluate the relative probability of a landslide occurring at a given location as a result of a given trigger (rainfall or earthquake) and associated return interval. The model assumes that all landslides occurring at a given location are the result of either an earthquake or heavy rainfall and calculates the annual probability of failure by integrating outputs from earthquake-induced landslide (Massey et al. 2021a) and rainfall-induced landslide (Massey et al. 2021b) source-susceptibility models, trained using catalogues of landslides mapped following earthquake- or rainfall-induced events.

The shaking data used to create earthquake-induced landslide outputs was derived from the New Zealand NSHM 2022 (Gerstenberger et al. 2022), and landslide susceptibilities were calculated using PGAs for ARLs of 100-, 250-, 500- and 1000-year earthquakes. The earthquake-induced landslide susceptibility for an Alpine Fault earthquake event is based on PGAs derived from the AlpineF2K rupture model (Bradley et al. 2017).

Rainfall data used to create the rainfall-induced landslide susceptibility forecasts was derived from the NIWA HIRDS V4 model, which simulates rainfall intensity at a 5 km grid resolution for a given range of ARLs. The landslide susceptibilities were calculated using 24-hour rainfall for ARLs of 50, 100 and 250 years (see Appendix 3 for further details). We note that there is no direct correlation between landslide occurrence and 24-hour rainfall accumulation and landslides may be triggered as result of longer or shorter rainfall intervals. However, we do find a reasonable correlation between landslide occurrence and 24-hour rainfall and therefore adopt this interval as a necessary simplification.

The LSS model output describes the mean annual probability of a given location being fully occupied by either a rainfall- or earthquake-induced landslide source in a given year. This was calculated by integrating the product of the susceptibility to a triggering event, as well as the frequency of triggering event, over the representative event return interval for all earthquake- and rainfall-induced landslide outputs. Expressed as $\text{m}^2/\text{m}^2/\text{kyr}$ (per thousand years), a value of 0.5 kyr^{-1} indicates that either 50% of the area is expected to be associated with a landslide source within a 1000-year period, or, alternatively, the entire area is expected to be associated with a landslide source over a 2000-year period (see Appendix A3.4 for further details).

2.2.2 Results and Uncertainties

Mean annual rainfall- and earthquake-induced landslide probabilities, as well as total annual probabilities of landslide initiation, are presented in Figure 2.2. Overall, the LSS model indicates that the greatest earthquake- and rainfall-induced landslide probabilities are in areas with steep topography, primarily in the region between Fox Glacier and Kokiraki. Relative probabilities for the two triggers vary across the study region, with rainfall-induced landslide probabilities being generally higher along the Southern Alps and earthquake-induced landslide probabilities being higher in the north of the region. Overall, mean annual rainfall-induced landslide probabilities are more variable, with maximum values commonly an order of magnitude greater than earthquake-induced landslide probabilities at the same location. However, this difference reduces when averaged across an area, and the spatially averaged rainfall-induced landslide probabilities are more commonly double those of earthquake-induced landslides. For example, the predicted mean annual rainfall-induced landslide probability in the Kokiraki area is approximately 0.30 kyr^{-1} (per thousand years), while the mean annual earthquake-induced landslide probability in the same area is approximately 0.10 kyr^{-1} (Figure 2.2a–c). However, it is important to note that both the magnitude and relative probability of rainfall- and earthquake-induced landslide occurrence varies across the region. In areas northeast of Greymouth,

for example, earthquake-induced landslide probability exceeds rainfall-induced landslide probability, although the overall probability of landslide occurrence is much lower than along the range front (Figure 2.2d–f).

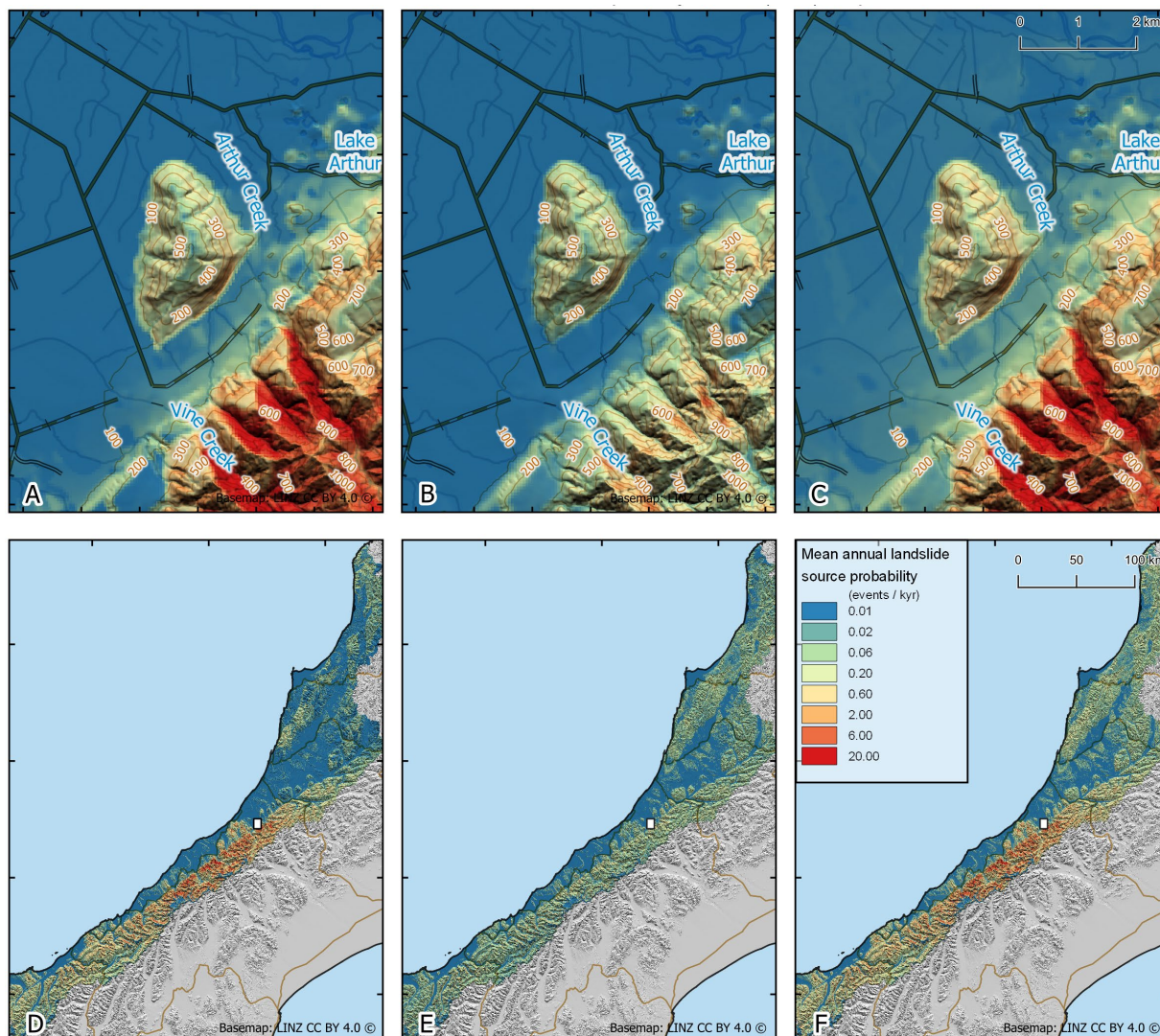


Figure 2.2 Selection of landslide source-susceptibility model outputs. (a, d) Mean annual rainfall-induced landslide probability. (b, e) Mean annual earthquake-induced landslide probability. (c, f) Total mean annual source probability. Legend categories are consistent across all maps. The location of the Kokiraki maps (a–c) are indicated by a white box on the regional overview maps.

The LSS model probabilities for rainfall- and earthquake-induced landslides determine how landslide-sediment production is distributed across the LSD model runout simulations (described in Section 2.3). While these probabilities do not affect the total amount of debris produced in a given cell, they do influence how debris is allocated across 112 individual runout simulations in the LSD model (described in Section 2.4). These simulations represent various combinations of landslide triggers, return intervals and landslide-size classes.

For example, if the probability of a rainfall-induced landslide is higher than that of an earthquake-induced landslide, a greater proportion of the annual sediment production will be assigned to rainfall-induced landslides. Within the category of rainfall-induced landslides, the specific amount of debris assigned to each return interval depends on its relative probability of landsliding, meaning that return intervals with a greater probability of landsliding will receive a larger share of the debris allocation (see Section A4.5 for a full description).

As landslide volumes, and therefore runout extents, vary for each runout simulation, the LSS model probabilities affect the distribution of landslide debris down-slope of landslide sources. For example, as earthquake-induced landslides are larger, and therefore overall more mobile than rainfall-induced landslides, locations with a greater probability of earthquake-induced landsliding will have a higher proportion of debris assigned to larger, more mobile landslides. This will lead to:

1. A lower APLR in locations close to landslide sources due to a reduction in landslide frequency (for a given erosion rate, the frequency of larger landslides must be less than that of smaller failures).
2. A higher APLR at locations far from source areas, as larger volumes are more mobile and therefore travel further from the source.

Uncertainties in the inputs used to calculate LSS probabilities have a moderate impact on the predicted APLR. Depending on the input, these uncertainties could cause a variation of up to $0.01 \times$ the 'most likely' APLR. This variation is strongest both close to the landslide source (where increasing the proportion of smaller rainfall-induced landslides will increase the inundation frequency) and far from the source (where increasing the proportion of larger, more mobile, earthquake-induced landslides will increase the probability of inundation). The impact of LSS model uncertainties is further discussed in Section A7.2.

2.3 Landslide Sediment-Production Model

2.3.1 Overview

The LSP model provides a means of estimating the volume of landslide sediment likely to be generated by events of a given trigger and return interval. In steep hill-slope terrains, landsliding is a primary driver of long-term erosion rates. By rapidly mobilising and transporting a mixture of sediment sizes, landslides contribute significantly to overall sediment flux and landscape evolution. The material exposed and deposited by landslides is further weathered and re-distributed by secondary processes such as sheet wash, rilling, gullying and piping, which contribute to the ongoing erosion of the landscape. Over time, the frequency and magnitude of landslides and high-magnitude rainfall events, combined with these secondary processes, shape long-term erosion and sediment-transport rates in the region.

2.3.1.1 Mean Annual Landslide Debris-Production Rate

We assume that landslides are the sole driver of mass wasting (the initial mobilisation and movement of soil or rock material) on hill slopes where landslides are determined to be kinematically feasible. Landslide-debris production is therefore assumed to be equal to the long-term erosion rate. We derive the long-term erosion rates from a combination of suspended-sediment-yield observations, estimates of soil and rock densities and measures of long-term tectonic uplift and erosion. This is a necessary simplification, and, while observational evidence suggests that landslides dominate mass wasting processes in much of the region, processes such as slope creep, gully formation, glacial erosion or fluvial under-cutting can also contribute to initial movement of soil and rock. Once sediment is mobilised, additional erosion processes (such as gullying and fluvial transport) contribute to the long-term transport of sediment through the landscape.

We base our estimation of erosion rates on previous studies quantifying specific sediment yield from hill slopes to rivers across New Zealand, as well as the specific density of geological units mapped throughout the country. This is calibrated against rates of long-term erosion and tectonic uplift. Hicks et al. (2011) undertook a detailed measurement campaign in order to determine mean annual sediment fluxes for 233 catchments across New Zealand. They then developed a 100-m-resolution spatially consistent specific-sediment-yield model to estimate sediment-delivery rates from topography within these catchments using a range of weighted-input variables, including precipitation,

local slope and erosion terrain (encompassing geology, soil cover and physiography). In order to convert the Hicks et al. (2011) specific-sediment-yield model into total erosion rates, we converted mass-based sediment loads to volumetric erosion rates using source-material densities from the digital rock-density catalogue of Tenzer et al. (2011). As Hicks et al. (2011) did not evaluate bed-load transport within the sampled rivers, calculating total sediment yield (and therefore total erosion in the contributing catchments) required that we determine a scaling factor to account for the additional component of sediment transport. We achieved this by comparing predicted suspended sediment yields with measured longer-term erosion rates in West Coast catchments (Hovius et al. 1997; Larsen et al. 2014; Roda-Boluda et al. 2023). We found that a constant suspended to total sediment-yield scaling factor of 1.5 was required to correlate specific sediment yields based on suspended sediment measurements to basin-averaged erosion rates within the study region (see Section A4.1 for further details).

The long-term erosion rate is assumed to be maintained by discrete landslide events generated in response to earthquake or heavy rainfall events. We therefore proportion the mean annual erosion at a given location across a full range of 'kinematically feasible' landslide volumes at that location, assigning a greater proportion of the annual erosion to the most commonly occurring landslide volumes. 'Kinematic feasibility' ensures that our hypothetical landslide sources have the physical characteristics required to slide down slope, and are not (for example) too flat or blocked by topographic features. The maximum feasible landslide volumes are calculated from the 25 m DEM, while the allocation of sediment production to smaller volume classes is based on empirical landslide frequency-magnitude relationships derived from landslides mapped in the study region. These aspects are discussed further in the following section; see Appendix 4 for a full description of LSP model inputs.

Once landslide sediment is generated on a hill slope, the movement of a landslide results in the generation of landslide debris with an associated volumetric expansion as cracks and voids form within the material. We therefore convert landslide sediment-production rates to equivalent debris-production rates by multiplying the former by a sediment bulking factor to capture the reduction in density as a result of weathering and disaggregation. We adopted a bulking factor of 1.3 based on the relative densities of rock and soil in the region. See Section A4.1.3 for full details of this calculation.

Results and Uncertainties

Calculated sediment-production rates for the present-day scenario are presented in Figure 2.3a, d. Calculated rates are highest along the range front to the east of the Alpine Fault and increase up to 30 mm/yr in the Mount Cook region, although are generally closer to 6 mm/yr along the range front. Calculated sediment production rates to the north of the region are considerably lower, in the order of 0.25 mm/yr, as may be expected given the regional geomorphological setting (e.g. Adams 1980).

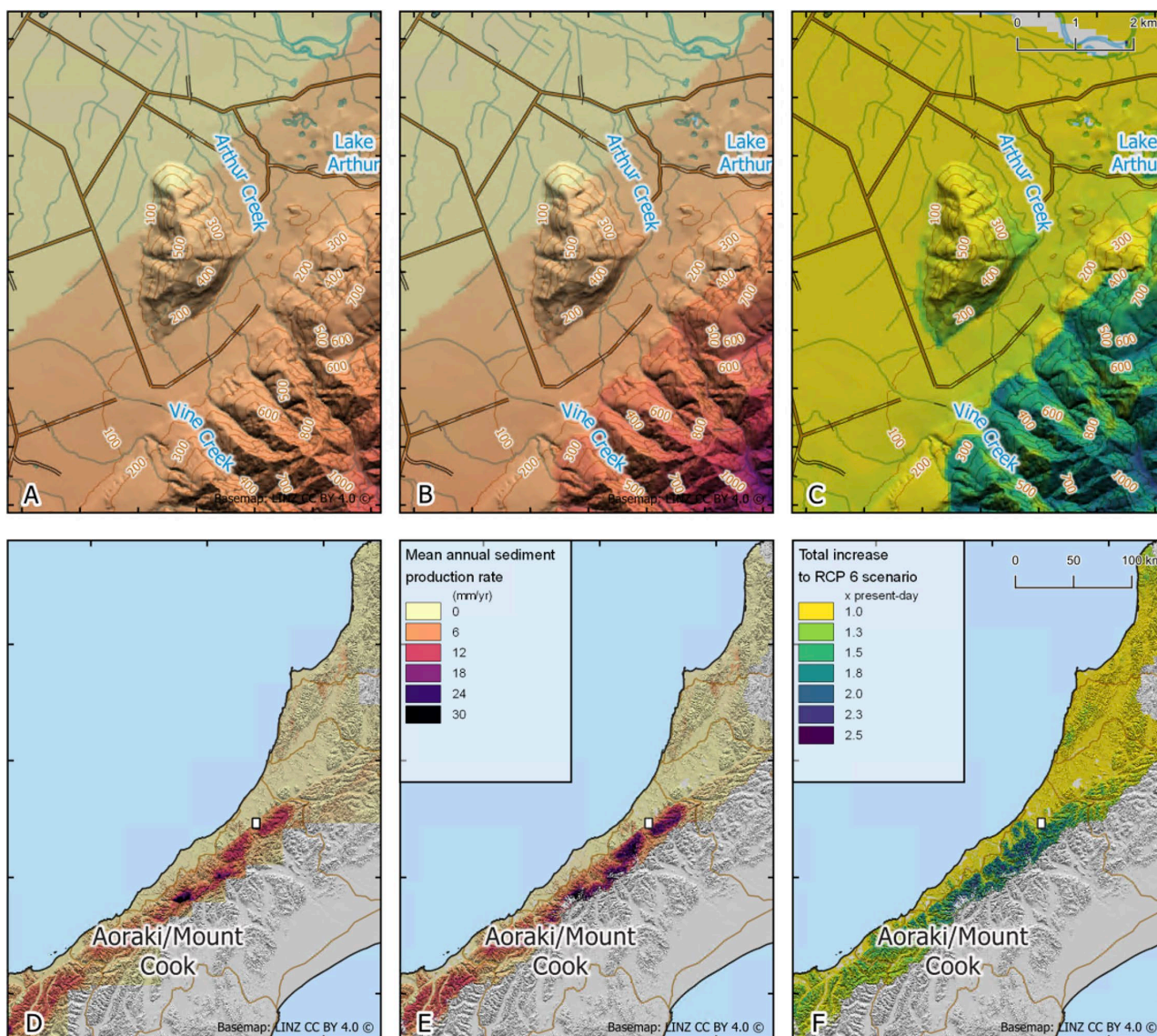


Figure 2.3 Selection of landslide sediment-production model outputs. (a, d) Mean annual sediment production. (b, e) Mean annual sediment production for the RCP6 2081–2100 climate scenario. (c, f) Change in total mean annual sediment production. Legend categories are consistent across maps (a), (b), (d) and (e) and maps (c) and (f). The location of the Kokiraki maps are indicated by a white box on the regional overview maps.

Catchment-averaged sediment-production rates derived from the regional erosion model adopted in this study compare favourably with bedrock-uplift rates derived from geological constraints (Adams 1980). This supports our assumptions that the rates adopted here likely reflect long-term averages spanning several thousand years and suggests that the landscape is in a state of ‘dynamic equilibrium’, such that long-term uplift and erosion are in balance. We find a similar favourable comparison between calculated landslide-derived erosion rates determined from a catalogue of thousands of landslides mapped along the range front (Hovius et al. 1997) and our adopted landslide-erosion model. This supports our assumption that the majority of erosion on slopes on which landsliding is kinematically feasible is driven by landslide processes. See Appendix A4.1.1 for further details on these comparisons.

The landslide debris-production rate directly affects the volume of source material available in LSD model simulations. As such, it has a dominant impact on both the calculated mean annual landslide-debris flux and the related frequency of inundation events. For consistency, the datasets employed in this study prioritise spatial uniformity. This necessitates a trade-off between local accuracy and

spatial coverage. The primary input to the LSP model is suspended sediment yield, based on estimates from Hicks et al. (2011). The associated uncertainties are estimated to be more than an order of magnitude at a 100 m resolution, decreasing to approximately 2× as sediment yields are averaged over larger areas (Hicks et al. 2011). Given that sediment yield dictates the rate of debris production in the landslide-source area (rather than debris runout), these uncertainties impact how accurately the LSP model captures the frequency of landsliding events across landforms of varying scales. Uncertainty can be expected to be higher for landslides originating from smaller landforms and lower for those originating from larger areas. Specifically, standard errors in debris-production rates (and therefore inundation frequencies and associated APLR) from areas smaller than 1000 m² can be expected to be greater than an order of magnitude. Although this will have little effect on the extent of inundation, care should be taken when adopting hazard or risk metrics for planning purposes in the vicinity of smaller landslide source areas.

We find that uncertainties associated with inputs affecting landslide debris-production rates have little impact on the extent of landslide-debris-inundation hazard, although these can lead to APLR variations in affected areas up to 3× the ‘most likely’ estimate. This is, unsurprisingly, one of the largest impacts on APLR, reflecting the primary link between landslide-debris production and inundation hazard. The impact of LSP model uncertainties is further discussed in Section A7.3.

2.3.1.2 Kinematic-Source Model

The possibility for landslides of a given volume class range to occur at a location is informed by a simple ‘kinematic’ model that ensures that sufficient topographic relief and geometric freedom is available for an appropriately sized landslide to occur. As we limit our analysis to avalanche- and flow-type landslides, and do not consider falls (i.e. rockfall), we do not evaluate kinematic potential for ‘fall’-type movements. Where insufficient relief is available for a given landslide volume class range, the total landslide-sediment production is distributed across all smaller volume classes. The amount of debris assigned to various volume classes is determined based on the probability distribution of earthquake- and rainfall-induced landslides observed in the region. Combined with data relating to erosion rates, this approach allows us to estimate the total landslide sediment production at a given location for all landslide volume ranges, considered triggers and return intervals.

An ‘excess topography’ condition is employed to determine the spatial extent and maximum possible depth of slope failure units, while ‘area-volume scaling’ is employed to determine the potential depth of failure within these units. The excess topography condition adopts a 20° angle to define the position of the deepest possible failure surface, reflecting the potential frictional strength of weak joints within the rock mass. Although likely to vary throughout the region, this value falls within the 8–27° frictional strength range for landslides with volume classes greater than 1, derived from a survey of landslides in similar soil and rock conditions in Western Oregon (e.g. Alberti et al. 2022).

The depth of failure close to the landslide margins is controlled by an area-volume scaling relationship based on limit-equilibrium principles. This allows us to relate the landslide-source geometry to cohesive strength properties of the landslide-source material (see Section A5.2). We adopt a representative cohesive strength of 50 kPa toward the upper limit of back-calculated cohesive strengths presented in Alberti et al. (2022), although well below the cohesive strength of fractured greywacke rock masses (commonly 400–1000 kPa, e.g. Read et al. [1999]). As the cohesive strength is used to determine scaling characteristics for all landslide volume classes and, as such, must represent landslides in both soils, as well as in weathered and fractured rock, selecting a low to intermediate value is appropriate for this regional study. We model eight landslide-source volume-class ranges with upper limits fixed at order-of-magnitude intervals (see Table 2.1 for further details). Section A5.2 provides associated calculations and further discussion of input variables.

An example of potential source areas is provided in Figure 2.4. The maximum landslide volume class in each kinematically feasible failure unit is determined by comparing the mean depth of all cells within a unit (see Figure 2.4a) to the representative mean depth of landslides within each volume-class range. Figure 2.5 presents maximum volume classes for each kinematically feasible unit. We note that the kinematic-source model should not be considered a substitute for detailed geotechnical assessment and is neither an exhaustive, nor prescriptive, description of potential landslide-source areas. Individual landslides may be more or less extensive than the maximum feasible failure units defined using this method.

We explore uncertainties associated with the derivation of potential source areas in the following section and recommend the incorporation of local geotechnical data in locations where uncertainties are greater than acceptable limits. In particular, the incorporation of material or site-specific constraints on friction and cohesion parameters, including the manner in which these parameters change with depth, can significantly reduce associated uncertainties. This data is not available on a regional scale and is therefore not incorporated in this study.

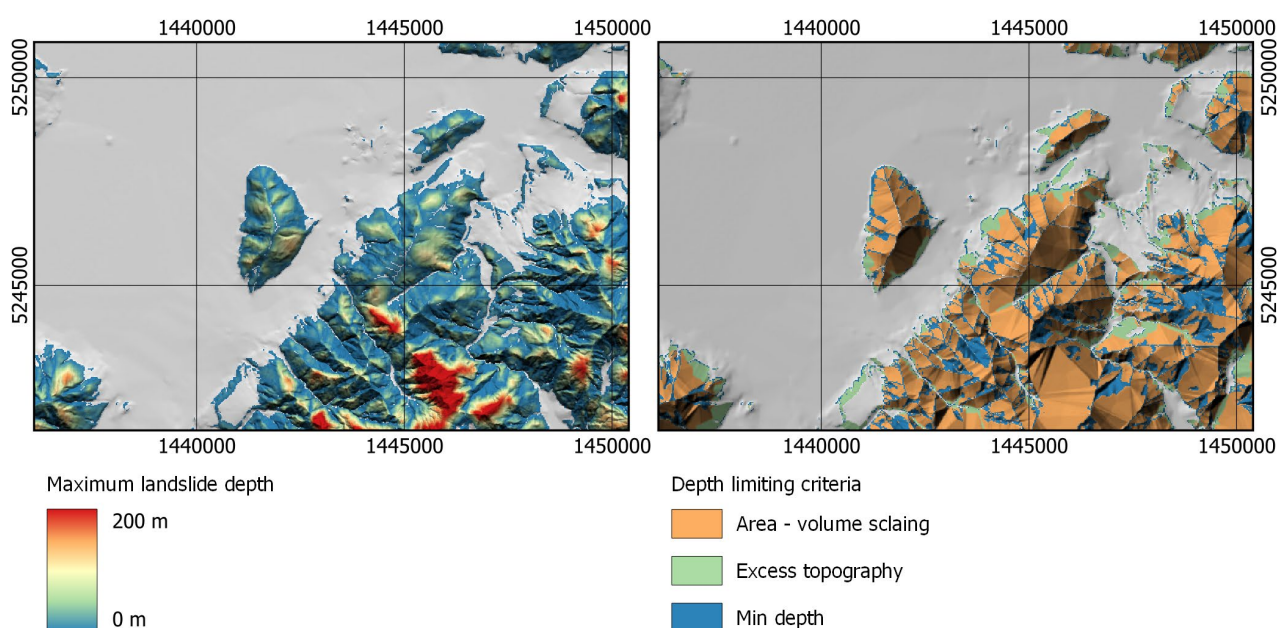


Figure 2.4 Calculated maximum landslide depths based on kinematic models (left) and depth-limiting criteria employed in the kinematic model (right). The hillshade image representing topography for the maximum depth figure is based on present-day topography, while the hillshade image representing topography for the depth-limiting criteria is derived from the calculated maximum-depth failure surfaces.

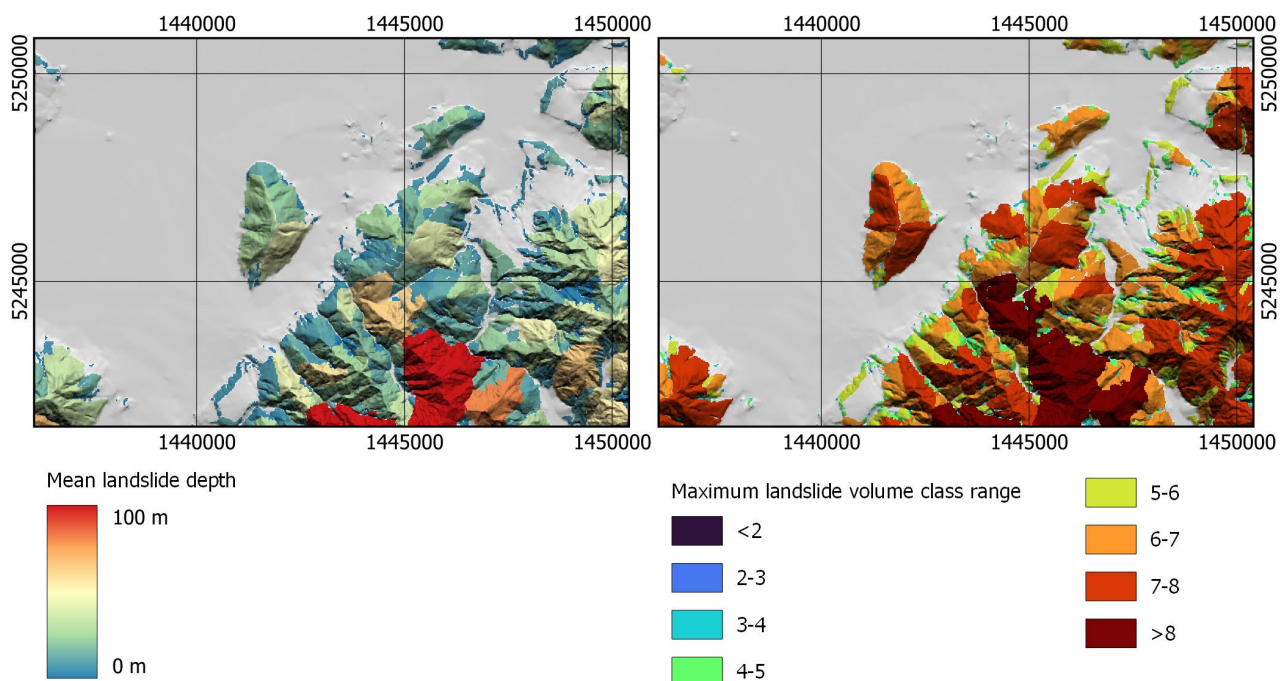


Figure 2.5 Depth to the kinematically feasible failure surface (left) and volume classes used to determine the maximum feasible volumes for the landslide sediment-production model (right).

Results and Uncertainties

We evaluate the probability of landslides of all volumes occurring within susceptible cells by dividing the landscape into kinematically feasible failure units and applying landslide frequency-volume statistics consistent with global observations of landslide occurrence (see Figure 2.6). The national DEM adopted in this study (LINZ 2014) is based on data derived from aerial photographs collected in the 1940s and has been down-sampled to 25 m resolution to meet computational constraints for this regional analysis. This raises significant uncertainties in the identification of landslide-source regions, particularly for landforms with areas less than 100,000 m², and can lead to debris inundation from smaller source areas not being identified (and therefore associated APLR not being calculated) and/or calculated runouts being less extensive than these would otherwise be with larger topography. Although not solely the result of the kinematic model, we estimate that the impact of inaccurate terrain representation in the national DEM can lead to a variation in APLR from that derived from a recent LiDAR DEM (LINZ 2022) by at least 0.79 orders of magnitude, while the nominal 25 m resolution for both the LSP and LSD analyses can be expected to result in uncertainties of at least 0.58 orders of magnitude. This is further discussed in Sections A7.3 and A7.6.2.

2.3.1.3 Landslide-Volume Distributions

Once a maximum landslide volume is determined for a given location, we employ empirical frequency-volume distributions to assign debris to all feasible volume-class ranges. As a first step, we compiled all mapped earthquake-induced ($n = 6359$) and rainfall-induced ($n = 7269$) landslide polygon datasets available for the region overseen by WCEM for which coverage can be reasonably assumed to be complete for given triggering events (see Table A1.2 in Appendix 1 for a complete list of datasets used). Mapped polygons were separated into source and runout by assuming that the source occupies a proportion of the total elevation range, and the volume of each individual landslide source was then calculated from the 8 m DEM using the same kinematic model described in the previous section. Resulting landslide frequency-volume distributions were found to be approximately log-normally distributed, similar to previous observations in international datasets (e.g. Brunetti et al. 2009). The calculated geometric mean volume of earthquake-induced landslides on a log₁₀ scale was 4.55 ± 0.60 (m³) and for rainfall-induced landslides was 3.92 ± 0.68 (m³) (see Appendix A4.3 for further details).

Results and Uncertainties

Table 2.1 presents a summary of calculated landslide areas and depths for each landslide volume-class range alongside proportional landslide-volume distributions derived from West Coast region landslides.

Table 2.1 Key attributes of volume-class ranges used for the landslide sediment-production, sediment-distribution and debris-inundation-risk models. RIL = rainfall-induced landslides, EIL = earthquake-induced landslides, CBD = central business district.

Class	Class Range	Geometric Mean			Proportional Contribution of Sediment (per m ²) (%)	
		Landslide Volume log ₁₀ (m ³)	Landslide Area (m ²)	Landslide Depth (m)		
					RIL	EIL
Family car or smaller	<1	0.5	3	1.1	<0.01	<0.01
Car to bus or large truck	1–2	1.5	16	1.9	0.02	0.00
Bus to house	2–3	2.5	89	3.6	2.56	0.05
House to Olympic swimming pool	3–4	3.5	484	6.5	34.44	7.09
Pool to supermarket	4–5	4.5	2630	12.0	53.29	60.13
Supermarket to container ship	5–6	5.5	14,295	22.1	9.48	31.69
Ship to CBD of typical city	6–7	6.5	77,711	40.7	0.19	1.04
CBD to large hill or small mountain	7–8	7.5	422,454	74.9	<0.01	<0.01

As larger landslides travel further than smaller landslides and are likely more damaging to buildings, the extent of APLR tends to increase where topography can support larger maximum volume-class ranges (a function of both geometric-mean volumes and standard deviations). In contrast, limiting the maximum potential volume at a given location will shift debris production to smaller volume class ranges, resulting in more frequent events and therefore increased inundation risk close to hill slopes. We find that uncertainties associated with both the geometric mean and standard deviation of volumes can significantly influence the predicted APLR, leading to variations of between 0.5× the most likely APLR at locations close to the landslide source and 0.001× at more distal locations. Uncertainties associated with the geometric-mean volume have the greatest impact on calculated APLR at distal locations, while changes in the standard deviation tend to more strongly affect APLR closer to the source. The impact of LSP model uncertainties is further discussed in Section A7.3.

2.3.1.4 Proportional Landslide Erosion for All Triggers, Return Intervals and Volume Classes

We assume that discrete landslide events induced by earthquakes or heavy rainfall maintain the long-term erosion rate. To estimate the erosion contributed by each trigger, we first compare the total probability of failure at a given location with the probability of failure for each LSS model scenario (i.e. each trigger and return interval combination). We then distribute the annual debris production associated with each LSS model scenario across kinematically feasible volume classes using the previously mentioned landslide frequency-volume distributions. In other words, we allocate the proportion of annual erosion associated with each trigger to a range of possible landslide volumes based on the proportions of landslides of given volumes observed to have previously occurred in the region. This is described in full in Appendix 4.

Results and Uncertainties

Figure 2.6 presents spatially averaged landslide debris-production rates for kinematically feasible hill slopes in the vicinity of Kokiraki. Overall, landslide sediment-production rates in this area approximate a log-normal distribution, consistent with input frequency-volume distributions (see Figure A4.5). However, these are skewed slightly (approximately half a volume class) toward larger volumes, as areas in the vicinity of Kokiraki associated with greater topographic relief, and therefore larger maximum possible volumes (see Figures 2.5 and A4.8), are also associated with higher erosion (and therefore landslide sediment-production) rates. This effect is a function of the extreme contrast in both relief and erosion rates specific to the vicinity of Kokiraki and is negligible when considering landslide debris-production rates across the entire WCEM study region.

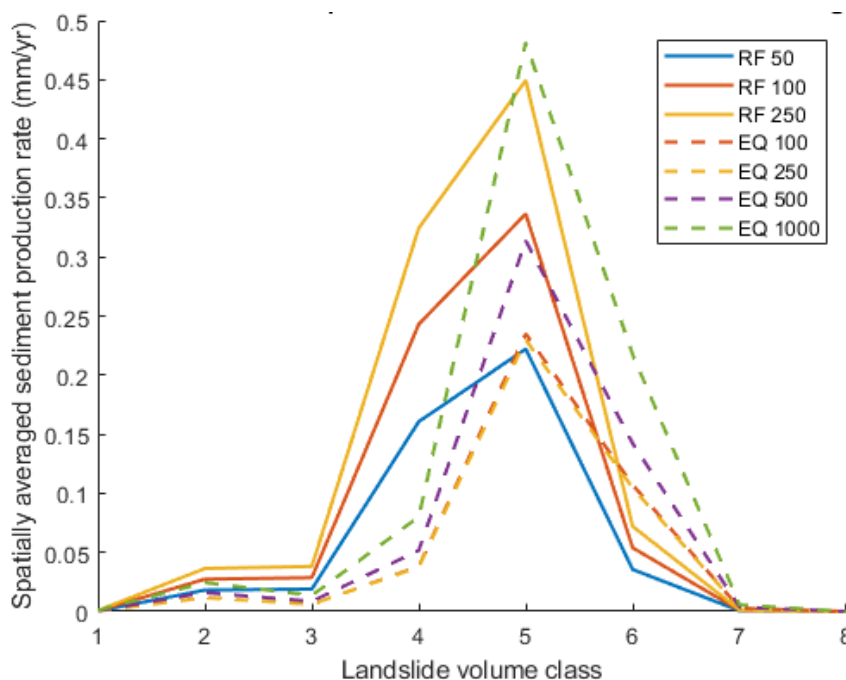


Figure 2.6 Landslide sediment-production frequency-magnitude relationships derived for the vicinity of Kokiraki using the landslide sediment-production model. Solid lines represent the mean annual sediment production by rainfall-induced landslides and dashed lines represent the mean annual sediment production by earthquake-induced landslides of various volume classes.

Uncertainties associated with the proportional distribution of debris volumes are related to the assumption that, where landsliding is kinematically feasible, long-term erosion rates are maintained by landslide events. As this assumption directly affects the rate of landslide-debris production, associated uncertainties behave in an essentially identical manner to those described for the mean annual landslide debris-production rate in Section 2.3.1.1, and APLR will tend to decrease proportionally with decreasing contributions of landslide erosion to the total erosion rate. However, we do note that the regional-scale datasets utilised in this study do not capture local or site-specific effects and, as such, may overlook sources of rapid debris generation, leading to potential under-estimation of localised landslide debris production. Areas with active erosion (such as fluvial and coastal erosion), ongoing slope instability (e.g. creeping or deep-seated landslides), temporary susceptibility increases (e.g. from vegetation loss) and recent human modifications (such as quarries and road cuts) often produce landslide sediment at much higher rates than regional erosion estimates. Such areas may exhibit local landslide debris-production rates several orders of magnitude above the regional values presented in this report. Further discussion on these limitations, variability in debris production and the impact of localised factors is provided in Section A7.3.

2.3.1.5 *Sediment Production for Event Scenarios*

Event-specific hazard assessments for Scenarios 1–3 (Section 2.1.4) are based on 24-hour precipitation totals derived from the relevant HIRDS V4 and New Zealand NSHM 2022 ARIs. As such, these do not represent specific trigger events but rather the potential debris production in a given location, if local precipitation or ground accelerations meet that of the ARI for the given location. The Alpine Fault scenario (Scenario 4) is based on a specific event forecast derived from the AlpineF2K rupture model (Bradley et al. 2017).

We calculate the volume of landslide debris generated in a scenario by comparing the probability of failure from the scenario-specific LSS model to the annual probability of failure at a location from all potential trigger events (derived from the annual LSS model). As we assume that all primary erosion is a result of landsliding, the total annual probability of landsliding represents sediment production at the annual rate. If the probability of failure as a result of a trigger is twice that of the mean annual probability (for example), then we can therefore assume that the volume of landslide debris produced will be twice the annual debris-production rate. To estimate sediment production for each scenario (e.g. Alpine Fault earthquake or heavy rainfall), we can therefore first calculate the ratio of the scenario-specific probability of failure to the mean annual probability of failure at each location. By multiplying the calculated mean annual sediment-production rate by this interval, we can then derive the probable total event-driven landslide-debris production for all feasible landslide volumes at the given location. See Appendix A4.6 for further details of this calculation.

2.3.1.6 *Sediment Production for the RCP6 2081–2100 Climate-Change Scenario*

In this study, we limit our assessment of future climate impacts to the data currently available. This is a necessary simplification and may not accurately capture the diverse effects of a future climate scenario. We opt to fix the earthquake-induced landslide sediment-production rates for the RCP6 2081–2100 climate-change scenario and increase the rainfall-induced landslide sediment-production rate in concert with the change in mean annual landslide probability from the present-day scenario. This ensures that the distribution of landslide volumes is maintained, while the frequency of future rainfall-induced landsliding increases without a commensurate reduction in the frequency of earthquake-induced landsliding. See Appendix A4.7 for full details of this calculation.

Results and Uncertainties

Calculated sediment-production rates for the RCP6 2081–2100 climate scenario are presented in Figure 2.3 (b, e). Figure 2.3 (c, f) demonstrates the predicted increase in sediment production from the calculated long-term erosion rates as a result of increased susceptibility to landsliding. As the increase in rate is directly tied to the increase in susceptibility derived from the LSS model output, the scale and distribution of increased erosion is similar to that that presented in Figure 2.11, with increases of up to 2.5× concentrated on the range front.

LSS model outputs for the RCP6 2081–2100 climate-change scenario indicate an increase in the mean annual probability of rainfall-induced landsliding (Section A3.5). However, these are based partly on present-day observations and cannot therefore account for any of the complex processes likely to drive future rates of landslide-debris production (e.g. weathering, deglaciation, vegetation change, wildfire, etc.). This point is crucial because, if landslides become more likely (i.e. the probability increases), there must be a corresponding change to keep the overall model consistent. Specifically, either the average volume of individual landslides must decrease or the total amount of debris produced must increase – or both. In fact, it is possible that the rapid pace of ongoing climate change will lead to a short-term (perhaps in the order of hundreds to thousands of years) imbalance in the rate of landslide-debris production and its removal from hill slopes through landsliding. The effects of climate change on both the size, and frequency of landslide occurrence are therefore inherently uncertain (see Appendix A4.7 for further discussion).

As uncertainties associated with many potential climate-change impacts are either unknown or cannot be quantified within the scope of this project, we are unable to quantify uncertainties for model outputs that rely on the RCP6 2081–2100 climate scenario. See Section 5.3.2 for recommendations regarding adoption of suitable uncertainty estimates.

2.4 Landslide Sediment-Distribution Model

2.4.1 Overview

The distance that a landslide travels (and therefore the potential for it to pass a given location) depends on (1) the initial gravitational potential energy of material in the landslide source and (2) the rate at which energy is gained or lost as the debris moves through the landscape. The initial energy of the landslide is a function of its initial volume and release elevation, while the rate of energy loss is a function of (among other factors) the materials that the landslide is composed of, the material along the travel path, the mode of movement and the topography along the runout path. Landslides may gain energy by entraining additional debris along the runout path. In this study, the location and potential volume of landslides is derived from the LSS and LSP models. The travel distance is then calculated using the LSD model.

Regional landslide-debris-inundation potential was modelled using the Gravitational Path Process (GPP) model developed by Wichmann (2017). This model simulates the movement of mass down-slope through a DEM from an initiation point (e.g. landslide-source area) to a deposition cell (e.g. landslide-runout area) using the single-flow-direction path-finding approach coupled with a random walk algorithm. We account for different modes of movement by modelling all trigger and source-volume cases using ‘fahrböschung’ (Heim 1932) methods for avalanche-type movements, while a two-parameter friction model (Perla et al. 1980) method is employed to represent flow-type movements.

The following sections briefly describe the derivation of inputs and modelling methods, while Appendix 5 provides a detailed description of the model implementation.

2.4.1.1 *Avalanche-Type Movements*

The ‘fahrböschung’ module (Heim 1932) of the GPP model was adopted to model avalanche-type movements in the region overseen by WCEM. We employ dry open-slope debris avalanche and rock avalanche fahrböschung angles for all landslide volume ranges derived from international and New Zealand datasets (Brideau et al. 2021b). For each volume class modelled, we adopt the 50th percentile fahrböschung representing the geometric mean of that volume class, recognising that we are not simulating runout of a single landslide volume but rather all possible volumes within the associated volume-class range (e.g. 10 up to 100 m³). The same volume-fahrböschung relationships are employed for both earthquake- and rainfall-induced avalanche-type movements.

2.4.1.2 *Flow-Type Movements*

The commonly named ‘PCM’ module (Perla et al. 1980) of the GPP model was adopted to model flow-type movements in the region overseen by WCEM. The PCM method is commonly used to represent debris-flow-type runouts (e.g. Gamma 1999; Mergili et al. 2012; Goetz et al. 2021). In the absence of any local data relating to the PCM model parameterisation for flow-type landslides, we have selected a conservative approach to parameterisation and adopt a drag coefficient that varies with catchment area (allowing increased mobility of channelised flows), as well as literature parameters derived for debris flows in Switzerland (Gamma 1999; Wichmann 2017). These have been qualitatively validated against mapped West Coast landslide-debris extents (see Section A5.5.2 for further details) to ensure that runouts from ‘flow’ models for both rainfall- and earthquake-induced landslides extend across debris-flow fans throughout the region (see Section A5.5.3 for further details).

2.4.1.3 'Avalanche' versus 'Flow' Ratio

As no data are available to constrain the probability of a given type of movement occurring in the region overseen by WCEM, we base our estimate of the relative probability of these two movement modes on observations following Cyclone Gabrielle (Leith et al., in prep.). This dataset indicates that the probability of avalanche-type movements is approximately 66%, while flow-type landslides occur 33% of the time. As no similar dataset is available for the study region, we assume that the relative probability of rainfall-induced landslide movement types is the same in this region. Anecdotal evidence suggests that flow-type movements are less common in association with earthquake triggers, so we therefore assume that flow-type movements are half as probable for earthquake-induced landslides (i.e. a ratio of 83% versus 17%). We note that this is a necessary simplification, and gathering additional data to better constrain the proportion of various movement types in the study region could significantly reduce uncertainties associated with this estimate (see Section A5.2 for further discussion).

2.4.1.4 Model Configurations

The landslide-debris-inundation hazard model accounts for both sediment transport and deposition. Each model run is configured such that the total volume of sediment released from each source point represents the total erosion by a given trigger and volume class integrated over a representative time interval. Sediment is introduced progressively from all designated source locations. This approach allows debris from multiple landslides of similar volume, and sharing a common runout path, to contribute to filling topographic depressions and forming depositional landforms. Maximum depositional depths are commonly in the order of a few metres, consistent with the scale of topography in the areas subject to landslide hazards. Finally, we run the LSD model in two separate configurations:

1. **Mean annual landslide-sediment distribution** resulting from all possible volume-class ranges, triggers and movement types.
2. **Scenario-based landslide-sediment distribution** resulting from sediment generated by a given trigger scenario. We adopt the same methods for combining the effects of all source volumes and movement types as described above.

Although the parameters controlling sediment delivery (or runout) in each configuration are essentially identical, the manner in which the location and volume of source debris is determined is unique for each configuration, as discussed in Sections 2.3.1.5 and 2.3.1.6.

Each LSD model output consists of an ensemble of 112 separate GPP model simulations to cover all considered triggers, volume classes, return intervals and movement types. The inputs for each model run were informed by mean annual sediment-production rates from the LSP model, as well as inputs specifically configured for the LSD model (see Appendix 5 for further details). In order to calculate the mean annual landslide-debris flux, we added together all calculated debris fluxes for all avalanche- and flow-type models, then applied a weighting to reflect the relative proportion of avalanche- and flow-type movements in the landscape before adding the output of both movement types together (see Section A5.7 for full details).

2.4.2 Results and Uncertainties

The mean annual landslide-debris flux for all considered triggers, volume classes, return intervals and movement modes in the vicinity of Kokiraki is presented in Figure 2.7. This indicates that, in general, landslide-debris flux is greater on steep slopes, close to the base of landforms with significant relief, and along the axis of convergent landforms (e.g. valleys), where debris is concentrated by the runout process. This is consistent with general observations in all geomorphologically active landscapes and provides confidence that the LSS, LSP and LSD models are capturing the most fundamental elements of landslide-debris-inundation hazards in this setting.

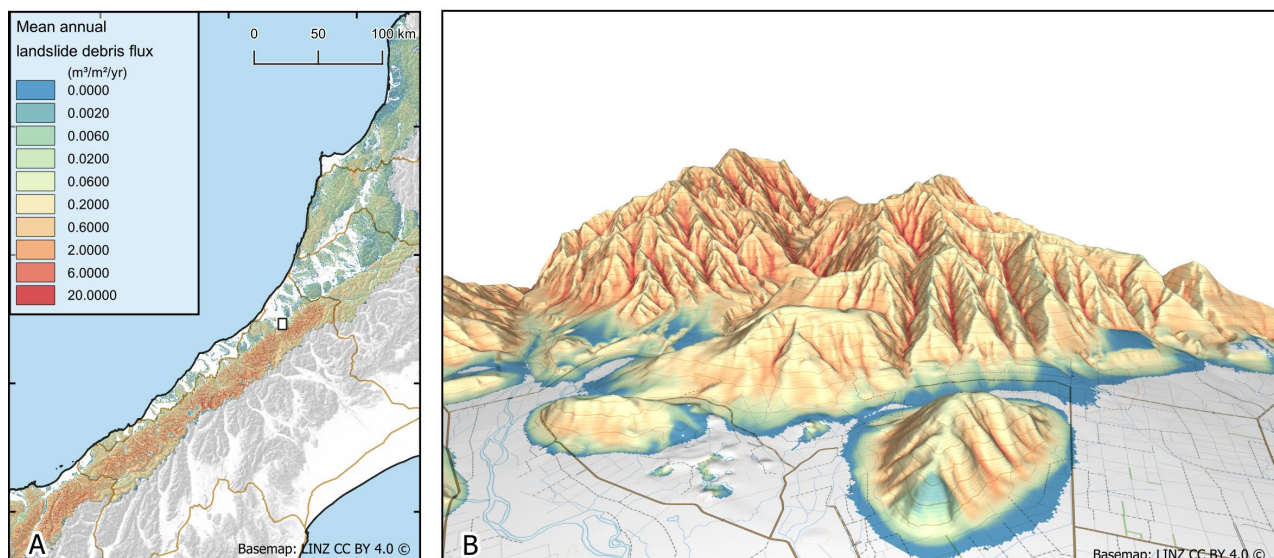


Figure 2.7 Present-day mean annual landslide-debris flux in the vicinity of Kokiraki (vertical exaggeration 1.5x).

Mean annual debris flux is fundamentally a function of landslide-debris production and landslide mobility. As a result, the magnitude of landslide-debris flux is greatest in areas where erosion rates are highest and slope gradients are sufficient to facilitate the down-slope movement of debris. The maximum extent of landslide-debris flux provides an indication of the maximum probable extent of landslide inundation from all kinematically feasible landslide-source regions. In most cases, this is defined by the largest (and therefore most mobile) feasible landslide source(s) in the contributing area, as determined by the kinematic-source model described in Section 2.3.1.2.

The magnitude of landslide-debris flux at a given location provides an integrated measure of landslide hazard in terms of the volume of landslide debris likely to pass a given location, although does not allow separation of the frequency or magnitude of potential debris-inundation events (hazard being defined here as the product of frequency and magnitude). As such, landslide-debris flux is particularly useful for assessing scenario- or event-specific hazards for which the inundation frequency is essentially 1 (assuming that all debris is released simultaneously), and the landslide-debris flux can therefore be considered to be the average magnitude of inundation at any given location. We note that the hazard assessment in this study uses a probabilistic model, and, unlike deterministic models, it therefore does not track specific landslide sources and runouts. As a result, debris flux observed at the location of discrete landslides following a triggering event is likely higher than the average landslide-debris flux estimated here. However, when summing the landslide-debris flux along a segment of a contour line (e.g. a road at the base of a slope), the cumulative flux can be expected to reflect the total debris that crosses that section. The longer the integration interval, the more accurately this cumulative landslide-debris flux represents actual debris volumes expected across the hill slope.

Aside from uncertainties associated with previously discussed LSS and LSP model inputs, landslide-debris flux outputs are a function of (1) the input variables used to define the fahrböschung ('avalanche') and PCM ('flow') model behaviours, (2) the general GPP model parameters and (3) the DEM used to simulate the runout paths. The source of uncertainties, and their effect on APLR, is discussed in detail in Section A5.9. Uncertainties in the fahrböschung model have the greatest impact on APLR near the landslide source (with a variation of up to $0.01 \times$ the most likely value at the closest location) but little effect near the maximum extent of the landslide-debris-inundation hazard zone, as more mobile flow-type movements commonly determine the inundation hazard far from the source. PCM-related uncertainties generally have minimal impact on APLR, as debris flow halts soon after the slopes become too gentle to support movement.

The random-walk component of the GPP model includes terms for debris spreading and persistence, reflecting how intact or fragmented the landslide mass is (see Section A5.3.2 for further details). These uncertainties can change the most likely APLR by up to 0.06× the most likely result near the source and by more than one million times at distant locations (where most-likely values are extremely small, so small variations therefore make large differences). However, as APLR at the most distant sites is usually negligible, such changes generally do not affect risk-tolerance thresholds for planning (see Section 5.4 for further details on risk-tolerance thresholds).

As landforms represented by the DEM determine the travel path of landslide debris, inaccuracies resulting from (for example) topographic changes since the original elevation data were generated in the 1940s (see Section 2.3.1.2), digital noise, interpolation errors or failure to accurately resolve landforms with lesser spatial extents can significantly change the travel path of debris sourced from smaller landslides. Smoothing of the DEM to improve runout-model performance for larger landslides mitigates much of the uncertainty associated with this input data (see Section A5.3.1 for further details). The accuracy of the national DEM employed here is estimated to generate spatial uncertainties of more than 6× the most likely APLR, while the 25 m resolution of the regional study is expected to generate uncertainties greater than 4× the most likely result. These two factors are the largest single source of uncertainty in this study, and care must therefore be taken when interpreting results (for example) in locations subject to inundation by smaller landslides, down-slope or smaller landforms (<100,000 m²) or where topographic changes may significantly alter the path of landslide debris runout. See Sections A7.4 and A7.6.2 for further discussion on DEM-related LSD model uncertainties, as well as mitigation strategies involving the use of up-to-date LiDAR datasets.

2.5 Landslide Debris-Inundation-Risk Model

2.5.1 Overview

The LDIR model is employed to both determine the probability of landslide-debris-inundation events (P) and evaluate associated APLR across the region overseen by WCEM.

Mean annual landslide-debris flux is the product of contributing landslide-event frequencies and magnitudes. It is therefore not possible to directly derive inundation-event frequency and magnitude (as is required for risk assessment) from LSD model outputs. Instead, the frequency of inundation events can be determined by comparing the landslide-debris flux at a given location to the volume of debris that is expected to pass that location if a landslide were to occur. Termed the ‘characteristic landslide debris flux’, we calculate the volume of debris that is expected to pass through the DEM at every location for every volume-class range. By dividing the mean annual landslide-debris flux by the characteristic flux, we are then able to calculate the total frequency of inundation by summing that of every trigger, volume, return interval and volume-class range. We then convert the inundation event frequency (1/year) to an annual probability of inundation (1) by employing a Poisson probability formula. Details of this calculation, and a benchmarking of the characteristic landslide-debris flux estimation method, are presented in Section A6.2.

APLR provides a measure of the likelihood that, within a given year (or for a given event), the damage to a building due to landslide-debris inundation will be significant enough that the cost of repairing or restoring the property (re-instatement cost) exceeds the cost of completely replacing it (replacement cost) (see Section 2.1.3 for details). This risk measure assesses the probability that the damage reaches a threshold where repair is no longer economically viable, making full replacement the more cost-effective option. We employ an empirical estimate of undifferentiated building vulnerability compiled in Massey et al. (2019) from New Zealand and international data, where the vulnerability of buildings to landslide damage has been related to landslide-inundation depth (see Section A6.3). We assume that inundation depth is equal to the geometric-mean depth of the landslide source for each volume-class range and calculate APLR by converting the inundation-event frequency to an annual probability,

multiplying this by the building vulnerability for each volume-class range. Given that all but the two smallest landslide volume-class ranges modelled in this study are assumed to generate inundation depths close to, or above, those required to cause 100% building damage, APLR varies from the inundation-probability metric only in areas where smaller ('family car'- or 'bus'-sized) landslides are dominant. Further details on this calculation are presented in Sections A6.3 and A6.4.

2.5.2 Results and Uncertainties

The annual probability of landslide-debris inundation for all considered triggers, volume classes, return intervals and movement modes is presented in Figure 2.8. This indicates that, in general, inundation probability is greatest within steep alpine catchments, where landslide debris-production rates are highest, as well as within convergent landforms (e.g. valley axes) and near the base of steep slopes, where the relatively steep path between the debris source and inundation location ensures that even smaller landslide events can reach the given location.

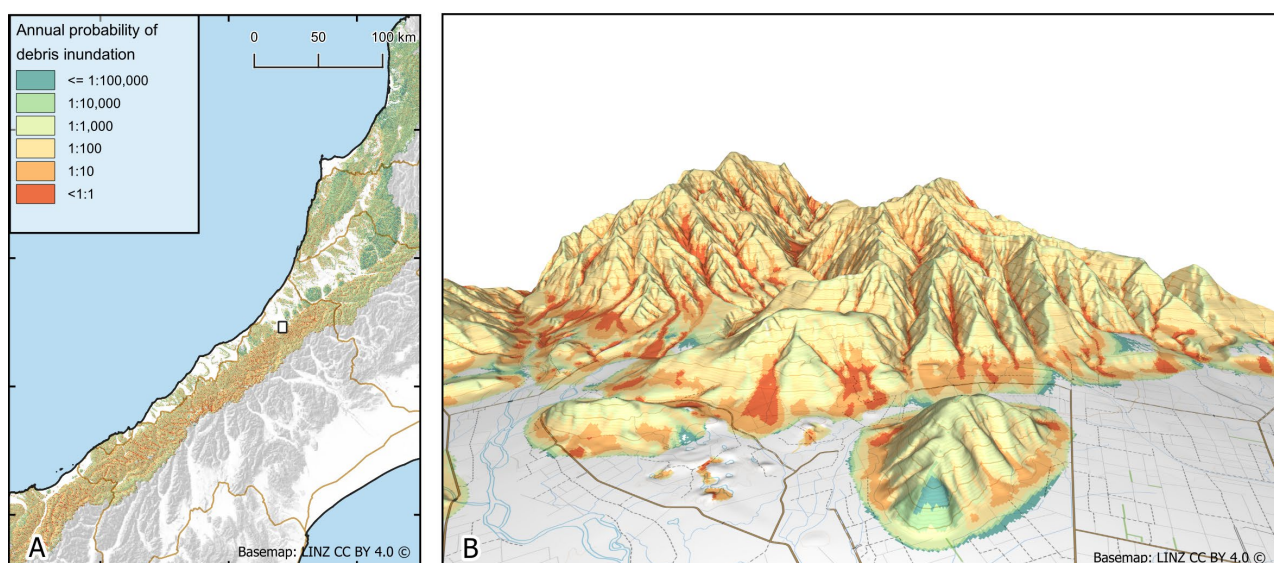


Figure 2.8 Annual probability of landslide-debris inundation in the vicinity of Kokiraki (vertical exaggeration 1.5×).

Landslide debris-production rates (presented in Figure 2.3) and landslide-debris flux (presented in Figure 2.7) both demonstrate a strong contrast between high rates in the mountainous terrain to the east of the Alpine Fault and significantly lower rates in less rugged topography towards the coast (west of the Alpine Fault). However, annual landslide debris-inundation probabilities demonstrate significantly less contrast between these two regions (Figure 2.8), as the lesser topographic relief west of the Alpine Fault limits debris production to smaller landslide classes. This effectively increases the predicted frequency of landslide events, as more small landslides are required to maintain a given debris-production rate. Despite significantly lower debris-production rates to the west of the fault, the probability of inundation therefore remains relatively high, as a relative increase in predicted frequencies partially balances the lesser availability of landslide debris in these areas (e.g. north of Greymouth).

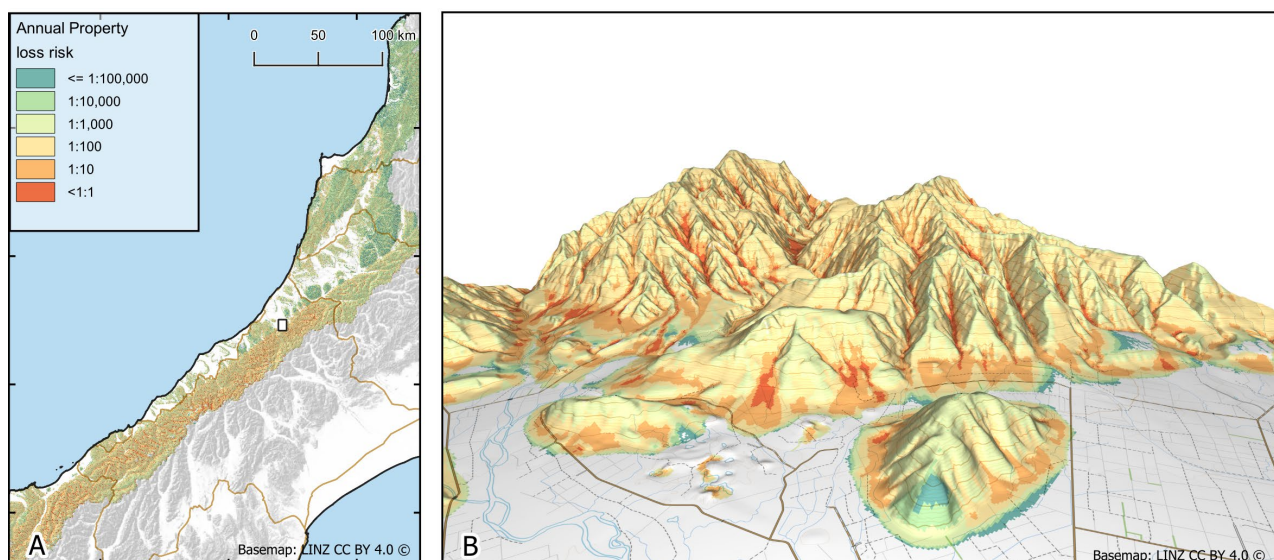


Figure 2.9 Calculated annual property loss risk in the vicinity of Kokiraki (vertical exaggeration 1.5×).

As APLR is closely tied to inundation probability, the two measures follow a very similar pattern across the region overseen by WCEM, with APLR typically slightly lower than P_i , reflecting the lesser vulnerability of buildings to smaller events (Figure 2.9). The most significant deviations between P_i and APLR occur in areas in which these smaller landslide classes dominate the risk calculation, such as adjacent to slopes from which only smaller landslides can be generated, and in debris-flow channels adjacent to steep slopes, where landslide debris flux is accumulated from a large number of cells generating shallow landslides.

APLR in the vicinity of Kokiraki is presented in Figure 2.9. Here, the annual probabilities of potentially destructive inundation events occurring along the axis of large debris-flow channels are commonly as high as 5% (0.05 1/yr), indicating that, on average, potentially destructive inundation events can be expected to occur in debris-flow channels every 20 years. With approximately 20 large debris-flow channels in the Kokiraki area, we may therefore expect to observe potentially destructive debris flows somewhere in the region every year. APLR in smaller debris channels and on planar slopes or convex fans tends to be between 0.1% and 2%, indicating that potentially destructive inundation events on individual slopes are likely to occur with a frequency of one in every period of 50–1000 years. This is consistent with general observations of event frequencies in this region and provides confidence that the LDIR model is capturing the most fundamental inundation processes in this setting (see Section 3.1 for further discussion on the frequency of damaging inundation events).

The LDIR model has uncertainties related to estimating the characteristic landslide-debris-inundation event magnitude down-slope of landslide sources, the assumed inundation depths for each volume class and the vulnerability of structures to debris inundation. While the first factor affects both probability and APLR calculations, the latter two only influence APLR. Uncertainty in event magnitude is difficult to quantify due to its dependence on debris-travel paths. However, a conservation-of-mass approach helps constrain characteristic fluxes, keeping event-frequency variation within one order of magnitude (see Section A6.2). Testing uncertainties in inundation depth and structure vulnerability by varying the critical depth from 2 m to 10 m shows a minimal impact on APLR – with a variation of up to 0.03× the most likely value at all locations (see Sections A6.5 and A7.5 for further details).



Figure 2.10 Landslides and debris flows generated by the December 2019 West Coast storm. The property in the foreground has a calculated present-day APLR of 5.3%. The calculated APLR for an RCP6 scenario is 5.7%. The risk from earthquake-induced flow-type movements is similar. There is no risk associated with avalanche-type movements from either earthquake- or rainfall-induced landslide events, as these do not travel as far as the property's location. We note that this assessment is based on a regional analysis and refer readers to Section 5.5 for further details on site-specific considerations. (Photo credit D Townsend, Earth Sciences New Zealand).

2.6 RCP6 2081–2100 Climate-Change Scenario

Consideration of the RCP6 2081–2100 climate-change scenario requires an adjustment of both the LSS model, in order to capture the spatio-temporal effects of increased landslide-induced precipitation on landslide-source generation, and the LSP model, in order to capture the effect of increased debris production as a result of more frequent landsliding.

To evaluate the change in probability of rainfall-induced landsliding for the RCP6 2081–2100 climate-change scenario, we increase 24-hour precipitation estimates for each LSS model scenario in line with NIWA's recommendations for the HIRDS V4 precipitation model (see Section A3.5 for further details). Figure 2.11 presents landslide-source probabilities for this climate scenario, as well as a comparison of the total change in landslide-source probability from present-day.

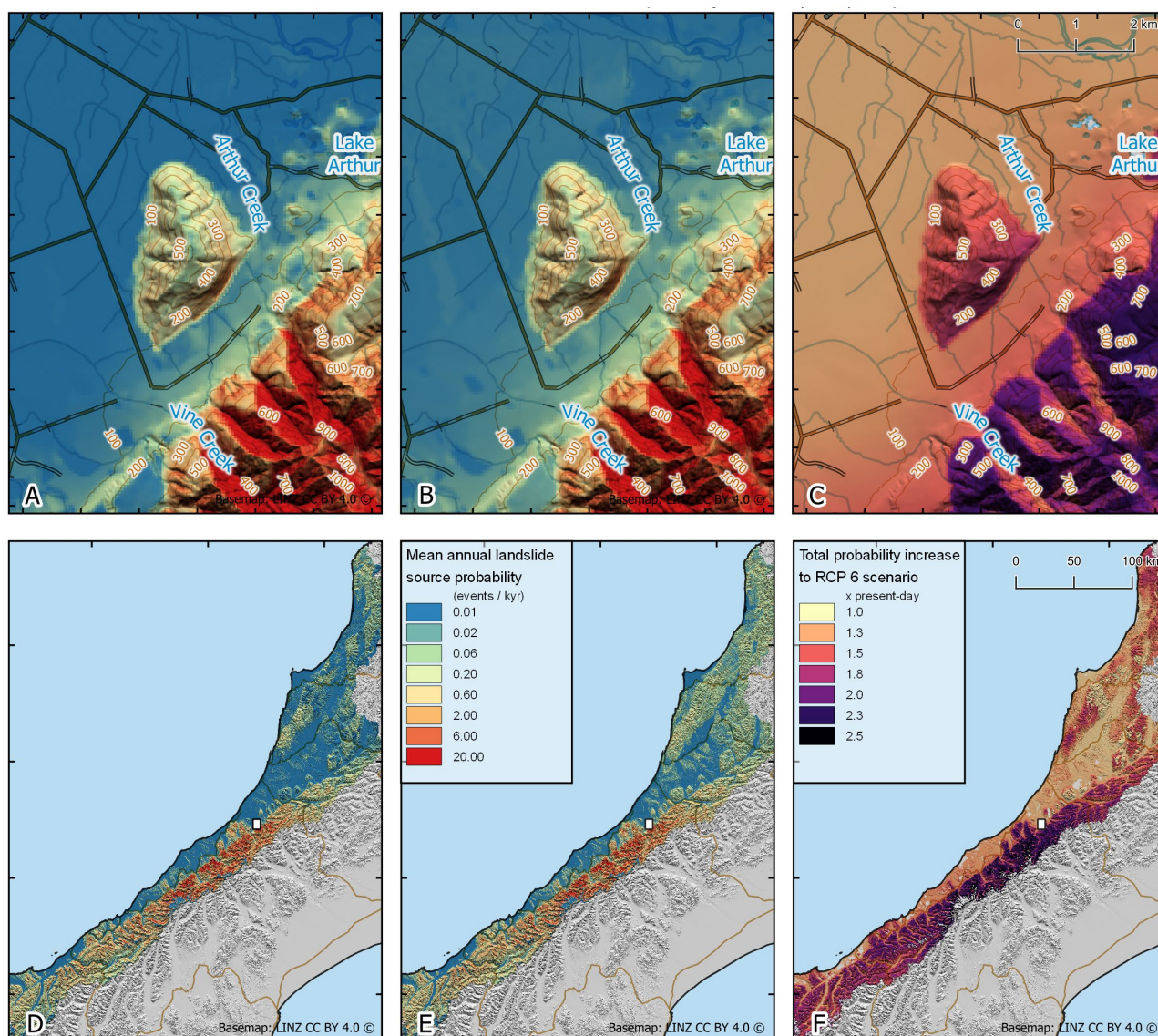


Figure 2.11 Selection of landslide source-susceptibility model outputs for the RCP6 2081– 2100 climate scenario. (a, d) Mean annual probability of rainfall-induced landslide initiation. (b, e) Total mean annual probability of landslide initiation, (c, f) Change in total mean annual source probability from present-day probability. Legend categories are consistent across maps (a), (b), (d) and (e) and maps (c) and (f). The location of the Kokiraki maps are indicated by a white box on the regional overview maps.

Due to the lack of regional data on how sediment-production and -transport rates may change under various climate-change scenarios, we use the change in LSS model rainfall-induced landslide probability – from present day to the RCP6 2081–2100 climate scenario – as an indicator for potential increases in erosion rates relative to long-term averages. We assume that (1) sediment-production rates from earthquake-induced landslides will remain consistent with present-day levels under the RCP6 2081–2100 climate scenario and (2) landslide-volume distributions will remain consistent with present-day observations. We then calculate the relative increase in rainfall-induced landslide debris production as a function of increased landslide susceptibility. This method is similar to that of Reid and Page (2003) and Neverman et al. (2023). Scaling the present-day rainfall-induced landslide debris-production rate with the LSS RCP6 2081–2100 climate scenario model output therefore enables us to capture the predicted immediate spatio-temporal increase in sediment production as existing unstable sources are exhausted. See Section A4.7 for a full description of landslide debris-production rates for this climate scenario.

The average increase in mean annual landslide sediment production derived from this method is approximately 50%. Unsurprisingly, this is not dissimilar to the predicted 31% increase in sediment yields for the same climate-change scenario in the West Coast region reported in Neverman et al. (2023). Figure 2.12 presents a comparison of mean annual debris flux for the present-day and RCP6 2081–2100 climate scenarios. In general, the maximum extent of landslide-debris inundation does not vary significantly, as the location and characteristics of the largest kinematically feasible landslides are unchanged. However, within this extent, the magnitude of mean annual debris flux is increased by up to an order of magnitude on the steep, linear slopes in the mountains in the southeast of the area. Although landslide debris production in this area only increases by approximately 2×, the cumulative effect of this debris running out downhill can cause the overall landslide hazard on these slopes to increase by an order of magnitude or more. That said, the increase in mean annual debris flux on debris fans extending from the range front is much more in line with the 2× increase in debris production. This latter increase is similar to observations throughout the region, where debris fans extending from relatively short, moderate gradient hill slopes demonstrate an approximate doubling of landslide-debris flux as a result of more debris being assigned to larger volume landslides in the source areas.

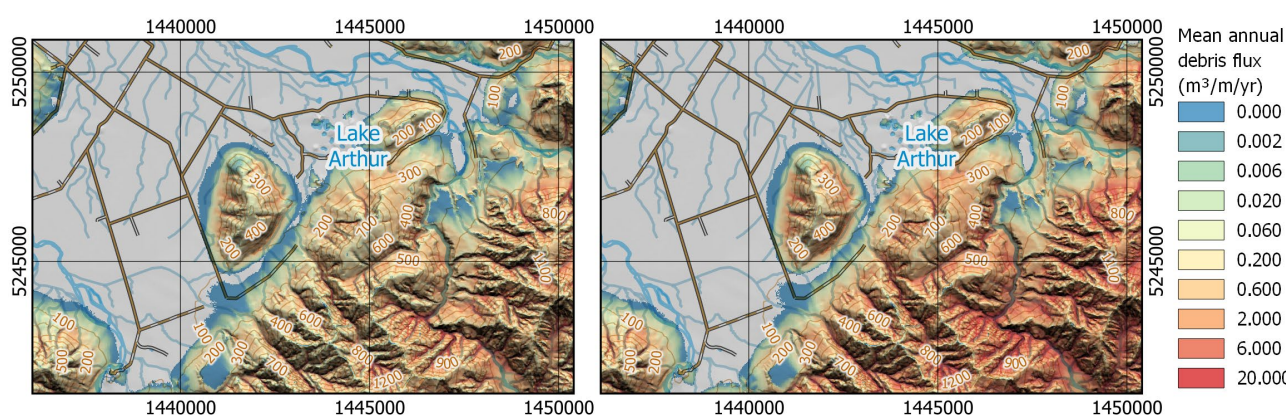


Figure 2.12 Left: Present-day mean annual landslide debris flux. Right: RCP6 2081–2100 mean annual debris flux derived from the ensemble of landslide sediment-distribution model results.

Changes in APLR in the RCP6 2081–2100 climate scenario are primarily a function of the landslide-debris flux and vulnerability of buildings to future landsliding. As we assume that landslide-volume distributions remain unchanged in the RCP6 2081–2100 climate scenario, neither the mobility of landslides nor the vulnerability of structures to inundation changes. As a result, the change in APLR is closely tied to that of landslide-debris flux, and we observe an approximate doubling of APLR in moderate- to low-gradient hill slopes where vulnerable structures are most commonly located. This is discussed further in Section 3.1.4. As mentioned in Section 2.3.1.6, a lack of constraints on input variables associated with the RCP6 2081–2100 climate scenario preclude the explicit quantification of uncertainties related to this scenario in this study. Instead, we recommend adopting the 2-sigma uncertainty for equivalent present-day outputs as the estimated 1-sigma uncertainty for the RCP6 2081–2100 scenario. See Sections 5.3.2 and A7.5 for further discussion on this topic.

2.7 Field Reconnaissance

Field reconnaissance was undertaken by a team of two GNS Science engineering geologists during 10–12 August 2023. The purpose of this reconnaissance was to (1) validate preliminary LSS and LSD model results, (2) consider characteristic debris-flux indicators and (3) identify additional risk contributors not considered to date. The reconnaissance focused on areas presenting a range of geomorphic characteristics and associated hazard scenarios and covered a region extending from Hokitika River in the south to Mokihinui in the north. An overview of the 89 localities visited during the field reconnaissance is presented in Figure 2.13. Geolocated observational data was recorded in a custom mobile application for later integration in GIS (geographic information system), alongside

182 geo-located reference photographs. Observations were classified as relating to (1) landslide source locations (13 entries), (2) landslide runout and/or fan extents (36 entries) and (3) commentary on the geomorphological setting or preliminary landslide-debris-inundation model performance (40 entries). See Section A5.5.3 for further details on the application of field observations to runout model validation.



Figure 2.13 Overview of field data collection during 10–12 August 2023. (a, b) Field photo locations and observation categories overlay on mean annual landslide-debris flux. (c) Debris-flow fan south of Lake Arthur (looking south). Calculated mean annual landslide-debris flux at the photo location is $0.8 \times 10^{-3} \text{ m}^3/\text{m}^2/\text{yr}$, and the mean annual APLR is 0.19%. (d) Shallow landslides on hillsides to the north of Lake Kanieri (looking northeast). Calculated mean annual landslide-debris flux at the photo location is $2.2 \times 10^{-5} \text{ m}^3/\text{m}^2/\text{yr}$ and APLR is 0.0012%. Landslide-debris flux at the location of the observed landslides is $6 \times 10^{-3} \text{ m}^3/\text{m}^2/\text{yr}$ and APLR is approximately 0.0013%. Legend categories are consistent across (a) and (b). The location of the Kokiraki maps are indicated by a white box on the regional overview maps.

3.0 Discussion

3.1 Consistency with Actual Experience

3.1.1 Alpine Fault Scenario Impacts

A comparison of the total sediment deposition resulting from the Alpine Fault scenario model and estimates of probable sediment production as a result of an Alpine Fault magnitude 8 (AF8) event provides a test for the LSP and LSD models. Robinson and Davies (2013) evaluated the probable total volume of landslide debris generated by an AF8 event based on a comparison with global earthquake-induced landslide catalogues. They estimated that over 1 billion m³ of landslide debris was likely to be created by the event. Based on results from the Alpine Fault LSD model presented in this study, the expected total landslide-sediment deposition is approximately 17 billion m³. Although a broad range, these two values are within 1.25 orders of magnitude. Given the uncertainties inherent in both methods, and differences in the data used (i.e. the AF8 susceptibility model was derived separately from the EIL models used to calculate annual landslide susceptibility), we consider the results to be within error.

3.1.2 Rainfall-Induced Landslide Damage

In order to evaluate the performance of the risk models presented here, we compare the predicted rate of annual building loss for all residential buildings in the study region to annualised records of natural landslide damage within the Natural Hazards Commission (NHC) Toka Tū Ake claims database.

We make use of a compilation of property data for the region (Scheele et al. 2023), based on CoreLogic property data, Land Information New Zealand (LINZ) property outlines and LINZ property parcels in order to classify the usage category for buildings across the region. We assume that all records classified as the 'Residential' or 'Lifestyle' use classes are residential buildings and that all listed claims are associated with rainfall events. In total, the dataset contains 48,000 buildings in the study area, of which 15,000 can be classified as residential. In order to evaluate the predicted average annual number of residential APLR events in the area, we sampled APLR at the centroid of all buildings and converted these into loss-event frequencies for both present day and RCP6 2081–2100 model climate scenarios. Results for both scenarios are presented in Figure 3.1.

In order to understand the principal driver of risk at all building locations in the study region, we separated out the building-loss frequencies associated with earthquake- and rainfall-induced avalanches and slides. The annual earthquake-induced landslide risk is approximately 7× that of rainfall-induced landslides. Figure 3.1a indicates that risk at the location of residential buildings is dominated by inundation from flow-type movements for both rainfall- and earthquake-induced landslides. This is perhaps unsurprising, given the significantly greater travel distance of this movement mode, but the very low relative proportion of avalanche-type movements intersecting building locations is reassuring, as these hazards are commonly associated with the presence of steep slopes and are therefore perhaps more readily recognised and avoided when selecting residential building sites.

The sum of modelled complete economic loss-event frequencies for rainfall-induced landslides under present-day climate conditions indicates an average of 1.6 residential-building losses across the study region per year. This compares favourably with the NHC Toka Tū Ake claims data for the study region, which shows that private-property owners have registered a total of 52 natural-landslide-related claims since 1997. On average, this equates to 2.0 claims per year, and, although no data are available to determine the proportion of economic loss associated with these claims, we expect many to be less than full-loss events. This higher frequency of claims therefore aligns with our estimate of the equivalent number of complete building losses. Given that there have been no significant landslide-inducing earthquakes since 1997, we are satisfied that (1) the NHC Toka Tū Ake landslide-related claims reflect rainfall events and (2) the APLR calculated in this study is adequately capturing the broader risk to existing residential-building stock. We note this is a statistical analysis of regional trends, appropriate for the regional-scale hazard and risk analysis presented here.

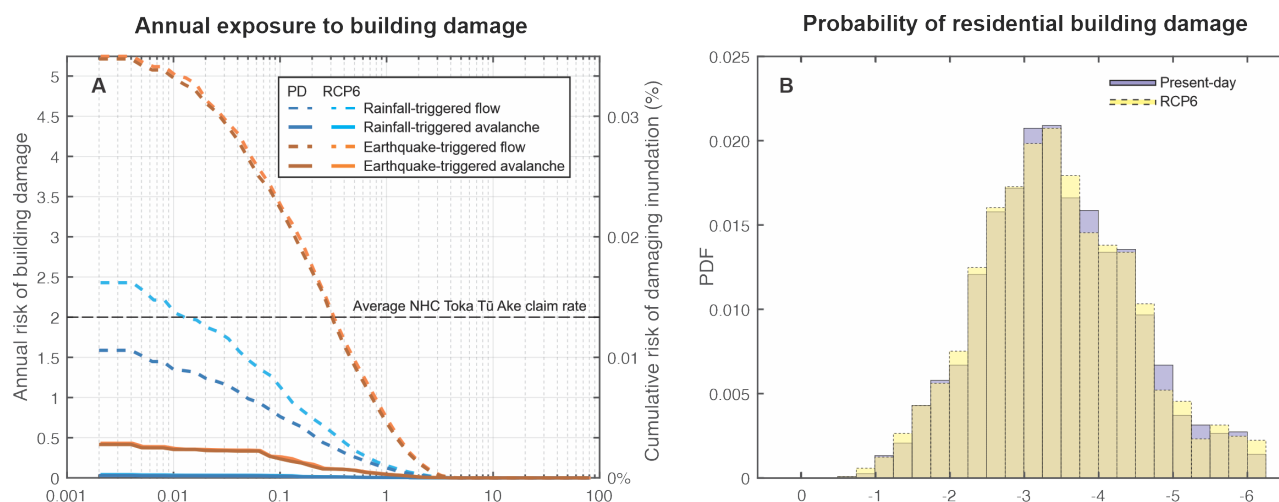


Figure 3.1 Annual property loss risk sampled at residential-building locations throughout the region overseen by West Coast Emergency Management. (a) Annual exposure to building damage: illustrates how the progressive exclusion of high-risk-building locations affects the overall annual property loss risk, showing that rainfall- and earthquake-induced flow movements dominate the risk profile. The risk is further differentiated between present-day (PD) and future (RCP6) climate scenarios. Values on the left x-axis indicate risk in terms of equivalent number of buildings with 100% damage, while the axis to the right indicates the total proportion of residential buildings with 100% damage. (b) Probability of residential building damage: represents the probability density function (PDF) of building-damage event-return intervals, indicating little systematic change in inundation probabilities under future climate conditions (RCP 6), as the majority of risk is associated with earthquake-induced landslides (which we assume are unaffected by climate change).

We evaluate the exposure profile of all residential buildings across the region by progressively excluding the highest risk structures from the datasets. This indicates that approximately 2% of all residential buildings (~300 structures) account for almost all rainfall-induced landslide risk. A slightly larger proportion (~3%) of structures account for the majority of earthquake-induced landslide risk, likely reflecting the greater reach of the generally larger volume events.

The annual risk of building damage from rainfall-induced landslides under the RCP6 2081–2100 climate-change scenario is estimated to be approximately 50% higher than present-day (Figure 3.1a). This is broadly in line with the increased landslide susceptibility and landslide-debris production in areas where the majority of the population lives. The estimated risk from earthquake-induced landslides at the location of residential buildings is unchanged under this future climate scenario. This reflects our assumptions that allow for greater rainfall-induced debris production under the future climate scenario, while leaving earthquake-induced landslide debris production unchanged. However, we note that significant uncertainties are associated with these assumptions and therefore suggest that this result should be treated with caution (see Sections 2.3.1.6 and 5.3.2).

3.1.3 Insights into an Alpine Fault Magnitude 8 Scenario

To evaluate the potential impact of an AF8 scenario on property damage, we can assess APLR at CoreLogic residential-building locations (Scheele et al. 2023) for this scenario. Results indicate that total APLR in the region equates to the equivalent of 477 buildings classified as either 'Residential dwelling' or 'Lifestyle' suffering total economic loss in the region. The majority of APLR is associated with flow-type movements (83%), while a lesser percentage is associated with avalanche-type movements (17%; see Figure 3.2a). In total, we find that 2400 'Residential dwelling' or 'Lifestyle' buildings are located within the maximum extent of the AF8 APLR. As discussed in Section 2.5.1, APLR provides an indication of the proportion of damage that a building is likely to sustain, rather than the number of buildings that suffer complete damage. As such, it is possible that all buildings within the maximum extent of the AF8 APLR suffer some degree of inundation damage. Figure 3.2b indicates the distribution of APLR across all of these buildings, indicating that, of the buildings that may be

inundated by debris, the majority can be expected to incur damage equalling approximately 30% (i.e. APLR of 0.3) of their replacement cost. Uncertainties associated with these calculations are discussed in detail in Section A7.5.

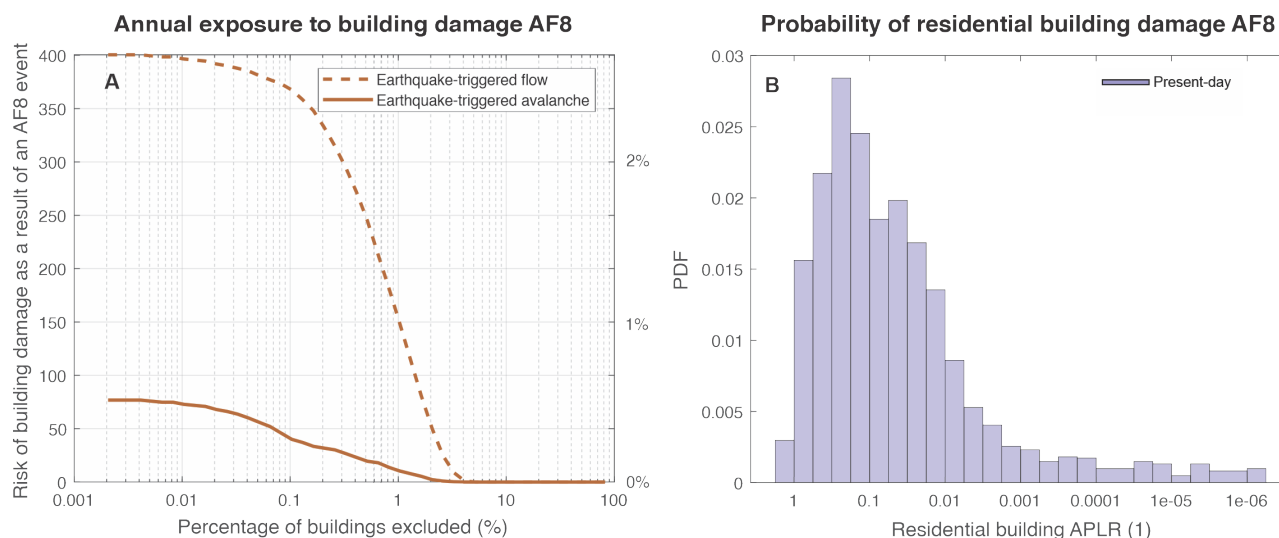


Figure 3.2 Expected annual property loss risk (APLR) for residential buildings in the region overseen by West Coast Emergency Management.

3.1.4 Insights into Overall Landslide Debris-Inundation Risk

As well as sampling present-day and future APLR at the location of residential buildings, we can gain insight into the hazard and potential risk across the landscape by sampling potential APLR at random points across the region (i.e. not just at building locations). In this case, we sampled 10,000 random points and, as with the residential-building analysis, separated out rainfall- and earthquake-induced flows and avalanches for the present-day and future climate scenarios. In order to maintain consistency with the insights presented in Sections 3.1.1–3.1.3, we employed APLR as our risk metric, although it is not expected that a building will be present at any of the random locations. The results of this landscape-wide assessment are presented in Figure 3.2. Similar to APLR sampled at building locations, we observe significantly higher risks associated with flow- rather than avalanche-type movements. However, we also observe a number of distinct differences, including that:

- The probability of damage to hypothetical buildings at random locations is between 3× and 10× higher than that of actual residential-building locations for most triggers and movement types. This suggests a general mitigation (intentional or otherwise) of associated hazards by good building-site selection.
- In terms of the relative proportion of flow- versus avalanche-type movements, the random locations indicate a much higher proportion of APLR associated with avalanche-type landslides. Again, this indicates that good, or fortuitous, site selection has largely mitigated avalanche-type landslide hazards at building locations.
- APLR associated with flow- and avalanche-type rainfall-induced landslides at random locations increases by approximately 60%, and 100%, respectively, under the RCP6 2081–2100 climate-change scenario. Risks associated with earthquake-induced landslides are unchanged, as should be expected based on the model inputs and assumptions.

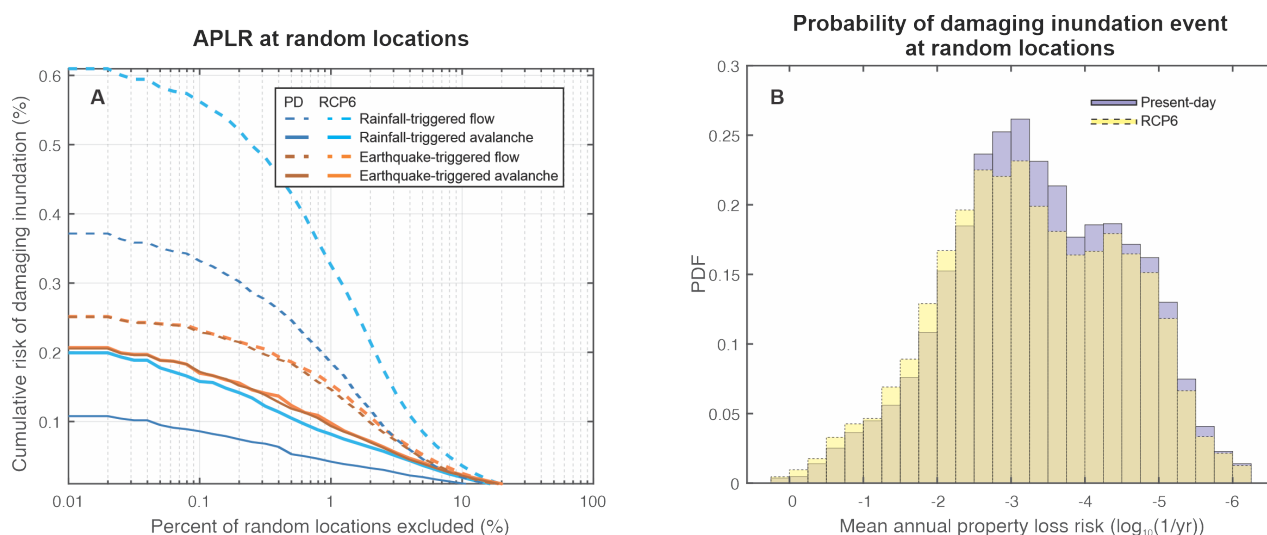


Figure 3.3 Hypothetical annual property loss risk (APLR) sampled at random locations throughout the region overseen by West Coast Emergency Management.

3.2 Landslide Source to Inundation Process Model Sensitivity to Key Uncertainties

The regional landslide-debris-inundation assessment presented here has been undertaken within the constraints of the datasets described in Appendix 2. In order to ensure consistency across the region, we limit our analysis to regionally consistent datasets. As a result, the current dataset contains a number of limitations, which may lead to under- or over-estimation of local hazard extents and associated risk. Sensitivities associated with LSS, LSP, LSD and LDIR model inputs and assumptions are mentioned alongside results in Section 2; expanded upon in Sections A3.6, A4.8 and A5.9; and discussed in detail in Appendix 7.

In order to quantitatively assess the impact of uncertainties associated with individual variables, we evaluate changes in calculated APLR at a series of locations distributed down-slope of a theoretical landslide source in a simplified 1D model (introduced in Section 2.1.5). This allows us to efficiently explore the input-parameter space without undue computational cost. However, we do note that this is a simplified model, designed to capture magnitude and trends in impacts, and is not designed to explicitly simulate inundation in a given geographic setting (see Appendix 7 for further details). Key findings from this assessment are discussed in the remainder of this section.

The down-slope movement of landslide debris is the principal hazard considered in this study, and, as such, uncertainties associated with factors controlling the potential size of landslides and long-term landslide debris-production rates have some of the greatest impacts on modelled APLR. These uncertainties include those associated with determining kinematic feasibility and deriving long-term debris-production rates, quantifying variability across the landscape (e.g. due to recent erosion, excavation or rejuvenation of existing creeping landslides) and forecasting the impact of climate change on future fracturing, weathering and erosion rates. Associated individual variable uncertainties can cause variations in the calculated APLR of up to about 2× the most likely value or more, depending on the scale of the landform, its history of modification or instability and the location of elements at risk.

As well as debris-production rates, variables affecting the volume of potential landslide sources also have considerable impact on the calculated APLR. In particular, the geometric-mean volume of earthquake- and rainfall-induced landslides, as well as the cohesion of critical joints, affect the potential volume distribution of landslides and where these may occur in the landscape. As larger landslides have the potential to travel greater distances, uncertainties associated with these variables indirectly control the distance that landslide debris travels and can cause variations in the calculated APLR of up to about 0.5× the most likely value.

As the LSD model simulates the movement of landslide debris down-slope through a DEM, uncertainties associated with the manner in which the DEM represents present-day topography can have a significant impact on the trajectory and extent of modelled landslide runout. In general, debris tends to travel farther, with less change in direction, on a coarser-resolution DEM. As a result, the extent of APLR can be greater on a lower-resolution (smoother) DEM, although the channelisation of debris, and therefore inundation hazard, along preferential travel paths will tend to be under-estimated. In addition, a more accurate DEM can be expected to better capture smaller landforms capable of re-directing or channelising debris, increasing deposition along the runout path and reducing the ability of the landslide runouts to spread. Both effects will reduce the spatial risk of landslide debris inundation.

The location and potential volume of landslide-source areas is based on an analysis of topography represented by the DEM employed in the LSP model. In this study, the national DEM (LINZ 2014) is derived from aerial photographs captured in the 1940s and has been down-sampled to 25 m resolution, consistent with the contracted specification. Failure of the DEM to accurately capture present-day topography can lead to mis-representation, or non-identification, of potential landslide-source areas. A local comparison of APLR results based on the national DEM with those calculated using a recent LiDAR-derived DEM in the Greymouth area indicates that the accuracy of the national DEM alone introduces uncertainties of ± 0.79 orders of magnitude (see Sections A7.6.2 and A7.6.3). Substituting the DEM used in this study with a LiDAR-derived DEM and running the analysis at a higher (8 m) resolution can be expected to reduce the geometric mean APLR by approximately 3.4 $\times$, while also reducing uncertainty by more than half an order of magnitude (see Section A7.6).

The uncertainties stated here are valid only for APLR outputs. Additional analysis is required to calculate uncertainties on other outputs (e.g. landslide-debris flux and probability of inundation).

4.0 Project Deliverables

The landslide-debris-inundation hazard and risk analysis evaluates the probability of landslide initiation and debris travel as (1) the mean annual product of foreseeable rainfall- and earthquake-inducing events and (2) a result of three credible landslide-inducing scenarios. These include:

- **Scenario 1:** Present-day precipitation triggers based on 50-, 100- and 250-year ARI 24-hour precipitation totals derived from the HIRDS V4 model.
- **Scenario 2:** Future precipitation triggers based on 50-, 100- and 250-year ARI 24-hour precipitation totals derived from the HIRDS V4 model rainfall projections for a future RCP6 scenario (Carey-Smith et al. 2018).
- **Scenario 3:** A regional earthquake trigger based on 100-, 250-, 500- and 1000-year ARI PGA derived from the New Zealand NSHM 2022 (Gerstenberger et al. 2022).
- **Scenario 4:** An Alpine Fault earthquake event (e.g. based on PGA derived from the AlpineF2K rupture model [Bradley et al. 2017]).

All model outputs are provided as geolocated rasters at a nominal spatial resolution of 25 m. The mean annual landslide-debris flux, mean annual probability of inundation (P_i) and mean APLR may be the most useful datasets in terms of hazard and risk, respectively.

- **Landslide-debris flux:** This dataset describes the average volume of landslide debris likely to pass a given location in a given year or in response to a given trigger. Landslide-debris flux can be useful for determining landslide-hazard zones (i.e. areas that have the potential for debris inundation) and scoping the scale of mitigation and/or remedial options in areas where inundation risk is deemed unacceptable.
- **Probability of inundation (P_i):** This dataset describes the annual probability of landslide debris of any volume inundating a given location. It can be useful for determining areas at risk of (or 'susceptible' to) any inundation events. P_i does not consider the vulnerability of elements in the study region.
- **APLR:** This dataset describes the annual probability of landslide debris damaging a hypothetical building beyond repair. It can be useful for determining areas at risk of (or 'susceptible' to) significant inundation events. APLR cannot be directly transferred to evaluate risk to elements with differing vulnerabilities (e.g. people, vehicles or isolated power/telecommunications infrastructure).

Due to uncertainties associated with the calculation of landslide debris-inundation hazard and risk in this study (see Section A7.6), we recommend that a maximum zoom be fixed at 1:500,000 for publicly facing GIS applications and/or data be down-sampled to a minimum pixel size of 150 m. These limitations may be relaxed where model results are derived from LiDAR-based DEM products (see Section A7.6.2).

Key landslide-debris flux and APLR deliverables are briefly described in the following section.

4.1 Deliverables for Landslide-Debris Flux

4.1.1 Mean Annual Hazard Maps (25 m resolution raster)

These maps indicate mean annual landslide-debris-flux hazard throughout the regions integrated over all foreseeable rainfall- and earthquake-inducing events (e.g. how much debris is likely to pass a specific location *in a given year* [m^3/m^2]).

To view the present-day mean annual landslide-debris flux for the region overseen by WCEM, see the dataset named '*WCEM_PD_MaterialFlux_MeanAnnual_25m*'.

4.1.2 Hazard Maps for Scenarios 1–4 (25 m resolution raster)

These maps indicate landslide-debris-flux hazard throughout the region as a result of landslides generated by events in Scenarios 1–4 (e.g. how much debris is likely to pass a specific location *for a given event* [m^3/m^2]).

To view the present-day landslide-debris flux associated with a HIRDS V4 50-year ARI precipitation event for the region overseen by WCEM, see the dataset named ‘*WCEM_PD_MaterialFlux_HIRDS_AR150_25m*’.

4.2 Deliverables for Probability of Inundation

4.2.1 Mean Annual Probability Maps (25 m resolution raster)

These maps delineate mean annual probability of inundation by any volume of landslide debris (e.g. the probability of some debris passing this location *in a given year*).

To view the RCP6 2081–2100 climate-scenario mean annual probability of inundation for the region overseen by WCEM, see the dataset named ‘*WCEM_RCP6_PI_MeanAnnual_25m*’.

4.2.2 Scenario-Specific Maps (25 m resolution raster)

These maps delineate the probability of inundation by any volume of landslide debris in a given scenario (e.g. the probability of some debris passing this location *in this scenario*).

To view the RCP6 2081–2100 climate-scenario AF8 scenario-specific probability of debris inundation for the region overseen by WCEM, see the dataset named ‘*WCEM_RCP6_PI_AF8_25m*’.

4.3 Deliverables for Annual Property Loss Risk

4.3.1 Mean Annual Risk Maps (25 m resolution raster)

These maps delineate mean annual probability that a hypothetical building will sustain damage such that it is uneconomic to repair (e.g. the *probability of a building being destroyed* in a given year).

To view the present-day mean annual APLR risk for the region overseen by WCEM, see the dataset named ‘*WCEM_PD_APLR_MeanAnnual_25m*’.

4.3.2 Scenario-Specific Risk Maps (25 m resolution raster)

These maps delineate the probability that a hypothetical building will sustain damage in a given scenario such that it is uneconomic to repair (e.g. the *probability of a building being destroyed* in a given scenario).

To view the present-day mean annual scenario-specific APLR risk for the region overseen by WCEM, see the dataset named ‘*WCEM_PD_APLR_AF8_25m*’.

5.0 Applying these Results

Application of Results for Planning Purposes
Key Metrics Landslide-debris flux ($\text{m}^3/\text{m}^2/\text{year}$): Volume of debris expected to pass through a location annually. Probability of inundation (P_i) (1/year): Likelihood that debris reaches a location in a given year. Annual Property Loss Risk (APLR) (loss/year): Probability that a generic building at a location will be damaged beyond economic repair annually.
Risk-Tolerance Thresholds - A risk-tolerance threshold for acceptability of APLR = $1 \times 10^{-5}/\text{year}$ (1 in 100,000) is recommended as a starting point for existing risks. - Thresholds may vary depending on activity type, societal norms and planning level.
Uncertainty Interpretation - Adopt uncertainties consistent with the 1-sigma (standard deviation) (84th percentile) confidence interval. Present-day climate: APLR uncertainty at 1-sigma is ± 1.25 orders of magnitude. RCP6 2081–2100 climate scenario: APLR uncertainty at 1-sigma is ± 2.75 orders of magnitude.
Practical Implication - When applying a risk tolerance threshold, uncertainty must be included. For example, if the threshold is $1 \times 10^{-5}/\text{year}$ and uncertainty is ± 1.25 orders of magnitude, then any location with APLR less than $5.6 \times 10^{-7}/\text{year}$ is statistically unlikely to exceed the threshold. - This means that locations with APLR values below the threshold adjusted for uncertainty can be considered as having Acceptable Risk under the current planning framework.
Use of Results for Planning Purposes (refer to Table 5.1). - Residual uncertainties limit the application of outputs for specific planning activities (see Table 5.2). - Raster datasets should be presented at a maximum zoom of 1:500,000 for publicly facing GIS applications and/or down-sampled to a minimum pixel size of 150 m. - Current outputs are suitable for Level A screening and possibly Level B planning purposes. - Reducing uncertainty by using new LiDAR data may make outputs suitable for Level B–C applications. - Outputs are not suitable for planning applications considered for Level D assessments without site-specific refinement. - Where risk exceeds thresholds or uncertainty is high, further analysis should: - Re-evaluate using higher-resolution data (e.g. 8 m LiDAR). - Incorporate local geotechnical and hazard information. - Re-classify sites based on refined risk metrics.
Refer to Section 5.3.3.2 for the decision-making framework and Sections 5.4 and 5.5 for recommended next steps and re-evaluation procedures.

5.1 Overview

Application of results from landslide-hazard or -risk analyses requires careful consideration. This report presents a ‘regional-scale basic quantitative landslide-debris-inundation hazard and risk analysis’. Where applicable, the methods employed here follow appropriate parts of the Australian Geomechanics Society framework for landslide-risk management (AGS 2007); key differences relate to the metric used to describe the frequency of landsliding and to derive the probability of spatial impact (see Appendix 8 for further details). The level of detail of the analysis is similar to ‘Level D’ basic quantitative hazard and risk analysis, as outlined in Table 4.2 of the Landslide Planning Guidance (de Vilder et al. 2024), although we note that a novel approach has been employed to calculate landslide debris-inundation hazard. We

suggest that the level of residual uncertainty currently limits the application of results to ‘Level A’ or ‘Level B’ planning purposes (de Vilder et al. 2024). We discuss determination of the required level of certainty, associated applicability of results and risk-acceptance thresholds for various applications in the following sections.

The application of LDIR model results should be evaluated in terms of hazard and risk, uncertainty and statistical confidence. Specifically, these can be defined as:

- **Risk:** The potential impact of a hazard, taking into account the likelihood of the event, vulnerability of affected entities and extent to which these are exposed. Expressed as an annual probability of occurrence, for example, 10^{-5} per annum.
- **Uncertainty:** The degree to which a value, prediction or outcome is unknown or variable. Expressed as an expected variation in the value of the prediction, for example, ± 1 order of magnitude.
- **Statistical confidence:** A statistical measure of the percentage of results that can be expected to fall within a specified range. Expressed as a percentage of all results, for example, 95%.

Although commonly used interchangeably, ‘uncertainty’ and ‘statistical confidence’ are distinctly different aspects of a hazard- or risk-based dataset. Here, the application of results from such datasets should therefore include determination of acceptable/tolerable thresholds for all three aspects. Figure 5.1 illustrates confidence intervals associated with a standard normal distribution. These statistical confidence intervals describe the proportion of data that falls within a given range of the mean (for example) in a normally distributed dataset. The value of the uncertainty represents the absolute magnitude of the variation at a given confidence level and must be derived from the dataset itself. In the following sections, we outline hazard and risk outputs from this study and suggest methods for determining appropriate risk, uncertainty and confidence thresholds.

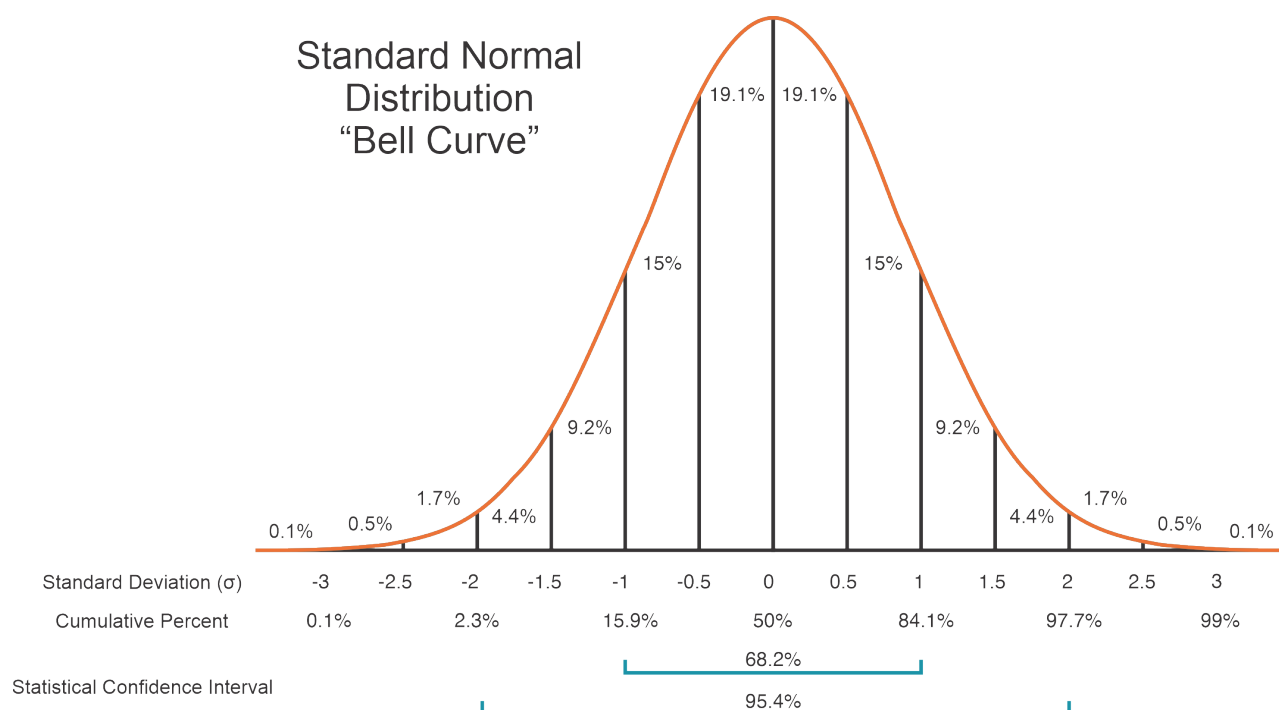


Figure 5.1 Standard normal distribution displaying the relationship between statistical confidence intervals described as standard deviations (sigma), cumulative percentage and central coverage probabilities.

Table 5.1 Five levels of susceptibility, hazard and risk analysis, with recommended applications (modified after Table 4.2 in de Vilder et al. [2024]).

Level	Description	Uncertainty / Confidence Level	Application
A	Susceptibility analysis	'Significant uncertainty remains over the frequency of landslides ... the impact of climate change ...'	This is the gateway assessment that determines where further assessment is required and where it will not be required.
B	Hazard analysis	'Significant uncertainty remains regarding potential consequences ... Uncertainty may also remain regarding landslide frequency ...'	This is the recommended minimum for plan-making and plan changes for rural (rural lifestyle and settlement), commercial and mixed use, industrial, residential (large lot or low density) and future urban zones.
C	Semi-quantitative risk analysis	'Uncertainty remains regarding landslide risk ...'	This is the recommended minimum for plan-making and plan changes for general residential, medium- and high-density residential and tertiary education zones.
D	Basic quantitative risk analysis	'... a moderate degree of confidence.'	This can form the basis for district plans, as well as site-specific analysis.
E	Detailed quantitative risk analysis	'... a high degree of confidence.'	This can form the basis for district plans; plan changes; and land-use, subdivision and building consents.

The Landslide Planning Guidance (de Vilder et al. 2024) outlines five levels of landslide susceptibility, hazard and risk analysis, providing methodological guidance, residual uncertainty estimates and potential applications. An extract of this outline is provided in Table 5.1, highlighting the five analysis levels and their description, the associated uncertainty or confidence level and possible applications for the analysis at each level. While this table can be interpreted sequentially from left to right – implying that a 'Level D' analysis 'can form the basis for district plans, as well as site-specific analysis' – uncertainties associated with the chosen analysis techniques or datasets may lead to a mis-match between the analysis level, magnitude of uncertainty and interpretation of an appropriate uncertainty level by the end user (e.g. 'significant uncertainty' may correspond to *some specific* order of magnitude, depending on the tolerance of the user group or application).

Where the stated uncertainty of an analysis does not meet the user's interpretation of 'significance', it may not be appropriate to match the application to the analysis level in the corresponding row. Instead, users should first determine the maximum acceptable uncertainty (and confidence) for each application level (e.g. ± 1.25 orders of magnitude at one standard deviation [1-sigma] for Level A and ± 0.5 orders of magnitude at two standard deviations [2-sigma] for Level E), then determine the applicability of a given hazard or risk dataset based on whichever is more limiting; the described analysis level or the reported uncertainty. This ensures that decision-making considers both methodological rigor and the practical implications of uncertainty in real-world applications.

The following sections outline recommendations regarding the determination of appropriate data outputs, risk-tolerance thresholds and associated uncertainties, as well as next steps and opportunities to re-evaluate hazard and risk.

5.2 Landslide-Debris-Flux Summary

The landslide-debris-flux outputs for the present-day climate scenario provide a 'most likely' landslide-debris-inundation hazard across the region. These are derived from our 'best estimates' of landslide susceptibility, debris production and sediment distribution. In terms of inundation extent, these are slightly conservative, as landslide-sediment distribution has been modelled at 25 m resolution, while

our sensitivity analyses indicate a general decrease in landslide travel distance with increasing model resolution. In terms of inundation magnitude, the relative smoothness of the 25-m-resolution DEM tends to reduce variability in the magnitude of debris flux, thereby slightly under-estimating the maximum flux in channels and over-estimating on gentle ridges and slightly convex landforms.

Landslide-debris flux is particularly useful for scenario-specific hazard assessments, where the inundation frequency is assumed to be 1 (i.e. all debris is released simultaneously). In such cases, landslide-debris flux represents the expected average magnitude of inundation at a given location.

As this study employs a ‘process-based’ hazard model rather than an ‘event-based’ approach (see Section 1.1 for details), individual landslide sources and runout paths are not explicitly tracked. As a result, the debris flux observed in association with specific landslide events following a given trigger is likely higher than the average landslide-debris-flux values presented here. However, when summing landslide-debris flux along a defined segment of terrain – such as a road at the base of a slope – the cumulative debris flux provides a more representative estimate of the total volume of debris crossing that section. The longer the segment used for integration, the more accurately this cumulative landslide-debris flux reflects actual debris volumes expected across the hill slope.

This makes landslide-debris flux a valuable tool for identifying areas with high debris-flow potential, assessing infrastructure vulnerability and supporting hazard-based land-use planning.

5.3 Summary of Annual Property Loss Risk

5.3.1 Present-Day Climate Conditions

The APLR outputs for the present-day climate scenario provide a ‘most likely’ APLR to hypothetical buildings in the area exposed to landslide debris-inundation hazards. These represent our ‘best estimates’ of landslide susceptibility, debris production, sediment distribution and property vulnerability. These are slightly conservative, as landslide-sediment distribution has been modelled at 25 m resolution, while our uncertainty analysis suggests that, on average, this may over-estimate risk by at least 2×.

We explore uncertainties resulting from model assumptions and input parameter ranges by testing combinations of 29 key input parameters and evaluating their impact at various locations along a hypothetical 1D profile. Uncertainties relating to the accuracy of the DEM and resolution of the LS-IPM analysis are evaluated by comparing results derived from the national DEM (LINZ 2014) against those derived from a recent LiDAR DEM (LINZ 2022) at resolutions of 8 m and 25 m. Based on results of these analyses, and allowing for uncertainties unable to be captured by these methods, we suggest that 68% of APLR results can be considered to fall within ± 1.25 orders of magnitude of the ‘most likely’ output, while 95% of APLR results can be considered to fall within ± 2.75 orders of magnitude. Although uncertainties are not normally distributed, we recommend treating these ranges as equivalent to 1- and 2-sigma intervals (i.e. the 84th and 98th percentiles), respectively.

These uncertainty bounds imply that an APLR of 10^{-4} per year, as presented in this report, could reasonably vary between $10^{-5.25}$ and $10^{-2.75}$ per year. However, it is important to note that values outside of this range are also possible. Specifically, there is a 5% chance that APLR values will be less than $10^{-6.75}$ or greater than $10^{-1.25}$ per year.

5.3.2 RCP6 2081–2100 Climate-Change Scenario

APLR maps for the RCP6 2081–2100 climate-change scenario represent a ‘best estimate’ based on ‘most likely’ estimates for all parameters for which the uncertainty can reasonably be determined. As all uncertainties on constrained parameters are identical to those of the present-day model, the associated uncertainty may be expected to remain unchanged. However, a number of unconstrained input parameters for the RCP6 climate scenario do not allow for a complete evaluation of uncertainties

(see Section 2.3.1.6 for further discussion). As such, it is possible that APLR may exceed our ‘best estimate’ by several orders of magnitude. Given these limitations, we conservatively recommend adopting a 1-sigma (84th percentile) uncertainty estimate of ± 2.75 orders of magnitude for hazard and risk outputs relating to this scenario, which is equivalent to the 2-sigma statistical confidence interval of the present-day model. This can be reduced to ± 1.75 orders of magnitude with the incorporation of a LiDAR-derived DEM and a ± 1.00 order-of-magnitude if the model resolution is also increased to 8 m or more (see Section A7.7). The 2-sigma (98th percentile) uncertainty cannot be constrained without additional data to better characterise input variability.

5.3.3 Applying Risk Metrics

5.3.3.1 Determining Tolerance Criteria

Risk evaluation is inherently uncertain. When using hazard- or risk-model outputs for specific applications – such as emergency preparedness or land-use planning, including plan changes, notices of requirement and consenting – it is essential to consider both the indicated risk level and associated uncertainty at an appropriate statistical confidence level.

For life-safety-critical structures, it is standard practise to adopt a precautionary approach, meaning that risk assessments should prioritise the upper bound of estimated risk rather than the central or lower values. Figure 5.2 provides a framework for evaluating both existing and new risks while accounting for residual uncertainty in risk calculations.

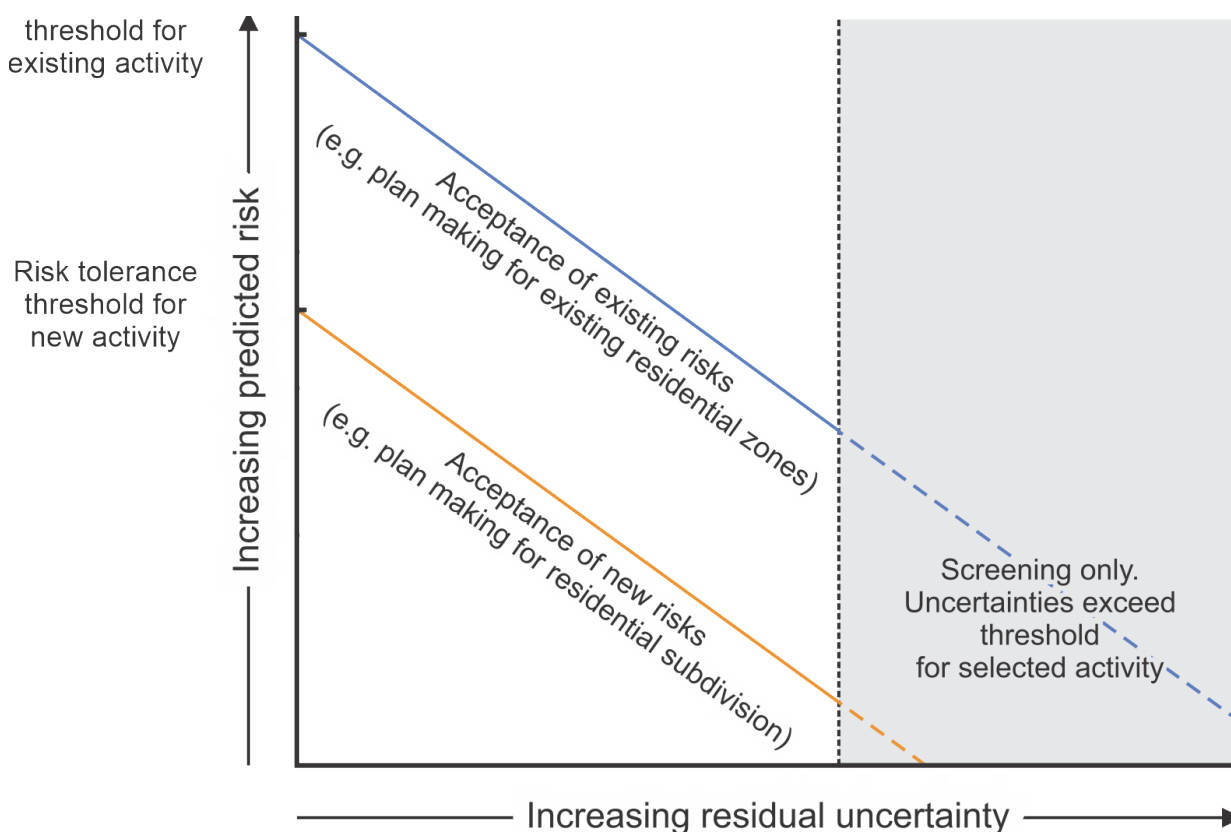


Figure 5.2 A framework for considering predicted risk (e.g. modelled annual property loss risk in this study) and associated uncertainty when planning for existing and new activities (adapted from a figure initially published by USBR [2025]). The acceptance threshold for existing risks (blue line) can be higher than that for new risks (orange line) for the same activity (e.g. residential housing). Predicted risks that fall below the respective acceptance threshold are considered acceptable for the given use case. If uncertainty is deemed too significant, risk predictions may be unsuitable for planning decisions. Instead, these can be used for screening and guidance where additional assessment is needed to refine risk estimates.

In this framework, the risk-acceptance threshold may be higher for existing risks than for new ones. This reflects the reality that existing developments may have different tolerances due to historical approvals, economic constraints or established land use, a concept adopted in the Proposed Otago Regional Policy Statement (Otago Regional Council 2021).

Adopting a precautionary approach, the appropriate predicted risk level at which a given activity can be considered acceptable decreases with increasing residual uncertainty. The gradient of each threshold represents a precautionary reduction in acceptable risk as uncertainty increases. Critical facilities (e.g. hospitals, emergency infrastructure) may require stricter standards, such as using a 2-sigma rather than 1-sigma uncertainty bound. This will result in the adoption of a greater representative uncertainty, and therefore a steeper gradient, meaning that the acceptable predicted risk will reduce more aggressively.

For example, if a study states a ± 1 order of magnitude uncertainty at 1-sigma, the acceptable predicted risk may be:

- equal to the risk acceptance threshold for less critical applications; or
- one order of magnitude lower than the threshold for more critical applications where the 84th percentile is deemed acceptable; or
- for the most critical applications, reduced by an uncertainty corresponding to the 98th percentile. If the corresponding uncertainty is too large, alternative options may need to be considered before proceeding.

This structured approach ensures that both uncertainty and confidence are explicitly accounted for in risk-based decision-making.

5.3.3.2 Creation of Regional Landslide-Debris-Inundation Hazard or Risk Maps

The following steps outline a process by which lifelines and service organisations may use datasets presented in this report to categorise landslide-debris-inundation risk for a given activity (e.g. a new development):

1. Determine an appropriate hazard or risk acceptance threshold (e.g. 10^{-5} per annum).
2. Define the maximum allowable uncertainty threshold (e.g. two orders of magnitude).
3. Determine an appropriate statistical confidence interval (e.g. 1-sigma).
4. Select a dataset that best represents landslide-debris-inundation hazard or risk for the activity (e.g. mean annual APLR). If the dataset represents a risk output, it is essential to ensure that the applied vulnerability function is appropriate to the considered activity (see Section 2.1.3).
5. Select a representative uncertainty from the dataset by referencing the statistical confidence interval determined in Step 3 to the reported statistical uncertainties of the dataset (e.g. ± 1.25 orders of magnitude at the 1-sigma confidence interval for mean annual APLR).
6. Check that the representative uncertainty reported for the dataset (e.g. ± 1.25 orders of magnitude; from Step 5) is less than the maximum allowable uncertainty for the activity (two orders of magnitude; defined in Step 2).
7. If the representative uncertainty exceeds the maximum allowable for the activity (which it does not in this example), application of the dataset may be limited to 'screening' purposes. Explore options to reduce either global or local uncertainties before proceeding. These may include increasing DEM accuracy and/or model resolution, refining model inputs, gathering additional data or adjusting assumptions. If the uncertainty is within acceptable limits, proceed to Step 8.
8. Calculate an 'adjusted tolerance threshold' by reducing the hazard- or risk-acceptance threshold determined in Step 1 by the representative uncertainty (identified in Step 5) (e.g. $10^{-6.25}$ per annum).

9. Compare the predicted hazard or risk from the dataset to the adjusted tolerance threshold and classify outputs as ‘Significant’, ‘Tolerable’ or ‘Acceptable’ (as proposed in Otago Regional Council [2021], or similar terminology from the provisional New National Policy Statement [Ministry for the Environment 2025]) based on whether the predicted level is above, near or below the adjusted tolerance threshold (in this example, the activity is likely to be considered acceptable in areas where APLR values are less than $10^{-6.25}$ per annum).

This approach provides a clear and transparent path for decision-making and allows for consistent application of guidance based on calculated risk and uncertainties, independent of the method employed to derive risk estimates.

5.4 Recommended Next Steps

Risk criteria established in other contexts, along with data on natural hazards and risk tolerance in New Zealand, can help inform the development of risk metrics and criteria for representative authorities in relation to landslide-debris-inundation risk within the study area. Such information can guide the definition of quantitative thresholds that align with existing practises and reflect New Zealanders' observed tolerance (or lack thereof) for risk associated with similar hazards (e.g. Taig et al. 2012; Kilvington and Saunders 2015; Massey et al. 2021b; Toka Tū Ake EQC 2023; de Vilder et al. 2024; ResOrgs [2025]).

Define a Sustainable Risk Threshold

Representative authorities should consider defining risk criteria to assess the tolerability of landslide-debris-inundation risk based on societal acceptance of comparable risk levels for given activities from other sources.

In this study, we calculate risk based on economic loss to hypothetical buildings (APLR), as this is more readily verifiable than life-based metrics at the regional scale. However, landslides do have the potential to cause fatalities, and life-based metrics such as Annual Individual Fatality Risk (AIFR) can be equally appropriate in local-scale studies. Where both metrics are known, a first-past-the-post principle in risk re-categorisation can eventually be employed to ensure that decisions prioritise whichever of the two metrics – fatalities or property damage – poses the higher threat.

In the proposed Otago Regional Policy Statement (Otago Regional Council 2021), the same tolerance threshold is currently proposed for both APLR and AIFR. Following this guidance, as well as other international and national risk-tolerance threshold examples (e.g. Toka Tū Ake EQC 2023; de Vilder et al. 2024) a sustainable APLR threshold may fall within the range of 1×10^{-6} to 1×10^{-4} per year (depending on whether the development is new or existing), in line with both New Zealand risk tolerances and international regulatory practises. A reasonable starting point for deliberation could be **1×10^{-5} per year** (equivalent to a 1 in 100,000 annual probability of property loss).

Define an Appropriate Level of Confidence

Risk-tolerability assessments should incorporate acceptable levels of confidence, recognising that all risk estimates have inherent uncertainty. Representative authorities should specify whether risk thresholds are based on mean values or 1- or 2-sigma (84th or 98th percentile) confidence bounds. Using Intergovernmental Panel on Climate Change terminology, the chance that true annual risk exceeds the 1-sigma threshold can be described as *Unlikely*, while exceedance of the 2-sigma threshold would be *Exceptionally unlikely* (Mastrandrea et al. 2010). The acceptable confidence should reflect the criticality of the activity, with more conservative confidence ranges (e.g. 2-sigma) required for high-risk applications (e.g. emergency infrastructure, densely populated areas). For context, Massey et al. (2021b) were requested to provide data describing the 1-sigma confidence level for the evaluation of AIFR as a result of landslide debris inundation in the Kaikōura district.

We suggest that adopting a **1-sigma** confidence interval is likely to be appropriate for most regional landslide-risk applications, as the cost associated with generating data sufficient to constrain 2-sigma uncertainties to acceptable thresholds is likely to outweigh benefits gained through the improved accuracy of the prediction.

Determine an Acceptable Uncertainty Threshold

There is an inherent trade-off between the spatial scale of a dataset and its absolute uncertainty at the local level. The representative authorities should determine a threshold at which uncertainty becomes significant enough to prevent the reasonable determination of acceptable risk for given activities. If the uncertainty on a model output is greater than the determined significance threshold, the results should instead be used for the identification of areas in which tighter constraints are required ('screening') before determining acceptability of certain activities.

As there is little precedent for setting specific uncertainty thresholds for different activities, we provide guidance based on expert opinion in Table 5.2. The table provides a starting point for determining approximate thresholds that can be used to evaluate data suitability, assuming a general 0.25 order-of-magnitude decrease in residual uncertainty across application levels A–D. For the most critical applications ('Level E'), the underlying uncertainty is not reduced further; instead, the required confidence is increased (e.g. from 1-sigma to 2-sigma) so that rare but extreme events are more reliably captured. These thresholds will inevitably vary depending on society's tolerance for uncertainty and the consequences of exceedance. Accordingly, West Coast Regional Council should carefully consider which thresholds are most appropriate for local planning purposes.

Table 5.2 Indicative order-of-magnitude uncertainty thresholds and associated confidence levels that may be applied to determine the utility of Annual Property Loss Risk datasets for a range of planning purpose levels.

Level	Approximate Uncertainty Threshold	Confidence	Example Implication	Application
A	$> \pm 1.25$	1-sigma (84 th percentile)	It is <i>unlikely</i> that the true annual number of events in an area will exceed about 18× the expected value.	This is the gateway assessment that determines where further assessment is required and where it will not be required.
B	± 1.00	1-sigma (84 th percentile)	It is <i>unlikely</i> that the true annual number of events in an area will exceed about 10× the expected value.	This is the recommended minimum for plan-making and plan changes for rural (rural lifestyle and settlement), commercial and mixed use, industrial, residential (large lot or low density) and future urban zones.
C	± 0.75	1-sigma (84 th percentile)	It is <i>unlikely</i> that the true annual number of events in an area will exceed about 6× the expected value.	This is the recommended minimum for plan-making and plan changes for general residential, medium- and high-density residential and tertiary education zones.
D	± 0.50	1-sigma (84 th percentile)	It is <i>unlikely</i> that the true annual number of events in an area will exceed about 3× the expected value.	This can form the basis for district plans, as well as site-specific analysis.
E	± 0.50	2-sigma (98 th percentile)	It is <i>exceptionally unlikely</i> that the true annual number of events in an area will exceed about 3× the expected value.	This can form the basis for district plans; plan changes; and land-use, subdivision and building consents.

Comparing the uncertainties for present-day and RCP6 APLR datasets provided with this report (both **greater than ± 1.25** orders of magnitude) with approximate uncertainty thresholds detailed in Table 5.2, we suggest that **present-day APLR outputs** are suitable to be employed for **‘Level A’** or **‘Level B’** planning applications, if presented at an appropriate spatial resolution (see Section 4). RCP6 2018–2100 climate-change-scenario outputs should be limited to **‘Scoping’**, or possibly **‘Level A’** planning purposes, unless spatial uncertainties are minimised by repeating the analysis using an 8 m resolution LiDAR DEM (see Section 5.3.2).

Communicate the Implications for this Hazard and Risk Analysis through the One Plan Process

Representative authorities should consider how to communicate the implications for landslide-debris-inundation hazard and risk through future Te Tai o Poutini Plan (One Plan) Change processes. As detailed in this section, landslide-debris flux and APLR outputs can form the basis for a range of planning applications, depending on the confidence, uncertainty and risk criteria adopted for various activities by representative authorities. Less-critical activities may include:

- Identifying land ‘susceptible’ to land-debris-inundation hazards in overlays and providing indications of where further analysis should be undertaken.

More-critical activities may include plan-making and plan changes in:

- Rural (rural lifestyle and settlement), commercial and mixed use, industrial, residential (large lot or low density) and future urban zones.
- General residential, medium- and high-density residential and education zones, as well as open space.

And as the District Plan moves from development to implementation:

- Site-specific analysis and consenting input.

Where stated APLR uncertainties do not meet the statistical confidence and uncertainty thresholds determined by West Coast Regional Council for selected activities, outputs may be used as a screening tool to guide where local refinement or more site-specific analyses are required (e.g. see Figures 6.1b and 6.1c of de Vilder et al. [2024] describing the process for resource and building consents).

Incorporate Event-Specific Landslide-Debris-Flux Outputs into Emergency-Management Plans

Datasets describing scenario-specific landslide-debris flux can be employed in a range of emergency-management applications. As these datasets provide an indication of the volume of material that may be expected to pass a given location in a given scenario, the outputs could be used, for example, for estimating probable volumes of landslide debris passing through sections of highway or entering river networks in response to heavy rainfall or earthquake events.

5.5 Re-Evaluation of Hazard and Risk and Re-Classification of Sites

Given the regional scale of the hazard and risk models provided with this report, a provision should be included whereby site-specific information for a site/dwelling could be used to re-evaluate the landslide risk, thus allowing the given site to be re-classified (e.g. changing its hazard-area status through a certification process). This process was allowed for in Christchurch City Council’s replacement District Plan (Quigley et al. 2020). In 2016, the Independent Hearings Panel agreed to this provision, provided that any re-assessment should follow the same method and approach adopted for the district-wide assessments.

The regional-scale basic quantitative landslide-debris-inundation hazard and risk analysis presented here is specifically configured to provide a physically based, adaptable and scalable regional hazard and risk analysis. Results should be expected to vary with the inclusion of higher-resolution or site-specific data.

When evaluating the potential impact of additional datasets on model uncertainties, we recommend that users reference Sections A7.1 and A7.6.3. Section A7.1 provides an indication of the relative change in uncertainties associated with each input variable in the LS-IPM assessment. Section A7.6.3 provides an evaluation of the relative impacts of improving DEM accuracy and model resolution. Incorporating data to more tightly constrain variables with the greatest uncertainty and largest impact on calculated APLR can be expected to result in the most impactful change in landslide hazard and risk. These should therefore be initial targets when considering refinement of results to allow re-classification of sites.

The effect of locally increasing the resolution of landslide-debris-flux and APLR predictions is particularly easy to test, and an example is presented for the Greymouth area in Figure A7.4 (see Section A7.6.2). Increasing the resolution of the LSP and LSD models can provide better representation of potential landslide sources and improve the tracking of potential landslide-debris-inundation paths. This is most relevant for locations close to hill slopes, down-slope of landforms with spatial extents less than 100,000 m² and areas of subtle channelisation. Incorporation of a more accurate topographic model may result in both increases and decreases in APLR, depending on the scale and variability of local landforms and their representation in the DEM. However, we overall find that reducing from 25 m to 8 m resolution and employing a recent LiDAR-derived DEM can be expected to reduce the mean APLR by approximately 3.4×, while also reducing 2-sigma (95th percentile) uncertainties from ±2.75 to ±1.0 order of magnitude (see Section A7.7).

In addition to a fundamental change in the DEM accuracy and model resolution, additional datasets may allow the revision of hazard and risk outputs by:

- Better constraining long-term sediment-production rates, for example, with the aid of sedimentological data, improved specific-sediment-yield estimates (possibly including Dymond et al. [2010], Hicks et al. [2019] and Neverman et al. [2023]), dating of depositional landforms or determination of local erosion rates.
- Better constraining landslide susceptibility with the aid of geotechnical data and/or mapping of historical landslides and improved observations of source geometry and/or runout characteristics.
- Better characterising landslide-source geometries. In particular, explicitly accounting for spatially variable, depth-dependent cohesion and friction estimates based on geological data.
- Better constraining the spatial distribution of potential landslide-source volumes by updating kinematic-source models for every landslide volume-class range.
- Generating characteristic landslide-debris-inundation frequency-magnitude distributions tailored to local site conditions with the aid of sedimentological, geotechnical or dynamic landslide-modelling data.
- Better constraining susceptibility estimates with refined or updated rainfall or earthquake scenarios.
- Refine estimates of building vulnerability using numerical or physical analogue models.

We recommend discussion with a geotechnical expert prior to undertaking any additional investigations.

6.0 Summary and Conclusions

WCEM commissioned GNS Science, now part of Earth Sciences New Zealand, to assess landslide hazards and risks across its jurisdiction, focusing on landslides generated by earthquakes and rainfall that potentially present a risk to property and life.

This study presents a regional-scale basic quantitative landslide-debris-inundation hazard and risk analysis, conducted in two phases:

- Stage 1 identified landslide-debris-inundation hazard-footprint areas (Leith and de Vilder 2022).
- Stage 2 integrated these hazard models with probabilistic landslide-initiation and -runout models to estimate annual building loss risks.

The study leverages advances from the MBIE-funded GNS Science Extreme Weather SSIF uplift, developed in response to Cyclone Gabrielle (Leith et al., in prep.).

Landslide-hazard metrics employed include:

- **Landslide-debris flux:** Quantifies the expected volume of debris passing a location per year or per event.
- **Probability of Inundation (P_i):** Represents the likelihood of debris reaching a location annually.
- **APLR:** Estimates the probability of a generic building sustaining damage beyond economic repair.

The methodology differs from traditional landslide-hazard and -risk models by considering debris movement from all potential source cells, rather than relying on a limited number of predefined landslide sources. This approach provides a spatially comprehensive regional assessment and aligns with applicable sections of the Australian Geomechanics Society Landslide Risk Management Guidelines (AGS 2007).

This analysis was conducted using spatially consistent datasets at 25 m resolution, aligning with a 'Level D' basic quantitative hazard and risk analysis (de Vilder et al. 2024). However, residual uncertainties vary spatially, necessitating the adoption of at least ± 1.25 orders of magnitude of uncertainty for present-day conditions and ± 2.75 orders of magnitude for future RCP6 (2018–2100) climate conditions. These uncertainty levels suggest that outputs are likely to be suitable for screening purposes (equivalent to 'Level A' or 'Level B' planning purposes as described in de Vilder et al. [2024]), and their use in higher-criticality decision-making should be carefully evaluated. West Coast Regional Council is advised to establish required confidence levels and associated uncertainty thresholds for various activities before applying landslide-debris-inundation outputs to planning decisions or policy changes.

We find that:

1. Landslide-debris-flux, P_i and APLR values are highest in areas near steep slopes, channelised gullies and debris fans in regions where annual landslide debris-production rates are greatest.
2. Rainfall-induced landslides dominate landslide-debris flux in range-front areas, while earthquake-induced landslides are the primary contributor northeast of Greymouth. This reflects the dominant landslide triggers in each setting.
3. Existing buildings are most exposed to debris flows, debris avalanches and rock avalanches (flow-type landslides), while fewer are at risk from debris slides (avalanche-type movements). This is due to the greater runout distances of flow-type landslides and historical urban planning that have limited development in areas prone to less mobile landslides.
4. 95% of APLR is concentrated in just 1% of existing buildings in the region overseen by WCEM.

5. Under RCP6 (2081–2100) climate-change scenarios, APLR for rainfall-induced landslides at existing buildings is projected to increase by approximately 50%.
6. Residual uncertainties vary spatially and increase with distance from landslide sources. These are particularly large in areas adjacent to topography with spatial extents less than 100,000 m².
7. The largest uncertainties are associated with the quality of the DEM used for runout modelling, spatial resolution of the modelling and sediment availability for landsliding.
8. Sediment availability and landslide-volume distributions are particularly uncertain for future climate scenarios.
9. Planning decisions should allow for site-specific assessments to refine hazard classifications. This may include:
 - a. Substituting the national DEM with improved topographic data.
 - b. Increasing the nominal spatial resolution of the LS-IPM analysis.
 - c. Site-specific hazard assessments.
 - d. More-detailed landslide-debris-inundation models.
 - e. Re-assessment of vulnerability functions for structures.

This study provides a spatially comprehensive assessment of landslide risk in the region overseen by WCEM, offering critical insights for regional planning and emergency management. It is recommended that West Coast Regional Council carefully consider hazard and/or risk thresholds, appropriate confidence levels and acceptable uncertainty thresholds prior to the implementation of study results in future Te Tai o Poutini Plan (One Plan) Change processes and emergency-management planning.

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APPENDICES

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APPENDIX 1 Datasets

The following datasets have been used for development of the landslide-debris-inundation hazard analysis conducted in this study.

Table A1.1 Digital elevation models.

Type	Description	Coverage	Reference
Raster	National digital elevation model (8 m ground resolution)	Full	LINZ (2014)

Table A1.2 Landslide catalogues.

Type	Description	Coverage	Number of Features	Reference
Vector	GNS Science landslide database	Full	1970	Rosser et al. (2017)
Vector	Shallow landslides	Partial	118	Embersson et al. (2016)
Vector	Shallow landslides	Partial	689	Hilton et al. (2011)
Vector	Shallow landslides	Full	7686	Hovius et al. (1997)
Vector	Rainfall- and earthquake-induced landslides	Partial	1643	England (2011)
Vector	2019 rainfall-induced landslides	Partial	1359	Wride and de Vilder (2021)
Vector	Shallow landslides	Partial	836	Leith (unpublished)
Vector	Land Cover Database (v5.0) landslides	Full	1102	LRIS Portal (2019)
Vector	Murchison earthquake landslides	Full	6134	Hancox et al. (2016)
Vector	Inangahua earthquake landslides	Full	1200	Hancox et al. (2014)
Vector	2021 rainfall-induced landslides	Full	669	Bain and Rosser (unpublished)

Table A1.3 Landslide triggers.

Type	Description	Coverage	Reference
Raster	ShakeMapNZ atlas and the New Zealand National Seismic Hazard Model (NSHM) 2022	Full	Gerstenberger et al. (2022)
Raster	Rainfall scenarios from the High Intensity Rainfall Design System (HIRDS) V4	Full	Carey-Smith et al. (2018)

APPENDIX 2 List of Landslide-Debris-Inundation Model Variables

Table A2.1 List of landslide-debris-inundation model variables.

Variable	Description	Value	Unit
A	Planimetric area of a landslide-source polygon	0	m ²
c	Average cohesive strength of landslide failure surface	50	kPa
α	Landslide area-volume scaling multiplier	-	1
γ	Landslide area-volume scaling exponent	1.36	1
V	Predicted volume of landslide source	-	m ³
$r_{(x,y)}$	Horizontal distance to the nearest failure-unit cell boundary	-	m
$D_{(x,y)}$	Maximum possible landslide depth at each pixel	N/A	m
θ_{ST}	Threshold slope angle for excess topography	20	°
θ_{NAT}	Threshold slope angle for surficial failures	20	°
SSY	Suspended sediment yield	-	t/m ² /yr
δ	Multiplier to convert SSY to total sediment yield	1.5	1
$\rho_{(x,y)}$	Rock density for constitutive units	-	t/m ³
S_{RIL}	Rainfall-induced landslide susceptibility	-	1/yr
S_{EIL}	Earthquake-induced landslide susceptibility	-	1/yr
dt_{RIL}	Rainfall-induced landslide probability-integration interval	-	yr
dt_{EIL}	Earthquake-induced landslide probability-integration interval	-	yr
$P_{\text{RIL}(T_0, T_{\text{max}}, x, y)}$	Rainfall-induced landslide annual probability	-	1
$P_{\text{EIL}(T_0, T_{\text{max}}, x, y)}$	Earthquake-induced landslide annual probability	-	1
$P_{(x,y)}$	Annual landslide probability	-	1
$\dot{E}_{(x,y)}$	Erosion rate	-	m/yr
ω_L	Proportion of eroded sediment generated through landsliding	1	1
η_L	Landslide-sediment bulking factor	1.3	1
$\rho_L(x,y)$	Landslide-debris density	-	t/m ³
$\dot{E}_{L(x,y)}$	Rate of sediment produced by landsliding at a given location	-	m/yr
$\dot{E}_{LD(x,y)}$	Depth-corrected landslide sediment-production rate	-	m/yr
$\bar{D}_{L(x,y)}$	Mean depth of landslide occurrence	-	m
$V_{L(c)}$	Volume of a landslide class (c) size	-	m ³
$A_{L(c)}$	Landslide class area	-	m ²
$\bar{D}_{L(c)}$	Mean landslide class depth	-	m
$K_{L(c)(x,y)}$	Possibility for landslides of each class size to occur	-	T/F
$\dot{E}_{L(c)(T,RI)(x,y)}$	Landslide-induced erosion rate	-	m/yr
$S_{S(x,y)}$	Event-specific landslide susceptibility	-	1
$E_{LS(x,y)}$	Event-specific landslide-sediment production	-	m
$M_{GPP(c)(T,RI)(x,y)}$	Landslide source-material thickness for each model run	-	m
σ	Landslide source-depth-integration interval	10 ⁴	yr
$\Phi_{GPP(\mu)(c)(T,RI)(x,y)}$	Modelled landslide-material flux (per trigger and movement type)	-	m ³ /m ² /yr
$P_{(\mu)(T)}$	Probability of a given movement type occurring (for a given trigger)	-	1

Variable	Description	Value	Unit
Φ_L	Mean landslide-debris flux	-	m ³ /m
R	Gravitational Path Process (GPP) model grid resolution	25	m
Subscript	Description	-	-
x,y	Spatial location of pixel centroid	-	-
T ₀	Lower limit of temporal-integration interval	-	-
T _{max}	Upper limit of temporal-integration interval	-	-
μ	Runout-model configuration	-	-
c	Landslide-volume class	-	-
T	Landslide trigger type	-	-
RI	Event return interval	-	-
L _s	Landslide-inducing scenario	-	-

APPENDIX 3 Landslide Source-Susceptibility Model

A landslide-susceptibility assessment is a quantitative or qualitative assessment of the spatial distribution of landslides that exist or potentially may occur in an area in response to a given trigger (Corominas et al. 2015). This landslide-susceptibility assessment forms the basis for the landslide-debris-inundation assessment, as it delineates the potential landslide-source areas from which landslide runout can be estimated.

The mean annual probability of failure for a grid cell is calculated by integrating the product of the susceptibility to a triggering event, and frequency of triggering event, over representative return intervals for a combination of foreseeable earthquake- and rainfall-induced landslide events. The shaking data used to create earthquake-induced landslide susceptibility outputs is derived from the New Zealand National Seismic Hazard Model (NSHM) 2022 (Gerstenberger et al. 2022). The landslide susceptibilities are calculated using peak ground accelerations (PGAs) for annual return intervals (ARIs) of 100-, 250-, 500- and 1000-year earthquakes. The rainfall data used to create the rainfall-induced landslide susceptibility forecasts come from the National Institute of Water & Atmospheric Research (NIWA)'s High Intensity Rainfall Design System (HIRDS) V4 model, which simulates the rainfall intensity at a 5 km grid resolution for a given range of ARIs. The landslide susceptibilities are calculated using the 24-hour rainfall for ARIs of 50, 100 and 250 years.

The landslide source-susceptibility (LSS) model is informed by outputs from Earthquake-Induced Landslide (EIL) Tool and Rainfall-Induced Landslide (RIL) Tool outputs trained on the region overseen by West Coast Emergency Management (WCEM). Each of these models is described in the following sections. Key landslide sediment-production (LSP) model assumptions and uncertainties are noted in Section A3.6, and a quantitative sensitivity analysis is undertaken in Section A7.2.

A3.1 Statistical-Modelling Methodology

To undertake the modelling, a sample grid at 32 m ground resolution was defined, and an input grid for each variable was created and aligned with the sample grid. A 32-m-resolution grid size was chosen as it was much less than the typical hill-slope lengths in the regions used for modelling, which can vary from 100 to >>1000 m. This resolution allowed easy aggregation of the inputs derived from the elevation data based upon the New Zealand 8 m Digital Elevation Model obtained from the Land Information New Zealand (LINZ) Data Service (LINZ 2014). For this analysis, only landslide-source areas, not debris trails, from each inventory were used. To reduce sample bias, (1) it was assumed that a grid cell is defined as being a landslide source (LS = 1) if its centroid falls within a landslide-source area, even if the grid cell is not fully occupied by the landslide source; and (2) all landslides within each dataset were used, regardless of their size.

A3.1.1 Model Training

Logistic regression is routinely used to forecast landslide occurrence (e.g. von Ruetten et al. 2011; Budimir et al. 2015; Lombardo and Mai 2018) by calculating landslide probability from a series of input 'predictor' variables. The method is used to estimate the coefficients for predicting the probability (P_{LS}) that $Y = 1$, given the values of one or more predictor variables. Here, the condition $Y = 1$ corresponds to the occurrence of a landslide, and $Y = 0$ corresponds to no landslide, within a sample grid cell on the ground. The regression coefficients were estimated using a maximum likelihood criterion. Each model was fitted using the equation:

$$P_{LS} = \frac{1}{1 + \exp^{-Z}} = \frac{\exp^Z}{1 + \exp^Z} \quad \text{Equation A3.1}$$

where the probability of a landslide occurrence (P_{LS}) is within the range 0–1 on a sigmoid curve and Z is a linear-fitting function for the set of landslide-related variables tested, expressed in the form of:

$$Z = b_0 + b_1X_1 + b_2X_2 + \dots b_nX_n \quad \text{Equation A3.2}$$

where b_0 , b_n and X_n represent the intercept of the model, the partial regression coefficients ‘parameter estimates’ and the conditioning factors, respectively. The parameter estimates for the different variables were derived by statistically comparing the mapped landslides with the features listed in Section A3.3.2, using the Statistica software (TIBCO Statistica™ 14.0.0²). For investigating the variables that best describe the landslide locations, we used an unbalanced dataset, given that the occurrence of a landslide ($Y = 1$) is much rarer than not ($Y = 0$). Therefore, our dataset is inherently biased toward no landslides ($Y = 0$) and, as a result, are naturally unbalanced. The regression coefficients were estimated in Statistica by maximising the likelihood function. The maximisation of the likelihood is achieved by an iterative method called Fisher scoring. The algorithm completes when the convergence criterion is satisfied or when the maximum number of iterations has been reached. Convergence is obtained when the difference between the log-likelihood function from one iteration to the next is less than 0.0000001.

For a variable to be included in the model, it must have a logical and statistically significant influence on P_{LS} . We used a significance level (p-value) of $p < 0.05$ (using the Wald statistic) as the threshold for inclusion in the model. Multiple combinations of variables were iteratively tested. To ensure that the variables included do not exhibit multicollinearity, we used the estimated correlation matrix of estimates between the variables. Note that we use the correlation matrix of estimates rather than the co-variance matrix of estimates. This is because the range of the values within each variable are relatively large – and vary considerably between each variable – which leads to very small co-variance values that are difficult to interpret. However, the correlation values range between -1 and 1, thus making it easier to interpret the correlation relationship between any two variables. Values of >0.5 were avoided by removing the given variable from the model, as these can exhibit multicollinearity. The final variable coefficients used in the models represent those variables that produced the best fit while meeting the significance level and multicollinearity criteria. This was done initially on all data from the combined events to determine the significant variables.

A3.1.2 List of Landslide Source-Susceptibility Model Predictors

Table A3.1 Predictor variables used in the logistic regression model with their ID codes, descriptions and units.

Variable ID	Description	Units
Landslide Susceptibility Factors		
Geology	The geology classification is from the geology layer for the whole of New Zealand and is based on the ‘dominant unit’ classification within the QMAP data (Heron 2020). The Geology field holds one out of seven possible values based on dominant unit, and a number code was assigned to each Geology classification and stored in the GeolCode field. This number code was used to generate a grid out of polygons using the MAXIMUM_COMBINED_AREA option.	-
Geology 1 (GeolCode 1)	Quaternary sands, silts and gravels. These materials typically form terrace deposits on the top of the steep coastal cliffs, as well as on inland slopes adjacent to the main rivers of the area. Many of these terraces have been incised by rivers.	Categorical
Geology 2 (GeolCode 2)	Neogene limestones, sandstones and siltstones, which are typically weak. These occur along sections of the coast north of Kaikōura and along the coast and inland from Greymouth to Karamea on the West Coast.	Categorical
Geology 3 (GeolCode 3)	Upper Cretaceous – Paleogene rocks, including limestones, sandstones, siltstones and minor volcanic rocks. These are typically weak (like the Neogene limestones and sandstones) and easily erodible, and can also contain thin clay seams, which are volcanic in origin. These rocks are typically exposed in narrow strips overlying the greywacke basement rocks in the Kaikōura region but are more prevalent within the area affected by the Murchison and Inangahua earthquakes.	Categorical

² <https://docs.tibco.com/products/tibco-statistica-14-0-0>

Variable ID	Description	Units
Geology 4 (GeolCode 4)	All intrusive and extrusive igneous rocks, ranging in age from Jurassic to Quaternary. Includes andesites, basalts, rhyolites, ignimbrites, dacites, granites and granodiorites. These represent the smallest (in land area) geology group within the area affected by the three earthquakes.	Categorical
Geology 5 (GeolCode 5)	Lower Cretaceous Torlesse (Pahau terrane) 'basement' rocks are predominantly sandstones and argillite, also known as greywacke. The greywacke rocks are typically moderately to well bedded and tend to be closely jointed. These form many of the coastal slopes, as well as the steeper inland Kaikōura mountain ranges, and are the dominant rock type affected by the Kaikōura earthquake.	Categorical
Geology 6 (GeolCode 6)	Quaternary lava. Predominantly basalt lavas. Not used in these analyses, as such materials are not present within the training area.	Categorical
Geology 7 (GeolCode 7)	Neogene debris, including landslide debris, alluvium, etc. Not used in these analyses, as such materials are not present within the training area.	Categorical
Land cover categories	The land-cover categories of LCDB v5.0 were obtained from the LRIS Portal. The data were grouped based on the polygon description, a code assigned to each group and the polygons then turned into integer grids using the MAXIMUM_COMBINED_AREA option. The chosen land-cover grid was based on its proximity in time (the closest in time) to the event triggering the landslides and thus is thought to represent the land cover at the time that the storm occurred. For this work, the land-cover grids LC1997 and LC2018 were used – the LC1997 classification for the Coromandel 1981 landslides and study area and LC2018 for the Hunua landslides and study area – as these represent the land-cover types at times closest to when the landslides occurred. To simplify the training, the land-cover grid codes were combined into three categories, see cells below.	Categorical
Land cover code 1 (LCC1)	Group 1 includes deciduous hardwoods and indigenous, exotic and harvested forest.	Categorical
Land cover code 2 (LCC2)	Group 2 includes: bare ground, urban, urban open (parks and open space), transport and landslides.	Categorical
Land cover code 3 (LCC3)	Group 3 includes: alpine vegetation, scrub, grassland and horticulture.	Categorical
Slope _{MEAN}	Local hillslope gradient generated in ArcGIS from the LINZ 8 m resolution digital elevation model, adopting the mean value of all 8 m cells that fall within each cell of the 32 m sample grid. This variable is a proxy for the static shear stresses in the slope.	Degrees (°)
Elev _{MEAN}	Local hillslope elevation taken from the LINZ 8 m resolution digital elevation model, adopting the mean value of all 8 m cells that fall within each cell of the 32 m sample grid. This variable represents the observation that topography can limit the size of the landslides. For example, slopes that are higher in elevation tend to have larger surface areas and can therefore generate larger landslides than slopes at lower elevations, which tend to have smaller surface areas (Massey et al. 2020a). It could also represent different climatic conditions and erosion processes that could dominate at different elevations.	Metres above mean sea level (mAMSL)
Aspect _{MEAN}	Grid-cell aspect re-sampled from the LINZ 8 m digital elevation model. Hill-slope aspect calculated in ArcGIS at 32 m resolution.	Degrees (°) 0–36
Curv _{MEAN}	Curvature generated in ArcGIS from the LINZ 8 m resolution digital elevation model. For each cell, the curvature value is calculated as a second derivative of the surface fitted through that cell and its eight surrounding neighbours. A negative value indicates that the surface is upwardly convex at that cell. A positive profile indicates that the surface is upwardly concave at that cell. A value of 0 indicates that the surface is flat. Curvature was aggregated to 32 m resolution, adopting the mean value of all 8 m cells that fell within each cell of the 32 m sample grid. This variable is a proxy for slope 'hollows' that represents topographic depressions where surface water might accumulate.	One hundredth (1/100) of a z-unit

Variable ID	Description	Units
Landslide Forcing Factors		
24 hr Rain	Grid of 24-hour rain amounts (from 9:00 am to 9:00 am), derived from NIWA's Virtual Climate Station Network (VCSN) model ³ at 5 km resolution. The rain values were attributed to the sample grid cell by taking the rain value at its centroid using bi-linear interpolation. The rain amount is the maximum value from all 24-hour rain grids that cover the duration of the storm.	mm
SMI	Grid of soil moisture (soil moisture indices; SMI) on the day before the storm, taken from NIWA's VCSN model at 5 km resolution. The SMI values were attributed to the sample grid cell by taking the SMI value at its centroid using bi-linear interpolation. SMI is calculated from 9:00 am to 9:00 am (24-hour period), from rainfall and evapotranspiration. The base value is -150 mm ('permanent wilting point') based on 'soil store capacity'. A value of '0' indicates that the soil is at 'field capacity' (amount of water held in the soil after the excess has drained away). A value greater than '0' indicates runoff. Note on soil moisture calculation: The NIWA model has one parameter, the soil store capacity (S_{max}). Rainfall is assumed to infiltrate into a soil store from which moisture is depleted by evapotranspiration loss. The model keeps track of the soil store for each time-step. When the soil store is full, it is assumed to be saturated and the excess rainfall becomes surface run-off. Evapotranspiration is assumed to continue at its potential rate until the soil water store drops to half capacity. Evapotranspiration then decreases linearly to zero when the store is empty. For the simulations here, an S_{max} value of 150 mm is used for all modelling grids.	mm

A3.1.3 Model Standardisation and Bootstrapping

To test the importance of each variable used in the model, we converted each one to their standard score using the formula:

$$z = \frac{x - \mu}{\sigma} \quad \text{Equation A3.3}$$

where z is the standard score, x is the data value of the variable, μ is the variables mean and σ is the variables standard deviation. This conversion normalises the distribution of the variable, which in turn allows the model coefficients of each variable to be interpreted as a measure of its importance relative to other variables in the model (Lombardo and Mai 2018). As we standardised each variable prior to use within the regressions, all resulting coefficient values are in the same unit-less scale and can be directly compared. Initial models were fitted using GeolCode as a categorical variable in the regression, and the results showed that GeolCode was statistically significant. Separate models were then fitted using GeolCode as a grouping variable. These GeolCode-grouped models performed statistically better than the model that included the GeolCodes as categorical variables.

Validation of the model results was done using bootstrapping (Efron and Tibshirani 1994), which allowed the variability of the parameter values for each variable to be estimated within each GeolCode group. Bootstrapping is a way to assess the robustness of the coefficients estimated for each variable derived from model fitting. For example, a robust estimate of the value for a given variable should have a narrow variation between the minimum and maximum and standard deviation either side of the mean. Conversely, a poor estimate would be one with a wider variation. In addition, a robust model should show little difference between the areas under the ROC (receiver operating characteristic) curves calculated for each of the 100 bootstrap models. To this end, we repeatedly drew random samples from the respective landslide datasets, where each sample represented 75% of the total GeolCode-specific dataset. A sample was drawn 100 times, logistic-regression models were fitted to the sampled dataset and the result statistics were calculated – minimum, maximum, mean and standard deviation of each variable parameter, along with the specificity, sensitivity and area under the ROC curve (ROC:AUC).

³ <https://niwa.co.nz/climate/our-services/virtual-climate-stations>

A3.1.4 Logistic Lasso Regression

We then used logistic Lasso (L1) regression to identify and cross-check the main variables that could be used to explain landslide occurrence while reducing over-fitting – this step essentially identifies the minimum number and therefore most important variables that can be used to explain landslide occurrence.

Statistica performs V-fold cross-validation to identify the optimal lambda value (hyper parameter) using minimum average error. The initial run is on the entire data to get the lambda sequence. The cross-validation procedure then splits the input data into 10 folds and runs the algorithm with each fold omitted. The average errors are calculated over each fold and their standard deviations computed. The errors were calculated using the mean squared error, which uses the squared residuals to calculate the mean cross-validated error. The logistic Lasso regression coefficients for the chosen variables were only used for variable selection, as the coefficients produced by the Lasso model are biased.⁴

The Lasso Regression module in Statistica uses a penalised maximum likelihood estimation (MLE) method to fit the linear and logistic regression models. The regularisation is performed over a grid of lambda values, the regularisation parameter (the L1 penalty). The module uses a cyclical coordinate descent to minimise the objective function and likelihood contribution, as well as the penalty, over a grid of lambda values successively (Friedman et al. 2010).

The main advantage of a Lasso regression model is that it can set the coefficients for variables it does not consider interesting to zero. This means that the model decides which variables should and should not be included. Another advantage of a Lasso regression is that the L1 penalty added to the model helps to prevent the model from over-fitting. One of the main disadvantages of Lasso regression is that the coefficients that are produced by a Lasso model are biased. The L1 penalty that is added to the model artificially shrinks the coefficients closer to zero, or, in some cases, all the way to zero. This means that the coefficients from a Lasso model do not represent the true magnitude of the relationship between the variables and the outcome (landslide probability) but rather a shrunken version of that magnitude.

A3.2 Earthquake-Induced Landslide Forecast Model

Version V2.1 of the earthquake-induced landslide-susceptibility model (Massey et al. 2021a) was used to generate the earthquake-induced landslide probability grids used in this report. A landslide-susceptibility model provides a quantitative or qualitative assessment of the volume (or area) and spatial distribution of landslides that exist or potentially may occur in an area (Corominas et al. 2015). For this work, a quantitative susceptibility model is used to estimate the probability (0–1) of landslides occurring under a given set of conditions. This statistical model is based on a logistic regression machine-learning approach, which is described in Massey et al. (2021a, 2022a, 2022b). This model requires several variables as inputs – in grid format, these factors are:

1. **Geology:** The dominant rock/soil type of the grid cell. This was based on linking the ‘GeolCodes’ used in the earthquake-induced landslide-susceptibility model V2.1 with appropriate geological units based on their mechanical properties. The available geological information was limited in detail and resolution (Table A3.1).
2. **Earthquake shaking:** Adoption of different PGAs from the New Zealand NSHM 2022, adopting the given return periods and a shear wave velocity (V_{S30}) of 750 m/s.
3. **Local slope relief:** The local height of a given grid cell relative to its surrounding grid cells.
4. **Slope angle:** How steep the given grid cell is.

⁴ <https://crunchingthedata.com/when-to-use-lasso/>

5. **Elevation:** The elevation of the given grid cell.
6. **Slope curvature:** The shape of the surface area defined by a given, and surrounding, grid cells.

Separate grids were generated for each of the given variables required by the earthquake-induced landslide-susceptibility model within the study area. The LINZ 8 m digital elevation model (DEM) was used to generate all of the variable grids used in the earthquake-induced landslide modelling, with a final grid resolution of 32 x 32 m used for the susceptibility forecasts used in the development of the LSP model. The earthquake-induced landslide-susceptibility model variables and their coefficients are shown in Tables A3.2–A3.6. Results from the model fitting – calculated as the Nagelkerke (pseudo R^2) and ROC: AUC – are shown in Table A3.7.

Table A3.2 GeolCode1 (Quaternary sands, silts and gravels): logistic regression coefficients for the different variables used in the model derived from bootstrapping.

Variable Coefficient	Intercept	Elevation	Slope	Local Slope Relief	Curvature	Peak Ground Acceleration
Minimum	-10.10	-0.0010	0.03	0.06	-0.23	2.64
Maximum	-9.93	-0.0008	0.04	0.07	-0.16	2.79
Mean	-10.00	-0.0009	0.03	0.06	-0.20	2.70
Standard deviation	0.04	0.00002	0.00	0.00	0.01	0.03
Skew	-0.22	0.6448	-0.34	0.27	0.80	0.11

Table A3.3 GeolCode2 (Neogene limestones, sandstones and siltstones): logistic regression coefficients for the different variables used in the model derived from bootstrapping.

Variable Coefficient	Intercept	Elevation	Slope	Local Slope Relief	Curvature	Peak Ground Acceleration
Minimum	-10.03	0.0017	0.05	0.02	-0.11	2.39
Maximum	-9.89	0.0017	0.06	0.02	-0.09	2.46
Mean	-9.97	0.0017	0.05	0.02	-0.10	2.44
Standard deviation	0.03	0.00002	0.00	0.00	0.01	0.02
Skew	0.55	0.2733	-1.02	-0.04	-0.36	-0.56

Table A3.4 GeolCode3 (Upper Cretaceous to Paleogene rocks, including limestones, sandstones and siltstones): logistic regression coefficients for the different variables used in the model derived from bootstrapping.

Variable Coefficient	Intercept	Elevation	Slope	Local Slope Relief	Curvature	Peak Ground Acceleration
Minimum	-8.42	-0.0003	0.03	0.02	-0.14	2.15
Maximum	-8.29	-0.0002	0.04	0.03	-0.12	2.22
Mean	-8.35	-0.0003	0.03	0.03	-0.13	2.19
Standard deviation	0.03	0.00003	0.00	0.00	0.01	0.02
Skew	0.09	-0.2147	-0.21	0.54	-0.66	-0.11

Table A3.5 GeolCode4 (All intrusive and extrusive igneous rocks): logistic regression coefficients for the different variables used in the model derived from bootstrapping.

Variable Coefficient	Intercept	Elevation	Slope	Local Slope Relief	Curvature	Peak Ground Acceleration
Minimum	-8.05	-0.0009	0.01	0.03	-0.16	1.94
Maximum	-7.82	-0.0007	0.01	0.03	-0.12	2.02
Mean	-7.94	-0.0008	0.01	0.03	-0.14	1.97
Standard deviation	0.05	0.00003	0.00	0.00	0.01	0.02
Skew	0.33	0.1051	0.14	0.00	-0.33	0.09

Table A3.6 GeolCode5 (Lower Cretaceous Torlesse [Pahau terrane] 'basement' rocks): logistic regression coefficients for the different variables used in the model derived from bootstrapping.

Variable Coefficient	Intercept	Elevation	Slope	Local Slope Relief	Curvature	Peak Ground Acceleration
Minimum	-10.04	-0.0005	0.04	0.03	-0.11	1.98
Maximum	-9.91	-0.0005	0.05	0.03	-0.09	2.01
Mean	-9.97	-0.0005	0.04	0.03	-0.10	1.99
Standard deviation	0.03	0.00001	0.00	0.00	0.00	0.01
Skew	-0.53	0.0185	0.23	0.23	0.14	0.87

Table A3.7 Results from the model fitting: calculated as the Nagelkerke (pseudo R^2) and area under the random operator characteristic curve (ROC: AUC) (Massey et al. 2021a, 2022a, 2022b).

GeolCode	Pseudo R^2	Mean ROC:AUC
1	0.23	0.91
2	0.28	0.89
3	0.14	0.82
4	0.09	0.76
5	0.17	0.86

A3.3 Western South Island Rainfall-Induced-Landslide Model

This section provides an overview of the development of the rainfall-induced-landslide model for the western South Island, which follows the same methodology adopted to develop the earthquake-induced landslide-susceptibility model. The following key steps were undertaken to establish the rainfall-induced-landslide model and its associated variables and coefficients:

A3.3.1 Area of Interest Definition

To define areas of interest for model training, a polygon was created around two separate landslide datasets. This involved adopting a 100 m buffer around all landslide sources and applying a convex hull interpolation around these buffers. This approach assumed that the mapped landslides accurately represent the full extent of landslides generated by storm events.

The two landslide datasets used were:

- **West Coast 2019**, containing 1395 landslide-source polygons (Wride and de Vilder 2021).
- **West Coast 2021**, containing 951 landslide-source polygons (Bain and Rosser, unpublished).

A3.3.2 Variable Selection

Statistical-based models are most used for mapping landslide susceptibility (Budimir et al. 2015; Reichenbach et al. 2018; Merghadi et al. 2020). Statistical-based modelling of landslide susceptibility is usually performed using classification algorithms to establish an empirical relationship between a binary dependent variable (landslides versus no landslides) and various static environmental factors, such as slope gradient and bedrock lithology (Lin et al. 2021). The established empirical relationship can then be used to estimate a relative spatial landslide-susceptibility index and produce the final landslide-susceptibility map. For this work, we also adopt ‘dynamic’ variables of rain amount and the soil-moisture indices to represent the magnitude of ‘forcing’, as landslide probability should scale with this magnitude (e.g. Chan et al. 2018).

The predictor variables used to train the models were chosen based on variables previously found to influence landslide occurrence (e.g. Budimir et al. 2015; Reichenbach et al. 2018; Chan et al. 2018; Merghadi et al. 2020; Lin et al. 2021). Based on these studies, we reduced the number of predictor variables used in the model training to the following (in no particular order):

1. 24-hour rainfall amount.
2. Soil-moisture indices.
3. Slope angle.
4. Elevation.
5. Slope aspect.
6. Slope curvature.
7. Geology.
8. Land cover.

These predictor variables and the methods used to calculate them are described in Table A3.1.

A3.3.3 Model Results

Once the main variables contributing to the landslide occurrence in each GeolCode were identified from the Lasso models, the chosen variables were then included in separate logistic-regression models using all of the training data within each GeolCode separately. The estimated coefficients for each variable included in the models were then used to forecast landslide occurrence across the entire area of interest using either HIRDS V4 24-hour rainfall amounts for different average recurrence intervals (ARIs) or event-specific ‘scenario’ rainfall amounts.

The chosen variables and their coefficients derived from the ‘best-fitting’ models are shown in Table A3.8.

Table A3.8 Results from the best-fitting logistic-regression models, their variables and mean coefficients and the model pseudo R^2 and area under the receiver operating characteristic curve (ROC:AUC).

Variable	GeolCode 1			GeolCodes 2 and 3 (Combined)			GeolCode 4			GeolCode 5		
	Mean Coefficient	Standard Error	84 th % Coefficient	Mean Coefficient	Standard Error	84 th % Coefficient	Mean Coefficient	Standard Error	84 th % Coefficient	Mean Coefficient	Standard Error	84 th % Coefficient
Intercept	-11.866	0.181	-11.611	-12.313	0.341	-11.834	-9.0031	0.2300	-8.6799	-10.756	0.121	-10.5860
Elev _{MEAN}	-0.0011	0.0002	-0.0008	-0.0027	0.0004	-0.0022	-0.0038	0.0002	-0.0035	-0.0027	0.0001	-0.0026
Slope _{MEAN}	0.120	0.004	0.125	0.091	0.007	0.100	0.0757	0.0051	0.0828	0.082	0.002	0.0844
Aspect _{MEAN}	-0.018	0.005	-0.011	-0.051	0.008	-0.040	-0.0584	0.0054	-0.0508	-0.009	0.002	-0.0065
Curv _{MEAN}	-0.256	0.040	-0.199	-0.166	0.060	-0.082	-0.1900	0.0362	-0.1391	-0.095	0.011	-0.0790
24 hr Rain	0.004	0.001	0.005	0.007	0.001	0.009	0.0017	0.0007	0.0026	0.0080	0.0002	0.0084
LCC1	-0.86	0.10	-0.719	N/A	N/A	N/A	N/A	N/A	N/A	-1.027	0.037	-0.975
LCC2	0.47	0.14	0.663	N/A	N/A	N/A	N/A	N/A	N/A	0.801	0.057	0.881
LCC3	1.00	N/A	1.0	N/A	N/A	N/A	N/A	N/A	N/A	1.000	N/A	1.0
Pseudo R^2	0.20			0.08			0.19			0.11		
ROC:AUC	0.917			0.838			0.904			0.846		

These results show that:

- Only GeolCodes 1 and 5 have land cover as a categorical variable.
- GeolCodes 2 and 3 were merged, as these not only had limited data with respect to the numbers of landslides but also because the fitted models had very similar variables and coefficients.
- Overall, the main variables are – in order of importance with respect to explaining landslide probability – GeolCode, rainfall, slope, elevation and then the others such as land cover, soil-moisture indices, aspect and curvature, which tend to have similar but lower levels of importance.
- Elevation is slightly correlated with rainfall but not enough to lead to over-fitting.
- With the exception of GeolCode 4, the soil-moisture indices variable was not shown to be statistically important in any of the other GeolCode regressions. It also had low importance in the GeolCode 4 regression and, when removed from the regressions, had little influence on the coefficients and model ‘goodness of fit’ statistics. As a result, the soil-moisture indices variable was not included in the final models used to forecast landslide probability.
- The relatively high ROC:AUC values indicate that, overall, the models are fitting the data well. Overall, the statistical models developed here provide a robust forecast of landslide probability at different levels of rainfall.
- However, the results from the models have a low pseudo R^2 , indicating that these cannot give accurate forecasts for individual grid cells. These may nevertheless give good overall estimates of the scale ‘intensity’ of landslide occurrence to be expected in individual rain events.

A3.4 Calculation of Slope Failure Probability

The earthquake- and rainfall-induced landslide models provide insight into the probability of a landslide occurring at a given location in response to rainfall triggers for 50-, 100- and 250-year ARI events, as well as seismic shaking associated with 100-, 250-, 500- and 1000-year ARI events.

In order to calculate the total annual probability of a landslide occurring at a given location [$P_{(x,y)}$], we integrate the rainfall-induced landslide probability (S_{RIL}) and earthquake-induced landslide (S_{EIL}) probabilities, normalised by their respective integration intervals ($dt_{RIL} = T_{RIL,max} - T_0$ and $dt_{EIL} = T_{EIL,max} - T_0$, respectively), where T_0 and T_{max} represent the midpoint between subsequent trigger intervals. To convert from the probability of a grid cell containing a landslide (as output from the earthquake- and rainfall-induced landslide models) to the predicted area of landslide sources (required for sediment-production models), we multiply both outputs by the ratio of the earthquake- or rainfall-induced landslide grid-cell area to the geometric-mean area of all landslides associated with that trigger ($\overline{A_L(T)}$; the derivation of this area is described later in Section A4.3):

$$P_{RIL(x,y)} = \frac{\int_{T_0}^T S_{RIL(T_0,T,x,y)} dt_{RIL}}{dt_{RIL}} \times \frac{\overline{A_L(EIL)}}{32^2} \quad \text{Equation A3.4}$$

$$P_{EIL(x,y)} = \frac{\int_{T_0}^T S_{EIL(T_0,T,x,y)} dt_{EIL}}{dt_{EIL}} \times \frac{\overline{A_L(RIL)}}{32^2} \quad \text{Equation A3.5}$$

$$P_{(x,y)} = P_{RIL(x,y)} + P_{EIL(x,y)} \quad \text{Equation A3.6}$$

A3.5 Landslide Source-Susceptibility Model Adjustment for the RCP6 2081–2100 Climate-Change Scenario

To adjust historical HIRDS V4 rainfall depth or intensity surfaces for climate change, we increased rainfall by a specific percentage per degree of warming. We selected this adjustment factor from Table A3.9 below, multiplied it by the chosen temperature increase and applied it to the historical HIRDS V4 rainfall estimates. For example, when estimating a 1-hour, 10-year rainfall event with a historical value of 35 mm, and assuming a temperature increase of 2.1°C, we first selected a percentage increase of 13.1% per degree of warming for this duration and frequency. We then multiplied 13.1% by 2.1 to get 27.5% and applied this to the historical estimate, resulting in a projected rainfall of 45 mm. This consistent percentage increase allowed us to apply the same adjustment across the entire HIRDS V4 grid. For shorter storm durations, we used the 1-hour duration percentage change factors, and, for return periods of over 100 years, we applied the 100-year factors. Temperature change values for different RCPs (Representative Concentration Pathways) and time periods were taken from Table A3.10, so, for RCP6 at the end of the century, we used a value of 1.63°C.

Table A3.9 Percentage-change factors to project rainfall depths derived from the current climate to a future climate that is one degree warmer (Source: Carey-Smith et al. 2018). ARI = Annual Return Interval.

Duration/ ARI	2-Year	5-Year	10-Year	20-Year	30-Year	40-Year	50-Year	60-Year	80-Year	100-Year
1 hour	12.2	12.8	13.1	13.3	13.4	13.4	13.5	13.5	13.6	13.6
2 hours	11.7	12.3	12.6	12.8	12.9	12.9	13.0	13.0	13.1	13.1
6 hours	9.8	10.5	10.8	11.1	11.2	11.3	11.3	11.4	11.4	11.5
12 hours	8.5	9.2	9.5	9.7	9.8	9.9	9.9	10.0	10.0	10.1
24 hours	7.2	7.8	8.1	8.2	8.3	8.4	8.4	8.5	8.5	8.6
48 hours	6.1	6.7	7.0	7.2	7.3	7.3	7.4	7.4	7.5	7.5
72 hours	5.5	6.2	6.5	6.6	6.7	6.8	6.8	6.9	6.9	6.9
96 hours	5.1	5.7	6.0	6.2	6.3	6.3	6.4	6.4	6.4	6.5
120 hours	4.8	5.4	5.7	5.8	5.9	6.0	6.0	6.0	6.1	6.1

Table A3.10 New Zealand land-average temperature increase relative to 1986–2005 for four future emissions scenarios. The three 21st century projections result from the average of six regional climate model simulations (driven by different global climate models). The early 22nd century projections are based only on the sub-set of models that were available and so should be used with caution (source: Carey-Smith et al. 2018).

	2031–2050	2056–2075	2081–2100	2101–2120
RCP 2.6	0.59	0.67	0.59	0.59 (4 model average)
RCP 4.5	0.74	1.05	1.21	1.44 (5 model average)
RCP 6.0	0.68	1.16	1.63	2.31 (CESM1–CAM5 only)
RCP 8.5	0.85	1.65	2.58	3.13 (3 model average)

A3.6 Key Landslide Source-Susceptibility Model Uncertainties and Assumptions

We note a number of constraints for the rainfall-induced landslide-susceptibility calculation:

- The model represents extrapolation of observations from two storm events, just two years apart. While the model results are statistically significant, these only represent the relationships between the variables used and the landslides generated by these two events.
- 24-hour precipitation data for each event are derived from a model and gridded at 5 x 5 km. The accuracy of precipitation totals at each landslide location is unconstrained. Other than for the GeolCode 4 model, the soil-moisture indices variable is not statistically significant in the models and so not included in the final models used for forecasting landslide probability.
- Soil moisture for each event is derived from a model and gridded at 5 x 5 km. The accuracy of soil-moisture indices totals at each landslide location is unconstrained.
- The rainfall totals did not allow sampling of impacts up to a 250-year ARI event. There is therefore no data to support predictions for higher-intensity events.
- The landslide data incorporates 2300 manually mapped landslide-source areas. The completeness of the mapping is unconstrained in terms of both spatial distribution and observed landslide sizes.
- The 2019 landslide catalogue covers landsliding in the northern half of the study area, while the 2021 landslide catalogue covers approximately 5% of the study region centred around the Kokiraki area.
- The catalogues cover similar geomorphological settings and rock types. The impact of precipitation events (in terms of the number of grid cells containing landslide sources) in other geological and geomorphological settings is therefore unconstrained.
- It is unclear whether the area-frequency distribution of landslides from the mapped events is representative of all geomorphological settings.
- It is unclear whether the area-frequency distribution from the mapped events is representative of all triggering-event magnitudes.
- Employing statistical datasets to describe the distribution of possible landslide areas ignores kinematic constraints and would suggest that the relative probability of giant landslides occurring on small hill slopes is equal to that in mountainous areas with similar slope angles.

- The model is trained on a 32 x 32 m grid of pixels containing landslide scars. This neither represents the exact number, nor exact area, of mapped landslides in the dataset. The uncertainty associated with calculating either of these two fundamental metrics from the rainfall-induced landslide output is dependent on grid resolution, landslide-area characteristics and landslide clustering in the landscape. Currently, this uncertainty is only constrained with respect to the training dataset; elsewhere, it is unconstrained.

APPENDIX 4 Landslide Sediment-Production Model

This section describes details of the landslide sediment-production (LSP) model, which is used to determine the volume of landslide debris released from each source pixel for both mean annual and scenario-based models in the present-day and RCP6 2081–2100 climate scenarios.

Key LSP model assumptions and uncertainties are noted in Section A4.8, and a quantitative sensitivity analysis is undertaken in Section A7.3.

A4.1 Determination of Landslide-Erosion Rates

A4.1.1 Determination of Landslide-Sediment Production

As discussed in Section 2.1.2, the selected mean annual erosion rates for this study are derived from regional observations.

We base our estimation of erosion rates on two previous studies quantifying river-borne suspended sediment yields from catchments across New Zealand (Hicks et al. 2011) and the specific density of geological units mapped throughout the country (Tenzer et al. 2011). Hicks et al. (2011) undertook a detailed measurement campaign during the 1990s that provided mean annual sediment fluxes for all 233 catchments. Using this data, along with a classification of catchment lithology and landforms and mean annual precipitation rates, they then calibrated a national model constraining specific sediment yield (SSY) to rivers on a 100 m resolution grid. The national calibration required local adjustments to address outliers in northwest Nelson, the central axial Southern Alps, McKenzie Country and Fiordland.

Spatially consistent erosion rates derived from suspended-sediment-yield and bedrock-density data can be tested against local observations of catchment-integrated denudation rates derived from ^{10}Be concentrations in sediment deposited in river beds. Davies et al. (2005) suggest that suspended sediment may represent 50% of total sediment yield for catchments in this region, and Robinson et al. (2016) therefore elected to multiply the SSY values by a factor of 2. However, more recent measurement of catchment-averaged ^{10}Be denudation rates (Larsen et al. 2014; Roda-Boluda et al. 2023) demonstrate a good correlation with the SSY model data when a factor of 1.5 is used to correct from the suspended component to total sediment yield (Figure A4.1a). This is lower than that earlier adopted by Davies et al. (2005) and Robinson et al. (2016), although well supported by the observational data, so we therefore adopt this value for the current hazard assessment.

Employing recent observations of river-borne sediment yield or denudation rates through ^{10}Be concentrations can raise questions with respect to the influence of earthquake-induced landslide-sediment contributions. Specifically, (1) are observed rates elevated as a result of recent earthquake-induced landsliding? (2) If these do not include a direct earthquake-induced landslide signal, do observed rates exclude the contribution from earthquake-induced landslides?

Regarding question (1): Observations of lacustrine sedimentation in Lake Ellery immediately to the west of the Alpine Fault indicate that seismically generated sediment may temporarily increase mean erosion rates by ~40% (Howarth et al. 2016). This is supported by seismically generated landslide models from Robinson et al. (2016), who suggested that co-seismic landsliding may increase erosion rates in some catchments by around 35%. Global studies indicate that the period of enhanced landslide-sediment production commonly decays exponentially to background levels over a period of up to seven years, depending on the return interval of the triggering event (Marc et al. 2015; Fan et al. 2018), with the phase of enhanced post-seismic sedimentation (incorporating enhanced instability and sediment transport) lasting on average 58 ± 15 years (Howarth et al. 2016). This reflects a period over which landslide deposits directly connected to river networks become exhausted of readily

transportable debris (see Croissant et al. [2019] and references therein). Given that the last earthquake to trigger regional landsliding in the region was the 1968 Inangahua earthquake (>56 years ago), suspended sediment yields observed by Hicks et al. (2011) almost certainly reflect rates of inter-seismic sediment transport. As such, these do not carry the short-term 35–40% increase in sediment output associated with fluvially connected post-seismic landslides and instead reflect more or less constant background rates of undifferentiated (earthquake- and rainfall-induced) landslide debris export via the river network. This is facilitated by a combination of secondary sub-aerial and fluvial processes, modulated by climatic factors (Croissant et al. 2019). We can therefore rule out the possibility that observed rates are elevated as a result of recent earthquake-induced landsliding.

Regarding question (2): Accounting for the relatively modest initial increase in earthquake-induced erosion rates, as well as rapid exponential decay, the associated increase in long-term erosion rates can therefore be expected to be approximately 4% over a 100-year seismic cycle, dropping to roughly 1–1.5% for a 300-year cycle (consistent with Alpine Fault recurrence intervals [Howarth et al. 2016]). These increases are negligible when compared to uncertainties associated with erosion-rate estimates in the study region (discussed later in this section). We therefore assume that the observed rates represent the combined transport of earthquake- and rainfall-induced landslide debris through secondary sub-aerial and fluvial processes and thereby capture the contribution of both triggers.

In order to convert the Hicks et al. (2011) SSY model into spatially distributed erosion rates $\dot{E}_{(x,y)}$, we must account for the additional proportion of sediment transported as bed load and divide the yield $[SSY_{(x,y)}]$ by the density of geological units underlying each catchment $[\rho_{(x,y)}]$. The digital rock-density catalogue of Tenzer et al. (2011) summarises measured densities of almost 10,000 specimens divided into 123 soil and rock types, consistent with the QMAP classification used in digital geological maps of New Zealand (Heron 2020). Equation A4.1 describes the method used to convert estimated suspended sediment yields to erosion rates in the region:

$$\dot{E}_{(x,y)} = \frac{SSY_{(x,y)} \times \delta}{\rho_{(x,y)}} \quad \text{Equation A4.1}$$

We can test the temporal validity of our adopted sediment-yield model by comparing against long-term geological uplift rates (Adams 1980) and landslide event-driven denudation rates (Hovius et al. 1997). Suspended-sediment-yield observations reflect erosion and sediment-transport processes spanning years to decades, while ^{10}Be sediment-yield calculations most commonly sample the effect of erosional processes over hundreds of years (~275 years in the sample area [Roda-Boluda et al. 2023]), and, although these have been shown to be sensitive to episodic landslide events well-connected to the fluvial system in the years immediately prior to sampling, the impact has been shown to be complex (Kober et al. 2012; Wang et al. 2017; Wilkinson et al. 2022), and, in the case of the Conway River catchment that was affected by the Kaikōura earthquake in 2016, sampling two years after the earthquake demonstrated no deviation from background rates (Wilkinson et al. 2022).

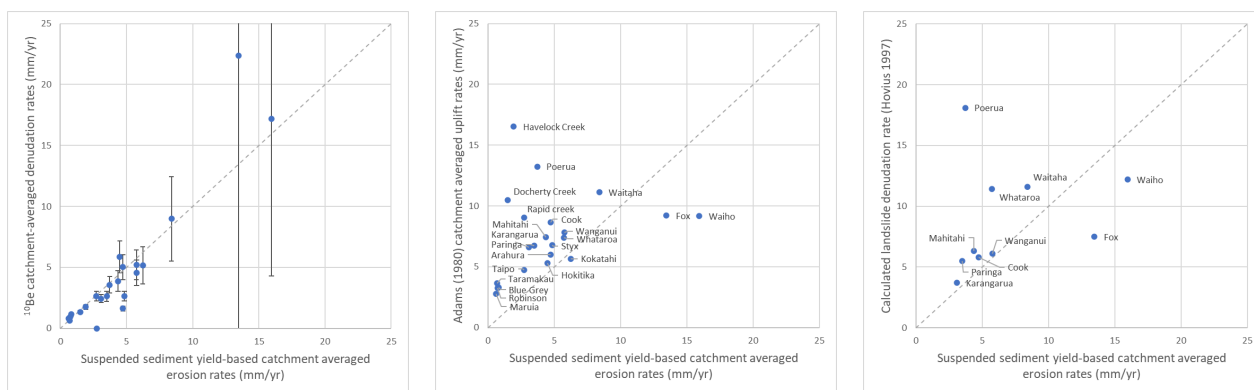


Figure A4.1 Compilation of various indicators of sediment production and erosion compared against mean rates estimated from suspended sediment yield (Hicks et al. 2011), the $1.5\times$ suspended to total sediment-yield correction factor determined in this study and bedrock densities (Tenzer et al. 2011) using the method presented here. (a) ^{10}Be catchment-averaged erosion rates derived for major West Coast drainage basins (Roda-Boluda et al. 2023). (b) Catchment-averaged contemporary bedrock-uplift rates (Adams 1980), which can be considered to be equivalent to erosion rates in steady-state landscapes. (c) Landslide denudation rates derived from mapped landslides (Hovius et al. 1997).

When a landscape is in a steady state, we can expect observed erosion rates to balance long-term bedrock-uplift rates. Adams (1980) developed a map of uplift across the Southern Alps based on a range of geological indicators (e.g. uplifted marine and river terraces) integrating uplift rates over thousands to tens of thousands of years. Aside from strongly glaciated Fox and Waiho river catchments, and the relatively small Poerua and Havelock Creek catchments, a comparison between the erosion rates adopted here and catchment-averaged uplift rates derived from geological indicators demonstrates general agreement between the two datasets, with an apparent systematic over-estimation of 2.5 mm/yr in the data derived from geological sources (Figure A4.1b). This over-estimation may be expected, as the geologically derived observations are biased toward areas in which uplift is occurring (in order to preserve uplifted landforms), and little data can be derived from areas of little or negative uplift regions. Overall, this suggests that the landscape is likely in a steady state, and our adopted erosion rates are consistent with long-term geological uplift rates, although significantly higher in the Fox and Waiho catchments. The discrepancy in these two catchments may reflect a short-term increase in landslide-sediment production or re-working of moraine deposits as a result of glacial retreat.

Directly calculating the proportion of long-term erosion effected by landslide processes from event-based catalogues is complicated due to the lack of temporal and spatial completeness of associated datasets, as well as (in most cases) a lack of direct volumetric measurements. However, Hovius et al. (1997) was able to estimate catchment-wide landslide denudation rates for a portion of the region from a catalogue of 7691 mapped landslides derived from aerial imagery spanning 40 years. The calculated denudation rates are compared against the erosion rates adopted in this study in Figure A4.1c, again indicating a good correlation between suspended-sediment-yield-based erosion rates adopted in this study and event-driven denudation by landslides when averaged across drainage basins. Although the rates calculated for the Fox and Waiho catchments are again higher than those estimated from aerial photo interpretation, the landslide catalogue employed by Hovius et al. (1997) relied on observing disturbances in vegetation and therefore includes almost no landslides on unvegetated slopes. The relatively high proportion of unvegetated or snow-covered slopes in these catchments likely therefore led to an under-estimation of the total landslide-driven erosion in these catchments. While re-mobilisation of moraine material has likely contributed to higher apparent sediment-yield rates in these catchments, the potential for a greater landslide contribution cannot therefore be ruled out. Overall, the good correlation between sediment yield, geological-uplift indicators, ^{10}B and landslide-catalogue-derived denudation rates supports the conclusion of Hovius et al. (1997) that the majority of erosion in the mapped catchments was the result of bedrock landsliding. We are therefore also confident that the erosion rates derived from sediment-yield data adequately capture landslide-sediment production for this regional landslide-debris-inundation assessment.

Uncertainties associated with the determination of erosion rates from these datasets are discussed in Section A4.8.

A4.1.2 Comparison between Adopted Denudation Rates and Global Erosion Datasets

In addition to comparing erosion rates adopted in this study to local datasets, we can gain further insight into potential uncertainties by comparing the basin-averaged erosion rates to observations compiled in global datasets. Long-term landslide-sediment-production rates in mountainous landscapes are a function of increasing local relief through tectonic uplift and fluvial incision, as well as reducing material strength through weathering and fracturing processes. Together, these competing processes lead to the development of ‘threshold hillslopes’, in which the mean topographic gradient in a drainage basin reflects the balance between constructive and destructive hill-slope processes (Montgomery and Brandon 2002).

Although the processes involved are complex, and both temporally and spatially variable, global compilations of long-term erosion rates derived from ^{10}Be concentrations in river-borne sediments indicate a positive relationship between the mean slope of the contributing river basin and spatially averaged erosion rates, which tend to range from 0.001 to 10 mm/yr (Figure A4.2) (Montgomery and Brandon 2002; Mishra et al. 2019). Although spatial and temporal variability within a basin can be expected to cause local variations of several orders of magnitude, Mishra et al. (2019) recently determined that the majority of spatially averaged erosion-rate observations for a given mean basin slope lie within an order of magnitude of the mean. Where the erosion rate for a given basin sits with respect to the mean depends on a range of physiographic factors, including precipitation (Mishra et al. 2019) and, to a lesser degree, vegetation cover (Larsen et al. 2023). These observations appear to hold for river basins in the region overseen by West Coast Emergency Management (WCEM), and a comparison of erosion rates derived from both suspended-sediment-yield and ^{10}Be observations with mean basin slopes indicate that catchments in the study region consistently plot ~1.5 orders of magnitude above the global mean for the associated basin slopes (Figure A4.2) – as may be expected, given the exceptionally high annual precipitation in this region (c.f. Mishra et al. 2019). The erosion rates adopted in this study are therefore consistent with global datasets and are unlikely to vary by more than an order of magnitude.

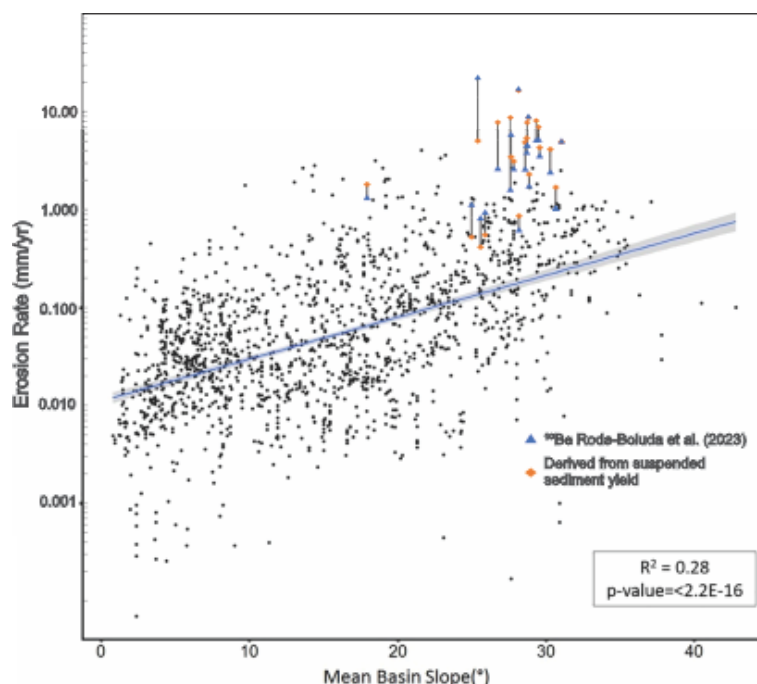


Figure A4.2 A global compilation of ^{10}Be -derived long-term erosion rates compared against the mean gradient in the contributing drainage basin. The ^{10}Be erosion rates and mean basin slope for catchments studied in Roda-Boluda et al. (2023) are indicated by blue triangles; orange diamonds represent estimated erosion rates derived from suspended-sediment yields. Modified after Mishra et al. (2019).

A4.1.3 Estimation of Landslide Sediment-Production Rates

A range of processes are responsible for erosion in steep and/or hilly terrain. These include fluvial and glacial erosion, soil creep, rain-splash erosion and overland flow, animal activity and landsliding. Landslides facilitate erosion by transporting bedrock uplifted through tectonic processes and/or sediments deposited as a result of a range of geomorphic processes down-slope to areas where material is either deposited or subsequently transported by fluvial processes. The long-term average rate of sediment produced by landsliding at a given location [$\dot{E}_{L(x,y)}$] can then be described as a function of the erosion rate at that location and the proportion of that eroded sediment generated through landsliding (ω_L). In the absence of good regional data for non-landslide erosion, we elect to ignore non-landslide erosion processes and treat all primary erosion as being a result of landsliding. This is the most conservative approach and likely leads to an over-estimation of landslide debris-production rates, especially in glacierised catchments. We adopt a bulking factor (η_L) to convert volumes of material produced through rock uplift (approximately 2650 kg/m³) into lower-density landslide debris (approximately 2000 kg/m³).

$$\dot{E}_{L(x,y)} = \dot{E}_{(x,y)} \times \omega_L \times \eta_L \quad \text{Equation A4.2}$$

A4.2 Kinematic Landslide Source Model

Identification of potential landslide-source areas was based on an analysis of landscape morphology, with the intention of determining the greatest kinematically feasible landslide-volume classes within the digital elevation model (DEM).

Our kinematic landslide source model allows us to estimate the largest hypothetical landslide that can occur at a given location based on an assumption of basic material-strength parameters (friction and cohesion) and an assessment of required geometric freedom through an analysis of local topography. The purpose of this step is not to evaluate slope stability but rather to define geometric constraints for the largest potential landslide sources. Therefore, we do not explicitly calculate the balance of driving and resisting forces for each hypothetical source.

We then assume that smaller landslides are able to occur anywhere that larger ones can occur. This is a notable simplification, as present-day local topography may have insufficient relief to support the generation of smaller landslides at some locations within a larger landslide body. However, given that (1) larger landslides can only occur on slopes with average gradients in excess of an assumed critical-failure angle (and mean slope angles must therefore equal or exceed this angle) and (2) failure of these slopes may occur progressively (such that future topography may support smaller failures where it is not currently possible), we suggest that this simplification is reasonable for a regional analysis.

We identified regions capable of generating landslides by calculating the ‘excess topography’ (Blöthe et al. 2015) above an assumed critical-failure plane, providing a measure of the thickness of bedrock or sediment overlying the assumed failure plane for every pixel in the DEM (see Figure A4.3; excess topography). This analysis was undertaken by filtering the topography using a moving window twice the diameter of the assumed largest volume class (see Equation A4.6) and a fixed angle (θ_{xst}) representing the assumed threshold basal angle for slope failure (i.e. critical-failure plane). We note that this is a necessary simplification for the current regional analysis, and our results do not preclude the potential for landslide-debris generation from lower basal-failure angles in specific settings. The intersection of resulting excess-topography surfaces defines the boundaries of maximum possible-failure units. We identify the boundaries by selecting all pixels in the resulting DEM with no contributing catchment area, excluding any isolated groups of zero-catchment-area pixels with total connected lengths less than the largest volume-class diameter, as these tend to sub-divide the failure units and limit potential failure volumes.

While the excess-topography criteria defines potential basal-failure planes, landslide area-volume relationships are used to limit the volume of landslides close to the margins of maximum possible-failure units (see Figure A4.3; landslide area-volume scaling). Similar relationships have been used to relate the planform area of mapped landslides to calculated volumes of up to 10,000,000 m³, although the relationship is best constrained for landslides less than 100,000 m³ (Guzzetti et al. 2009; Larsen et al. 2010; Massey et al. 2020b). This relationship is commonly described using a power-law equation of the form:

$$V = \alpha A^\gamma \quad \text{Equation A4.3}$$

where V is the total landslide volume, A is planimetric area and α and γ are scaling parameters representing the mean fit for landslides in a given dataset. Comparisons of global landslide datasets indicate that scaling parameters are consistent across a wide range of landslide sizes, locations and triggers. Observations generally indicate that $\alpha < 1$, and varies on a logarithmic scale, while $\gamma \approx 1.4$, although this can range between $1 < \gamma < 1.5$ (Guzzetti et al. 2009; Larsen et al. 2010; Massey et al. 2020b). Klar et al. (2011) demonstrated a probable mechanical control underpinning this relationship and developed analytical solutions to relate the scaling parameters to mechanical properties of 2D and 3D landslide geometries for which the analytical solution for the limit-equilibrium equation indicates that (for $\gamma = 1.36$) α can be related to the mechanical properties of the landslide source by the following equation:

$$\alpha = k \left(\frac{c}{\rho_L(x,y)} \right)^d \quad \text{Equation A4.4}$$

where k is a dimensionless constant, d and γ are derived from empirical datasets, c is the average cohesive strength of the failure surface and $\rho_L(x,y)$ is the bulk density of the landslide material. We adopt parameters consistent with the more generic 2D model, assuming that the landslide depth is proportional to the length of its source and that $k = 0.45$, $d = 0.28$ and $\gamma = 1.36$ (Klar et al. 2011).

We select a representative cohesive strength of 50 kPa, which is near the upper limit of back-calculated values reported in Alberti et al. (2022) but remains significantly lower than the cohesive strength typical of fractured greywacke rock masses (400–1000 kPa, as described by Read et al. [1999]). As cohesive strength is used to determine scaling characteristics for all landslide volume classes – covering both soils and weathered or fractured rock – a low to intermediate value is considered appropriate for this regional-scale study. As discussed here, cohesive strength is highly dependent on the type of materials present and their physical condition (compaction, weathering, fracture density, etc.). These properties tend to vary with depth from the surface, and landslide area-volume relationships should therefore theoretically also vary with increasing depth from the surface. Although we currently have no data to better constrain this relationship in the study area, explicitly accounting for spatially variable, depth-dependent cohesion values could reduce uncertainties in the landslide-debris flux and annual property loss risk (APLR) datasets. Further discussion regarding selection of the cohesive strength and associated uncertainties can be found in Section A7.3.

The landslide area-volume scaling relationship described in Equation A4.5 was applied to a grid describing the horizontal distance to the nearest failure-unit cell boundary [$r_{(x,y)}$], where, assuming a representative cylindrical volume, the maximum landslide depth at each pixel [$D_{(x,y)}$] was calculated by:

$$D_{(x,y)} = \frac{V_{(x,y)}}{A_{(x,y)}} = \frac{\alpha (\pi r_{(x,y)}^2)^\gamma}{\pi r_{(x,y)}^2} \quad \text{Equation A4.5}$$

Landslide ‘scarps’ that form the lateral and upper margins of evacuated landslide-source areas are commonly planar features, defined by the mechanics of failure or pre-existing discontinuities in the rock mass. As such, pre-failure surface topography has little impact on the form of scarps formed adjacent to landslide margins. In order to remove the effect of topography on the geometry of scarps, which we derive from area-volume scaling relationships, we first applied a linear interpolation to

generate an envelope between the failure-unit boundaries (i.e. the margins of hypothetical largest possible landslides). We generate planar failure surfaces consistent with the failure-unit margins by subtracting the residual between this plane and the DEM topography (to generate a planar surface within the margin of the failure), then subtracting depths calculated from the area-volume scaling relationship. Although this step will cause an over- or under-estimation of volumes derived from the scaling relationship (as actual topography can lie both above and below the planar surface), the relationship is not meant to provide an accurate representation of landslide geometry, and, as such, it must be treated as a guideline rather than a hard and fast rule. Our approach ensures that we define maximum landslide volumes that are kinematically feasible, while also maintaining approximate area-volume scaling relationships derived from regional landslide observations.

Shallow failures originating from soil or weathered bedrock may initiate on hill slopes with gradients less than that assumed for the kinematic model. In order to capture these features, we assigned a depth of failure equivalent to a Class 1 landslide to all cells not already classified with a surface gradient of more than θ_{NAT} (see Figure A4.3).

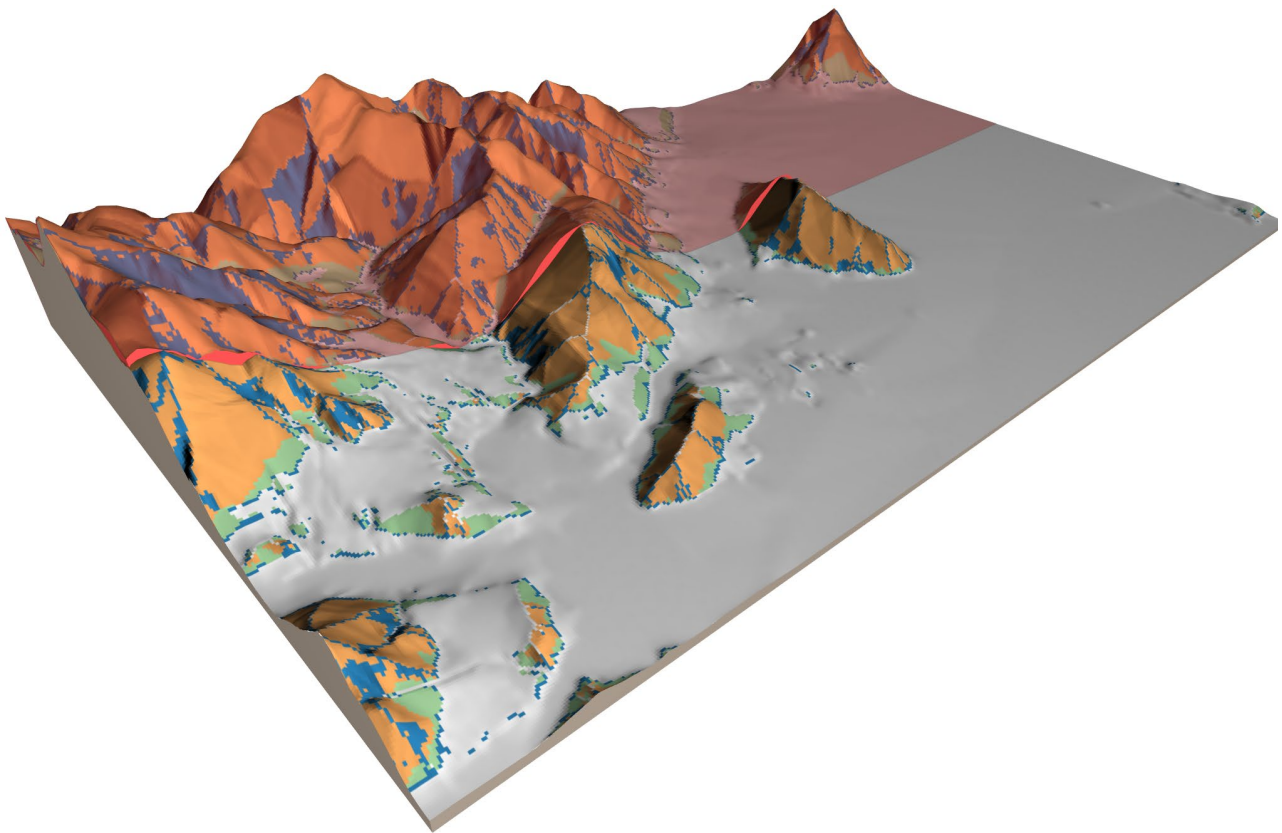


Figure A4.3 Example of the maximum depth surface derived from the kinematic landslide source model (foreground). Surface topography is superimposed in the red-shaded region for comparison (background). Green denotes the threshold slope angle for excess topography (θ_{XST}), orange denotes the landslide area-volume scaling [$D_{(x,y)}$] and blue denotes steep slopes otherwise not captured (θ_{NAT}).

A4.3 Characteristic Landslide-Volume Distributions

The contribution of landsliding to long-term erosion rates varies as a function of the volume of sediment mobilised in the landslide-source area, as well as the total frequency of landslide events. The relative erosional contribution by each landslide-volume class requires additional insight from local landslide inventories. In particular, statistics describing the landslide volume-frequency relationship are required to distribute sediment associated with a given trigger across each of the various landslide-size classes.

Landslide volume-frequency relationships have been shown to demonstrate self-similarity across a range of spatial scales and geographic settings, likely reflecting physical controls associated with slope geometry and soil or rock strength (Brunetti et al. 2009). While some studies have employed empirical area-volume scaling relationships to estimate the total volume of sediment produced from individual triggering events (e.g. Marc et al. 2016), very few employ true volume measurements required to accurately describe the frequency distribution of source volumes. Brunetti et al. (2009) compiled a global database of landslides with known source volumes (Figure A4.4) and found the probability density of landslide volumes to be approximately log-normally distributed about a geometric-mean source volume. This is consistent with recent findings from a number of authors (Medwedeff et al. 2020; Moreno et al. 2023). Although the geometric-mean volume and associated standard deviation varied from location to location, most datasets were centred between 10 and 10,000 m³, with ranges varying from ± 1 to 2 orders of magnitude. In this section, we compare these distributions to those derived from landslide sources in the WCEM study region.

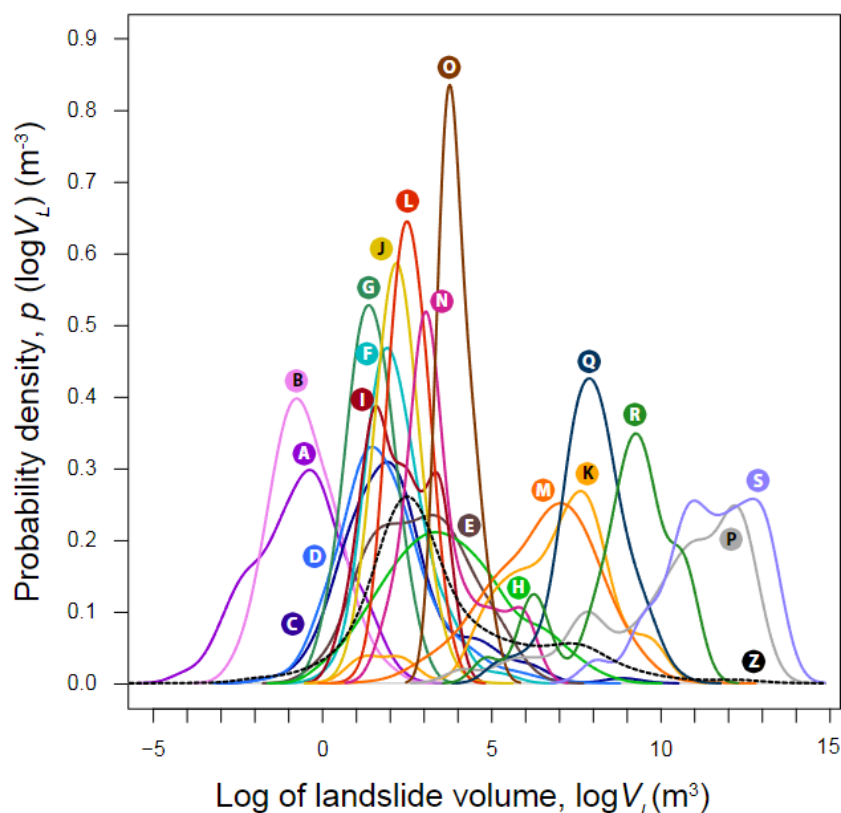


Figure A4.4 Probability-density distributions derived from the log of calculated landslide volumes from a compilation of 19 mapped landslide catalogues from around the globe, as well as planetary observations (Brunetti et al. 2009).

There are few rainfall-induced landslide-source areas accurately mapped in the study region and no accurately mapped earthquake-induced landslide sources. In order to evaluate the landslide area-volume frequency distribution for rainfall- and earthquake-induced landsliding in the region, we therefore compiled all mapped landslide polygon datasets available for the region overseen by WCEM for which the coverage can be reasonably assumed to be complete for given triggering events. Rainfall-induced landslides have been derived from studies incorporating undifferentiated triggering events, with the assumption that a majority are generated by rainfall (Hovius et al. 1997; Hilton et al. 2011; Leith, unpublished; Emberson et al. 2016; Wride and de Vilder 2021), while earthquake-induced landslides are derived from the M_w 7.1 1968 Inangahua and M_w 7.3 1929 Murchison earthquakes (Hancox et al. 2014, 2016).

Where landslides were not mapped with separate source and runout polygons, we used an in-house machine-learning model to categorise landslides, distinguishing between different types of movement based on the shape and topographic characteristics of landslide features and comparing these with the categories represented in IFFI (the Italian Landslide Inventory⁵). Relatively wide landslide polygons with little vertical extent, for example, are more likely representative of (less mobile) rotational landslides, whereas long, narrow polygons with a large vertical extent are more likely to reflect more mobile debris flows. A summary of polygons used to generate source areas is presented in Table A4.1.

Table A4.1 Summary of polygons used for volume estimation and model validation. Polygons were mapped as landslide outlines (including source and runout). We used an in-house machine-learning model to categorise polygons into landslide types based on geometric characteristics of the DEM within the polygons. A transfer-learning model was then used to designate the upper proportion of the polygon as the landslide ‘source’. While all landslides were used to determine earthquake- and rainfall-induced volume distributions, only landslides likely to be associated with ‘flow’ or ‘avalanche’ movement types were included in the runout model validation (see Section A5.4.4 for details).

	Number of Landslide Polygons	Proportion of Elevation Range Classified as ‘Source’ (%)	Landslide Category
Included in Model Validation	26	30	Complex rock slide
	1043	34	Rock slide – medium
	146	38	Rock slide – large (rock avalanche)
	414	40	Debris flow
	8746	55	Rock slide – small
Not Included in Model Validation	382	58	Slow earth flow
	23	70	Soil slide – small
	1316	71	Rotational/translational slide
	16	74	Complex landslide
	342	75	Slow earth flow
	403	78	Rotational/translational slide
	90	81	Rotational/translational slide

We used the same machine-learning model to categorise landslide outlines mapped following the 2016 Kaikōura earthquake (Massey et al. 2020a), for which the proportional fall height separating source from runout and deposit is known. This allowed us to determine representative source areas for each landslide category based on the proportional elevation ranges occupied by source areas in the Kaikōura earthquake dataset. Finally, we used the same machine-learning model to classify mapped landslide outlines in the region overseen by WCEM and divide these into source and runout categories based on the elevation ranges derived for the Kaikōura dataset. The probable volume of each landslide source was then calculated from the 25 m DEM using the kinematic-source model described in Section A4.2, with landslide region boundaries defined by the calculated source-area extent. This allowed us to determine source volumes for all mapped earthquake- and rainfall-induced landslides in the study region, as well as build statistical models based on calculated volume distributions (Figure A4.5).

⁵ <https://www.progettoiffi.isprambiente.it/?lang=en>

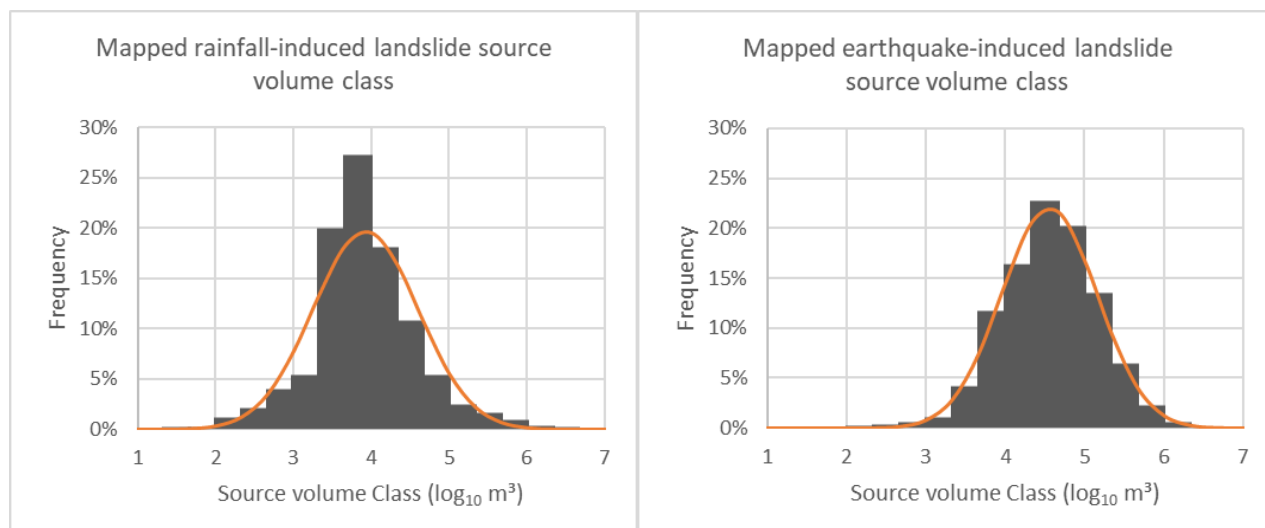


Figure A4.5 Landslide frequency-volume plots for all landslide sources in the rainfall- and earthquake-induced landslide datasets employed in this study (Table A1.2).

In line with the findings of Brunetti et al. (2009), landslide source frequency-volume plots for the West Coast region demonstrate approximate log-normal distribution (Figure A4.5). Overall, we observe a greater mean volume for earthquake-induced landslides, although the ranges for both datasets are similar. This is consistent with observations from international datasets (see Brunetti et al. [2009] and references therein) and likely represents a difference in the trigger process rather than the local impact of topographic or bedrock strength properties (Brunetti et al. 2009). Table A4.2 provides a summary of the observations employed in the dataset, as well as the calculated geometric mean and 1-sigma distribution of the source-volume statistics for earthquake- and rainfall-induced landslide-source volumes in the region.

Table A4.2 Summary landslide frequency-volume statistics for rainfall- and earthquake-induced landslides in the study region.

Trigger	Observations per Volume Class								Volume Distribution ($\log_{10} \text{ m}^3$)
	1	2	3	4	5	6	7	>7	
Earthquake	0	4.55 ± 0.60	68	1073	3769	1403	39	0	4.55 ± 0.60
Rainfall	4	3.92 ± 0.68	522	3821	2485	358	43	2	3.92 ± 0.68

The geometric mean and standard deviation of landslide-volume distributions for both earthquake- and rainfall-induced landslides are employed to determine the proportion of landslide-debris production assigned to each landslide class range. These are explicitly incorporated in Equations A4.10 and A4.11 in Section A4.5.

A4.4 Landslide-Volume Classes

The LSP and LSD models require potential landslide source volumes to be divided into discrete volume-class ranges. We employ a similar approach to previous studies (de Vilder et al. 2021) and adopt a common logarithm with which to sub-divide the classes. Selecting the full range of volume classes and the range defining each interval requires some trial and error, as significant trade-offs exist between computational performance and accuracy of results. In general, selecting fewer classes with larger volume-range intervals leads to a linear decrease in computation time, as each model can be run in parallel. However, larger intervals tend to lead to an over-estimation of the total material available to slide, as discretising the intervals generates an inherent over-estimation of the material available with respect to the output of the landslide sediment-production model. Although this is primarily controlled

by the effects of topographic relief and class boundaries, we find that selecting volume classes spanning order-of-magnitude ranges (i.e. integer limits) tends to lead to an over-estimation of the total volume of debris available by approximately 20%. This effect typically reduces to less than 1% difference between total annual debris production when volume ranges are reduced to 33% of an order of magnitude.

We opt to separate source volumes into order-of-magnitude (i.e. full decadal) ranges between 10 m^3 and $100,000,000 \text{ m}^3$, favouring a three-fold decrease in simulation time, with more conservative estimates of material flux and debris extent as a result. LSD model runs for a 150 km^2 section in the vicinity of Kokiraki indicate that the full order-of-magnitude volume-class ranges lead to a 20% higher mean flux but just 1% greater inundation area with respect to identical models run on 33% order-of-magnitude ranges (see Figure A4.6). We note that, as described in the following section, larger volume landslides are only simulated in the LSD model where the kinematic-source model allows.

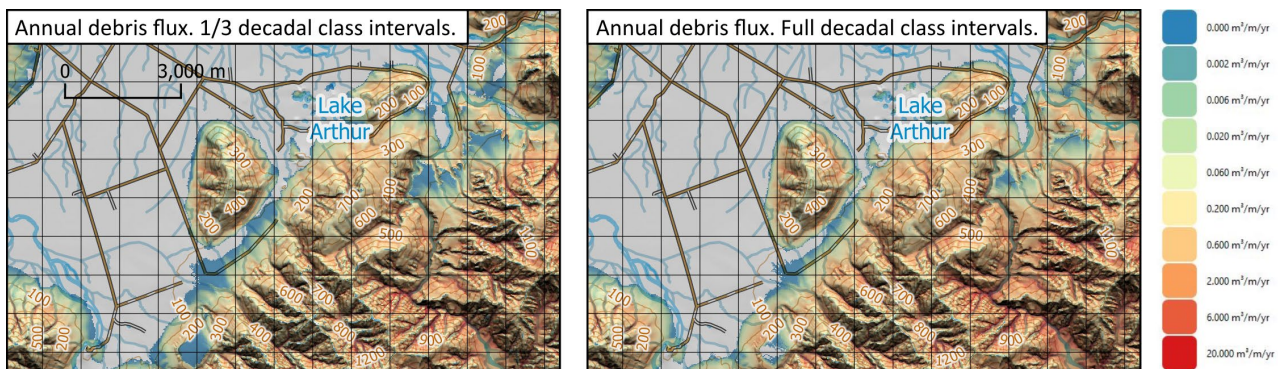


Figure A4.6 Comparison of combined annual landslide-debris-flux outputs from preliminary landslide sediment-distribution model runs incorporating 33% and full decadal class intervals. These outputs are illustrative only and may not reflect landslide-debris-inundation hazards at the indicated location.

A4.5 Mean Annual Landslide-Debris-Production Rates

In order to calculate the mean annual landslide-sediment-production rate for each landslide volume-class range, we employ the characteristic landslide frequency-volume relationships presented in the previous section to distribute calculated annual landslide sediment production across the range of volumes that can be released from each grid cell. This requires that we first convert landslide volumes to representative areas by employing the inverse of the area-volume scaling relationship described in Equation A4.3, i.e.

$$A_{L(c)} = \sqrt[\gamma]{\frac{V_L}{\alpha}} \quad \text{Equation A4.6}$$

where V_L is landslide volume, A_L is the corresponding area and α and γ are scaling parameters. Calculating the mean depth $[\bar{D}_{L(c)}]$ corresponding to each volume-class boundary is then trivial:

$$\bar{D}_{L(c)} = \frac{V_{L(cg)}}{A_{L(cg)}} \quad \text{Equation A4.7}$$

Comparing the maximum possible landslide depths from the kinematic model with the mean depths for each landslide-class boundary then allows us to identify the possibility for landslides within each class to occur at each pixel location $[K_{L(c)(x,y)}]$. We assume that landslides of a given class range can occur if the mean depth of the upper bounding volume is less than that derived from the kinematic model for each region (see Figure A4.7).

$$K_{L(c)(x,y)} = D_{(x,y)} > \bar{D}_{L(c)} \quad \text{Equation A4.8}$$

Similarly, the maximum kinematically feasible landslide volume at a given location $[V_{L(max)(x,y)}, \text{m}]$ can be denoted by:

$$V_{L(max)(x,y)} = \max(V_{L(c)} \times K_{L(c)(x,y)}) \quad \text{Equation A4.9}$$

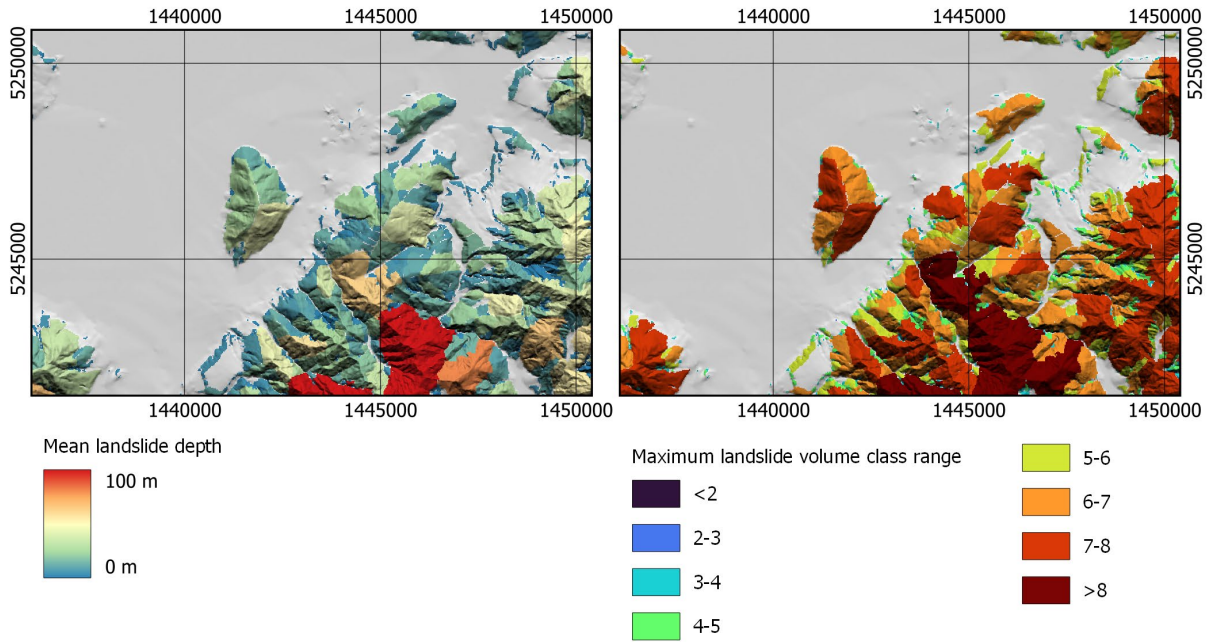


Figure A4.7 Calculated maximum landslide depths based on kinematic models (left) and maximum volume-class ranges based on the mean depth within each kinematically feasible region (right).

Calculating the likelihood of valid volume classes occurring at each location in the landscape then requires the incorporation of characteristic landslide frequency-volume distributions. We opt to describe the likelihood of a landslide of a given volume occurring $[N_{(x,y)(T)}, 1]$ using the probability density function (PDF) of the log-normal distribution. This is described in Equation A4.10, below:

$$N_{(x,y)(T)} = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{V_{L(max)(x,y)} - V_{\mu(T)}}{V_{\sigma(T)} \sqrt{2}} \right) \right] \quad \text{Equation A4.10}$$

Here, $V_{L(max)(x,y)}$ is the maximum kinematically feasible landslide volume at a given location; $V_{\mu(T)}$ is the mean of the landslide volume PDF for a given trigger; $V_{\sigma(T)}$ is the standard deviation of the PDF (derived from observational data; see Section A4.3); and erf denotes the error function, which is a standard mathematical function used in probability and statistics.

We account for increased proportionality of lower-volume landslides at locations in which the kinematic model suggests that larger landslides are infeasible by normalising the PDF by the cumulative distribution function up to the upper depth limit (assuming that lower volumes can occur at any feasible location). The probability of a landslide of a given volume class and trigger occurring at each location $[N_{L(c)(T)(x,y)}, 1/\log_{10}(\text{m}^3)]$ is then given by a conditional formula in which proportions are either equal to the volume-range-normalised PDF (when the depth class is kinematically feasible) or set to zero:

$$N_{L(c)(T)(x,y)} = \begin{cases} \frac{1}{\sqrt{2\pi V_{\sigma(T)}^2}} e^{-\frac{(V_{L(cg)} - V_{\mu(T)})^2}{2 V_{\sigma(T)}^2}} & \text{if } 0 \leq \bar{D}_{L(c)} \leq D_{(x,y)} \\ 0 & \text{otherwise} \end{cases} \quad \text{Equation A4.11}$$

where $V_{L(cg)}$ is the geometric mean of the volume class interval.

In order to determine the proportion of erosion generated by each valid volume-class range $[D_{L(c)(T)(x,y)}, \text{m}^3/\text{m}^2]$, we calculate the probability of landsliding by integrating the likelihood of occurrence with respect to the breadth of the class range $[\omega_{(c)} = \log_{10}(V_{L(c)} - V_{L(c-1)}), \log_{10}(\text{m}^3)]$ and multiply by the mean erosional depth of the interval $(\bar{D}_{L(cg)}, \text{m})$, calculated by substituting $V_{L(cg)}$ into Equations A4.7 and A4.8).

$$D_{L(c)(T)(x,y)} = N_{L(c)(T)(x,y)} \times \omega_{(c)} \times \bar{D}_{L(cg)} \quad \text{Equation A4.12}$$

where c again denotes the upper limit of the volume-class range, and cg represents the geometric mean of the volume-class range.

The normalised proportion of erosion by each volume-class range and trigger $[V_{L(c)(T)(x,y)}, 1]$ can then be determined by dividing the proportion of erosion generated by each volume-class range by the sum of erosion for all feasible volume-class ranges.

$$V_{L(c)(T)(x,y)} = \frac{D_{L(c)(T)(x,y)}}{\sum_{c_{min}}^{c_{max}} D_{L(c)(T)(x,y)}} \quad \text{Equation A4.13}$$

The mean annual landslide-sediment-production rate for each volume class range, trigger and return interval at each location within the landscape $[\dot{E}_{L(c)(T,RI)(x,y)}, \text{m/yr}]$ is then calculated by multiplying the mean annual landslide-sediment-production rate (Equation A4.2) by the proportional contribution from each volume class and trigger (Equation A4.13), as well as the mean probability of failure over the temporal integration interval (Equation A4.12). Finally, this needs to be normalised by the total probability of failure (Equation A4.10). This is described in Equation A4.14:

$$\dot{E}_{L(c)(T,RI)(x,y)} = \dot{E}_{L(x,y)} \times \frac{N_{(x,y)}(T_{RI-1}, T_{RI}) \times V_{L(c)(T)(x,y)}}{N_{(x,y)}} \quad \text{Equation A4.14}$$

This process ensures that the calculated sediment-production rates are accurately scaled and reflect the contributions from different landslide classes, triggers and probabilities of occurrence. The sum of calculated erosion rates for all landslide-size classes, triggers and return intervals, i.e. $\sum \dot{E}_{L(c)(T,RI)(x,y)}$, will then equal the estimated landslide-induced erosion rate, i.e. $\dot{E}_{L(x,y)}$, everywhere that landsliding is feasible based on kinematic constraints. Figure A4.8 presents calculated mean annual landslide-debris-production rates for present-day and future RCP 6 2081–2100 climate-change scenarios. The rates presented in Figure A4.8 differ from long-term sediment-production rates presented in Figure 2.3, as landslide-debris-production rates include the effect of the landslide sediment bulking factor (η_L ; see Equation A4.2).

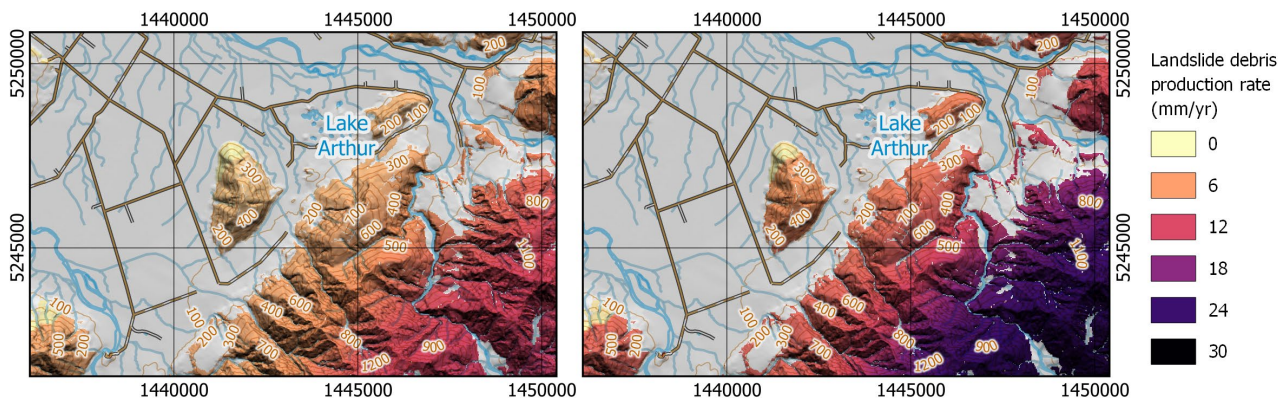


Figure A4.8 Left: Calculated mean annual landslide-debris-production rates for the present-day. Right: A future RCP6 2081–2100 climate-change scenario.

By assessing the range of feasible landslide-size classes in the DEM, it is possible to evaluate the probable erosion by each volume-class range, return interval and trigger. Figure A4.9 presents an example of the mean annual landslide-sediment-production rates calculated for a single pixel in the DEM. Each of the 112 nodes in the plot represents the input sediment contribution for an individual Gravitational Path Process (GPP) model run.

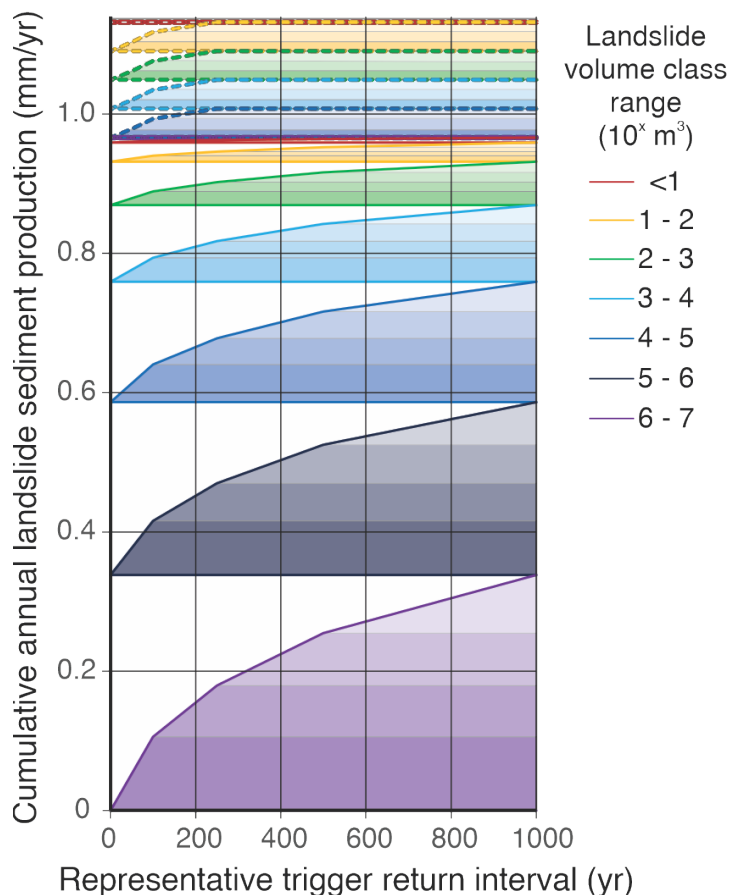


Figure A4.9 Landslide sediment-production (LSP) model output describing cumulative annual sediment production for a given grid cell, separated by landslide volume class (dashed lines = rainfall-induced landslide, solid lines = earthquake-induced landslide). In this case, the calculated landslide erosion rate is 1.1 mm/yr, of which LSP model results predict that approximately 90% is a result of earthquake-induced landsliding (solid lines). The majority of long-term erosion at this location is facilitated by large (Class 6–7) earthquake-induced landslides (violet solid lines) with relatively short (100-year) return intervals (denoted by the darkest violet bar). These large, somewhat frequent, events account for an average sediment production rate of 1 mm/yr at this hypothetical location.

A4.6 Scenario-Specific Landslide-Sediment Production

The probable sediment production for specific landslide-inducing scenarios (e.g. 50-, 100- and 250-year ARI rainfall scenarios and an Alpine Fault magnitude 8 [AF8] scenario) is determined by comparing the event-specific probability of failure to the mean annual probability of failure at a given location. The sediment produced in each scenario [$E_{LS(x,y)}$] can be calculated by substituting the probability of failure and integration interval in Equation A4.14 with the calculated landslide susceptibility associated with the given scenario [$S_{S(x,y)}$]. As susceptibility is not annualised, this substitution has the effect of altering the resultant units from an annual sediment production (m/yr) to a scenario-specific contribution (m):

$$E_{LS(x,y)} = \dot{E}_{L(x,y)} \times \frac{S_{S(x,y)}}{N_{(x,y)}} \quad \text{Equation A4.15}$$

As with the calculation of mean annual sediment production, scenario-specific sediment production models do not allow for the determination of exact locations and volumes of landslide debris. Rather, these indicate the probability that sediment from landslides of given volumes will originate from each cell in the model. The calculated sediment flux, and associated deposition, must therefore be considered as probabilities, rather than predictions for the given scenario.

A4.7 Landslide Sediment-Production Adjustment for the RCP6 2081–2100 Climate-Change Scenario

Without regional data describing the manner in which rates of sediment production and sediment transport are likely to change in response to the diverse impacts of climate change, we adopt the change in the landslide-source-susceptibility (LSS) model rainfall-induced landslide probability from the present-day to RCP6 2081–2100 climate-change scenario as a proxy for increased erosion rates with respect to long-term averages. We assume that earthquake-induced landslide sediment-production rates under an RCP6 climate-change scenario will remain the same as the present-day. This allows us to calculate $P_{RCP6(x,y)}$, the mean annual probability of landsliding under the RCP6 scenario, by substituting appropriate susceptibility values into Equations A3.4–A3.6, such that:

$$P_{RCP6(x,y)} = P_{RIL_RCP6(x,y)} + P_{EIL(x,y)} \quad \text{Equation A4.16}$$

In order to maintain earthquake-induced landslide sediment-production rates in the face of increased rainfall-induced landslide susceptibility, we increase the landslide-sediment-production rate in concert with the increase in mean annual landslide probability [i.e. from $P_{(x,y)}$ in Equation A3.6 to $P_{RCP6(x,y)}$ in Equation A4.16] with the help of a weathering-rate multiplier (W):

$$W = 1 + \frac{P_{RCP6(x,y)} - P_{(x,y)}}{P_{(x,y)}} \quad \text{Equation A4.17}$$

The increase in available sediment due to increased weathering ($\dot{E}_{L_S_RCP6(x,y)}$) can then be defined as a function of the long-term erosion rate and weathering-rate multiplier (W):

$$\dot{E}_{L_S_RCP6(x,y)} = \dot{E}_{L(x,y)} \times W \quad \text{Equation A4.18}$$

A4.8 Key Landslide Sediment-Production Model Assumptions and Uncertainties

We note a number of uncertainties associated with the mean annual landslide-sediment-production rate calculation:

- We base our estimates of present-day landslide-sediment-production rates on a derivative of rates of specific sediment yield (SSY) presented in Hicks et al. (2011). They report a standard factorial error (SFE) of between 1.55 and 1.8 for the majority of studied catchments, noting that glaciated catchments on the West Coast may be associated with SFEs of ~2–3 (an SFE of 1.8 is equivalent to a geometric standard deviation of 1.8, meaning one ‘sigma’ on the log scale corresponds to multiplying or dividing by 1.8). The authors recommend against applying the models to predict sediment yields from catchments less than 10 km², raising the question of applicability at the local slope scale, as applied here. In this study, we do not expect SSY, and therefore calculated landslide debris-production rates, to accurately represent present-day activity on individual hill slopes across the approximately 25,000 km² of the region overseen by WCEM. However, evidence suggesting that the landscape is in a steady state (see Section A4.1.1) and that, on average, denudation rates derived from SSY estimates represent long-term, spatially integrated erosion rates provides confidence that this dataset is adequately capturing regional variability in landslide debris-production rates. That said, we note that uncertainties associated with SSY inputs generate some of the greatest uncertainties in APLR predictions (see Section 8.3), and therefore identify local refinement of the landslide sediment-production models with appropriate local input data as a high priority for local re-evaluation of hazard and risk (see Section 5.5).

- We assume that present-day rates of landslide-sediment production reflect long-term erosion rates. Although the contributing datasets are regionally consistent, these do not capture spatial and temporal changes in rates associated with destabilisation of slopes by retrogressive landsliding, river erosion, coastal retreat, glacial retreat, anthropogenic activities (e.g. excavation of road cuts, quarrying, mining or removal of retaining structures), vegetation change (deforestation), short-term climatic changes or other effects that may locally enhance or decrease the long-term rate of landslide-sediment production. Although regionally accurate, this may lead to local over- or under-estimation of landslide-debris-inundation hazard.
- We assume that our calculated long-term erosion-rate model reflects long-term erosion rates throughout the study region. Although independent data derived from catchments along the range front support this assumption, there is little data to constrain the accuracy of the model in other areas. This may lead to local over- or under-estimation of landslide-debris-inundation hazard in areas beyond the range front.
- We assume that all erosion is driven by landslide processes where landsliding is kinematically feasible. Adopting the long-term erosion rate as a landslide-sediment-production rate means that the LSP model provides an upper bound on regional landslide-sediment generation.

We note a number of uncertainties associated with the kinematic-model calculation:

- We assume that the threshold gradient used for the excess topography calculation is isotropic and spatially homogeneous. In reality, this is likely to vary with rock or soil strengths, as well as with underlying structural controls. Varying this gradient will alter the distribution of the maximum feasible landslide volumes. A steeper gradient will bias sediment production toward lower volume and more frequent landslide classes.
- We assume that the adopted cohesion is spatially consistent and invariant with landslide volume. In reality, this is likely to vary with rock or soil strengths. Varying the cohesion will alter the distribution of the maximum feasible landslide volumes. A lower cohesion will bias sediment production toward lower volume and more frequent landslide classes.
- We assume that the calculated distribution of maximum landslide volumes is representative of the maximum possible volume of landslides sourced from slopes throughout the study region. We do not explicitly model potential landslide-source areas. This may lead to local over- or under-estimation of landslide-debris-inundation hazard.
- We assume that the topography in the DEM is an accurate representation of the ground surface. The 8 m DEM is derived from the January 2012 Land Information New Zealand (LINZ) Topo50 20 m contours, which largely reflect topography digitised from 1940 aerial photographs. We have down-sampled this data to 25 m resolution for the purposes of this regional study. The DEM therefore likely under-represents the smaller landforms (less than approximately 100,000 m²), and smaller landslide source areas may therefore not be identified (see Section A7.6.2 for further details on this topic).

We note a number of uncertainties associated with the calculation of landslide-volume distributions:

- We include no directly measured landslide volumes in this study and base our estimated geometric-mean volumes on a combination of mapped landslide areas and DEM analysis. Given the resolution of the source imagery and the base DEM, this is most likely to have resulted in an over- rather than under-estimation of landslide volumes and would result in an over-estimation of landslide hazard.
- We assume that landslide-volume distributions are consistent across the region. As landslide size is a function of a range of factors, including material strength, joint patterns, vegetation strength and geomorphological setting, it is likely that landslides in some areas are consistently larger than assumed, while landslides in other settings will be consistently smaller.

Given the above assumptions and uncertainties, we have elected to adopt 'best estimates' for all input variables while adopting conservative ranges for associated uncertainties. This ensures that LSP model results most closely reflect the input datasets and assumptions described in this report, while conveying the overall level of uncertainty associated with inputs to the LSP model (see Appendix 7). We recommend that West Coast Regional Council consider appropriate precautionary reductions in acceptable hazard or risk metrics based on an evaluation of appropriate confidence intervals and reported model uncertainty (as discussed in Section 5).

APPENDIX 5 Landslide Sediment-Distribution Model

This section describes details of the landslide sediment-distribution (LSD) model used to inform the landslide-debris-inundation risk assessment.

Regional landslide-debris-inundation potential was modelled using the Gravitational Path Process (GPP) model developed by Wichmann (2017). We employ the GPP model in two distinct configurations, employing different runout models to simulate avalanche- and flow-type landslide runouts. In both cases, we use the fully featured GPP model with both material deposition and sink filling enabled as described in Wichmann (2017). The selection of input parameters for each configuration is discussed later in this section.

Key LSD model assumptions and uncertainties are noted in Section A5.9, and a quantitative sensitivity analysis is undertaken in Section A7.4.

A5.1 Landslide-Source-Material Thickness

Landslide source material thicknesses were informed by the calculated probability of sediment production within the study region to assess the combined probability of debris inundation. To achieve this, we ran an ensemble of GPP models capturing the full range of triggers, return intervals, class sizes and runout mechanisms. The landslide source-material thickness and distribution for each model run (M_{GPP}) was determined by multiplying the erosion rate derived for the given input parameters by an integration interval (σ) to infill topography, prevent small depressions from trapping and/or redirecting debris and generate sufficient deposition to mimic single landslide events:

$$M_{GPP(c)(T,RI)(x,y)} = \dot{E}_{L(c)(T,RI)(x,y)} \times \sigma \quad \text{Equation A5.1}$$

We adopt an integration interval of 10,000 years, reflecting the approximate interval since deglaciation of the region following the Last Glacial Maximum. This effectively ensures that the magnitude of debris deposited in each model run is similar to the scale of post-glacial sedimentary landforms in the region (such as debris-flow fans and incised river channels), enabling modelled runouts to overcome topographic obstacles where sufficient landslide debris is available. While increasing the integration interval is an effective means of reducing the effects of minor topographic features on local flow paths, it has little impact on the overall model output. An increase of two orders of magnitude (from 0.1 to 10 kyr), for example, decreased the mean annual debris flux in a sample region by <1% while increasing the proportional area affected by debris flux by 2.7% (see Section A5.6 for further details).

All volumetric outputs (deposition and material flux) were normalised by the integration interval on completion of each model run (see Equation A5.2).

A5.2 Probability of ‘Avalanche’ versus ‘Flow’ Movement Types

We assume that all landslide-debris transport is a function of either ‘avalanche’- or ‘flow’-type movements. Typically, initial open-slope avalanche-type movements develop into flow-type landslides, and the latter mode of movement can therefore be expected to be generally less common than the parent movement mode. However, few landslide datasets draw a distinction between movement modes for rapid landslides, making the proportional attribution of types of movement complicated. Recently, a catalogue of 140,000 landslides mapped following Cyclone Gabrielle, primarily in soft sedimentary rocks of the Hawke’s Bay region, indicated that 66% of mapped landslides were avalanche-type movements, while 33% were flow-type movements (Leith et al., in prep.). Given that (1) lithologies in the Hawke’s Bay region are better known for flow-type behaviours than generally stronger lithologies in the region overseen by West Coast Emergency Management (WCEM) and (2) lower-gradient topography in Hawke’s Bay favours flow-type movements, we consider it unlikely that flows

in the region overseen by WCEM make up more than 33% of the total movement types. As flow-type movements are generally more mobile than avalanche movement types, we conservatively adopt the same relative probability of movement for rainfall-induced landslides observed in the Hawke's Bay region, allowing for a largest-probable proportion of more mobile flow-type movements. Anecdotal evidence suggests the proportion of flow-type movements for earthquake-induced landslides is less than that for rainfall-induced events, and we therefore reduce the relative probability of flows for earthquake-induced landslides by 50% (i.e. 83% 'avalanche' and 16% 'flow'). Uncertainties associated with this assumption are discussed in Section A5.9 and tested in Appendix 7.

A5.3 Landslide-Runout Simulation

A5.3.1 Landslide-Runout Modelling

The distance that landslide debris travels from its source is called the landslide travel (or runout) distance (e.g. McDougall 2017). The debris-inundation area is the ground area covered by debris as it moves, including the source, transport and deposition zones.

There are two main methods to estimate landslide-debris runout: simplified or continuum mechanics-based methods. Simplified methods include empirical, stochastic and physically based modelling approaches and typically use data describing the extent of landslide runout from existing catalogues to calibrate simple physical models based on readily available datasets, such as topographic and volumetric data, making these easier to apply for large-scale studies (e.g. Wichmann 2017). However, their accuracy depends on the quality and quantity of regional datasets, and the ability of these datasets to capture physical aspects of landslide runout is limited.

Continuum mechanics-based methods more directly consider physical factors such as landslide material, properties of the travel path and internal fragmentation processes, requiring detailed data and calibration from representative landslides (e.g. Hungr and McDougall 2009; Christen et al. 2012). The incorporation of key physical considerations in these models means that they can reproduce detailed aspects of landslide runout, more accurately reproducing complex runout paths. However, the increased complexity increases computational requirements, and model accuracy is often constrained by input-data-availability limitations. As a result, simplified methods are still commonly used in situations in preliminary studies or regional investigations.

A5.3.2 Gravitational Path Process Model

The GPP model (Wichmann 2017) employs empirical, stochastic and physics-based approaches in order to simulate the movement of mass down-slope through a DEM from an initiation point to a deposition cell using the single-flow-direction path-finding approach coupled with a random-walk algorithm. This means that source material is moved downslope through the DEM cell-by-cell using a random walk algorithm based on a multiple-flow-direction approach, taking into account particle energy, topography, and a set of user-defined parameters. The model includes components that allow DEM modification through sink filling and material deposition, allowing for example, landslide debris to progressively infill, then overflow basins; or the formation of landslide deposits that alter the path of subsequent failures. The model is open-source and has been successfully used for a number of regional landslide hazard studies (see Wichmann [2017] and references therein).

We employ a temporally integrated scenario-modelling approach to assess runout, accepting that, although we know the spatially distributed long-term average sediment-production rate for each landslide trigger, return interval and volume class, we do not know the specific location of landslides in any given event. Instead, we use M_{GPP} to generate a temporally integrated landslide intensity throughout the landscape and propagate sediment down-slope. A significant benefit of this approach is the ability to model the downslope transport of material from landslide sources nominally smaller than the resolution of the input grid. A single iteration of the GPP model effectively tracks a packet of sediment

down-slope from each source cell. Each packet is supplied with a set of rules regarding movement, deposition and stop criteria, whose operation is independent of the volume of sediment being moved down-slope. As such, a large volume of sediment, representing multiple sub-pixel landslide sources, can be moved through the topography while obeying rules consistent with a smaller-sized landslide. Although the implementation of this method prevents the capture of specific landslide physics (primarily those associated with momentum and internal interactions, e.g. super elevation and block sliding), it allows us to capture probabilistic debris transport from small landslides across a wide region.

Landslides tend to smooth terrain, as they entrain and deposit soil and rock along the runout path. Although the GPP model includes a sediment-deposition component, this does not account for entrainment and deposition of debris where velocities are high along the landslide path. In order to account for this process and effectively smooth terrain along the runout path, we prepared the DEM by running a median filter with a moving window diameter determined by the cube root of the geometric-mean landslide volume (to conservatively approximate the landslide-footprint area). This reduced the magnitude of topographic irregularities, allowing for increased dispersion and persistence of debris sourced from larger-volume landslides.

We simulated landslide runout using approaches designed to capture the two most common runout types, avalanche- and flow-type movement modes. The avalanche-type movement was modelled using an energy line, or ‘fahrböschung’ principle (Heim 1932), commonly used to capture the travel distance of rockfall, debris flows and rock avalanches. Here, we employ the avalanche-type model to capture the probability of inundation by debris slides, debris avalanches and some rock avalanches (see Section 1.4.2).

Flow-type movements were modelled using the PCM model (Perla et al. 1980), which was initially developed to model avalanche runout and has since been applied to model debris flows and large rock slides. The following sections describe the fundamentals of each runout model, as well as data used to parametrise each implementation. Here, we employ the flow-type model to capture the probability of inundation by debris flows and some rock avalanches (see Section 1.4.2).

In both cases, we use the fully featured GPP model with both material deposition and sink filling enabled, as described in Figure A5.1. The selection of input parameters for each configuration is discussed later in this section. While generally appropriate for regional studies, we must note that this analysis cannot capture dynamic aspects of landslide movement, such as material fragmentation and dispersion, or run-up of the landslide due to the effects of momentum. This latter constraint can lead to errors in path estimation where rock avalanches or debris flows have the energy to run up and over topographic barriers (e.g. ridges or moraine walls).

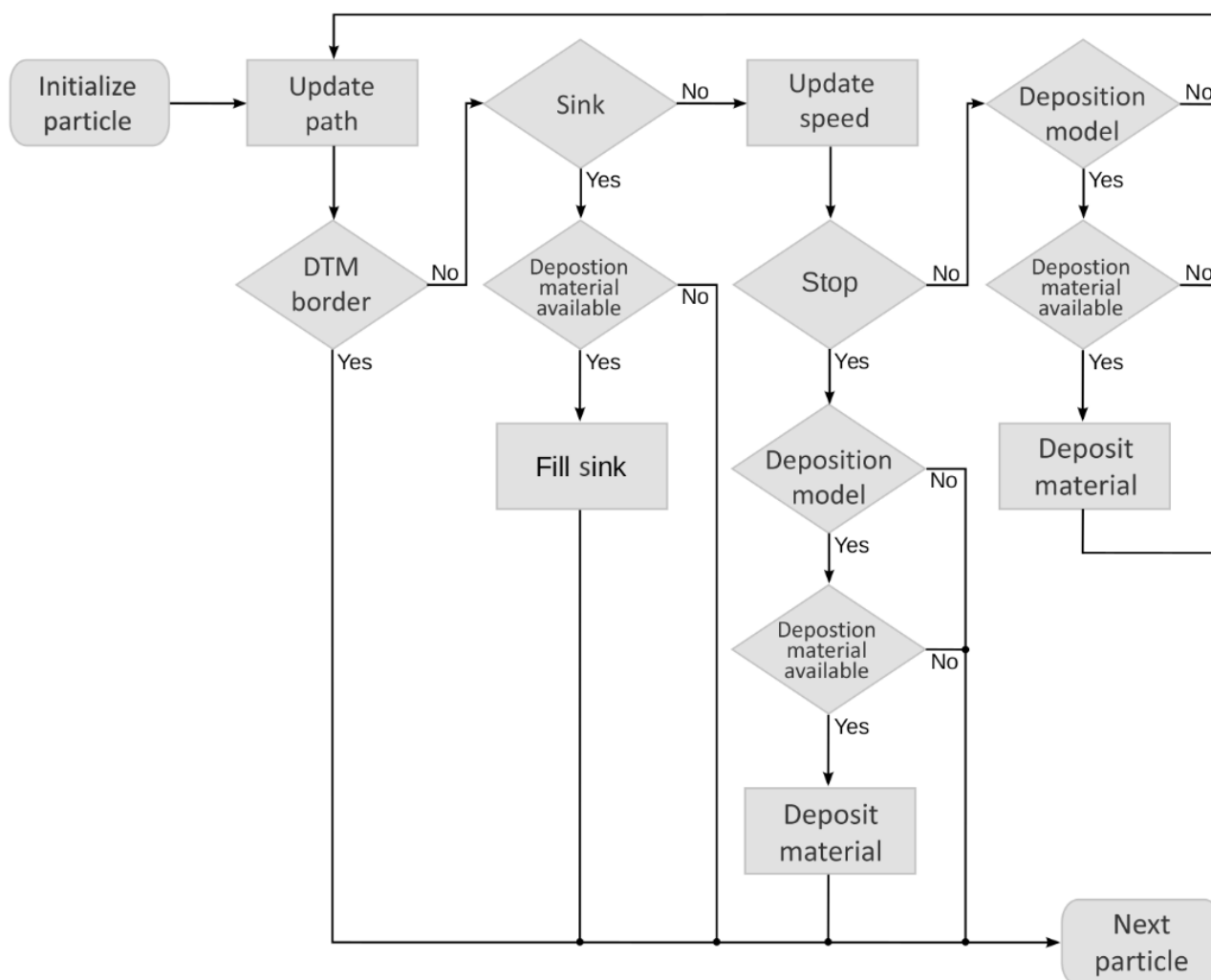


Figure A5.1 Flowchart of the fully featured Gravitation Path Process model used in this analysis. A particle is initiated at each cell in the DEM associated with a potential landslide-source area. 'Sinks' are basins within the DEM, defined as cell (or group of cells) with no down-slope node. Deposit material is derived from the landslide depth grid created during the susceptibility assessment.

A5.4 'Avalanche' Movement Types

A5.4.1 Empirical 'Fahrböschung' (or 'Energy Line') Principle

Heim (1932) proposed that the distance that a landslide travels is proportional to its fall height. The tangent of the ratio of the fall height (ΔH) to horizontal runout distance (L) between the crest of the source zone and toe of the deposit, known as the energy line, or 'fahrböschung', has subsequently been correlated with landslide volume (V) to generate empirical relationships similar to those presented in Figure A5.2 (Corominas 1996). Measurement of the slope crest and deposit toe have since been compiled for many different landslide types and trigger conditions (e.g. de Vilder et al. [2022] and references therein). From these compilations, a best-fit linear regression (in log-log space) between $\Delta H/L$ and V can be derived for each landslide type (debris avalanche, rock avalanche and debris flow) and trigger (seismic/dry and rainfall/wet).

These empirically-based relationships between $\Delta H/L$ and V integrate the effect of different site conditions (e.g. source geology, local topography, grain size of failed material, water content of source material, incorporation of erodible material along the travel path, vegetation, buildings, the presence [or not] of mitigation measures). This range of site-specific conditions results in the variability of observed landslide-debris runout and inundation areas. The variability in the landslide-debris runout

and inundation data also allows for the probability of runout exceedance or for limits of confidence to be defined for the prediction of runout for each landslide volume (e.g. Li 1983). For example, the best-fit (blue) line in Figure A5.2 represents an exceedance probability of 50%, i.e. half of the landslides of the given volume and type will travel farther than this line.

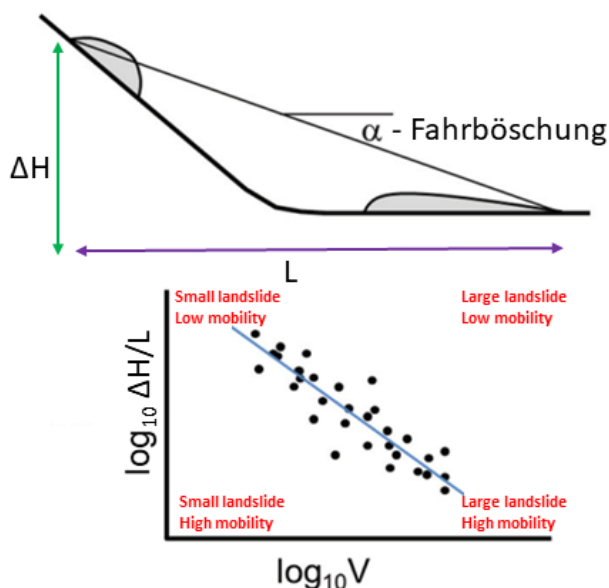


Figure A5.2 Schematic representation of the fall height (ΔH) and runout distance (L) parameters for a landslide and the conceptual relationship between $\Delta H/L$ and the landslide volume (V) (modified from McDougall [2017]).

A5.4.2 Fahrböschung Data

Parameters controlling avalanche-type runout are varied depending on the simulated volume allowing (for example) larger landslides to travel further than smaller landslides originating from the same location. This is consistent with observed landslide behaviours in a range of settings.

To estimate rainfall- and earthquake-induced avalanche-type movements, we adopt empirical runout relationships derived for (1) dry open-slope debris avalanches for volumes less than 100,000 m³ and (2) rock avalanches for larger volumes in Brideau et al. (2021a) (Figure A5.3). The dry debris-avalanche and rock-avalanche empirical relationship has been compiled from debris and rock-slope failures that are associated with earthquake-induced landslides (e.g. Port Hills and Kaikōura events) or with large volume (>100,000 m³) rock avalanches. The bi-linear behaviour (in log-log space) of the relationship between $\Delta H/L$ ratio and volume had previously been noted by other researchers (e.g. Scheidegger 1973; Hermanns et al. 2012; Brideau et al. 2020). Table A5.1 summarises the fahrböschung (and equivalent $\Delta H/L$ ratio) for each of the volume classes investigated in this project. The best-fit lines (and associated statistics) for $\Delta H/L$ as a function of volume plots were determined using a least-squares method. Assuming that the data are normally distributed, the 1%, 10%, 25%, 75%, 90% and 99% runout exceedance probability lines were calculated (Figure A5.3).

Through a process of trial and error, we found the 50th percentile dry open-slope debris avalanche fahrböschung presented in Brideau et al. (2021a) to best represent a majority of landslides in the study region (see Table A1.2). Although this fahrböschung percentile led to a minor over-estimation of the runout of most mapped landslides, the fahrböschung derived for wet channelised debris flows presented in the same reference generated similar, although subjectively worse, representations of more extensive landslide runouts than the flow-type model described below (see Section A5.4.4 for further details on model validation). As few landslides in the region overseen by WCEM have been classified as wet or dry, and none have been classified based on movement mode; objective analysis of the model performance for flow- and avalanche-type landslides is not possible within the scope

of this study. Given the 25 m resolution of this study, we found little difference between runout extents for other runout-exceedance probabilities and therefore elect to only model the 50th percentile for each LSD model run. See Section A5.9 for further discussion on related uncertainties.

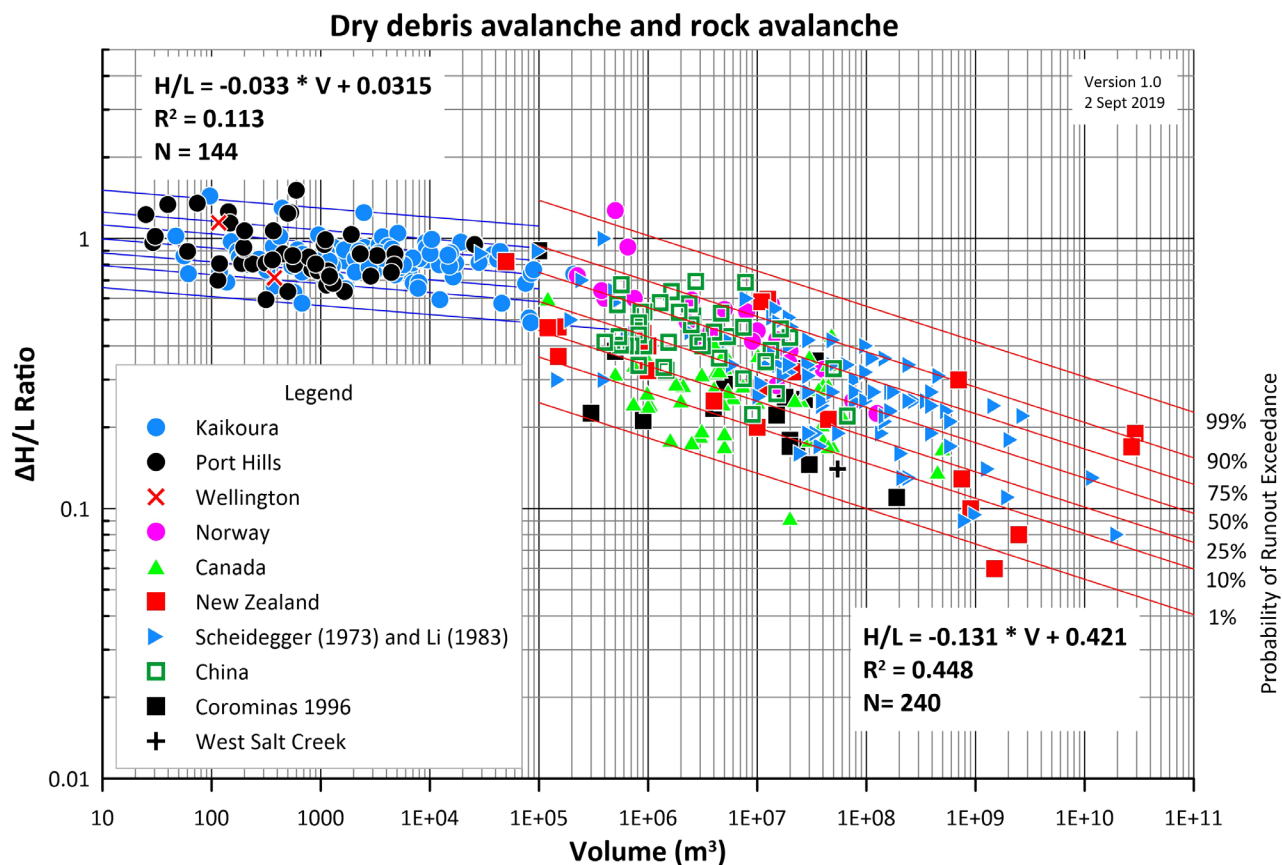


Figure A5.3 Empirical relationship between $\Delta H/L$ ratio and volume in open-slope dry-debris avalanches (<1,000,000 m³) and rock avalanches (>1,000,000 m³) (Brideau et al. 2021a).

Table A5.1 Summary of fahrböschung and $\Delta H/L$ values for each volume class of avalanche-type movements used in this project. See Figure A5.3 for graphical representation of the data considered.

Volume (m³)	50% Runout-Exceedance Probability	
	Fahrböschung (°)	$\Delta H/L$
10	45	1.0
100	43	0.93
1000	41	0.87
10,000	38	0.78
100,000	30	0.58
1,000,000	23	0.42
10,000,000	18	0.32

A5.4.3 Gravitational Path Process Avalanche-Type Model Implementation

All release areas were run in parallel and processed in ascending elevation order each iteration. This is consistent with our goal to capture mean annual sediment transport rather than simulate discrete sources occurring independent of each other. Given that we run a range of simulations from each source cell to capture all possible runout scenarios, 20 iterations were found to produce a reasonable runout prediction without unnecessary cost on computation time. We selected low values

of ‘Initial deposition on stop’ and ‘Deposition slope threshold’ in order to prevent debris dams from forming and to maximise runout on sloping topography. The friction model employed the fahrböschung principle, with angles for each volume class and trigger type determined by dry open-slope debris-avalanche volume-fahrböschung relationships (see previous section).

A ‘Dispersion slope threshold’ of 45° was adopted to prevent dispersion of the random-walk model on steeper topography. We adopt a default ‘Exponent of divergence’ of 2, and the ‘Persistence factor’ (which determines the probability that a particle changes direction) was set to 1 in order to allow maximum dispersion. Additional parameters used in the avalanche-type model are listed in Table A5.2.

Table A5.2 List of input parameters for the Gravitational Path Process (GPP) avalanche-type model.

GPP Avalanche-Type Model Input Parameters	Value	Unit
Friction model	Fahrböschung	-
Deposition model	Slope and on stop	-
Dispersion slope threshold (no dispersion on steeper slopes)	45	°
Exponent of divergence	2	1
Persistence factor	1	1
Processing order	Release areas in parallel	-
Initial deposition on stop	2	%
Deposition slope threshold (no deposition on steeper slopes)	2	°
Minimum path length (fixed to DEM resolution)	25	m
Maximum deposition along path	20	%
Iterations (number of model runs from each start cell)	20	1

A5.4.4 Model Validation

To qualitatively assess the validity of the source area and volume calculations, we compared modelled runouts from landslide-source polygons derived from datasets presented in Table A1.2.

Landslide-debris volumes for each source polygon were calculated using the kinematic-source model presented in Section A4.2. These were used as inputs to simulate landslide runouts from all source areas expected to be associated with avalanche- or flow-type runouts. Over-estimation of landslide-source volumes could be expected to lead to more extensive runouts than mapped, while under-estimation could be expected to generate modelled runouts that do not extend as far as mapped slides. Although the 25 m resolution DEM adopted for this study is likely too coarse to provide a detailed representation of individual landslide runouts, we found a reasonable correlation between modelled runout and mapped landslide outlines, providing confidence in both our source and runout parameter selections. Example outputs for avalanche- and flow-type landslides are provided in Figure A5.4.

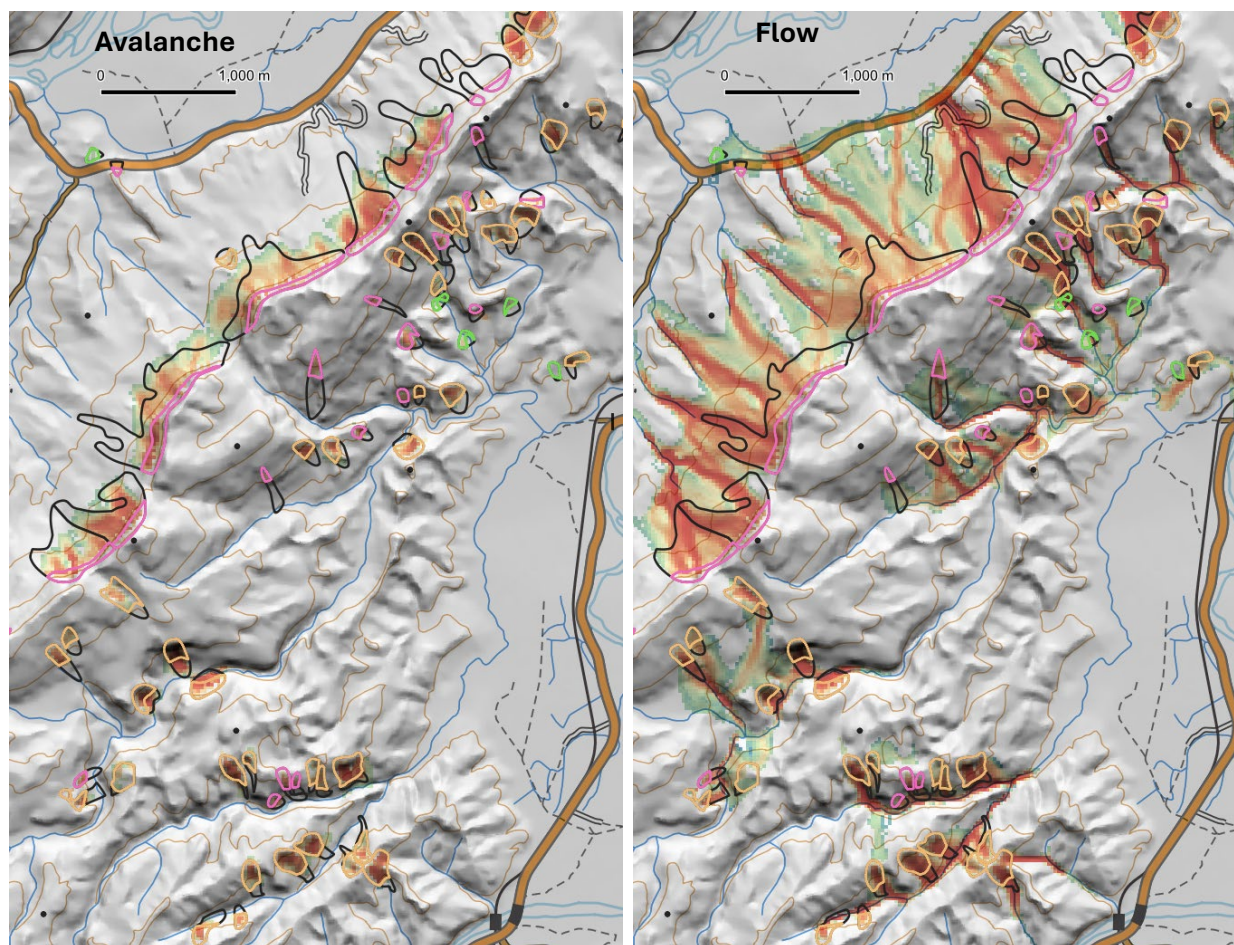


Figure A5.4 Mapped landslide outlines resulting from the 1968 Inangahua earthquake. Landslide-source areas are derived from in-house machine-learning models (coloured polygons), overlain on modelled 50th percentile avalanche-type runouts (left) for mapped landslides resulting from an earthquake trigger and flow-type runouts (right) resulting from the same trigger. Coloured polygons represent landslide sources and are coloured by classification (orange = rock slide – medium, pink = rock slide – small, green = rotational/translational slide).

Runouts associated with the 1968 Inangahua earthquake are most commonly consistent with modelled avalanche-type movement (evident in the correlation of modelled and mapped runout extents; Figure A5.4), although more channelised landslides are better captured by flow-type movements. This may be expected, as the earthquake occurred near the end of summer, when ground conditions are typically dryer. The LSD model assumes that the runout of 83% of all earthquake-induced landslides is consistent with avalanche-type movements, while 16% are assumed to be flow-type movements.

See Section A5.9 for further discussion on the impact of LSD model uncertainties on calculated hazard and risk outputs.

A5.5 ‘Flow’ Movement Types

A5.5.1 PCM Model Principle

The PCM model (Perla et al. 1980) was adopted to model flow-type movements in the region; specifically, debris flows (see Section 1.4.2). This is a two-parameter friction model commonly used to reproduce avalanche- or flow-type behaviours (Wichmann 2017). The model itself takes a centre-of-mass-based approach to evaluate down-slope motion by balancing the accumulation of energy of a particle as it travels down-slope under gravity against two energy-loss terms describing the coefficient of sliding friction and the mass to drag ratio.

A5.5.2 Gravitational Path Process Flow-Type Model Implementation

Similar to the fahrböschung model, the GPP implementation of the PCM model uses a random-walk model to determine the likely path of debris as it moves down-slope, employing an iterative Monte Carlo method to evaluate probable runout paths. We adopt identical persistence and spreading terms as those adopted for the avalanche-type movement models described in Section A5.4.3. Parameters controlling flow-type runout are varied depending on the catchment area that the material flows over, allowing (for example) landslides in channels to travel further than landslides on open slopes. This is consistent with observed landslide behaviours in a range of settings.

Calibration of the PCM model can be complicated, as the inclusion of two energy-loss terms means that back-calculating runout parameters from a mapped debris extent leads to a non-unique solution. In addition, the GPP model allows users to select either a globally consistent, or spatially variable coefficient of sliding friction. A globally consistent coefficient allows for similar treatment of terrain resistance and is ideally suited to unconfined flows over consistent ground cover, while a spatially variable coefficient of sliding friction is commonly combined with metrics describing up-slope catchment area and allows models to incorporate the increased efficiency of debris transport in channelised flows. A recent study by Goetz et al. (2021) presented a method to develop an optimal parameterisation based on a catalogue of 521 mapped rainfall-induced debris-flow sources and deposits in a single river basin in central Chile. Goetz et al. (2021) trialled both spatially consistent and spatially variable coefficients of sliding friction and adopted the spatially consistent option, in part due to the reduced complexity and also a slight improvement in predictive ability of the spatially consistent model with an optimised friction parameter (Mergili et al. 2012; Wichmann 2017). However, it is, important to note that Goetz et al. (2021) elected to adopt previously recommended spatial variability scaling parameters and did not seek to optimise the spatially variable model, which may have yielded improved results.

A lack of suitable mapped landslide data within the study region makes a local calibration of the PCM model difficult, as available landslide inventories do not discriminate between avalanche- and flow-type movements. This invalidates the principal assumption of Goetz et al. (2021), that all mapped landslides are flows, and prevents the adoption of a similar optimisation technique for this study. Instead, we assume that the mode of movement is dominantly ‘channelised’ flow and adopt a spatially variable friction parameter based on the ‘most likely’ parameters derived for debris flows in Switzerland (Gamma 1999). We then adopt an intermediate mass-to-drag ratio based on suggested ranges for debris flows (Wichmann 2017; Goetz et al. 2021) to describe the acceleration of debris on steep slopes. A list of all flow-type movement GPP input parameters is provided in Table A5.3 below.

Table A5.3 List of input parameters for the Gravitational Path Process (GPP) flow-type model.

GPP Flow-Type Model Input Parameters	Value	Unit
Friction model	PCM model	-
Deposition model	Slope and on stop	-
Dispersion slope threshold (no dispersion on steeper slopes)	45	°
Exponent of divergence	2	1
Persistence factor	1	1
Processing order	Release areas in parallel	-
Initial deposition on stop	20	%
Deposition slope threshold (no deposition on steeper slopes)	25	°
Minimum path length (fixed to DEM resolution)	25	m
Sliding friction coefficient multiplier (Gamma 1999)	0.19	1

GPP Flow-Type Model Input Parameters	Value	Unit
Sliding-friction coefficient exponent (Gamma 1999)	-0.24	1
Upper sliding-friction coefficient limit (Gamma 1999)	0.3	1
Lower sliding-friction coefficient limit (Gamma 1999)	0.045	1
Mass-to-drag ratio (Wichmann 2017; Goetz et al. 2021)	60	m
Initial velocity (Wichmann 2017)	1	m/s
Iterations (number of model runs from each start cell)	20	1

A5.5.3 Model Validation

We evaluate the flow-type model performance by comparing the extent of modelled debris from flow-type movements against the extent of debris fans within the region. This evaluation was undertaken through a combination of field investigations and GIS (geographic information system) analysis. During the field survey, GNS Science engineering geologists noted the locations and/or extent of 36 individual debris fans (see Section 2.7). Of these, all observations either coincided with landslide-debris fluxes derived from the flow-type models or, in the case of observations marking the extent of a fan, were within 25 m of the modelled extent. As no consistent map of debris-fan extents exists within the region, we undertook a qualitative assessment to compare modelled flow-type extents with landforms demonstrating common debris-flow fan attributes (see Section 1.4.2.2). This assessment was undertaken using a combination of aerial photographs and hillshade DEM models, using either the 8 m national DEM or a 1 m LiDAR DEM where available. Overall, we find an excellent correlation between the extent of modelled debris and the furthest reaches of debris-flow-fan landforms. As expected, maximum fluxes are almost always at the apex of fans and decrease down-slope across the entire surface of fans, with a concentration of modelled debris visible in channels that clearly cross fans in the 8 m DEM. This is consistent with expectations for debris-flow-type landslides, and we are therefore confident that the flow-type models are adequately approximating the distribution of debris fluxes relating to this process with respect to the model input parameters, although we have little data with which to evaluate the magnitude of the annual flux.

See Section A5.9 for further discussion on the impact of LSD model uncertainties on calculated hazard and risk outputs.

A5.6 Deposition Model

The deposition routine in the GPP model employs a sink-filling method that is modified from Gamma (1999). The routine:

1. Identifies the over-flow cell and sink depth.
2. If the current iteration lacks sufficient material to fill the sink's depth, all available material is deposited and the process halts.
3. Otherwise, the sink is filled to a height that maintains a user-defined minimum slope to the overflow cell.
4. To prevent forming another sink, material is placed on the path above the sink, ensuring that enough material remains to maintain the minimum slope.

If the available material is insufficient, the angle is gradually reduced until a minimal downward slope is preserved. Any remaining material is used in subsequent iterations.

For avalanche-type movements, we employ the 'deposition on stop' option with an initial deposition height below 100%. In this configuration, the given percentage of material (available per run) is deposited in the stopping cell and the remaining material (per run) is used to fill the DEM up-slope

(in order to preserve a slope for subsequent runs). This necessary approximation allows the model to generate quasi ‘fan’ deposits with constant surface slopes determined by material availability, although this means that the sum of deposited material can be lower than the amount of material in the start cell, depending on the terrain. This may be consistent with our consideration of annualised landslide-debris flux, as fluvial processes can be expected to erode over steepened deposits.

For flow-type movements, we employ the ‘deposition along the path (slope)’ option. In this case, the material flux is reduced by the amount deposited on the path, i.e. below the deposit, the material flux gets lower. If all material available for this run has been deposited, the material flux reduces to zero.

A5.7 Mean Annual Landslide-Debris Flux

The probability of landslide sediment passing a location in the study region can be derived from the material flux returned for each iteration of the GPP model ensemble. Where the input for the model is the calculated landslide sediment-production rate for each scenario (in m/yr), the material flux returned from each iteration of the ensemble $[\Phi_{GPP(\mu)(c)(T,RI)(x,y)}]$ therefore reflects the volume of material passing through a given unit area per year ($m^3/m^2/yr$). Combining the material-flux outputs for flow- and avalanche-type model configurations then requires that the output is scaled by the probability of each movement type in the study region (P_{μ} , where the subscript denotes the mode of movement). The mean annual landslide-debris flux (Φ_L) can then be written as:

$$\Phi_{L(x,y)} = \sum \frac{\Phi_{GPP(\mu)(c)(T,RI)(x,y)}}{\sigma} \times P_{(\mu)} \quad \text{Equation A5.2}$$

Figure A5.5 presents a selection of landslide-debris-flux outputs from GPP model runs. The three upper panels represent rainfall-induced avalanche outputs overlain on a hillshade derived from the DEM used for each model. The reduction in the detail of each DEM with increasing volume class is a reflection of the smoothing used to prepare the DEM for modelled runout of larger source volumes (see Section A5.3 for further details). Source-volume-class range 4–5 demonstrates the largest debris flux for rainfall-induced landslides, while volume-class range 6–7 presents the highest debris flux for earthquake-induced slides. These volume-class ranges are notably higher than those that may be expected to generate the greatest volume of debris when considering just the mean landslide volume class assigned to each trigger (3.92 and 4.55, respectively; see Section A4.4). This skew toward greater fluxes at larger volumes reflects local characteristics of the area, in particular, a coincidence of higher erosion rates in source areas that support larger landslide volumes. This leads to (1) a greater volume of debris being associated with larger landslide sources and (2) lower fahrböschung angles and therefore greater mobility of larger volume landslides. The increasing mobility of larger avalanche-type landslide volume classes is evident when comparing the extent of volume-class 6–7 earthquake- and rainfall-induced slides, which fan out on the flat terrace around Kokiraki, to that of volume-class 2–3 slides, for which the debris rarely extends to the toe of the hillslopes (upper six panels in Figure A5.5). Flow-type runouts for each trigger in the lower six panels of Figure A5.5 are similar, as we adopt identical flow-type model parameters for earthquake- and rainfall-induced slides (see Section A5.5). The primary difference between the two trigger types is then a result of the increased sediment-production rates calculated for volume-class 4 and 6 earthquake-induced landslides with respect to their rainfall-induced counterparts (see Figure A5.5). Although the probability of earthquake-induced landslides in the vicinity of Kokiraki is notably less than that of rainfall-induced landslides, the impact of this is masked by the larger mean volumes and greater mobility of larger flow-type slides (due to a smoothed topographic model). The mean annual flux of earthquake-induced landslides is therefore similar to that of rainfall-induced slides (see the lower two rows of Figure A5.5).

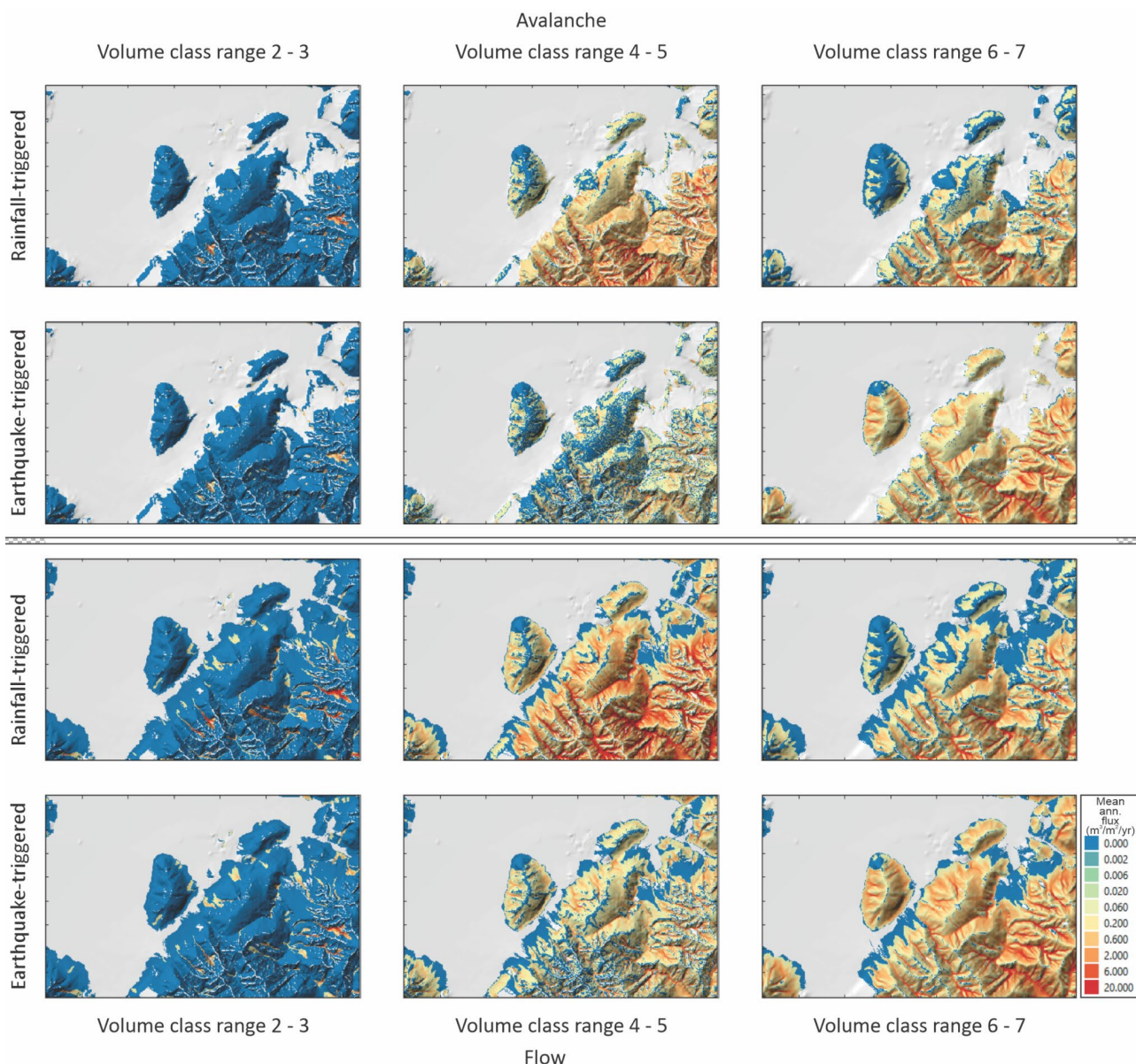


Figure A5.5 Mean annual material flux derived from Gravitational Path Process runout models for selected volume class sizes, triggers and movement types.

A5.8 Scenario-Specific Landslide-Sediment Distribution

Landslide sediment-distribution models for each event-specific scenario were generated using the same model steps as described in Sections A5.1–A5.7, although landslide source-material thicknesses are derived directly from scenario-specific landslide-sediment-production-model depths (see Section A4.6), and only flow- and avalanche-type movement models for the appropriate trigger are simulated.

A5.9 Key Landslide Sediment-Distribution Model Uncertainties and Assumptions

The LSD model variables contribute the most uncertainty in this study due to limited local data constraints, with most parameters varying by 50%.

The proportion of flow-type movements determines the likelihood of landslides occurring as avalanche or flow types. This variable is perhaps the least constrained in the region, as no local data exist that explicitly categorise flow- or avalanche-type landslides. Although not linked to the GPP model, it has

the greatest impact on annual property loss risk (APLR), especially at locations far from the landslide source, where shifting to the more mobile flow type can increase APLR by $10^{0.4}\times$. We note a number of uncertainties associated with the proportion of flow-type movements in the calculation:

- Currently, we assume that the proportion is the same for both rainfall- and earthquake-induced landslides; however, this is possibly not the case, as experience suggests that earthquake-induced landslides commonly have a lesser travel distance and therefore are more likely associated with avalanche-type movements. A re-analysis of existing datasets may shed further light on the relative proportions of each movement type in the region overseen by WCEM.
- There may be a seasonal bias to consider, as earthquake-induced landslides may occur during wet periods, potentially increasing the proportion of landslides that transition to flow-type movements. Again, a re-analysis of existing datasets (e.g. the late summer Inangahua and mid-winter Murchison earthquake landslide catalogues [Hancox et al. 2014, 2016]) may shed further light on the relative proportions of each movement type in the region overseen by WCEM.

We note that, although we have undertaken a qualitative evaluation of model performance (see Sections A5.4.4 and A5.5.3), neither the PCM ('flow'), nor Fahrböschung ('avalanche') models have been locally calibrated. Our parameter selection therefore reflects our 'best estimate', although the absolute accuracy of this is difficult to quantify and likely to vary across the region. However, we are able to quantify uncertainties associated with parameter election. These are discussed below:

- PCM model inputs have minimal impact on APLR, as the sliding-friction coefficient, tied to hillslope gradient, strongly controls runout in our 1D model, leading to velocity reductions once the slope falls below a threshold.
- Uncertainty in the fahrböschung angle can alter APLR by up to $10^{-1.7}\times$ near the landslide source, although obviously has no effect beyond the maximum runout extent.
- The GPP persistence factor, which affects both fahrböschung and PCM model runouts, significantly affects APLR, potentially increasing uncertainty from $10^{-1.6}\times$ close to the source to an unconstrained value far from the source, where the 'best estimate' debris flux (and therefore APLR) is almost zero. Although we expect that this solution is a numerical artifact associated with the 1D model employed in our sensitivity analysis, it does highlight the care that needs to be taken when evaluating landslide-debris flux and APLR estimates far from landslide sources. As such, inclusion of a 'maximum credible extent' outline capturing the maximum reach of any debris may be a useful addition to hazard overlays.
- Similarly, DEM resolution influences landslide-debris mobility by altering slope-gradient noise, with APLR varying between $10^{-1.6}\times$ and $10^6\times$ at sample locations within 1D models when the grid size changes from 8 m to 25 m. This trend increases with distance from the landslide source, and, while the magnitudes of the values are partly a numerical effect, we expect that debris-flux changes can disproportionately affect APLR in low-flux areas.

Given the above assumptions and uncertainties, we have elected to adopt 'best estimates' for all input variables while adopting conservative ranges for associated uncertainties. This ensures that LSD model results most closely reflect the input datasets and assumptions described in this report, while conveying the overall level of uncertainty associated with LSD model inputs (see Appendix 7). We recommend that West Coast Regional Council consider appropriate precautionary reductions in acceptable hazard or risk metrics based on an evaluation of appropriate confidence intervals and reported model uncertainty (as discussed in Section 5).

APPENDIX 6 Landslide Debris-Inundation-Risk Model

This section describes details of the Landslide Source to Inundation Process Model (LS-IPM) used to convert the landslide-debris-inundation hazard output from the landslide sediment-distribution model into annual property loss risk (APLR).

A quantitative sensitivity analysis is undertaken in Section A7.5.

A6.1 List of Landslide Debris-Inundation-Risk Model Variables

In addition to variables listed in Table A2.1, the following table describes variables introduced in the LS-IPM workflow.

Table A6.1 Landslide debris-inundation-risk model variables.

Variable	Description	Value	Unit
Ω	Characteristic landslide-debris spreading factor	1, 3	1
$\Phi_{L(c)(T)}$	Characteristic landslide-debris volume	-	m ³ /m
N_{LS}	Number of potential landslide sources based on source-area calculations	-	1
P_i	Probability of inundation by landslide debris	-	1
Λ	Structural vulnerability	-	1
APL_{LS}	Mean annual property loss risk	-	1/yr
Subscript	Description	-	-
x,y	Spatial location of pixel centroid	-	-
T_0	Lower limit of temporal-integration interval	-	-
T_{max}	Upper limit of temporal-integration interval	-	-
μ	Runout model configuration	-	-
c	Landslide volume class	-	-
T	Landslide trigger type	-	-
RI	Event return interval	-	-

A6.2 Landslide Debris-Inundation-Event Frequency and Magnitude

The landslide-debris flux for a single event is a function of the landslide-source volume, mobility of the landslide debris, topographic routing and proximity to the landslide source. However, mean annual landslide-debris flux is the product of contributing event frequency and inundation event magnitude. As such, separating out the frequency and magnitude of inundation events (as is required for risk analysis) from the LSD model output requires additional assumptions (or site-specific information) with respect to either the frequency of inundation events at a given location or the magnitude of inundation. Here, we evaluate the probability of inundation by rare, independent landslide debris-inundation events by employing a Poisson probability formula. In this case, the annual probability of inundation (P_i) can be derived from the expected number of inundation events per year (λ):

$$P_{i(\mu)(c)(T,RI)(x,y)} = 1 - e^{-\lambda_{(\mu)(c)(T,RI)(x,y)}} \quad \text{Equation A6.1}$$

where λ can be described as a function of the mean annual landslide-debris flux (ϕ_{GPP} , i.e. the mean annual magnitude of impact) and the characteristic debris flux at the inundation location for a given landslide source volume (ϕ_c , i.e. the magnitude per event):

$$\lambda_{(\mu)(c)(T,RI)(x,y)} = \frac{\Phi_{GPP(\mu)(c)(T,RI)(x,y)}}{\Phi_{C(\mu)(c)(T,RI)(x,y)}} \quad \text{Equation A6.2}$$

Although the mean annual debris flux for each combination of trigger, volume class, return interval and movement type can be directly derived from individual outputs from the LSD ensemble (see Section A5.7), the characteristic debris flux is not a direct output of the LSD model. As the landslide sediment-production (LSP) and LSD models include a probabilistic consideration of source-debris production, routing of landslide debris and deposition of debris along the travel path, it is not possible to directly correlate the magnitude or frequency of landslide-debris production in source areas to the characteristic debris flux passing a given location down-slope.

To estimate characteristic inundation-event magnitudes, we compare the Gravitational Path Process (GPP) model outputs to the landslide geometries and spreading characteristics defined for the LSP and LSD models. For each LSD iteration, we assume that all inundation events at a given location have a uniform magnitude and that each event results from the failure of a single, independent landslide source. This approach enables us to model characteristic-inundation magnitude by combining assumed landslide-source properties with inputs and outputs from the GPP model.

The characteristic landslide-debris flux can be described as a function of the unit volume of the initial landslide source, the area of landslide sources contributing to a given cell and the degree of spreading between the source and a given location. The unit volume of the landslide source [$\Phi_{L(c)}$] is defined as the average volume of debris that can be expected to pass through one linear metre of slope as a result of a single landslide of a given class size occurring. This is the product of the mean slope-parallel length and mean depth, multiplied by 1 m:

$$\Phi_{L(c)} = \sqrt{A_{L(c)}} \times D_{L(c)} \times 1 \quad \text{Equation A6.3}$$

If debris were to travel from a landslide source downhill on a planar surface without deposition or spreading, the unit volume of the landslide source could be considered the characteristic debris flux at any given location. However, a combination of debris convergence or divergence due to topographic effects, as well as spreading due to the random-walk component of the GPP model, means that this case becomes increasingly unlikely as (1) topographic effects become stronger with increasing distance from the debris source and (2) the degree of spreading increases with decreasing slope gradient. As such, we develop a simple model to allow for a progressive transition of the characteristic debris flux from the unit-source volume in steeper cells to negligible flux in low-gradient cells with large source areas. We employ a probabilistic model mirroring the random-walk approach adopted in the GPP model (Wichmann 2017) to calculate a debris-spreading factor, separating the characteristic-flux model for steeper source areas from that in shallower-gradient runout areas. In the shallower-gradient runout areas, we calculate a theoretical dispersion of debris based on the distance that debris travels from the landslide source, as well as the gradient of topography along the shortest path. This dispersion factor is employed to calculate a characteristic debris flux (Φ_c) from the unit volume of the landslide source for each volume-class range, as described in Equation A6.4:

$$\Phi_{C(\mu)(c)(T,RI)(x,y)} = \frac{\Phi_{L(c)}}{D_{(x,y)}} \quad \text{Equation A6.4}$$

where $D_{(x,y)}$ represents the theoretical dispersion of landslide debris between the source and inundation location. The dispersion factor is therefore a function of the distance between the nearest landslide source and a given location, weighted by the spreading factor (ω):

$$D_{(x,y)} = \frac{\int_{\text{path from sources to } (x,y)} (1 - \omega_{(x,y)}) R d\ell}{1/2 \times D_{L(c)}} \quad \text{Equation A6.5}$$

where R is the grid resolution of the GPP model and $D_{L(c)}$ is the mean depth of the landslide-class range (Table A2.1). The spreading factor reflects the probability of debris continuing in the same direction based on the random-walk model outlined in Wichmann (2017):

$$\omega_{(x,y)} = \frac{1 + \min\left(p\left(\frac{\tan\beta_{i(x,y)}}{\tan\beta_{thres}}\right)^a, 1\right)}{2} \quad \text{Equation A6.6}$$

Here, all variables reflect GPP model inputs. β_i is the local slope, β_{thres} is the slope threshold (above which no spreading occurs), a is the exponent to control the amount of divergent flow and p is the persistence factor. As β_i decreases from β_{thres} toward zero, ω will decrease from 1 to 0.5. All input parameter values are listed in Tables A5.2 and A5.3. We note that Equation A6.5 considers the shortest path between landslide-source areas and inundation locations rather than the travel path between the material source and a given location. This is a necessary simplification, as each down-slope location can be intersected by multiple travel paths, which prevents derivation of a unique dispersion factor. As the spreading factor is lowest on steeper hillslopes (where landsliding is kinematically feasible) and greatest on flatter slopes (where travel paths typically extend in a linear manner from source areas), this simplification provides a reasonable representation of spreading with increasing down-slope distance from source areas.

Substituting Equations A6.4–A6.6 into Equation A6.2 allows us to estimate the number of landslide debris-inundation events per year (λ). Substituting this frequency into Equation A6.1 then provides an estimate of the annual probability of landslide-debris inundation (P_i) for a given set of conditions.

We note that the model presented in Equation A6.4 provides an approximation of characteristic debris flux at a given location and is not a substitute for local observations or detailed landslide runout analysis. In particular:

- The concentration of debris in convergent, steep topography can lead to an over-estimation of λ , as the flux passing a given location from a single landslide source may be as much as the full landslide volume, rather than the unit volume (as assumed in Equation A6.2). As such, the calculated inundation frequency will exceed the frequency of source events by a factor of $\max\left(\frac{\sqrt{A_{L(c)}}}{R}, 1\right)$, depending on the degree of topographic convergence. This effect is most pronounced along valley axes and for larger landslide classes, for which the characteristic length may be up to two orders of magnitude greater than the grid resolution. However, as the DEM is smoothed using a moving window scaled by the landslide volume (see Section A5.3.2), convergent topography is reduced for larger size classes, and this effect is therefore minimised.
- Our consideration of debris spread is not strictly tied to the debris path between the landslide-source and -inundation location. We assume that spreading between the source and inundation location varies as a function of the local slope, without any consideration of topographic concavity, convexity or distinct flow paths along the route. However, the characteristic-flux estimate is based on a conservation of mass approach, bounded by the landslide unit volume on slopes close to or above the slope threshold (presumably near the landslide source; see Equation A6.4), and a proportion of the unit volume is determined as a function of the number of potential contributing landslides on flat ground (presumably distal to the landslide source). While the natural variability in the DEM makes it difficult to quantify associated uncertainties, these bounds suggest that the calculated flux likely has a similar uncertainty to that described above.

The probability of inundation for a given set of conditions can be derived from Equation A6.1. Considering all movement types, volumes, triggers and return intervals, the total annual inundation event frequency (λ_{LS}) can then be calculated as the sum of landslide inundation-event frequencies (Equation A6.2) for all parameter combinations:

$$\lambda_{LS(x,y)} = \sum \lambda_{(\mu)(c)(T,RI)(x,y)}$$

Equation A6.7

In the following section, we present LSP and LSD model results calculated for a simple block model in order to demonstrate inputs and outputs of the characteristic debris flux model. We summarise results in terms of inundation-event frequency, as this can be directly related to the input mean annual sediment-production rates.

A6.2.1 Validation of Landslide Debris-Inundation-Event Frequency Model

The calculation of landslide-inundation frequency can be demonstrated by modelling landslide debris flux from two discrete representative landslide sources (outlined by blue squares in figure below). Figure A6.1a, b illustrates the mean annual debris flux and contributing area outputs from LSD model runs combining avalanche and flow movement types from landslide sources representing the geometric mean of Class 4 and 5 landslides. We specify a mean annual erosion rate for the landslide-source area of 1.5 mm/yr, a sediment bulking factor of 1 and set erosion rates outside of the sources to zero. The slope angle is set at 30°, and the slope threshold is set to 20° to prevent spreading on the hillslope. Based on the area-volume scaling relationship presented in Equations A4.6 and A4.7, the mean depth for this volume class is 10 m. By dividing the landslide depth by the erosion rate, we can determine that the theoretical mean annual recurrence interval for each slide will be 666 years, or, alternatively, that the frequency of landslide occurrence will be 0.0015 events/yr.

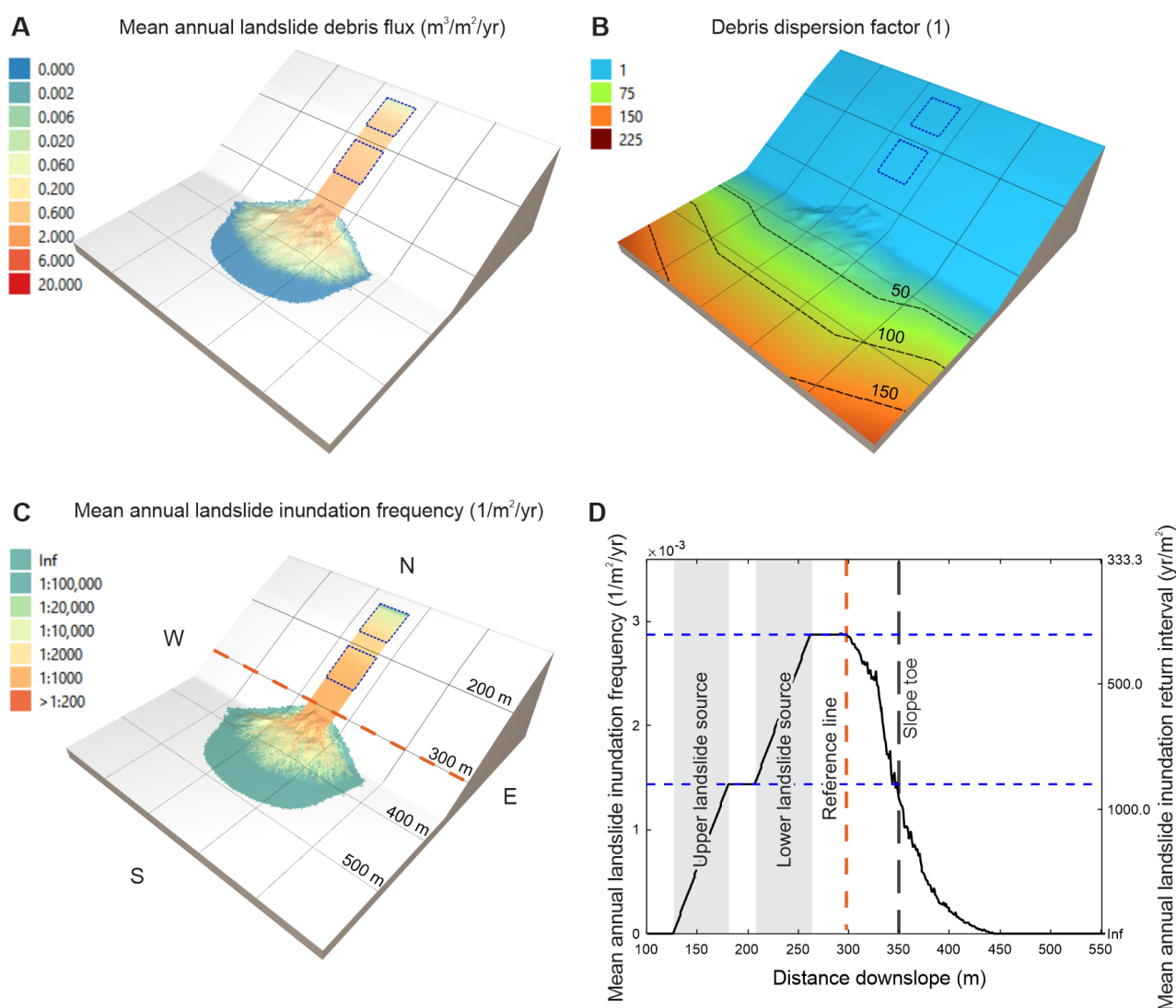


Figure A6.1 Example of model inputs to calculate mean annual landslide debris-inundation frequency from two representative landslide sources.

The mean annual frequency of inundation derived from Equation A6.7 is presented in Figure A6.1c, while Figure A6.1d presents the mean model output along a full-width swath profile from the crest to the toe of the modelled landslide deposit. These two figures indicate that the calculated frequency of inundation increases from zero at the top of the uppermost landslide (125 m down-slope) to almost equal the theoretical mean frequency of landslide occurrence (dashed blue line) at the lower limit of the upper landslide source (175 m downslope). Although the input erosion rate and assumed mean depth of failure is constant throughout the source area, and the frequency of occurrence in this area will also therefore be constant, the calculated frequency of inundation by the characteristic landslide (i.e. geometric mean of Class 4 and Class 5 landslides) increases as the profile progresses down-slope through the source region. This keeps increasing until the contributing area derived from the modelled up-slope area matches the expected contributing area at the lower limit of the upper landslide source (see Figure A6.1). A section of constant inundation frequency from 180 m to 210 m then reflects the lack of a source at this location, and, as such, the mean annual debris flux through these cells is constant. The mean annual inundation frequency then increases to almost the theoretical mean frequency for two events (upper dashed blue line in Figure A6.1; 'Lower landslide source'), before levelling off until the location of the reference line at 300 m (see Figure A6.1). This represents the upper limit of a depositional fan that formed through the model runs and marks the upper limit of debris spreading as a result of a combination of (1) topographic dispersion on a depositional fan formed through the model runs and (2) the initiation of debris spreading as the topographic gradient of the fan and lower model surface were both below the slope threshold.

The reduction of inundation frequency beyond the 300 m reference line reflects the fact that our swath profile captures only a portion of the model along the centerline of the slides. As debris both spreads laterally and is deposited along the path, the material flux, and therefore the derived frequency of inundation along the centerline, reduces respectively. The majority of debris stops prior to 400 m down-slope, with a thin apron extending out to 430 m (note the non-linear colour scale presented in Figure A6.1a). A broader area of zero debris extends out to 500 m down-slope; however, the deposition prior to this point has removed all debris from the runout model, and the continued runout is purely a numerical artefact. As such, the calculated inundation frequency represented in Figure A6.1c, d provides a suitable approximation of the annual probability of inundation from debris derived from the two landslide sources.

A6.3 Probability of Loss (Vulnerability)

The physical vulnerability to landslide-debris-inundation events can be defined as the probability of a building being damaged to a degree at which the cost to repair or restore it (re-instatement cost) would surpass the cost of fully replacing it (replacement cost). APLR therefore describes the likelihood that damage will reach a level where repairs are no longer economically feasible, making full replacement the more cost-effective choice.

In order to evaluate building vulnerability to landslide-debris inundation, we adopt the building damage dataset ($n = 168$) compiled in Massey et al. (2019) from New Zealand and international data, where the vulnerability of buildings to landslide damage has been related to landslide debris-inundation depth (Figure A6.2). Their analysis suggests that, between 0 m and 4.0 m inundation depth, the building-damage ratio (repair cost divided by replacement value) varies as a sigmoid logistic function, increasing gradually to 30% damage for debris depths up to 1.5 m height and 80% or more damage being incurred for depths greater than 3.0 m. The same vulnerability function was recently employed to evaluate vulnerability to debris flows and rock fall in the Queenstown Lakes District (Woods et al. 2021).

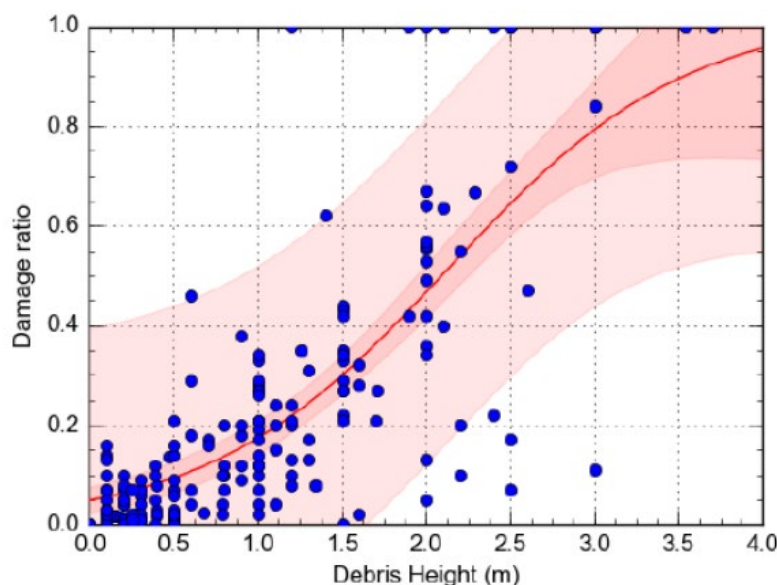


Figure A6.2 Building vulnerability to falling debris and debris flows over a range of common landslide inundation depths ($n = 168$). Data represents all building types. Darker red shading represents $\pm$ one standard deviation, while lighter red shading represents the 95% confidence interval (Massey et al. 2019).

The methods employed in this study do not allow the calculation of debris height for individual landslide events. For the purpose of calculating APLR, we instead assume that the height of debris when it impacts a building is equal to the mean depth of the landslide source. This allows us to then convert the calculated probability of inundation to APLR throughout the study region (see Appendix A6.4 for full details of this calculation). Although debris height will vary in reality as a result of factors such as spreading, channelisation, entrainment and interaction with buildings, we note that the building-vulnerability function adopted in this study (Massey et al. 2019) predicts a mean of 100% damage for debris heights of 4 m and is invariant for all debris heights exceeding 4 m (see Figure A6.2). As the geometric-mean source depth adopted in the LSP model for the 'house'-size landslide-class range (classes 2–3) and above exceeds 4 m (see Table 2.1), this assumption means that we estimate a mean of 100% damage for inundation by any debris for 'house'-sized landslides and above. The geometric-mean depth of 'family-car'-sized landslides therefore results in this class range being assigned a mean damage ratio of 25%, while the damage ratio associated with inundation by debris from 'bus'-sized landslides is 65%. Given the shorter travel distance of lower-volume landslides, and therefore lower potential for spreading, assuming an inundation depth similar to that of the source is not unreasonable for these size classes. On the other hand, the increasing potential for large landslides to transport large volumes of extremely coarse (e.g. house-sized and greater) debris to the full extent of the runout increases the potential damage associated with inundation. Assuming 100% damage for inundation resulting from landslides greater than 'house' size is therefore also not unreasonable. A quantitative analysis of uncertainties associated with this assumption is presented in Section A7.5. Depending on the proximity of the inundation location to the landslide source, we estimate the associated uncertainty to result in an approximate 3% change in calculated APLR.

We note that determining the probability and depth of inundation with a higher level of confidence, as may be suitable for plan changes and building consents in areas where a larger number of properties may be subject to a large hazard event, requires site-specific geological observations and consideration of all potential failure mechanisms and triggers. Such an analysis should be supported by appropriate physical modelling of runout processes (de Vilder et al. 2024).

A6.4 Mean Annual Property Loss Risk

It is assumed that multiple landslides of various source volumes may be triggered at the same time. Therefore, it is important in the risk calculation to ensure that a building is not completely damaged more than once, if it is hit by debris. For example, a building occupying a given grid cell at the time of an earthquake could be damaged by debris from one source volume or from multiple source volumes combined. Therefore, although the probability of damage increases with the increasing volume of debris passing through a given portion of slope, it cannot exceed 1.

To calculate the annual property risk values for each grid cell, the following steps were undertaken:

- **Step 1:** The probability of damage for each landslide-source volume, trigger type and return interval was calculated based on the probability of inundation (Equation A6.1), where:

$$APR_{LS(\mu)(c)(T,RI)(x,y)} = P_{i(\mu)(c)(T,RI)(x,y)} \times \Lambda(\Phi_{L(c)}) \quad \text{Equation A6.8}$$

Λ is vulnerability, defined as probability of total building damage by debris. If $APR_{LS(\mu)(c)(T,RI)(x,y)} \geq 1$, then the value should be 1.

- **Step 2:** The contribution to each grid cell from each landslide-volume class per trigger type and return interval is then calculated as the product of the probability of damage from all landslides within the representative return interval for each trigger type, where:

$$APR_{LS(T,RI)(x,y)} = 1 - \prod_{i=1}^n 1 - APR_{LS(\mu_i)(c_i)(T,RI)(x,y)} \quad \text{Equation A6.9}$$

- **Step 3:** For both rainfall and earthquake triggers, the total building damage risk of a given grid cell is then calculated as a product of the probability of damage from landslides per trigger type and return interval, where:

$$APR_{LS(x,y)} = 1 - \prod_{i=1}^n 1 - APR_{LS(T,RI)(x,y)} \quad \text{Equation A6.10}$$

A6.5 Key Landslide Debris-Inundation-Risk Model Uncertainties and Assumptions

Aside from the uncertainties associated with the landslide source-susceptibility (LSS), LSP and LSD models, uncertainties related to the LDIR model arise from (1) the method employed to estimate the characteristic landslide-debris-inundation event magnitude at locations down-slope of landslide sources (2) the assumed inundation depth for each volume-class range and (3) the vulnerability of structures to inundation by debris of a given depth. While (1) applies to both the probability and APLR calculation, (2) and (3) only affect the calculated APLR. Determining uncertainties resulting from the estimated characteristic landslide-debris-inundation event magnitude is difficult, as this is closely tied to the characteristics of the debris travel path (from landslide sources to inundation locations). However, as we adopt a conservation-of-mass approach to approximately balance the production and spreading of landslide debris, the range of characteristic fluxes is reasonably tightly constrained and variation in calculated event frequency is therefore unlikely to vary by more than an order of magnitude. We test the impact of uncertainties associated with both (2) and (3) by varying the critical inundation depth between 2 m and 10 m, allowing for uncertainties in the inundation depth-vulnerability function presented in Massey et al. (2019), as well as uncertainties associated with spreading and thinning of debris from larger volume landslides. The impact of this reasonably large uncertainty range on calculated APLR is just a $10^{-1.5\times}$ variation from the ‘most likely’ case at locations close to landslide sources (where inundation by smaller landslides is most likely) and no variation at most distal locations (where only the largest landslide volumes are able to reach). See Section A7.5 for a more detailed discussion of associated uncertainties.

Given the above assumptions and uncertainties, we have elected to adopt 'best estimates' for all input variables while adopting conservative ranges for associated uncertainties. This ensures that LDIR model results closely reflect the input datasets and assumptions described in this report while also conveying the overall level of uncertainty associated with the LDIR model inputs (see Appendix 7). We recommend that West Coast Regional Council consider appropriate precautionary reductions in acceptable hazard or risk metrics based on an evaluation of appropriate confidence intervals and reported model uncertainty (as discussed in Section 5).

APPENDIX 7 Landslide Source to Inundation Process Model Uncertainties and Sensitivity Analysis

A7.1 Sensitivity Analysis

The accuracy of this regional landslide-debris-inundation hazard and risk analysis is dependent on a range of uncertainties associated with the input datasets and model variables. In this section, we adopt likely uncertainty ranges for each variable in order to:

1. Quantify the model sensitivity to each input variable by calculating annual property loss risk (APLR) variation from mean input values.
2. Quantify the total change in APLR from that calculated from 'best estimate' inputs using statistically representative combinations of input uncertainties.

As it is impractical to quantify uncertainties in 2D across the region, we instead adopt a representative 1D topographic profile, assuming that dispersion of debris is consistent with that which may be expected on a planar hillslope. We adopt baseline 'best estimate' input variables either derived from input datasets or regionally consistent variables adopted for this study. The selected topographic profile is described by a steep ($\sim 45^\circ$), linear hill slope that occupies the first 100 m of the profile length before transitioning to a topographic profile represented by an exponential function that gradually reduces to a $\sim 6^\circ$ gradient 5000 m from the starting position. We re-calculate a profile for each iteration of the sensitivity analysis and introduce a random gradient noise, calculated based on an assumed vertical digital elevation model (DEM) precision $\pm 50\%$ of the horizontal resolution, in order to reproduce inherent variability in the available DEM models. The profiles are smoothed using the same landslide volume-class-based window used to prepare the DEM for Gravitational Path Process (GPP) model runs (see Section A5.3.2). An example of 1D topographic profiles calculated for each landslide-volume class is presented in Figure A7.1. We note that profiles are only calculated to the maximum extent of flow-type movements, and, as such, profiles for classes 1–5 do not extend across the full 5000 m of the 1D model.

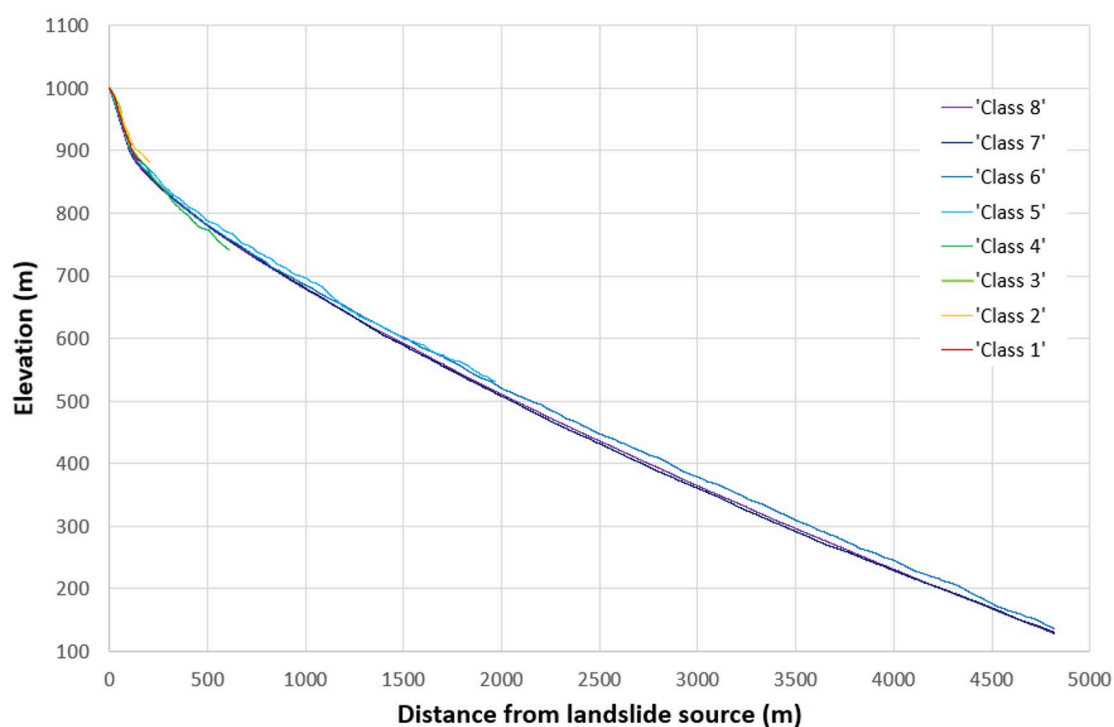


Figure A7.1 Example 1D topographic profiles employed to quantify model uncertainties. Note: the vertical scale is exaggerated for clarity.

In order to quantify model uncertainties, we implemented all equations of the landslide source-susceptibility (LSS) and landslide sediment production (LSP) models for a single landslide-source grid cell in a Microsoft Excel spreadsheet. We then incorporated equations for the fahrböschung and PCM models and calculated the resulting runout for debris derived from the source cell. For the APLR calculation, we assume that the material flux passing a given location is equal to the source volume, as long as that location is within the calculated runout extent. All equations for the APLR model were then implemented in the Microsoft Excel spreadsheet in order to calculate the landslide-debris-inundation risk at fixed locations down-slope of the source cell. Depending on the nature of the input variables, we describe uncertainties as either a mean and standard deviation or as a linear range between maximum and minimum credible limits. The variables tested, along with assumed mean values, standard deviations (for normally-distributed data) and ranges (for linear distributions), are listed in Table A7.1.

Table A7.1 List of variables, assumed baseline values and ranges employed in the sensitivity calculation. Standard deviation / error values are only valid for normally distributed and standard factorial error (SFE) data, while ranges are only valid for linearly distributed data. Variable names contain a prefix denoting the model component that these relate to (LSS, LSP, LSD, LDIR). ARI = annual return interval; RIL = rainfall-induced landslide; EIL = earthquake-induced landslide.

ID	Variable	Description	Mean	Standard Deviation/ Error	Range	Distribution
1	LSS_Pril50	50-year ARI RIL probability (ls_cell/cell/event)	0.000265	6.80E-05	N/A	Normal
2	LSS_Pril100	100-year ARI RIL probability (ls_cell/cell/event)	0.000308	6.80E-05	N/A	Normal
3	LSS_Pril250	250-year ARI RIL probability (ls_cell/cell/event)	0.000375	6.80E-05	N/A	Normal
4	LSS_Peil100	100-year ARI EIL probability (ls_cell/cell/event)	0.00526	6.80E-04	N/A	Normal
5	LSS_Peil250	250-year ARI EIL probability (ls_cell/cell/event)	0.00574	6.80E-04	N/A	Normal
6	LSS_Peil500	500-year ARI EIL probability (ls_cell/cell/event)	0.00624	6.80E-04	N/A	Normal
7	LSS_Peil1000	1000-year ARI EIL probability (ls_cell/cell/event)	0.00692	6.80E-04	N/A	Normal
8	LSP_SEDssy	Suspended sediment yield (kg/m ² /yr)	2	1.8	N/A	SFE
9	LSP_SEDs2t	Suspended to total sediment-yield multiplier (1)	1.5	0.5	N/A	Normal
10	LSP_SEDrho	Bedrock density (kg/m ³)	2650	250	N/A	Normal
11	LSP_SEDnL	Sediment-bulking factor (1)	1.3	0.2	N/A	Normal
12	LSP_SEDdw	Proportion of total erosion attributed to landslides (%)	0.6	N/A	0.2–1	Linear
13	LSP_SEDcohesion	Cohesion of critical joints [log ₁₀ (kN/m ²)]	2	2	N/A	Normal
14	LSP_RILmean	Mean RIL volume [log ₁₀ (m ³)]	3.92	1	N/A	Normal

ID	Variable	Description	Mean	Standard Deviation/ Error	Range	Distribution
15	LSP_RILstdev	EIL volume standard deviation [$\log_{10}(\text{m}^3)$]	0.68	0.5	N/A	Normal
16	LSP_EILmean	Mean EIL volume [$\log_{10}(\text{m}^3)$]	4.55	1	N/A	Normal
17	LSP_EILstdev	EIL volume standard deviation [$\log_{10}(\text{m}^3)$]	0.68	0.5	N/A	Normal
18	LSD_res	Grid-cell resolution (m)	16.5	N/A	8–25	Linear
19	XSTgradient	Angle of assumed basal failure plane (°)	20	N/A	15–25	Linear
20	LSD_PCMmu	Initial basal friction for PCM model (°)	5	2	N/A	Normal
21	LSD_PCMmd	Mass-to-drag ratio for PCM model [$\log_{10}(1)$]	1.74	N/A	1.3–2.18	Linear
22	LSD_PCMmuExp	Basal friction area scaling exponent for PCM model (1)	-0.24	0.02	N/A	Normal
23	LSD_PCMmuMin	Minimum basal friction for PCM model (H/V)	-0.75	N/A	-1.4 to -0.097	Linear
24	LSD_PCMmuMax	Maximum basal friction for PCM model (H/V)	-0.75	N/A	-1.4 to -0.097	Linear
25	LSD_GPPpersistence	Persistence factor for PCM model	2	N/A	1–3	Linear
26	LSD_GPPspreading	Spreading factor for PCM model	1.75	N/A	1.5–2	Linear
27	LSD_FAHRpercentile	Fahrböschung angle percentile (%)	50	N/A	5–95	Linear
28	LSD_ProbFlow	Proportion of flow-type movements (1)	0.33	0.3	N/A	Normal
29	LDIR_CritFlux	Debris flux at maximum vulnerability [$\log_{10}(\text{m}^3/\text{m}^2)$]	6	N/A	2–10	Linear

We quantified relative sensitivities to each variable by setting all model inputs to mean values (note: although the ‘mean’ value often represents the ‘best estimate’, it may differ in some cases; for example, where the best estimate does not represent the mid-point of the range) and varying the selected variable across the credible range. Total uncertainty was quantified by setting all model inputs to ‘best estimate’ values and employing statistical models to evaluate the full range of potential input combinations. For both approaches, we determined the change in APLR as a proportion of the baseline APLR value (either the ‘mean’ or ‘best estimate’, depending on the approach) at five positions down-slope of the source (100 m, 150 m, 300 m, 600 m and 1200 m).

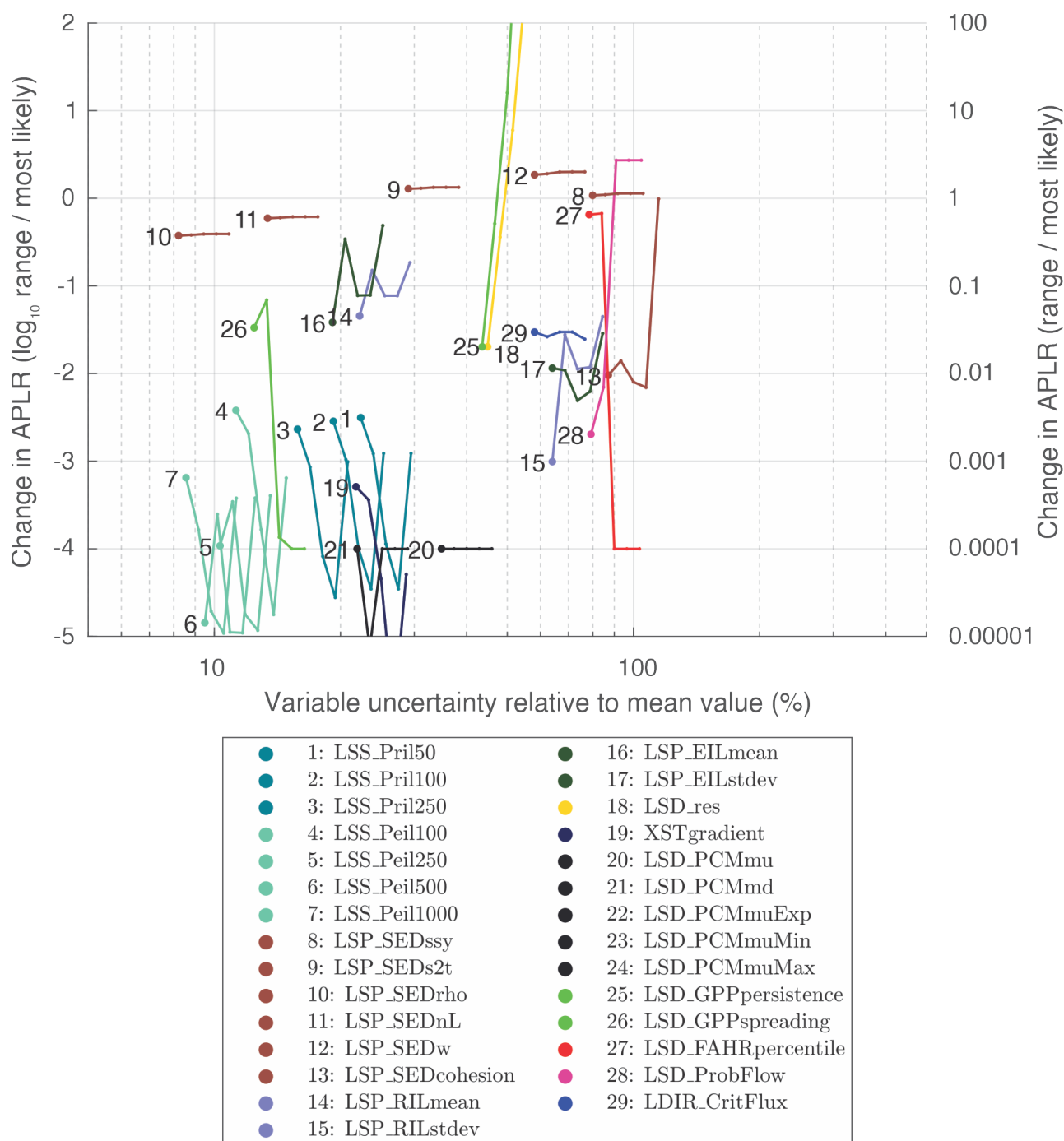


Figure A7.2 Landslide Source to Inundation Process Model sensitivity to uncertainties in model variables. Numbered points correspond to descriptions in the legend. Uncertainties associated with variables 20–24 have no impact on calculated risk at the sample locations and therefore are not plotted here. We note that both cohesion (c) (13) and the mass-to-drag ratio of the PCM model (21) are varied on a log scale so that a 100% uncertainty represents an order-of-magnitude increase or decrease in the variable value.

The sensitivity of the calculated APLR to uncertainties in each of 29 key input variables is presented in Figure A7.2. The point and corresponding 'tail' of each trace represents the change in risk at five set distances down-slope of the landslide-source location (100 m, 150 m, 300 m, 600 m and 1200 m). The point marks the change in APLR at 100 m, while the tail marks progressively greater distances from the source. Tails are centred horizontally about the normalised variable uncertainty and offset from left to right to aid visibility.

Traces in the lower left of the plot are associated with both lower relative uncertainties and lower impact on the calculated APLR than those in the upper right (i.e. lower model sensitivity). A general lower-left to upper-right trend indicates increasing model sensitivity to variables with greater uncertainties. For example, the uncertainty on the mean earthquake-induced landslide probabilities (parameters 4–7 in Figure A7.2) is relatively low (approximately $\pm 10\%$ of the mean value) and the resulting impact on the calculated APLR is between $10^{-5}\times$ and $10^{-3.1}\times$ the most likely APLR value, depending on the proximity to the source. In contrast, the LSP specific-sediment-yield variable (parameter 8 in Figure A7.2) exhibits a high uncertainty, with a standard deviation (1.8) that is approximately 90% of its mean (2), resulting in a variability in the APLR approximately $10^{0.1}\times$ the calculated ‘most likely’ solution.

A7.2 Landslide Source-Susceptibility Model Uncertainties

Uncertainties associated with the LSS model inputs are relatively tightly constrained, with a $<10\%$ variable uncertainty for earthquake-induced landslide susceptibilities (4–7 in Figure A7.2) and $<20\%$ uncertainty tested for rainfall-induced landslide susceptibilities (1–3 in Figure A7.2). These uncertainties result in a $\sim 10^{-2.5}\times$ variation from the most likely APLR for most cases; again, with greatest variability associated with more distal locations. Although the earthquake- and rainfall-induced landslide susceptibilities do not affect the total volume of debris generated at a given location, these indirectly impact the APLR by determining the proportion of sediment that is attributed to rainfall- (smaller, less mobile) and earthquake-induced (larger, more mobile) landslides.

A7.3 Landslide Sediment-Production Model Uncertainties

Uncertainties associated with the LSP model inputs (parameters 8–17 in Figure A7.2) lead to the greatest changes in APLR, typically between $10^{-2}\times$ and $10^{0.3}\times$ of the ‘most likely’ solution. In particular, we observe an almost 1:1 relationship between variable uncertainty and change in risk for those variables that determine the rate of landslide-debris production (parameters 8–11 in Figure A7.2), with little difference between each sample location. This reflects the first-order control that landslide-debris availability plays in determining risk to down-slope structures and also highlights the importance of refining estimates of present-day landslide sediment-production rates for local or site-specific APLR assessments. The regional-scale datasets adopted in this study should not be considered appropriate for local or site-specific assessments, and failure to recognise localised sources of more rapid debris-generation may, for example, lead to a proportional under-estimation of local APLR. In particular, areas of active erosion (e.g. by fluvial and coastal processes), ongoing slope instability (e.g. creeping or deep-seated landsliding), short-term increases in susceptibility (e.g. due to vegetation loss) and recent anthropogenic modification (e.g. quarries and road cuts) are likely to demonstrate rates of landslide-sediment production several orders of magnitude greater than the assumed regional erosion rates employed in this assessment. These locations can be expected to locally present APLR several orders of magnitude greater than those presented here.

Uncertainties related to DEM resolution and the cohesion of weak joints in the rock mass (c) (parameter 13 in Figure A7.2) affect the landslide area-volume scaling terms in Equations A4.3 and A4.4 and, by proxy, the maximum relief required to support larger landslide-volume classes (Equation A4.5).

Selecting a higher cohesive strength affects landslide-debris-inundation modelling in two opposing ways:

- It increases the theoretical mean depth associated with each landslide volume-class range (Equation A4.3).
- It increases potential failure volumes by steepening the gradient of scarps within hypothetical landslide sources (Equation A4.5).

While these two effects might initially appear to offset each other, the net impact of increasing cohesive strength is a reduction in the proportion of the landscape capable of supporting larger landslides. This occurs because, while the theoretical mean depth of landslide volume-class ranges is unrestricted, the actual depth achievable is constrained by available excess topography.

As a result, a higher cohesive strength increases the proportion (and frequency) of smaller, lower-volume landslides with shorter runout distances. In practical terms, this means:

- Landslide risk increases in areas with high excess topography, where smaller landslides become more frequent.
- Risk decreases at more distal locations, as fewer large, highly mobile landslides are expected.

For further details on the LSP model assumptions and uncertainties, see Section A4.8.

Although the runout distance of given avalanche-type volume classes is dependent on a number of LSD model variables, the relative change in avalanche mobility between volume classes is greater than the uncertainty associated with a single volume class, and the terms determining whether or not a given volume class is feasible at a given location can therefore dominate the variation in APLR. We test a range of cohesion values spanning four orders of magnitude (encompassing all likely conditions from weak soil to intact strong rock). This leads to a variation in APLR of just $10^{-2}\times$ at locations close to the source and $10^0\times$ at the farthest location, where a larger-volume ‘avalanche’ failure is able to inundate the position with the lowest cohesion value.

The landslide volume-class distributions for earthquake- and rainfall-induced triggers are determined by two parameters describing the geometric mean and standard deviation of each dataset (parameters 14–17 in Figure A7.2). We test a $0.2\times$ uncertainty in the geometric mean of each volume-class range and $0.75\times$ uncertainty in the standard deviation of each range. We observe a $10^{-1.4}\times$ to $10^{-0.3}\times$ change in the most likely APLR as a result of uncertainties in the geometric means of each trigger and $10^{-3}\times$ to $10^{-0.4}\times$ change in the most likely APLR as a result of standard-deviation uncertainties. As landslide mobility scales non-linearly with volume, the impact of uncertainties in parameters describing earthquake-induced landslide-volume distributions (with a larger geometric-mean volume) are slightly larger than the rainfall-induced landslide uncertainties at equivalent down-slope distances.

A7.4 Landslide Sediment-Distribution Model Uncertainties

With little local data to directly constrain the GPP model-input parameters, we allow the majority of variables to vary by 50%. In general, uncertainties on the PCM model inputs (parameters 20–24 in Figure A7.2) have little to no impact on APLR for all sampled positions. This reflects the strong control of the sliding-friction coefficient on runout, as, once the local slope reduces below the specified limit, the modelled velocity rapidly reduces to zero. As slope gradient varies little between the sample locations in our idealised 1D profile, the calculated extent of flows also varies little for the full range of input values. Testing the full range of fahrböschung angle (parameter 27 in Figure A7.2) uncertainties (5–95% probability of exceedance) leads to a change in calculated APLR of up to $10^{-1.8}\times$ at locations close to the landslide source, decreasing to 0% at locations beyond the extent of potential ‘avalanche’ runout. We note that, while our 1D profile represents a useful middle-ground to represent natural settings, more complex variations in real-world topography (e.g. waterfalls or cliffs) will lead to non-linear relationships between PCM inputs and runout extents, and, while useful for illustrative purposes, the specific relationships determined here are therefore not applicable to real-world settings.

In contrast to the minor impact that most PCM model inputs have on APLR, variation of the GPP persistence factor (parameter 25 in Figure A7.2) generates a large change in APLR, particularly at greater distances from the landslide source pixel ($10^{-1.6}\times$ to $10^9\times$ the most likely value). The persistence factor determines the probability of debris travelling in the same direction as the previous cell, and a higher persistence factor leads to more debris passing directly from the source cell to inundation cell.

The particularly strong influence of this variable results from two principal sources specific to the Monte-Carlo simulation: (1) as this factor must be determined empirically, its potential range is largely unconstrained; and (b) the spreading behaviour is difficult to reproduce in our 1D model (e.g. 2D effects of debris leaving the travel path and later returning). We therefore consider the large change in APLR to at least, in part, be a numerical anomaly.

The DEM resolution employed in the LSD model (parameter 18 in Figure A7.2) also plays an important role in determining runout distances. In our 1D model, the DEM resolution affects the numerical noise in slope-gradient estimates. A lower DEM resolution smooths topography, reducing noise and therefore the probability of debris encountering conditions that will cause the material to slow to a stop in the LSD model. The runout distance of debris therefore increases with decreasing resolution (see Section A7.1). Varying the DEM resolution from 8 m to 25 m leads to a change in APLR of between $10^{-1.6} \times$ and $10^6 \times$, with associated sensitivity increasing rapidly with increasing distance from the source. Similar to the persistence factor, this is in part a numerical anomaly, as the 1D model adopted here cannot fully capture 2D effects of variations in DEM resolution. However, we do note that the strong increase in sensitivity at greater distances can be expected in the 2D model, as APLR change in areas with no debris flux (for example) will be infinite with even the smallest increase in debris flux. Uncertainties associated with the DEM resolution are further explored in Appendix A7.6.

A7.5 Landslide Debris-Inundation-Risk Model Uncertainties

The LDIR model is affected by the LSD model resolution (parameter 18 in Figure A7.2), the LSD model spreading factor (parameter 26 in Figure A7.2) and the debris height assumed to be associated with 100% damage (parameter 29 in Figure A7.2). As both LSD model variables are discussed in the previous section, we only discuss here the relative impact of variability in the critical debris height. As mentioned in Section A6.3, the debris height is compared against the assumed inundation depth, which for this study is the mean depth of the landslide volume-class range. We vary the critical debris height between 2 m and 10 m, which effectively implies that inundation by anything larger than ‘house’-sized landslides (at the lower end), or ‘supermarket’-sized landslides (at the upper end) will result in 100% damage. Changing this variable therefore only affects the risk calculated as a result of smaller, less mobile landslides. As our 1D model indicates that all sample locations have the potential for inundation by ‘Olympic swimming pool’ (the largest volume class affected) -sized flow-type movements, the critical debris height affects the APLR at all locations. However, this effect is relatively small (approximately $10^{-1.6} \times$; see Figure A7.2), as the shape of the sigmoidal function employed to describe vulnerability allows for the greatest change in damage ratio at moderate debris heights, while damage associated with the smallest and largest debris heights varies little irrespective of the critical depth.

A7.6 Total Uncertainty

A7.6.1 Parametric Uncertainties Resulting from Model Assumptions and Inputs

We employed a Monte Carlo approach to evaluate parametric uncertainties resulting from model assumptions and variability in model inputs on the calculated APLR. Combining this approach with Latin Hypercube Sampling (LHS), we undertook a thorough exploration of the input parameter space for linear, standard factorial error and normally distributed inputs.

To represent uncertainties at specific LSD model resolutions, we explored the input parameter space with the resolution fixed at 8 m, then 25 m, and compared results against the ‘most likely’ 25 m output derived from ‘best estimate’ parameters (as this provides a comparison with the outputs of this study). APLR was evaluated for each parameter combination at each of the same five down-slope positions as in the individual parameter analysis. The Monte Carlo simulation results for each location were compiled to generate an empirical cumulative distribution function (CDF), which captured the variability in APLR due to uncertainties in the input parameters at fixed model resolutions. This approach allowed for a robust assessment of APLR under a representative range of input variability.

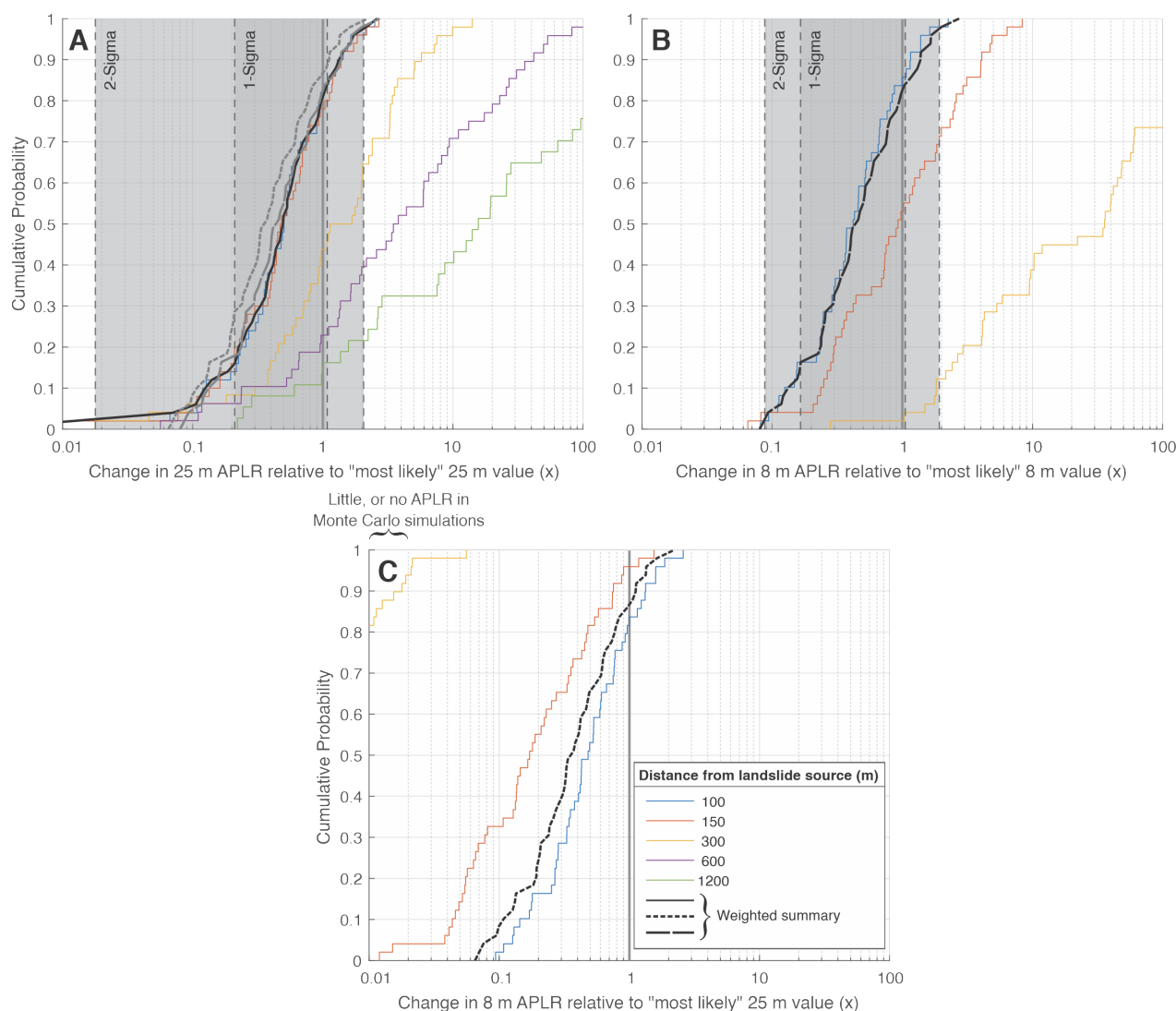


Figure A7.3 Calculated variation in annual property loss risk (APLR) as a result of Monte Carlo simulation of Landslide Source to Inundation Process Model (LS-IPM) inputs for (a) 25 m LS-IPM results with respect to the baseline 25 m model, (B) 8 m LS-IPM results with respect to the baseline 8 m model and (c) 8 m LS-IPM results with respect to the baseline 25 m model. There is no inundation at 600 m or 1200 m in the 8 m LS-IPM instances. An APLR change of 1 indicates that Monte Carlo analysis results are identical to the ‘most likely’ solution derived from parameters adopted in this study. Black solid and dashed curves represent weighted summaries derived from all sample locations. Grey dashed curves in (a) represent the weighted summaries presented in (b) and (c). Grey shaded regions represent 1- and 2-sigma confidence intervals.

Figure A7.3 presents results of the Monte Carlo analysis for calculated APLR at five sample points located at a range of distances from the landslide-debris source. The point at which each cumulative probability curve passes the dashed vertical line (indicating a match between the CDF and ‘most likely’ APLR) indicates the proportion of model configurations that return results less than the ‘most likely’ scenario. In order to generalise APLR uncertainties for both the 25-m- and 8-m-resolution LSD model simulations, we calculated a weighted CDF, normalising the proportional change in APLR by the baseline 25 m APLR at each of the five sample locations (100 m = 1.3 1/yr, 150 m = 7×10^{-1} 1/yr, 300 m = 7×10^{-3} 1/yr, 600 m = 3×10^{-6} 1/yr and 1200 m = 4×10^{-13} 1/yr). The generalised uncertainties are presented as heavy black curves in Figure A7.3. A statistical summary of the results is presented in Table A7.3.

Results at 25 m resolution (Figure A7.3a) can be considered an analogue for the outputs of this study. Results at 8 m resolution provide an indication of variability in APLR with respect to the ‘most likely’ baseline of the 8 m model (Figure A7.3b). This can be considered a representation of the impact of uncertainties in input variables at a higher model resolution. In order to provide an indication of the potential change in APLR when re-calculating runout on a higher-resolution DEM, we provide a comparison of results simulated for the 8-m-resolution model referenced to the 25 m model baseline (Figure A7.3c).

We find that locations closer to the landslide source (i.e. 100 m and 150 m locations) generally experience a smaller variation in APLR for both 25 m and 8 m LSD model configurations, and, aside from approximately 5% of the outputs, which indicate little to no inundation potential, all samples for these closer locations plot within an order of magnitude (i.e. between $0.1\times$ and $10\times$) of the ‘most likely’ value. At farther distances (300 m, 600 m and 1200 m), the proportional variation increases significantly, suggesting a wider range of potential outcomes (Figure A7.3a, b). However, as the calculated ‘most likely’ APLR is lower at greater distances from the source, the ratio between the baseline and re-calculated values can be exaggerated, and the absolute APLR value may remain negligible, even when considering an increase of up to $1000\times$.

Increasing the DEM resolution from 25 m to 8 m in our 1D model results in a lower APLR at all sample locations, lowering the weighted mean APLR by approximately $2\times$, as can be observed by comparing the horizontal position of the weighted summaries in Figure A7.3a. This is consistent with the observed change in 2D model results for the Greymouth area, presented later in Section A7.6.2, for which we find the geometric-mean APLR reduced by $3.4\times$ when changing from the 25 m regional DEM to the 8 m LiDAR-derived DEM. The difference between the two values can readily be explained by considering the limitations of the 1D model (described above), the specific topographic characteristics of the Greymouth area and the variation in DEM accuracy when changing from the regional DEM to the more recent LiDAR-derived model.

Although the variability in APLR at the 100 m location is very similar for both the 8 m and 25 m LSD models, APLR at both the 150 m and 300 m sample locations decreases by between $5\times$ and more than $100\times$ (Figure A7.3c). In fact, no debris travels to the 600 m or 1200 m sample points in any of the 8 m simulations. This reflects the cumulative impact of DEM resolution on calculated travel distance, and, in particular, the greater likelihood of smaller landslides either depositing debris or reaching a stop condition earlier on a less smooth (higher-resolution) DEM.

As APLR reduces exponentially with increasing distance from the landslide source, the generalised weighted CDF for both LSD model resolutions closely represents the 100 m and 300 m sample locations. Weighted CDFs for both the 25 m and 8 m configurations (Figure A7.3a and b, respectively) are skewed toward APLR values less than the ‘most likely’ solution, with approximately 85% of configurations returning APLR lower than the ‘most likely’ solution. In other words, there is a higher chance that our 25 m ‘most likely’ scenario over- rather than under-estimates the calculated APLR. We note that this is primarily a function of the input-parameter space and physical controls on landslide runout rather than an indication of conservatism or optimism in our selection of the ‘most likely’ scenario. In some cases, our assumed input values represent the physical upper limit of input parameters (e.g. variation in the proportion of primary erosion by landsliding can only vary below our assumed 100%) and changing parameter values can therefore only decrease APLR from the ‘most likely’ value.

Despite the skewness of the data, we find that 68% of weighted simulation results for the 25 m LSD resolution fall within ± 0.35 orders of magnitude of the geometric mean, while 95% of weighted simulation results fall within ± 1.0 order of magnitude of the geometric mean (Figure A7.3a). Comparing the change in the weighted 8 m LSD resolution outputs to the baseline 8 m values indicates that 68% of results fall within ± 0.40 orders of magnitude of the geometric mean, while 95% of data fall within ± 0.67 orders of magnitude of the geometric mean (Figure A7.3b).

Along with reducing the mean APLR with respect to lower-resolution models, running models at higher resolution reduces uncertainty at higher confidence intervals by more tightly constraining outliers in the results (e.g. by eliminating areas to which debris is not able to travel). However, without additional local data, uncertainties in the LSS, LSP, LSD and LDIR model parameters mean that the potential for more extreme variations will always remain (e.g. in association with presently active instabilities not captured in the LSP model-input data).

Table A7.2 Summary statistics for annual property loss risk (APLR) variability based on 1D Monte Carlo simulation results.

Model	Weighted Geometric Mean (x 'most likely' solution)	Relative Change in the Weighted Geometric Mean	Variability in APLR at 1-Sigma Confidence Interval (order of magnitude)	Variability in APLR at 2-Sigma Confidence Interval (order of magnitude)
25 m	0.5×	N/A	±0.35	±0.98
8 m	0.42×	N/A	±0.40	±0.67
8–25 m	N/A	2×	N/A	N/A

A7.6.2 Spatial Uncertainties Relating to Digital Elevation Model Accuracy and Resolution

Lower-resolution, less-accurate DEMs tend to produce smoother topography with lower-gradient hill slopes and fewer resolved ridges and channels, particularly around smaller landforms. This introduces several systemic effects:

1. Reduced identification of small landforms as potential landslide-source areas.
2. Lower estimated maximum volumes of kinematically feasible landslides.
3. Increased mobility of landslide debris.
4. Greater spread of debris across the landscape.

In order to evaluate spatial uncertainties associated with DEM accuracy and resolution, we generated two trial APLR outputs for the area around Greymouth at 25 m and 8 m resolution, using a LiDAR-derived DEM collected between 2020 and 2024 as the topographic data source (LINZ 2022). Aside from the input DEM and resolution of the LSP and LSD components of the model (as these two resolutions are tied to one another), all other inputs and parameters were unchanged from the regional study presented in this report. A comparison of the APLR results derived from the 25 m and 8 m LiDAR-derived studies is presented alongside results of the (25 m resolution) regional analysis based on the national DEM (LINZ 2014) in Figure A7.4.

In general, results of all three studies are similar, with the two 25 m studies (Figure A7.4a, b) demonstrating a consistent range of APLR values across the region. This said, areas of particularly high APLR values in the 8 m study are less extensive than the 25 m studies, reflecting the greater channelisation of debris (i.e. fewer planar slopes supporting spreading of debris) in the better-resolved topography.

However, particularly notable is the progressive increase in the number of potential landslide-source areas resolved when comparing results derived from the regional study presented in this report to those generated from the LiDAR-derived DEM. This is apparent when comparing the extent of landslide debris sourced from hills to the southwest of Wharemoa where the national DEM does not adequately resolve the hill slopes between the plateau and coast (Figure A7.4A). As a result, the LSP and LSD components of the regional study neither generate potential landslide-source areas nor associated debris runout and APLR in areas down-slope. In contrast, the 25 m trial output derived from the LiDAR-derived DEM (Figure A7.4b) captures significant APLR in this area and is supported by a similar result from the 8 m resolution output (Figure A7.4c). In addition, the 8 m results include source areas along smaller

landforms, such as the banks of the Grey River and abandoned sea cliffs southwest of Wharemoa not resolved in the 25 m models. Overall, we find that landforms with spatial scales less than 100,000 m² are not well represented in the regional study, and debris inundation (and associated APLR) from these smaller source areas may not be identified.

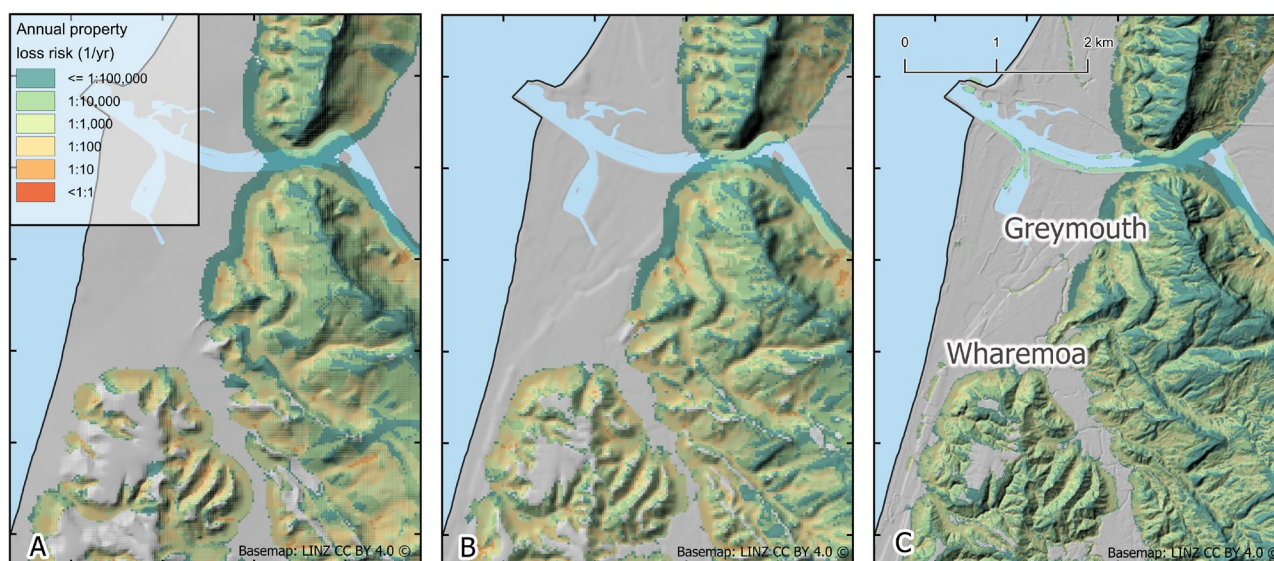


Figure A7.4 Comparison of annual property loss risk in the Greymouth region calculated on (a) the 25 m regional digital elevation model (DEM) employed in this study, (b) the 2020–2024 LiDAR-derived DEM down-sampled to 25 m resolution and (c) the 2020–2024 LiDAR-derived DEM down-sampled to 8 m resolution. The basemap for (a) is the 8 m national DEM, while the recent LiDAR-derived DEM is employed as a basemap at 25 m and 8 m resolution for (b) and (c).

A statistical analysis of the change in APLR from the LiDAR-derived results to the 25 m regional result is presented in Table A7.2 and Figure A7.5. In general, we find that the regional APLR results vary from the LiDAR-derived results in a log-normal manner, with the regional APLR being, on average, 1.1× higher than the 25-m-resolution LiDAR model and 3.4× higher than that of the 8-m-resolution LiDAR model. While the increase in average APLR is primarily a result of debris spreading more and travelling further in the LSD model (see Section A5.9), the broad-variation APLR values (represented by the wide confidence intervals) reflects both increases and decreases in APLR at various locations. This is a result of the combined impact of improved DEM accuracy (e.g. changing the trajectory of debris) and improved performance of the LSP and LSD model components (e.g. altering the stopping position of debris), as evident from the Monte Carlo simulation results presented earlier.

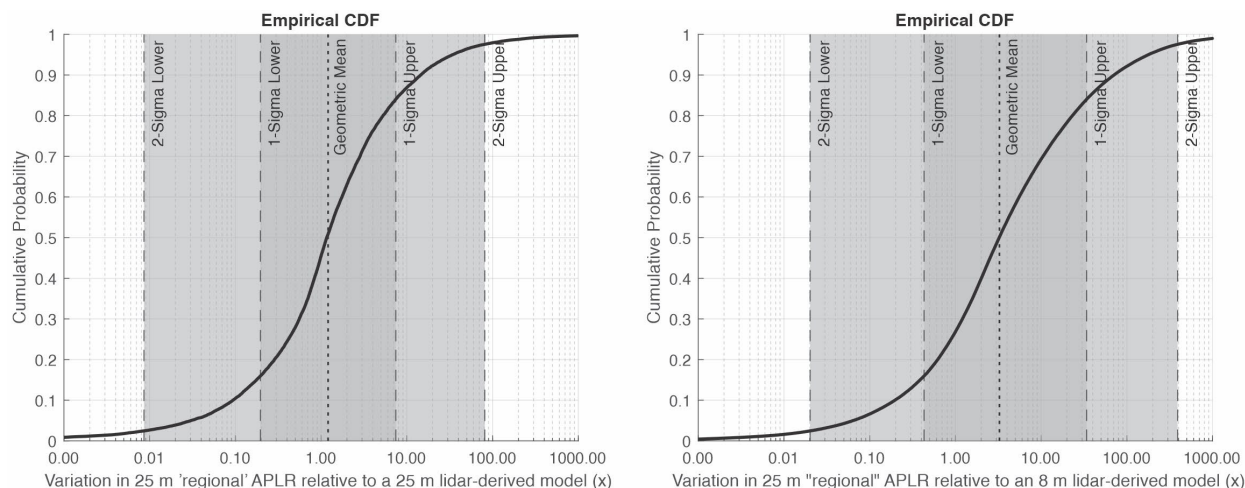


Figure A7.5 Cumulative density function demonstrating the change in predicted annual property loss risk (APLR) in the Greymouth area from LiDAR-derived results to the regional analysis presented in this study. The change in source DEM accuracy and resolution. A change in accuracy is captured in the variation from the 25 m national DEM results to 25 m LiDAR-derived results (left), while the combined effect of accuracy and resolution is captured in the change from the regional analysis results to the 8 m LiDAR-derived DEM results (right). A variation greater than 1 indicates that the regional study presented here likely over-estimates APLR values, while a variation less than 1 indicates that APLR results are higher in the LiDAR-derived models. Grey shaded regions represent 1- and 2-sigma confidence intervals.

Table A7.3 Summary statistics for change in relative annual property loss risk (APLR) in the Greymouth area, from LiDAR-derived results, to the regional analysis presented in this study. DEM = digital elevation model.

	Relative Change in the Geometric Mean	Variability in APLR at 1-Sigma Confidence Interval (order of magnitude)	Variability in APLR at 2-Sigma Confidence Interval (order of magnitude)
25 m LiDAR-Derived DEM to 25 m Regional DEM	1.1×	±0.79	±1.98
8 m LiDAR-Derived DEM to 25 m Regional DEM	3.4×	±0.94	±2.14

We find that the majority of the APLR variability is associated with the accuracy rather than resolution of the 25 m national DEM. Changing the source DEM and maintaining the nominal 25 m resolution leads to a variation in APLR of ± 0.79 orders of magnitude at the 1-sigma confidence interval (see Table A7.2), reflecting a significantly more complete catalogue of potential source areas and accurate representation of morphological controls on debris runout. Increasing the resolution of the models to 8 m then only leads to an additional ± 0.15 order-of-magnitude change in variability (to ± 0.94 orders of magnitude). The increase in resolution causes a similar change in variability at the 2-sigma confidence interval. A qualitative inspection of results in Figure A7.4b and c indicates that, aside from the general decrease in APLR as a result of reduced landslide-debris mobility, as well as limited additional source areas on smaller landforms, the overall pattern of APLR is otherwise consistent with the 25 m LiDAR-derived model results.

A7.6.3 Combined Parametric and Spatial Uncertainties

In order to provide a combined measure of uncertainty, including parametric and spatial uncertainties, we employ the Root-Sum-of-Squares method. This is a widely accepted statistical approach for combining independent uncertainties in log-transformed space. Assuming that the uncertainties are independent and normally distributed, the total uncertainty can be defined as:

$$\sigma_{total} = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \dots} \quad \text{Equation A7.1}$$

where $\sigma_{a,b,c,\dots}$ represents the uncertainty of each contributing factor in log-space.

A7.6.3.1 Distinguishing Contributions to Spatial Uncertainties

Although the relationship between topography (including local relief and morphological complexity) and the accuracy of a DEM at various spatial resolutions is complex, we expect that the 8-m-resolution (i.e. 64 m² cells) LiDAR-derived DEM will adequately capture landslide debris-production and runoff in this region. Further increasing the DEM resolution is likely to result in only minor improvement in APLR accuracy as:

1. The area of cells is significantly less than that of the common ‘House to Olympic swimming pool’ landslide-size range (geometric-mean source area of 484 m²; see Table 2.1).
2. The LSD model includes a volume-class-based DEM smoothing step prior to simulating landslide runoff (see Section A5.3.2).

We can estimate the relative contributions of DEM accuracy and resolution to the spatial APLR uncertainty by evaluating the various 2D model results for the Greymouth area. We assume that:

1. The total spatial uncertainty associated with the regional DEM accuracy and model resolution is approximately equal to its APLR variability relative to the 8 m LiDAR-derived results (e.g. ± 0.94 orders of magnitude at 1-sigma; see Table A7.4).
2. Uncertainties due to the accuracy of the national DEM can be characterised by comparing APLR results from the regional study to those derived from the 25 m LiDAR-derived DEM (e.g. ± 0.79 orders of magnitude at 1-sigma, see Table A7.4).
3. Uncertainties associated with the change in resolution from the regional to 8 m model can be isolated by removing the effects of DEM accuracy from the total spatial uncertainty.

Given these assumptions, we can rearrange Equation A7.1 to solve for (c) the unknown contribution of combined DEM and model resolution to the total spatial uncertainty. The results of this calculation are presented in Table A7.4.

A7.6.3.2 Total Uncertainty

In order to calculate the total (parametric and spatial) APLR uncertainty on the regional-study results, we combine parametric uncertainties (addressed in the 1D Monte Carlo simulation) and spatial uncertainties (due to DEM accuracy and model resolution) using Equation A7.1. The results are presented in Table A7.4 and indicate that the total estimated uncertainty for the regional LS-IPM analysis based on the national DEM is ± 1.04 and ± 2.45 orders of magnitude at 1 and 2-sigma, respectively. As the calculated uncertainties do not always follow a normal distribution, these should be considered ‘equivalent’ to standard deviations rather than directly reflecting the traditional statistical definition.

As this analysis, and those presented below, include significant assumptions, we consider it prudent to conservatively round estimated uncertainties up to the nearest 0.25 order of magnitude, or, alternatively, if a value lies within 0.10 orders of magnitude of the next 0.25 increment, it is rounded up to the next 0.5 interval. For example, a value of 0.97 is rounded up to 1.25, and a value of 1.15 is also rounded to 1.25. (see Table A7.4). This step is based on expert opinion and is intended to prevent over-interpretation of the model results and calculated uncertainties.

Isolating the contributions of DEM accuracy, as well as combined DEM and model resolution, on APLR uncertainty allows us to estimate uncertainties for additional model configurations. In particular:

- Uncertainties for a regional 25-m-resolution analysis based on a LiDAR-derived DEM can be estimated by assuming that the LiDAR-derived DEM accurately represents the ground surface such that the DEM accuracy contribution to the spatial uncertainty can be neglected. Adopting only the model resolution component of the spatial uncertainty then allows us to estimate total uncertainties associated with this configuration to be ± 0.67 and ± 1.45 orders of magnitude at 1- and 2-sigma, respectively (Table A7.4).
- Uncertainties for an 8-m-resolution analysis based on a LiDAR-derived DEM can be estimated by maintaining the assumption that uncertainties relating to DEM accuracy can be neglected and that uncertainties associated with the 8 m combined DEM and model resolution shall be less than those of the 25 m analysis. In this case, we estimate associated uncertainties to be approximately half those of the lower-resolution model, and, adopting parametric uncertainties relating to the 8 m model presented in Table A7.2, we estimate total uncertainties to be ± 0.47 and ± 0.83 orders of magnitude at 1- and 2-sigma, respectively.

Table A7.4 Calculation of total annual property loss risk (APLR) uncertainties due to combined uncertainties associated with model assumptions and parameters, DEM accuracy and the combined effects of DEM and landslide debris-inundation-risk model resolution. Uncertainties are presented for 25 m analyses based on the national and LiDAR-derived DEMs, as well as an 8 m analysis based on the LiDAR-derived DEM. Inputs denoted 'estimated' are derived based on expert judgement, as well as assumptions described in the text above.

Uncertainty	Source of Uncertainty	25 m National DEM (order of magnitude)		25 m LiDAR-Derived DEM (order of magnitude)		8 m LiDAR-Derived DEM (order of magnitude)	
		1-Sigma	2-Sigma	1-Sigma	2-Sigma	1-Sigma	2-Sigma
Parametric	Assumptions and parameters (see Section A7.6.1)	± 0.35	± 0.98	± 0.35	± 0.98	± 0.40	± 0.67
Spatial	DEM accuracy	± 0.79	± 1.98	± 0 (estimated)	± 0 (estimated)	± 0 (estimated)	± 0 (estimated)
	Combined DEM and model resolution	± 0.58	± 1.07	± 0.58	± 1.07	± 0.25 (estimated)	± 0.5 (estimated)
Total	Total uncertainty	± 1.04	± 2.45	± 0.67	± 1.45	± 0.47	± 0.83
	Recommended conservative estimate	± 1.25	± 2.75	± 0.75	± 1.75	± 0.75	± 1.00

A7.7 Summary of Uncertainties and Recommendations

A7.7.1 Parametric Uncertainty

Parametric APLR uncertainties associated with assumptions and inputs are estimated based on a 1D Monte Carlo simulation. Spatial uncertainties are estimated based on a 2D analysis of the national and LiDAR-derived DEMs in the area local to Greymouth. Although this analysis has not explored the full parameter space, we expect that the results provide a reasonable representation of both the relative contributions to and absolute magnitude of regional LS-IPM uncertainty.

A7.7.2 Uncertainties due to Digital Elevation Model Inaccuracies

The accuracy of the national DEM (LINZ 2014) employed in this regional analysis is likely the single greatest source of LS-IPM uncertainty. Inaccuracies in the DEM, and its failure to represent smaller landforms (particular those with spatial extents less than 100,000 m²) can lead to a failure of the analysis to identify landslide-source areas and associated runouts, as well as errors associated with the calculation of landslide-debris mobility and travel paths. The next most significant source of uncertainty is the 25 m resolution of the source DEM and the LS-IPM analysis, which tends to lead to an over-estimation of debris spreading and mobility across the landscape. However, uncertainties associated with model assumptions and input parameters are not dissimilar to those related to resolution at both the 1- and 2-sigma confidence intervals. Of these uncertainties, the greatest contributors to variation in APLR are those that determine the rate of landslide debris production (e.g. the erosion rate and proportion of primary erosion by landslide processes) and empirical GPP model parameters with little constraint on potential ranges (e.g. the persistence factor). Overall, uncertainties are spatially variable and generally increase with increasing distance from landslide-source areas as inaccuracies in the DEM and uncertainties relating to landslide debris mobility are compounded. With the adoption of a LiDAR-derived DEM for the study region, as well as reduction of the resolution of the input DEM and LS-IPM calculation to 8 m or less, we expect model assumptions and parameters to become the largest single source of residual uncertainty.

A7.7.3 Uncertainties due to Digital Elevation Model and Model Resolution

It is more likely that LS-IPM results from this regional analysis over- rather than under-estimate APLR across the study area. This is in part because our selection of ‘best estimate’ input parameters is naturally biased toward higher debris-production rates and greater landslide-debris mobility, as some parameters (such as the proportion of primary erosion by landslides) have an upper limit at, or close to, the adopted value. For the 25 m analysis, our ‘most likely’ solution is approximately 2× the weighted geometric mean derived from the 1D Monte Carlo simulation. Adopting a lower-resolution DEM and LP-ISM analysis tends to lead to greater landslide mobility, as the smoother DEM tends cause debris to travel further and spread more across the landscape. From our 2D models, we find that the geometric mean APLR for the 25 m regional analysis is approximately 3.4× that of the same model on the 8 m LiDAR-derived DEM, while the 1D Monte Carlo simulation similarly indicates that the geometric-mean-weighted APLR for the 25 m resolution model resolution will be approximately 2× that of the 8 m resolution model. Finally, we investigate the effect of DEM accuracy by comparing the 25 m 2D model results for the national and LiDAR-derived DEMs in the Greymouth area. This indicates that the geometric-mean APLR derived from the national DEM is approximately 1.1× that of the identical model based on a LiDAR-derived DEM. We note that this over-estimation relates to geometric-mean APLR result, and includes significant increases in APLR at some locations, as well as significant decreases in APLR in others.

A7.7.4 Present-Day Model Uncertainties

For the present-day 25 m regional LS-IPM analysis presented here, we recommend adopting an uncertainty of ±1.25 orders of magnitude to represent the 1-sigma confidence interval (~68% of results) and ±2.75 orders of magnitude to represent the 2-sigma confidence interval (~95% of results). If a LiDAR-derived DEM is used to represent topography, these uncertainties can be reduced to ±0.75 and ±1.75 orders of magnitude, respectively. Increasing the resolution of the DEM and LS-IPM analysis to 8 m and employing a LiDAR-derived DEM for the analysis is estimated to further reduce the APLR uncertainty to ±0.75 and ±1.00 orders of magnitude at 1- and 2-sigma confidence intervals, respectively. This is described in Table A7.4.

A7.7.5 RCP6 2021–2100 Model Uncertainties

For the RCP6 2081–2100 climate scenario, we recommend adopting a representative 1-sigma uncertainty of ±2.75 orders of magnitude (i.e. the present-day uncertainty at the 2-sigma confidence interval). A lack of constraint on the extreme limits of key input variables does not allow us to provide

an RCP6 2081–2100 climate-scenario uncertainty recommendation at the 2-sigma confidence level. For further details of unconstrained variables, see Section 2.3.1.6. For a discussion on recommended uncertainties, see Section 5.3.2.

A7.7.6 Reducing Uncertainties

Reducing uncertainties associated with model assumptions and input parameters will require the employment of new methodologies, or datasets, to constrain key input variables; in particular, those toward the upper right of Figure A7.2. This may include the consideration of sediment-production rates at local scales, employing geological or historical datasets, the probability of avalanche versus flow movement modes by re-analysing existing landslide catalogues, local fahrböschung distributions for rainfall- and earthquake-induced landslides and allowing for depth-dependent and/or material-specific cohesion values.

APPENDIX 8 Alignment with Australian Geomechanics Society Landslide Risk Management Guidelines

A8.1 Introduction

This section presents the steps taken in this basic quantitative regional hazard and risk analysis in terms of the good practise outlined in the Australian Geomechanics Society's Landslide Risk Management Guidelines (AGS 2007).

Using Figure 1 of AGS (2007), this study applies a new methodology to the 'Hazard Analysis' phase of the landslide risk management framework. As in conventional studies, we combine desk- and field-based data on geomorphology, geology, groundwater and slope stability to build a geotechnical model of potential landslide sources.

Traditional event-based approaches then estimate hazard magnitude and frequency from landslide inventories and use empirical or physically based models to predict runout from discrete sources.

In contrast, this study adopts a process-based approach designed for regional-scale application. Instead of modelling a finite set of events, we account for debris production and movement from all feasible sources across the landscape. Hazard is expressed in terms of debris flux (volume per unit area per year) and probability of inundation, providing a spatially comprehensive assessment without the requirement to consider discrete landslide footprints.

Here, hazard magnitude and frequency are defined by debris-production rates, informed by geomorphic-process rates (e.g. tectonic uplift, erosion), landslide inventories and the geotechnical landslide-source model. Spatial impact is calculated with empirical and physically based debris-transport models, using conventional approaches to derive model inputs from international datasets and landslide behaviours in the study area. We employ a deterministic model of characteristic landslide debris flux to convert the spatial hazard output to a magnitude-frequency relationship for landslide-debris inundation, supporting consequence analysis and completing the 'Risk Analysis' phase of the AGS (2007) framework.

The 'Consequence Analysis' considers the vulnerability of buildings to debris inundation, using depth-dependent damage ratios to estimate APLR. Buildings are treated as permanent elements at risk, and inundation depth is used to quantify the likelihood of economic loss.

More specific detail on how this new approach aligns with, deviates from or does not use the steps outlined in AGS (2007) is provided in the sections below.

A8.2 Hazard Analysis

A8.2.1 Data Gathering / Desk Study

1. Assemble relevant data and record their sources.

Data employed in this study are summarised in Appendix 1.

A8.2.2 Field Investigation Requirements

1. Complete investigations sufficient to establish a geotechnical model, identify geomorphic processes and associated process rates.

The geotechnical and geomorphological models employed in this study are presented in Sections 2.2 and 2.3). The LSP model presents geotechnical and kinematic constraints on landslide debris

production, while the LSS model describes spatiotemporal patterns in landslide debris production in response to a range of triggers.

2. Inspect the site and surrounds, including field mapping of the geomorphic features.

Limited field mapping and geomorphological analyses undertaken in this study were undertaken to validate model outputs and refine the geotechnical model. This is detailed in Section 2.7.

3. Determine the subsurface profile from exposures or subsurface investigation, such as by boreholes and/or test pits.

This element is not considered appropriate for this level of regional hazard analysis.

4. Assess likely groundwater levels and responses to trigger rainfall events.

Antecedent groundwater conditions based on climatological models are considered as an input to the LSS model; see Section A3.3.

5. Prepare a cross-section drawing (to scale) through selected parts of the site to demonstrate the geotechnical model of site conditions and on which landslides may be identified.

This element is not considered appropriate for this level of regional hazard analysis. However, we do calculate a kinematic source model for the whole region within the LSP model. A 3D representation of the largest potential landslide at given locations (defined by the kinematic source model) is detailed in Section A4.2.

6. Take into account slope-forming process rates associated with the geotechnical model and landslides.

The landscape is considered to be in a steady state, such that slope-forming processes reflect the balance between bedrock uplift and denudation through, for example, fluvial, glacial and hillslope erosion; see Section A4.1.1. Landslides are considered to be the primary erosional processes on geomorphically active hillslopes, an observation supported by a comparison of catchment-wide uplift and erosion rates with calculated landslide debris-production rates (see Section A4.1.1). The rate of landsliding is considered to be limited by the generation of unstable sediment (regulated by the rates of relief production and rock strength degradation); see Section 2.1.2.

7. Identify landslides types/locations appropriate to the geotechnical model based on local experience and general experience in similar circumstances.

The potential for landslides of a given volume class range to occur at a specific location is informed by the kinematic source model; see Section A4.2. Parameterisation of the model is based on frictional and cohesive strength properties of representative hillslope materials derived from global datasets. We justify the appropriateness of our parameter selection and discuss opportunities to employ a more detailed kinematic source model in Section A4.2. We assume that landslide debris production at a location is the result of landslide volume-class ranges (encapsulating all landslide types) up to the maximum volume determined from the kinematic source model; see Section A4.4.

8. If required, further detailed investigations should be completed to better define the model, landslides, triggers, frequency (likelihood) or design of stabilisation measures to control the risk.

This element is not considered appropriate for this level of regional hazard analysis.

A8.3 Landslide Characterisation

1. Characterise the landslides based on the desk study and field investigations.

The probable landslide volume characteristics for rainfall and earthquake triggers are informed by regional landslide catalogues and comparison with international datasets; see Section A4.3.

The probability of landslides moving as slides or flows in response to potential triggers is based on experience from previous landslide events both elsewhere in New Zealand and globally; see Section A5.2.

A8.4 Frequency Analysis

A8.4.1 Techniques for Frequency Analysis

1. Adopt a frequency-analysis technique appropriate to the level of study and complexity of the geotechnical model and slope-forming process.

As we employ a process-based, rather than event-based, methodology, the explicit determination of landslide initiation frequency is not used. Instead, the method presented here requires quantification of the rate of landslide-debris production per unit area (i.e. $\text{m}^3/\text{m}^2/\text{yr}$); see Section A4.5. This is numerically equivalent to the frequency of landslide initiation events, where each event has a known debris-production volume per unit area (i.e. $1/\text{yr} \times \text{m}^3/\text{m}^2$). However, the intrinsic relationship between the landslide debris-production rate and slope-forming processes, as well as the lack of a requirement to evaluate individual landslide frequencies, has significant numerical advantages over event-based approaches. This is particularly true for the scale and geotechnical complexity of the regional hazard analysis presented here. See Section 2.1 for further details.

2. Gather local and historical knowledge of slope performance and landslide characteristics and occurrence. The resulting inventory enables assessment of frequency.

We measure 'slope performance' through a combination of landslide susceptibility and sediment-production rates. The LSS model is trained on catalogues of previous landslide events; see Section A3.1. Landslide sediment-production rates are compared against both local basin-averaged erosion rates and denudation rates from mapped landslides in Section A4.1.1.

3. Empirical methods based on slope-instability ranking systems.

These methods are not employed in this study, as the LSS and LSP models provide the required metrics.

4. Relationship to geomorphology and geology.

The LSS and LSD models allow the probability of a volume of landslide debris being produced at a given location to be tied to geological and geomorphological attributes; see Sections 2.2 and 2.3. Assumptions required to project these slope-performance indicators into a future climate scenario, as well as possible sources of error, are discussed in Sections A3.5 and A4.7.

5. Prepare a statistical evaluation of rainfall and relate to history of landsliding and population of slopes within area of similar slope type.

The RIL and EIL components of the LSS model allow a correlation between the magnitude of landslide-triggering events (24-hour precipitation, or PGA) and the probability of slope failure; see Section 2.2.

6. Consider use of simulation models and Monte Carlo sampling analyses to derive a frequency of failure.

These methods are not employed in this study, as the LSS and LSP models provide the required metrics.

7. Use a knowledge-based expert judgment or 'degree of belief' method that combines experience, expertise and general principles.

A 'degree of belief' approach is employed to convert specific sediment yield to landslide sediment-production rates. This is based on general geomorphological principles and is appropriate for

regional studies where objective data are lacking. Constraints on model variables are derived from regional and global datasets; see Section 2.1.

8. Other methods.

The mean annual rate of landslide-debris production (or alternatively, frequency of landslides of a given size occurring) at a given location in response to any trigger is determined as a function of slope-forming processes; in particular, the landslide sediment-production rate, the relative annual probability of rainfall- and earthquake-triggered landslides and the volume characteristics of landslides associated with either trigger; see Section A4.5. The probable volume of debris produced at a given location in response to a given event is determined by comparing the probability of failure in the given event to the mean annual probability calculated for that location; see Section A4.6.

A8.4.2 Estimation of Annual Probability (Frequency) of Each Landslide

1. Use ‘best estimates’ for frequency but consider range, uncertainty and sensitivity.

As stated in Section A8.3 (1), the process-based approach adopted here does not require an evaluation of the frequency of initiation of individual landslides. Instead, we employ a related metric that describes the rate of debris production by feasible landslides at a given location. ‘Best estimates’ of contributing parameters are derived from regional and global datasets. Various scenarios are tested through a Monte Carlo analysis of variables contributing to the geological model (e.g. the sediment production rate, the proportion of sediment contributing to landslides and the suspended load to total sediment yield multiplier). See Sections A4.1 and A7.3 for further details.

2. Estimates of frequency may be derived by partitioning the problem to *(Annual probability of trigger event) x (Probability of sliding given the trigger event)* over the range of trigger events.

The rate of debris production is estimated by partitioning the mean annual rate of debris production by kinematically feasible volume-class ranges and the relative probability of triggering events; see Section A4.5.

3. Complete a review of the assessed frequency in relation to the implied cumulative frequency of the event occurring within the design life and known performance within the area.

An example of the proportion of landslide debris generated by various landslide volume-class ranges in response to both rainfall and earthquake triggers and all considered return intervals is presented in Section 2.3.1.4. We discuss the consistency between the modelled and theoretical distribution of debris production by various triggers and landslide volume ranges in the same section.

A8.4.3 Assess the Travel Distance and Probability of Spatial Impact of the Elements at Risk

The LSD model is employed to assess the volume of debris travelling from kinematically feasible landslide-source areas downslope through the landscape (landslide-debris flux). The model employs a combination of empirical and physically-based methods and accounts for slope characteristics, the mechanism of debris movement and characteristics of the downhill path. See Section 2.4 for an introduction to the LSD model. A sensitivity analysis of parametric and spatial uncertainties is presented in Sections A7.4 and A7.6.

The LDIR model is employed to convert the calculated landslide-debris flux (from the LSD model) to a probability of spatial impact. See Sections 2.5 and 2.1.3 for a brief overview.

We note that the metric from which we calculate the probability of spatial impact differs slightly from that described in AGS (2007), which states that it is important to estimate the movement of a ‘slide mass’ (commonly accepted to be the total volume of landslide debris) downslope by landslide

processes. Instead, we consider the movement of a unit volume of landslide debris from portions of a potential landslide-source area. The specific volume of debris is determined using a probabilistic model (see Section A5.1). Although physically related quantities (the probability of a landslide occurring in an area can be considered unity where the sum of landslide-debris production equals the volume of a representative ‘slide mass’), there are significant differences in the manner in which the probability of spatial impact needs to be calculated from these two metrics.

Determining the probability of spatial impact from the metric specified in AGS (2007) requires the consideration of (1) the probability of a given failure occurring and (2) the probability of the slide mass travelling to a specific location. In the simplest case, a location can be considered as being impacted by a ‘slide mass’ when any portion of the calculated movement overlaps with that location. Although not explicitly specified in AGS (2007), determining the probability of impact has typically involved the calculation of landslide movement either from discrete sources or a discrete-source region and subsequent mapping of spatial impacts back to the combined probability of a range of failure and transport scenarios. While calculating the probability of impact from discrete sources provides the best possible representation of spatial impact probabilities, it is computationally infeasible to calculate all possible landslide types from all possible sources in regional studies. However, reducing the range of discrete sources employed in inundation calculations to computationally feasible numbers can significantly degrade the spatial accuracy of the resulting impact probability assessment. The consideration of discrete-source regions, on the other hand, allows a complete consideration of the probability of ‘slide masses’ initiating within a region, as well as empirical estimates of inundation extents. However, this provides little to no insight into the probability of spatial impact within the calculated extent of inundation.

In the process-based model presented here, the probability of failure is encoded into the unit volume of debris released from all valid sources distributed across a hillslope. Rather than mapping discrete movement paths back to the probability of a given failure occurring, we can therefore calculate the probability of spatial impact by directly comparing the volume of debris passing a location (the ‘landslide-debris flux’) to a ‘characteristic landslide-debris flux’ expected if a landslide of a given size were to inundate that location. When the mean annual, or scenario-based, landslide-debris flux equals the characteristic flux at a location, the probability of a landslide inundating that location is considered to be unity. By pre-calculating the characteristic landslide-debris flux for all landslide-volume classes at all locations across a region, and tying this to the physically based calculation of probabilistic landslide-debris transport from all possible source cells, we are able to shortcut the requirement to explicitly tie inundation to discrete landslide sources and provide a reasonable representation of inundation probability at full resolution, while cutting computational cost by several orders of magnitude. Uncertainties relating to the calculation methodology are presented in Section A7.5.

We note that the specification of a method to assess the travel distance and calculate spatial probability of inundation is outside of the scope of AGS (2007). As such, the method presented here only deviates from the guidelines in its adoption of a unit debris volume, rather than the ‘slide mass’, as the metric from which the probability of spatial impact is calculated.

A8.5 Consequence Analysis

A8.5.1 Elements at Risk

We consider undifferentiated buildings to be the elements at risk; see Section 2.1.3 for a brief overview.

A8.5.2 Temporal Spatial Probability

We consider buildings to be permanently located, therefore the temporal spatial probability can be neglected.

A8.5.3 Evaluation of Consequence to Property

We assume that the height of landslide debris is equal to the mean depth of the representative landslide source; see Section A6.3. This allows us to adopt a vulnerability function to relate the height of landslide debris (i.e. the extent of damage likely to property arising from each potential landslide) to a 'damage ratio', describing the ratio of the indicative cost of the damage to the estimated market value (see Section A6.3).

A8.5.4 Evaluation of Consequence to Persons

Consequence to persons is beyond the scope of this study.

A8.6 Risk Estimation

A8.6.1 Quantitative Risk Estimation

In order to calculate APLR, we evaluate the product of the probability of total economic damage from all landslides for every assessed trigger type and return interval. This is described in Sections 2.5 and A6.4.

A8.6.2 Semi-Quantitative and Qualitative Risk Estimation for Risk to Property

As we undertake a quantitative risk estimation, this step is not required.

A8.6.3 Risk Matrix for Property Loss

This is beyond the scope of the current study.

A8.6.4 Estimation of Risk of Loss of Life

This is beyond the scope of the current study.

APPENDIX 9 External Review and Responses

On 12 November 2024, GNS Science (now part of Earth Sciences New Zealand as of 1 July 2025), engaged Manaaki Whenua – Landcare Research (now part of the Bioeconomy Science Institute) to undertake peer-review of this GNS Science consultancy report (CR2025/28) written for the West Coast Civil Defence & Emergency Management Group (now West Coast Emergency Management). Deliverables from the review included a brief written statement outlining an assessment of methods, quality of analysis and robustness of key findings, as well as any suggestions for improvement in these aspects or improvements in report clarity. Feedback on document formatting, spelling and style were not required. In addition, two one-hour meetings were held online to discuss any issues identified in the report that required further discussion. The review and all related documentation were delivered to GNS Science on 17 January 2025.

The brief written statement (*italics*) and responses from Earth Sciences New Zealand (in blue) are as follows:

17 January 2025

INSTITUTE OF GEOLOGICAL AND NUCLEAR SCIENCES LIMITED, 1 Fairway Drive, Avalon, Lower Hutt, New Zealand (GNS SCIENCE)

Dear Kerry Leith,

This letter serves as project deliverable for the peer-review of a GNS Science consultancy report titled 'WCCDEM regional landslide debris inundation assessment' written for the West Coast CDEM group. As commissioned by GNS, this letter and the accompanying commented report, give "a brief written statement outlining an assessment of methods, quality of analysis, and robustness of key findings, and any suggestions for improvement in these aspects or improvements in report clarity."

The aim of the WCCDEM regional landslide debris inundation assessment report is to produce a regionally consistent estimate of landslide debris inundation risk. The level of suitability is 'screening or basic'. The methodology does not nor claim to assess local landslide susceptibility. Also, it does not model initiation or flow paths from individual events. Rather the model applies a probabilistic approach over a long timescale to approach regionally consistent coverage. We think the authors did a tremendous job in developing their methodology and we support the basic principles of the approach. Given the available data and the large extent of the West Coast region, the approach is sensible.

As with all modelling, but especially here with data limitations, the authors are required to make simplifications and assumptions. These should be chosen consciously in such a way that results still reflect reality and/or reliably answer research objectives. Transparent communication is important. We think in general the authors do a good job of this communication by summarizing uncertainty under each module chapter. In certain sections of the methodology, we urge the authors to provide more clarity. These are mostly related to the validity of the probabilistic approach. We listed our points in the corresponding subsections below. This is prefaced by general points that we'd like to raise attention to and is followed by general miscellaneous comments.

General Points

We have three key observations. (1) The assessment assumes all sediment transport happens through landslides. (2) sediment becomes available at a constant rate at each location through uplift (one for the current climate and one for RCP6, scaled by increased RIL probability as we understood it.) (3) The scenario is applied to 10,000 years to account for sufficient sediment production. These points mean that the model output depends mainly on where and at which spatial extent landslides occur. Where is treated relatively simply. The slope threshold (>20°) and logistic regression on an assumed

representative sample gives landslide susceptibility. One model is for those earthquake-induced and one for rainfall-induced. The volume of landslides follows a probability distribution from an inventory and is capped by 'kinematic feasibility'. Our interpretation of all mentioned above is that the quality of results ultimately hinges on the realistic representation of topography. This goes for both the landslide initiation and subsequent runout using kinematic models.

Generally, this accurately captures the concept of the LSS, LSP and LSD models. However, some clarification is required. Specifically:

1. All primary sediment production occurs as a result of landslides. Primary sediment production differs from sediment transport.

As described in Section 2.3.1.1:

"We assume that landslides are the sole driver of mass wasting (the initial mobilisation and movement of soil or rock material) on hill slopes where landslides are determined to be kinematically feasible. Landslide-debris production is therefore assumed to be equal to the long-term erosion rate. We derive the long-term erosion rates from a combination of suspended-sediment-yield observations, estimates of soil and rock densities and measures of long-term tectonic uplift and erosion. This is a necessary simplification, and, while observational evidence suggests that landslides dominate mass wasting processes in much of the region, processes such as slope creep, gully formation, glacial erosion or fluvial under-cutting can also contribute to initial movement of soil and rock. Once sediment is mobilised, additional erosion processes (such as gullying and fluvial transport) contribute to the long-term transport of sediment through the landscape."

2. Sediment availability is correlated with a specific sediment-yield model, which itself has been developed based on observations of suspended sediment yield in rivers. We apply a uniform scaling factor to convert suspended sediment yield to total sediment yield based on a correlation of spatially averaged erosion rates derived from ¹⁰Be data from catchments along the range front. Although we find that these also correspond to long-term uplift rates, as well as landslide erosion rates in the same catchments, we are not specifically correlating uplift (such that an area of subsidence may have negative sediment-production rates).

This is described in Section 2.3.1.1:

"We base our estimation of erosion rates on previous studies quantifying specific sediment yield from hill slopes to rivers across New Zealand, as well as the specific density of geological units mapped throughout the country. This is calibrated against rates of long-term erosion and tectonic uplift."

3. The 10,000-year factor is simply a numerical adjustment for the modelling. It has little impact on the results.

This is described in Section A5.1:

"We adopt an integration interval of 10,000 years, reflecting the approximate interval since deglaciation of the region following the Last Glacial Maximum. This effectively ensures that the magnitude of debris deposited in each model run is similar to the scale of post-glacial sedimentary landforms in the region (such as debris-flow fans and incised river channels), enabling modelled runouts to overcome topographic obstacles where sufficient landslide debris is available. While increasing the integration interval is an effective means of reducing the effects of minor topographic features on local flow paths, it has little impact on the overall model output. An increase of two orders of magnitude (from 0.1 to 10 kyr), for example, decreased the mean annual debris flux in a sample region by <1% while increasing the proportional area affected by debris flux by 2.7% (see Section A5.6 for further details)."

4. We agree, the realistic interpretation of topography has a fundamental influence on calculated LDF and LDIR. This is a fundamental dataset for the study.

This is discussed in Section A4.8:

“We assume that the topography in the DEM is an accurate representation of the ground surface. The 8 m DEM is derived from the January 2012 Land Information New Zealand (LINZ) Topo50 20 m contours, which largely reflect topography digitised from 1940 aerial photographs. We have down-sampled this data to 25 m resolution for the purposes of this regional study. The DEM therefore likely under-represents the smaller landforms (less than approximately 100,000 m²), and smaller landslide source areas may therefore not be identified ...”

and Section 2.4.2:

“Aside from uncertainties associated with previously discussed LSS and LSP model inputs, landslide-debris flux outputs are a function of ... (3) the DEM used to simulate the runout paths.”

“As landforms represented by the DEM determine the travel path of landslide debris, inaccuracies resulting from (for example) topographic changes since the original elevation data were generated in the 1940s (see Section 2.3.1.2), digital noise, interpolation errors or failure to accurately resolve landforms with lesser spatial extents can significantly change the travel path of debris sourced from smaller landslides. Smoothing of the DEM to improve runout-model performance for larger landslides mitigates much of the uncertainty associated with this input data (see Section A5.3.1 for further details). The accuracy of the national DEM employed here is estimated to generate spatial uncertainties of more than 6× the most likely APLR, while the 25 m resolution of the regional study is expected to generate uncertainties greater than 4× the most likely result. These two factors are the largest single source of uncertainty in this study, and care must therefore be taken when interpreting results (for example) in locations subject to inundation by smaller landslides, down-slope or smaller landforms (<100,000 m²) or where topographic changes may significantly alter the path of landslide debris runout. See Sections A7.4 and A7.6.2 for further discussion on DEM-related LSD model uncertainties, as well as mitigation strategies involving the use of up-to-date LiDAR datasets.”

This is important to state because this means the resolution used in the analyses, the DEM quality and possible resampling techniques should be well thought out. We understand the authors are obliged to use a generalisable elevation model so a description of the quality and the degree of feature preservation at a resolution of 25 and 32 m is vital. Specifically related to this is the computation of slope angle with resolution. A smooth down-sampled DEM reduces slope angle depending on the method used. This could affect landslide susceptibility as it is based on a slope threshold ...

These are fair points. The susceptibility model is trained on DEM data at the same resolution as the model is applied. As such, the specific gradient values are somewhat irrelevant, as we employ a statistical rather than physical approach. Although this is a possible source of error, the error is captured in the uncertainty estimates of the earthquake- and rainfall-induced landslide models.

In Section A3.6, we note:

“The model is trained on a 32 x 32 m grid of pixels containing landslide scars. This neither represents the exact number, nor exact area, of mapped landslides in the dataset. The uncertainty associated with calculating either of these two fundamental metrics from the rainfall-induced landslide output is dependent on grid resolution, landslide-area characteristics and landslide clustering in the landscape. Currently, this uncertainty is only constrained with respect to the training dataset; elsewhere, it is unconstrained.”

... and likely the ‘kinematic feasibility’ (see further below). To summarise, the authors should state clearly the quality of the DEM and its derivatives and if possible, conduct and present a sensitivity analysis for various DEM resolutions.

In terms of capturing the kinematic feasibility, this is also a possible source of error. However, we note that kinematic feasibility is not entirely necessary, as in Section A4.2:

“Shallow failures originating from soil or weathered bedrock may initiate on hill slopes with gradients less than that assumed for the kinematic model. In order to capture these features, we assigned a depth of failure equivalent to a Class 1 landslide to all cells not already classified with a surface gradient of more than θ_{NAT} (see Figure A4.3).”

That said, we now note the impact of DEM resolution on model uncertainties:

In Section 3.2:

“The down-slope movement of landslide debris is the principal hazard considered in this study, and, as such, uncertainties associated with factors controlling the potential size of landslides and long-term landslide debris-production rates have some of the greatest impacts on modelled APLR. These uncertainties include those associated with determining kinematic feasibility and deriving long-term debris-production rates, quantifying variability across the landscape (e.g. due to recent erosion, excavation or rejuvenation of existing creeping landslides) and forecasting the impact of climate change on future fracturing, weathering and erosion rates. Associated individual variable uncertainties can cause variations in the calculated APLR of up to about 2× the most likely value or more, depending on the scale of the landform, its history of modification or instability and the location of elements at risk.”

Section A4.8:

“We assume that the topography in the DEM is an accurate representation of the ground surface ... The DEM therefore likely under-represents the smaller landforms (less than approximately 100,000 m²), and smaller landslide source areas may therefore not be identified ...”

Section 5.5:

“The effect of locally increasing the resolution of landslide-debris-flux and APLR predictions is particularly easy to test, and an example is presented for the Greymouth area in Figure A7.4 (see Section A7.6.2). Increasing the resolution of the LSP and LSD models can provide better representation of potential landslide sources and improve the tracking of potential landslide-debris-inundation paths. This is most relevant for locations close to hill slopes, down-slope of landforms with spatial extents less than 100,000 m² and areas of subtle channelisation. Incorporation of a higher-resolution topographic model may result in both increases and decreases in APLR, depending on the scale and variability of local landforms and their representation in the DEM. However, we overall find that reducing from 25 m to 8 m resolution and employing a recent LiDAR-derived DEM can be expected to reduce the mean APLR by approximately 3.4×, while also reducing 2-sigma (95th percentile) uncertainties from ±2.75 to ±1.0 order of magnitude (see Section A7.7).”

Section 6:

“Residual uncertainties vary spatially and increase with distance from landslide sources. These are particularly large in areas adjacent to topography with spatial extents less than 100,000 m².”

We now include a full quantitative assessment of spatial uncertainties associated with the DEM accuracy and model resolution in Section A7.6.2.

Landslide Source Susceptibility [LSS]

We don't quite get whether the return interval for RIL or EIL is lower. First the text explicitly states: "For example, the predicted mean annual RIL probability in the Kokiraki area is approximately 0.30 kyr^{-1} , while the mean annual EIL probability in the same area is approximately 0.10 kyr^{-1} ". But then: "higher probabilities of landsliding for the shortest return interval events will result in a larger proportion of debris being assigned to earthquake-triggered events,". Further, we don't understand whether and why EIL are larger. Is it because the rarer occurrence in susceptible areas makes for more sediment availability or because of the superimposed size distribution from the inventory? This is generally an interesting point that should be stated and compared to research more clearly. For example, research by de Vilder et al. (2023) for the Kaikoura district indicates that RIL dominate the risk profile. If you conclude EIL is dominant on the West Coast, we're curious for a discussion on the difference.

The relative importance of earthquake- or rainfall-induced landslides varies spatially, based on the estimated PGAs or 24-hour rain amounts for the given ARIs used. This can be observed by comparing rainfall- and earthquake-induced probability in Figure 2.2d, e.

This is discussed in Section 2.2.2:

"Mean annual rainfall- and earthquake-induced landslide probabilities, as well as total annual probabilities of landslide initiation, are presented in Figure 2.2. Overall, the LSS model indicates that the greatest earthquake- and rainfall-induced landslide probabilities are in areas with steep topography, primarily in the region between Fox Glacier and Kokiraki. Relative probabilities for the two triggers vary across the study region, with rainfall-induced landslide probabilities being generally higher along the Southern Alps and earthquake-induced landslide probabilities being higher in the north of the region. Overall, mean annual rainfall-induced landslide probabilities are more variable, with maximum values commonly an order of magnitude greater than earthquake-induced landslide probabilities at the same location."

Regarding the proportion of debris assigned as a result of LSS outputs, this is discussed in the LSP model (Section 2.3.1.4). However, we discuss potential implications in Section 2.2.2:

"The LSS model probabilities for rainfall- and earthquake-induced landslides determine how landslide-sediment production is distributed across the LSD model runout simulations (described in Section 2.3). While these probabilities do not affect the total amount of debris produced in a given cell, they do influence how debris is allocated across 112 individual runout simulations in the LSD model (described in Section 2.4). These simulations represent various combinations of landslide triggers, return intervals and landslide-size classes."

Regarding the use of aspect (page 71). Including it as 0 to 360 is not a good application in regression because it's circular and not a gradient. Rather use Northerness and Easternness, the cosine and sine of aspect respectively.

This is a good point, and we agree that aspect can be circular rather than a gradient. Aspect control on landslide susceptibility was initially checked using the frequency-ratio method. The frequency ratio is the relative frequency of grid cells that are affected by landslides ($Y = 1$) and their associated factors (e.g. aspect), compared with the relative frequency of cells that are not landslides ($Y = 0$), within the given factor. All grid cells within each GeolCode grouping were used in these analyses. The frequency-ratio results showed that aspects in the north to east orientations – at the lower end of the aspect gradient (0–60°) – were found to be most susceptible to landslides.

To investigate whether using a circular versus gradient approach had any statistical importance in the LR regressions, we re-ran the LR models adopting the cosine and sine approach. Overall, the results were similar, with either a minor decrease or increase in the overall model performance (AUC and R^2) – for each GeolCode – when compared to the original corresponding model results. These results are thought to be because: (1) aspect has a relatively small statistical significance in the models compared to the other factors; and (2) the landslide susceptible aspects – based on the datasets used – represent a gradient, noting that this may not be the same for other landslide datasets. Given these results, it was decided to keep the original model results.

Performance is measured using AUC and R^2 . It is not clear to us how they are related to the landslide inventory. If they are all based on the inventory points, what are the control, i.e. landslide absence points? If you use every cell in the study area you are inflating the accuracy.

The landslide absence points are the $Y = 0$ grid cells, used in each ‘bootstrap’ sample. For model training, LR models were fitted to the data (grid cells) in each bootstrap sample (each sample comprised 75% of the data), randomly taken from each GeolCode-specific dataset. A total of 100 bootstrap samples were taken from each GeolCode-specific dataset. The best-fit models were then used to calculate the AUC and R^2 of each LR model. The values presented represent the mean values based on the results from all 100 models.

Landslide Sediment Production [LSP]

In nature, landslide size is constrained on the low end by the ratio between mass (increasing with volume) to passive earth pressure (cross-sectional area dependent). The high-end is constrained by landscape heterogeneity (paraphrased from Milledge et al. 2014). We don't fully understand the approach the authors take to landslide dimensions. Especially the often mentioned ‘kinematic constraints’ and specifically the background to Figure A5.7a are not apparent? The authors need to be clearer in their methods here.

This is clarified in Section A4.2:

“Identification of potential landslide-source areas was based on an analysis of landscape morphology, with the intention of determining the greatest kinematically feasible landslide-volume classes within the digital elevation model (DEM).

Our kinematic landslide source model allows us to estimate the largest hypothetical landslide that can occur at a given location based on an assumption of basic material-strength parameters (friction and cohesion) and an assessment of required geometric freedom through an analysis of local topography. The purpose of this step is not to evaluate slope stability but rather to define geometric constraints for the largest potential landslide sources. Therefore, we do not explicitly calculate the balance of driving and resisting forces for each hypothetical source.

We then assume that smaller landslides are able to occur anywhere that larger ones can occur. This is a notable simplification, as present-day local topography may have insufficient relief to support the generation of smaller landslides at some locations within a larger landslide body. However, given that (1) larger landslides can only occur on slopes with average gradients in excess of an assumed critical-failure angle (and mean slope angles must therefore equal or exceed this angle) and (2) failure of these slopes may occur progressively (such that future topography may support smaller failures where it is not currently possible), we suggest that this simplification is reasonable for a regional analysis.”

The fixed relationship between volume and area (and hence depth) of a landslide does not do justice to the constraints mentioned above and to complex local soil depth variation. While we agree with the necessary simplification, we think the authors should state this shortcoming more explicitly.

Technically, yes, we agree – although many studies adopt landslide area-volume relationships with one or two parameters and no consideration for non-linearity or spatial variability. However, in our study, the area-volume relationship is tied to cohesion. In this case, we have added the following statements:

In Section A4.2, we state:

“As discussed here, cohesive strength is highly dependent on the type of materials present and their physical condition (compaction, weathering, fracture density, etc.). These properties tend to vary with depth from the surface, and landslide area-volume relationships should therefore theoretically also vary with increasing depth from the surface. Although we currently have no data to better constrain this relationship in the study area, explicitly accounting for spatially variable, depth-dependent cohesion values could reduce uncertainties in the landslide-debris flux and annual property loss risk (APLR) datasets. Further discussion regarding selection of the cohesive strength and associated uncertainties can be found in Section A7.3.”

In Section 5.5, we state:

“Better characterising landslide-source geometries. In particular, explicitly accounting for spatially variable, depth-dependent cohesion and friction estimates based on geological data.”

In Section A4.8, we state:

“We assume that the adopted cohesion is spatially consistent and invariant with landslide volume. In reality, this is likely to vary with rock or soil strengths. Varying the cohesion will alter the distribution of the maximum feasible landslide volumes. A lower cohesion will bias sediment production toward lower volume and more frequent landslide classes.”

In Section A7.3, we state:

“Selecting a higher cohesive strength affects landslide-debris-inundation modelling in two opposing ways:

- *It increases the theoretical mean depth associated with each landslide volume-class range (Equation A4.3).*
- *It increases potential failure volumes by steepening the gradient of scarps within hypothetical landslide sources (Equation A4.5).*

While these two effects might initially appear to offset each other, the net impact of increasing cohesive strength is a reduction in the proportion of the landscape capable of supporting larger landslides. This occurs because, while the theoretical mean depth of landslide volume-class ranges is unrestricted, the actual depth achievable is constrained by available excess topography.

As a result, a higher cohesive strength increases the proportion (and frequency) of smaller, lower-volume landslides with shorter runout distances. In practical terms, this means:

- *Landslide risk increases in areas with high excess topography, where smaller landslides become more frequent.*

- Risk decreases at more distal locations, as fewer large, highly mobile landslides are expected.

For further details on the LSP model assumptions and uncertainties, see Section A4.8."

As sediment flux is the key output of the model, derivation of source volumes for both RIL and EIL is critical. The total combined source volume for RIL and EIL is determined by the suspended sediment yield estimator of Hicks et al. (2011). It is important for the authors to consider whether or not the sediment gauging records used by Hicks et al. appropriately represent earthquake events, and if they span suitable time periods to capture the time taken for all source material to work through the system. In section 5.1.1 the authors state that the observations in Hicks et al. (2011) almost certainly reflect interseismic sediment production. The model is therefore likely underestimating the total debris flux. If the sediment yield estimator loads can be thought of as not containing EIL loads, are there alternative options to estimate an EIL component, such as a scaling factor or alternative modelling approach that could be used estimate an additional EIL component?

This is now clarified in Section A4.1.1:

"Employing recent observations of river-borne sediment yield or denudation rates through ¹⁰Be concentrations can raise questions with respect to the influence of earthquake-induced landslide-sediment contributions. Specifically, (1) are observed rates elevated as a result of recent earthquake-induced landsliding? (2) If these do not include a direct earthquake-induced landslide signal, do observed rates exclude the contribution from earthquake-induced landslides?"

Regarding question (1): Observations of lacustrine sedimentation in Lake Ellery immediately to the west of the Alpine Fault indicate that seismically generated sediment may temporarily increase mean erosion rates by ~40% (Howarth et al. 2016). This is supported by seismically generated landslide models from Robinson et al. (2016), who suggested that co-seismic landsliding may increase erosion rates in some catchments by around 35%. Global studies indicate that the period of enhanced landslide-sediment production commonly decays exponentially to background levels over a period of up to seven years, depending on the return interval of the triggering event (Marc et al. 2015; Fan et al. 2018), with the phase of enhanced post-seismic sedimentation (incorporating enhanced instability and sediment transport) lasting on average 58 ± 15 years (Howarth et al. 2016). This reflects a period over which landslide deposits directly connected to river networks become exhausted of readily transportable debris (see Croissant et al. [2019] and references therein). Given that the last earthquake to trigger regional landsliding in the region was the 1968 Inangahua earthquake (>56 years ago), suspended sediment yields observed by Hicks et al. (2011) almost certainly reflect rates of inter-seismic sediment transport. As such, these do not carry the short-term 35–40% increase in sediment output associated with fluvially connected post-seismic landslides and instead reflect more or less constant background rates of undifferentiated (earthquake- and rainfall-induced) landslide debris export via the river network. This is facilitated by a combination of secondary sub-aerial and fluvial processes, modulated by climatic factors (Croissant et al. 2019). We can therefore rule out the possibility that observed rates are elevated as a result of recent earthquake-induced landsliding.

Regarding question (2): Accounting for the relatively modest initial increase in earthquake-induced erosion rates, as well as rapid exponential decay, the associated increase in long-term erosion rates can therefore be expected to be approximately 4% over a 100-year seismic cycle, dropping to roughly 1–1.5% for a 300-year cycle (consistent with Alpine Fault recurrence intervals [Howarth et al. 2016]). These increases are negligible when compared to uncertainties associated with erosion-rate estimates in the study region (discussed later

in this section). We therefore assume that the observed rates represent the combined transport of earthquake- and rainfall-induced landslide debris through secondary sub-aerial and fluvial processes and thereby capture the contribution of both triggers.”

The model also appears to use the gridded sediment yield estimator pixel values to determine source volumes. Is the spatial variability in the grid representative of EIL processes?

This is now discussed in Section A4.8:

“We base our estimates of present-day landslide-sediment-production rates on a derivative of rates of specific sediment yield (SSY) presented in Hicks et al. (2011). They report a standard factorial error (SFE) of between 1.55 and 1.8 for the majority of studied catchments, noting that glaciated catchments on the West Coast may be associated with SFEs of ~2–3 (an SFE of 1.8 is equivalent to a geometric standard deviation of 1.8, meaning one ‘sigma’ on the log scale corresponds to multiplying or dividing by 1.8). The authors recommend against applying the models to predict sediment yields from catchments less than 10 km², raising the question of applicability at the local slope scale, as applied here. In this study, we do not expect SSY, and therefore calculated landslide debris-production rates, to accurately represent present-day activity on individual hill slopes across the approximately 25,000 km² of the region overseen by WCEM. However, evidence suggesting that the landscape is in a steady state (see Section A4.1.1) and that, on average, denudation rates derived from SSY estimates represent long-term, spatially integrated erosion rates provides confidence that this dataset is adequately capturing regional variability in landslide debris-production rates. That said, we note that uncertainties associated with SSY inputs generate some of the greatest uncertainties in APLR predictions (see Section 8.3), and therefore identify local refinement of the landslide sediment-production models with appropriate local input data as a high priority for local re-evaluation of hazard and risk (see Section 5.5).”

Landslide Sediment Delivery [LSD, Section 2.4]

GPP is applied for avalanche movements, PCM for flow types. A division of 2/3 avalanche type and 1/3 flow type landslides is mentioned based on data from Cyclone Gabrielle. Is this sampled randomly and assigned to each ‘chunk’ of available sediment coming down as landslide flux?

For each class size and return interval, we run two models with identical source debris inputs. One for flow and one for avalanche. The outputs are then averaged using the 2/3 to 1/3 ratio for rainfall-induced landslides and 5/6 to 1/6 ratio for earthquake-induced landslides.

Section 2.4.1.4:

“In order to calculate the mean annual landslide-debris flux, we added together all calculated debris fluxes for all avalanche- and flow-type models, then applied a weighting to reflect the relative proportion of avalanche- and flow-type movements in the landscape before adding the output of both movement types together (see Section A5.7 for full details).”

This is also detailed in Equation A5.2.

The PCM model is designed snow avalanches (Perla et al., 1980). Why did you choose this one for flow type landslides? Snow does have different properties than soil/rocks. This should be explicitly stated with one or multiple examples where it is proven this model can be applied to landslides as well.

In Section 2.4.1.2, we note:

“The PCM method is commonly used to represent debris-flow-type runouts (e.g. Gamma 1999; Mergili et al. 2012; Goetz et al. 2021).”

This is expanded upon in Section A5.5.2.

The LSD model is described as allowing deposition of source material to occur along the flow path, yet the primary assumption of the model framework is that inputs and outputs of material from a slope are balanced, and this assumption is used to validate the results. These two points are at odds. As the deposited material appears to remain on slope without subsequent re-entrainment, the sediment load delivered to the stream network must no longer equate to that estimated by Hicks et al. (2011), and fluxes of sediment down the flow path may be underestimated. Are the authors able to quantify what proportion of sediment remains on slope? If material does remain on slope, then the assumption also needs to be made that the data used in Hicks represents net delivery to stream and not the gross erosion from slopes and would need to be scaled to provide gross erosion rates.

We can quantify the sediment that is deposited on hill slopes by the primary landslide movement. However, we do not expect it to stay there long-term, as secondary processes move the debris into the rivers.

This is described in Section 2.1.2:

“The landslide-debris-inundation hazard assessment is based on a geomorphologically consistent evaluation of landslide-sediment production and distribution across the region by landslide processes. We consider the volume and rate of landslide initiation to be limited by the rate of debris production on hill slopes (Figure 2.1). Once initiated, landslide debris then travels through the hill-slope system as primary ‘runout’ (i.e. as debris flows or debris avalanches from the landslide source) and is either directly deposited in river channels, which then flush the sediment from the landscape, or deposited on hill slopes before being moved to river channels by secondary debris-transport processes such as sheet wash, rilling, gullying and other fluvial or glacial mechanisms. These secondary processes are not considered in the current study; however, these play an important role in the geomorphological system, as they act as a buffer between landslide deposits and the river system. As secondary transport processes operate at a more or less constant rate through time (e.g. Croissant et al. 2019), we can expect average rates of sediment transport in rivers, for example, to reflect long-term rates of landslide-debris production in the contributing landscape.”

Landslide Debris Inundation Risk [LDIR, Section 2.5]

The resolution of the modelling at 25m (or 32m depending on the module) is too coarse to model small and median scale landslides in a meaningful way. The highest available regionally consistent resolution is 8m and using this could improvement the quality of the analysis. However, the authors choose the coarser resolution due to computational constraints, which is understandable. After re-reading it is however not clear how small landslides are still included in the analysis as claimed. For example, the class of 40- 100 m² house-sized landslides occupy less than 1/5th of a single cell. If, as the authors claim, the centerpoint is key would that mean a whole cell (625 m²) is considered an active landslide? This would then affect characteristics and runout length. All in all, the authors need to write this part of the methodology more clearly and double check whether small landslides are accurately represented.

This is discussed in A5.3.2:

“We employ a temporally integrated scenario-modelling approach to assess runout, accepting that, although we know the spatially distributed long-term average sediment-production rate for each landslide trigger, return interval and volume class, we do not know the specific location of landslides in any given event. Instead, we use M_{GPP} to generate a temporally integrated landslide intensity throughout the landscape and propagate sediment down-slope. A significant benefit of this approach is the ability to model the downslope transport of material from landslide sources nominally smaller than the resolution of the input grid. A single iteration of the GPP model effectively tracks a packet of sediment down-slope from each source cell. Each packet is supplied with a set of rules regarding movement, deposition and stop criteria, whose operation is independent of the volume of sediment being moved down-slope. As such, a large volume of sediment, representing multiple sub-pixel landslide sources, can be moved through the topography while obeying rules consistent with a smaller-sized landslide. Although the implementation of this method prevents the capture of specific landslide physics (primarily those associated with momentum and internal interactions, e.g. super elevation and block sliding), it allows us to capture probabilistic debris transport from small landslides across a wide region.”

Miscellaneous

Comparisons of contemporary and long-term degradation rates should be reported in proportional terms as well as absolute terms, as the small units (mm/yr) can be misleading.

Reporting of units has now been adjusted for consistency.

Certain references (see commented report) include links that don't work. For transparency these should be addressed.

All references have now been checked for consistency.

Frequently the manuscript reads wordy. It is understandable as it is challenging to correctly describe many interdependent assumptions on complex processes. A critical check for conciseness could nonetheless improve quality of the manuscript. Specific sections are commented on in the attached manuscript.

The manuscript has now been edited for conciseness.

References

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de Vilder S, Massey C, Brideau, M, Lukovic B, Morgenstern R, Townsend D, Rosser B 2023. Including the impact of climate change in quantitative risk analysis: example Kaikoura, New Zealand.

With kind regards,

Feiko van Zadelhoff
Andrew Neverman



8.2 West Coast Regional Council –Hydrology Telemetry Improvement Project

Author Shanti Morgan, Group Manager Environmental Science

Authoriser Darryl Lew, CEO

Public Excluded No

Report Purpose

To inform the Environmental Management Committee of the \$400,000 in funding received through the Regional Infrastructure Fund (RIF) to support the West Coast Regional Council's (WCRC) Telemetry upgrades Project, with a total project cost of \$600,000. The remaining \$200,000 (40%) is covered through local share already budgeted for in the council's Long-term Plan.

Report Summary

- The WCRC has secured \$400,000 in RIF funding as part of a National Telemetry Project to upgrade and modernise the region's telemetry and flood warning network.
- The project has a total value of \$600,000, with a 60/40 funding split (60% RIF, 40% local share).
- The local share (\$200,000) is already allocated in the approved 2025/2026 Annual Plan.
- The project will improve the resilience, reliability, and reach of WCRC's flood warning and hydrological monitoring network.
- Key milestones include network review, procurement, installation of upgraded communication systems, and site commissioning across critical flood and rainfall sites through to March 2028.

Recommendation

It is recommended that the Committee resolve to:

1. *Receive the report.*
2. *Note that \$400,000 in Regional Infrastructure Funding has been secured, with the project's total cost of \$600,000 covered by a 60/40 cost-share arrangement.*
3. *Delegate authority to the Chief Executive Officer to execute the Telemetry project contract, valued at \$400,000, on behalf of the West Coast Regional Council.*
4. *Note that the local share contribution of \$200,000 is already included in the 2025/2026 Annual Plan budget.*

Issues and Discussion

Background

The West Coast Regional Council (WCRC) operates a regional telemetry network that supports flood-warning, hydrological monitoring, and environmental data collection. The current network includes a mix of radio, satellite, and cellular communication systems, many of which are due for replacement or upgrade.

A major finding of the enquiries following Cyclone Gabrielle was the failure of real-time monitoring and communications infrastructure, and the consequent inability to deliver timely warning information to impacted communities. For example, the independent panel reviewing the event in the Hawke's Bay region noted that "power and equipment outages during the night of Cyclone Gabrielle did render our telemetry system ineffective, and HBRC resorted to manual observations relayed back to others to make informed decisions."

Similarly, the national inquiry into the North-Island severe weather events pointed to the fact that communications and warning systems were "non-existent or insufficient", and that a "striking disconnect" existed between the way communities and agencies viewed the situation, in part due to lack of interoperable platforms and real-time data flows.

To improve resilience, coverage, and data reliability, WCRC has joined the National Telemetry Project, a nationwide initiative aimed at standardising and strengthening regional telemetry systems to support climate adaptation, emergency response, and community safety.

Current situation

WCRC has secured \$400,000 from the Regional Infrastructure Fund to co-fund a comprehensive upgrade of the West Coast telemetry network.

The total project cost of \$600,000 is made up of both operating and capital expenditure including hardware acquisition, consultant reviews, installation, and communications infrastructure upgrades.

The Council's existing telemetry network continues to experience persistent communication issues, particularly at remote and high-altitude sites. These challenges are primarily due to ageing radio infrastructure, variable cellular coverage, and environmental factors such as terrain shadowing and storm-related interference. The resulting data gaps and delays reduce the reliability of flood warning and hydrological information, creating operational inefficiencies and

increased risk during flood events. Addressing these issues is therefore a key driver for the proposed upgrade.

The project will be delivered over three financial years, with milestone payments tied to specific deliverables. Major activities include:

- Review and assessment of current network performance and upgrade options;
- Installation of new cameras, radios, and satellite communications;
- Progressive upgrades to flood warning and alpine rainfall sites and;
- Installation of a new digital radio network for regional coverage.

The final system commissioning and closeout is forecast for March 2028.

This project will significantly enhance real-time flood monitoring, improve communication redundancy, and strengthen the resilience of data systems that support public safety and infrastructure management across the West Coast.

Note: This report is for information purposes only.

Considerations

Implications/risks

The project is fully funded, with local share provided in existing budgets, minimising financial risk.

Procurement will follow Council policy to ensure transparency and value for money. Risks relate primarily to hardware delivery timeframes and contractor availability, which will be managed through staged milestones and contingency planning.

Significance and Engagement Policy assessment

There are no issues within this report which trigger matters in this Policy.

Mana whenua views

Staff are not aware of any issues within this report which would impact mana whenua.

Views of affected parties

Staff are not aware of any views of affected parties which impact on matters discussed in this report.

Financial implications**Current budget**

The project's 40% local share (\$200,000) is funded through the 2025/2026 Annual Plan and includes \$110,000 of budgeted CAPEX for hydrological site upgrades and \$80,000 of OPEX and staff time.

The additional funding allows for a more comprehensive region wide review than was originally planned for in LTP.

Future implications

None anticipated. Ongoing maintenance will be absorbed within existing hydrology budgets. System changes are expected to increase redundancy and reduce staff time required to maintain the network.

Legal implications

Not applicable

8.3	Options Assessment Report: Re-installation of Sofar Spotter Wave Buoy – Westport Coast
Author	Samwell Warren –Manager Hydrology
Authoriser	Shanti Morgan, – Group Manager – Environmental Science
Public Excluded	No

Report Purpose

This report evaluates options for re-instating the Sofar Spotter wave buoy off the coast of Westport, following two previous deployment failures attributed to mooring system malfunction.

It outlines the technical considerations, operational risks, indicative costs, and the relative benefits and limitations of each option. The purpose is to inform a clear recommendation on whether, and under what conditions, the buoy should be reinstated so that it can provide reliable offshore wave climate data to support operational forecasting, harbour safety, and coastal hazard assessments.

Report Summary

This report presents four options for re-establishing offshore wave monitoring at Westport following the loss of two Sofar Spotter wave buoys, both attributed to mooring failures in a highly energetic marine environment. The options considered are:

1. **Reinstating the existing Sofar buoy** with an upgraded version of the current mooring system.
2. **Investing in a professionally designed, advanced mooring system** tailored to West Coast conditions.
3. **Not reinstating the Sofar buoy** and discontinuing offshore wave monitoring at this site.
4. **Revisiting NIWA's 2022 proposal** for an ocean-grade buoy system and fully contracted monitoring service.

The options vary significantly in upfront cost, long-term cost, reliability, and operational risk. Lower-cost solutions carry a higher probability of further mooring failure and asset loss, while the more robust options require unbudgeted investment. Council direction is sought on the preferred path, acknowledging both the high value of reliable real-time wave data for coastal hazard management and harbour operations, and the constrained funding available within the Hydrology programme.

Recommendation

It is recommended that the Committee resolve to:

1. *Receive the report.*
2. *Notes the four options for reinstating offshore wave monitoring at Westport, including the respective costs, risks, and implications of each.*
3. *Approves the staff-preferred option (Option 2) to invest in a more advanced, purpose-designed mooring system for the existing Sofar Spotter buoy, at an estimated unbudgeted capital cost of \$45,000 and a moderate residual probability of asset loss.*

Issues and Discussion

Background

The Sofar Spotter wave buoy was deployed off the coast of Westport to improve real-time understanding of offshore wave conditions influencing the Buller coastline, including the harbour entrance, coastal infrastructure, and the broader coastal hazard environment.

The buoy provides key inputs for:

- Harbour and bar crossing safety.
- Coastal hazard and erosion assessments.
- Validation of MetOcean and forecast models.
- Emergency management and response planning.

Two separate deployments have failed due to mooring system malfunction. The most recent loss indicates that the mooring, rather than the buoy itself, is the primary point of vulnerability. Likely failure mechanisms include shackle loosening, chafe wear, and high dynamic loading under long-period swell events. The coastal environment off Westport is particularly demanding, characterised by:

- Very high wave energy, with swells frequently exceeding 3–5m.
- Long-period swell (12–18s) resulting in high mooring loads.
- Strong currents and interactions with the Buller River plume during high flows.
- Elevated sediment and debris near the river mouth.
- Limited weather windows for safe installation, inspection, and retrieval.

These factors lead to accelerated wear, fatigue, and load cycling on mooring systems and significantly increase the risk of failure if the system is not designed specifically for such conditions.

Given the repeated losses and the ongoing need for reliable offshore wave data, Council is now asked to consider whether, and how, offshore wave monitoring at Westport should be reinstated.

Current situation

No real-time offshore wave data is currently being collected for the Buller coastline; harbour operations and coastal hazard monitoring are instead relying on modelled outputs and regional-scale datasets.

The existing 2025/26 budget within the Hydrology programme is insufficient to fully fund a high-specification offshore mooring system without re-prioritisation or additional funding.

Staff have worked with suppliers to identify a range of deployment options, from relatively low-cost upgrades of the existing mooring configuration through to a professionally designed, high-specification system and alternative externally managed solutions.

Council direction is now required on the preferred option to guide procurement and deployment planning.

Options Assessment

Four options have been assessed in terms of upfront cost, long-term cost, reliability, risk of asset loss, data continuity, operational complexity, and suitability for the West Coast environment.

OPTION 1 – Reinstate Using the Existing Mooring System with Improved Shackles and Fittings

This option involves reinstating the Sofar Spotter buoy using the existing mooring design, with targeted improvements to hardware and fittings.

Scope:

- Replacement of all hardware with marine-grade, certified components.
- Improved shackle locking system.
- Replacement of chafe-prone sections.
- Pre-deployment load testing.
- Deployment using existing vessel and procedures.

Advantages:

- Lowest upfront cost.
- Fastest reinstatement.
- Operational familiarity with existing design.
- Minimal procurement lead time.

Limitations / Risks:

- Still may not withstand West Coast extreme sea states.
- Failure modes may persist under long-period swell loading.
- Higher probability of another loss requiring retrieval (if possible) or replacement of the wave buoy unit.
- Reliability uncertain; past failures suggest design limitations, not just hardware.

Indicative Cost: \$23,847.33

OPTION 2 – Install an Upgraded, Purpose-Designed Advanced Mooring System

This option includes investing in a professionally engineered mooring solution designed for high-energy offshore environments. This may include helical anchors, heavier-duty chain, elastic mooring components, multi-point anchoring, or hybrid chain-rope systems to reduce dynamic loads.

Key Features May Include:

- High-capacity elastic mooring elements.
- Reduced shock loading on the buoy via energy-dissipating links.
- Stronger anchoring footprint.
- Redundant connectors.
- Professional design and certification.
- Manufacturer-recommended offshore deployment method.

Advantages:

- Most technically reliable option.
- Greater long-term security, reduced chance of buoy loss.
- Lower maintenance and fewer retrievals.
- Better data continuity for coastal hazard and forecasting needs.
- Aligns with best practice for exposed coasts.

Limitations / Risks:

- Higher upfront cost.
- Requires procurement lead time.
- Not guaranteed, but significantly lowered failure risk.
- If failure still occurs, replacement cost is higher.

Indicative Cost: \$45,000

OPTION 3 – Do Not Reinstate the Buoy

Discontinue attempts to deploy the Spotter buoy due to repeated failures and challenging environmental conditions.

Advantages:

- No additional cost.
- Removes operational and reputational risk from repeated failures.
- Allows resources to be redirected to lake seiche monitoring at Lake Moana.

Limitations / Risks:

- Loss of real-time offshore wave intelligence for:
 - Coastal hazard monitoring
 - Buller harbour operations
 - Forecast model validation
 - Emergency management
- Increased dependence on offshore MetOcean models, which may be less accurate.
- Impacts on scientific, engineering, and community information services
- Undermines long-term datasets needed for coastal change assessments at Westport.

Indicative Cost: *Loss of Wave buoy due to non-use*

OPTION 4 – Revisit NIWA’s Ocean-Grade Buoy System Proposal

This option revisits NIWA’s 2022 proposal for supply, deployment, and operation of an ocean-grade wave buoy system, with NIWA providing a fully contracted monitoring service.

Advantages:

- Continued Monitoring of wave environment off Westport
- Theoretical best designed system including buoy for conditions, with NIWA expertise.
- No in house expertise or personnel required, completely contract led.
- Removes operational and reputational risk from repeated failures.
- Allows existing buoy to be re-purposed as measure wave seiche at Lake Moana.
- The Sofar wave buoy could be retained and used elsewhere on coast with less extreme wave action.

Limitations / Risks:

- High initial cost
- High operational cost relative to other options
- Not guaranteed to succeed

Indicative Cost: \$250,000

Table of Options Assessment

Option	Upfront Cost	Long-Term Cost	Reliability	Risk of Loss	Data Continuity	Operational Complexity	Environmental Suitability
Option 1 – Existing Mooring + Improved Shackles	Medium	Medium (due to possible repeat failures)	Low–Moderate	High	High (if successful)	Low	Marginal
Option 2 – Advanced Mooring System	High	Lower	Moderate	Moderate	High (if successful)	Moderate	Good
Option 3 – Do Not Reinstate	None	None	N/A	None	Low / None	None	N/A
Option 4	Highest	High	Moderate – High	Low	High	High (but external)	Best

Considerations

Implications/risks

Across the four identified options, the key implications and risks are:

Technical and Operational Risk

- **Mooring failure:**
 - Highest under Option 1 (incremental improvement to an already stressed design).
 - Reduced, but not eliminated, under Option 2 (purpose-designed system).
 - Substantially mitigated under Option 4 (professionally provided service), noting no system is failure-proof.
- **Loss of asset:**
 - Each failure has potential replacement and retrieval costs in the order of \$15,000 for the Sofar Spotter wave bouy unit alone.
- **Operational downtime:**
 - Repeated failures result in extended periods without real-time data, affecting navigational safety and coastal hazard monitoring.
- **Unbudgeted capital costs:**
 - Option 2 requires an unbudgeted capital investment (~\$45,000).

- Option 4 involves significantly higher capital and/ongoing service costs (~\$250,000).
- **Opportunity cost:**
 - Funding allocated to offshore wave monitoring may limit investment in other monitoring priorities (e.g. inland flood, seiche, or groundwater networks).

Strategic and Service Impacts

- **Data continuity and quality:**
 - Options 1, 2, and 4 provide for ongoing offshore wave data, with Option 2 and 4 supporting higher reliability and better long-term records.
 - Option 3 removes local empirical data and increases reliance on modelled products.
- **Harbour safety and coastal hazard management:**
 - Real-time wave data is an important input for navigation safety, harbour decision-making, and public information during high-energy coastal events.
 - Discontinuing monitoring (Option 3) may reduce the quality of advice available to harbour users and emergency managers.

Reputational Risk

- Repeated deployment failures (particularly under a lower-cost approach) may undermine confidence in Council's monitoring programme and investment decisions.
- Conversely, not reinstating the buoy at all may be perceived as reducing support for harbour safety and coastal hazard monitoring, particularly by stakeholders who value the data.
- Re-deployment of the Sofar Spotter wave buoy unit may not be well received by the Westport community given the funding for the unit and deployment costs incurred to date have been borne under the "Sea level and River monitoring" project arm of the "Building Westport's Flood Resilience" programme of works. The funding partner (DIA) has made it very clear that no further funding is available for wave buoy related costs under the "Sea level and River monitoring" project at Westport.
- The "Civil Defence Emergency Management" project arm of the "Building Westport's Flood Resilience" programme of works is underspent HOWEVER, there is a strong indication that any underspends within the wider Resilient Westport programme will be reprioritised towards Westport structural flood protection works.

On balance, staff consider that the benefits of reinstating offshore wave monitoring using a robust, purpose-designed mooring system (Option 2) outweigh the additional unbudgeted cost, when compared with the high risk of further failure under Option 1 and the significant service loss under Option 3. Option 4 remains technically strong but is difficult to justify within current budget constraints.

Significance and Engagement Policy assessment

There are no issues within this report which trigger matters in this Policy.

Mana whenua views

Staff are not aware of any issues within this report which would impact mana whenua.

Financial implications

Current implications

FY2025/26 Budget

There is no budget within the 2025/26 financial year to support any of the options presented in this paper.

Options identified will result in a overspend of allocated Capex within the environmental science budget which has been fully committed for the FY.

Councillors may consider a delayed employment to ensure budgeting can be provisioned in the 2026/27 financial year.

Legal implications

Not applicable

8.4 October Flood Reports**Author** Samwell Warren, Hydrology Manager**Authoriser** Shanti Morgan, Group Manager Environmental Science**Public Excluded** No**Report Purpose**

To present the Environmental Management Committee with a summary of the hydrological conditions and flood responses across the West Coast during the October 2025 rainfall events, including key return periods, catchment behaviour, and implications for flood warning, asset management, and future planning.

Report Summary

October 2025 was marked by repeated heavy rainfall on already saturated catchments, resulting in two clusters of significant flood events.

The 10–12 October events produced notable but generally moderate floods across several major rivers and set high antecedent conditions. The 20–25 October events then generated locally significant floods in catchments such as Karamaea, Grey, Inangahua and Haast, with some peaks estimated in the 10–20-year ARI range, while many other sites experienced moderate but hydrologically important events.

Together, these events highlight how multi-event storm sequences can elevate flood risk, compress warning lead times and stress-test river protection assets, even when individual peaks are not record-breaking. They also provide valuable data to refine flood frequency analysis, rating curves, and flood warning thresholds, and to inform river scheme management and climate adaptation planning.

Recommendation

It is recommended that the Committee resolve to:

- 1. Receive the report.*

Issues and Discussion**Background**

The West Coast experienced an unusually wet winter and spring leading into October 2025, with multiple frontal systems and long periods of above-average rainfall. This produced:

- Persistently high river baseflows;
- Saturated soils, especially in western and alpine catchments; and
- Increased sensitivity to subsequent storm events.

In response to a series of significant rainfall and flood events in October, the Hydrology team prepared two detailed technical reports:

- Flood Event Report: 10–12 October 2025 – describing the first cluster of significant events; and
- Flood Event Report: 20–25 October 2025 – describing the second cluster, including the 20–21 and 23–25 October events.

These reports document rainfall totals and intensities, hydrograph responses, estimated return periods and historical comparisons at key sites throughout the region. Together, they provide a coherent record of October 2025 as an important month in the West Coast flood record.

This cover report summarises key findings across both reports, and sets out the risks, implications, and recommended actions for WCRC.

Current situation

During October 2025 the West Coast experienced two clusters of significant rainfall and flood events on already saturated catchments. The first, from 10–12 October, produced widespread heavy rain and generally moderate floods across several major rivers, which in turn raised baseflows and soil moisture levels. The second cluster, from 20–25 October, generated locally significant floods in catchments such as Karamea, Grey, Inangahua and Haast, with some peaks estimated in the 10–20-year ARI range while many other sites experienced moderate but hydrologically important events. Together, these events provide valuable information on catchment behaviour, return periods and warning lead times, and are described in detail in the two attached technical reports for 10–12 October and 20–25 October 2025.

Note: This report is for information purposes only.

Considerations

Implications/risks

Short Warning Lead Times and Public Safety

- **Risk / implication:** Several catchments (e.g. Waipuna, Ahaura, Haast, Karamea) demonstrated very short lead times, limiting the warning window for CDEM and communities and increasing reliance on robust, real-time information and clear internal procedures.
- **Mitigation / Council response:**
 - Hydrology is reviewing the performance of real-time sites in these catchments, prioritising maintenance, power and telemetry resilience, and

identifying any gaps where additional or upgraded gauges would materially improve lead time.

- The CDEM and Hydrology teams will continue to refine event monitoring protocols and pre-agreed triggers for escalation and public information, aligned with MetService warnings.

Climate and Adaptation Planning

- **Risk / implication:** October 2025 illustrates the type of compound event pattern (multiple storms on saturated catchments) that may become more frequent or intense under climate change, potentially increasing long-term flood risk and pressure on communities and infrastructure.
- **Mitigation / Council response:**
 - The Environmental Science and Planning teams will integrate the October 2025 data and narratives into WCRC's climate adaptation and natural hazards work programme, including support to territorial authorities on hazard provisions, adaptation planning and community engagement.
 - Hydrology will provide event summaries and return-period information in formats suitable for use in hazard mapping, modelling updates and planning evidence.

Data Quality, Models and Organisational Learning

- **Risk / implication:** If not captured and analysed systematically, significant events like those in October 2025 represent missed opportunities to improve rating curves, models, design flows and public communication, weakening the evidence base for future decisions.
- **Mitigation / Council response:**
 - Hydrology will continue its programme of post-event reporting, including using October 2025 data to refine flood frequency analyses and rating curves at key high-flow sites.
 - Outputs will be shared across WCRC (Hydrology, River Engineering, Natural Hazards & CDEM) to ensure consistent use of updated information in scheme reviews, modelling, and community information.

Significance and Engagement Policy assessment

There are no issues within this report which trigger matters in this Policy.

Mana whenua views

Staff are not aware of any issues within this report which would impact mana whenua.

Views of affected parties

Staff are not aware of any views of affected parties which impact on matters discussed in this report.

Financial implications**Current budget**

Flood response sits with council annual plan budgets. However, repeated events can have implications on BAU operations.

Future implications

Not applicable

Legal implications

Not applicable

Attachments

Attachment 1: Hydro event report 10–12 October 2025

Attachment 2: Hydro event report 20–25 October 2025



Flood Event Report

10 –12 October 2025

West Coast Regional Council Hydrology
November 2025

Prepared by:

Izelda Mulder, Hydrology Data Analyst

Samwell Warren, Hydrology Manager

For any information regarding this report please contact:

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Revision	Description	Date
1	First Draft	24/10/2025
2	Final Draft	7/11/2025

Quality Assurance Statement		
Reviewed by:	Samwell Warren (Hydrology Manager)	
Approved for release by:	Shanti Morgan (Group Manager Environmental Science)	

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Contents

Executive Summary.....	6
Rainfall characteristics:	6
Hydrological impacts:.....	6
Event summary	8
1. Buller River Catchment	10
2.2. Karamea River Catchment	16
2.2.1. River flows and levels.....	16
2.3. Mokihinui River	18
2. Grey	20
3. Westland	Error! Bookmark not defined.
4.1. Hokitika River.....	Error! Bookmark not defined.
Appendix	27
A. Rainfall summary table	27
B. Flood observations (photos and extra notes).....	28
C. MetService warnings	29

Executive Summary

A significant short-duration rainfall event occurred across the West Coast between 10–12 October 2025, with the most intense rainfall on 10 October.

MetService issued Orange Heavy Rain Warnings for Buller, Grey, and Westland districts on 9 October. The front moved faster and earlier than forecast, producing rapid river rises, especially in the Grey District, where Ahaura and Waipuna Rivers exceeded 5-year return periods, prompting a precautionary school evacuation at Ahaura.

Rainfall characteristics:

- Most rainfall fell in a 6 - to 12 - hour window.
- Waipuna recorded intensities above the 5 - year Annual Return Interval (ARI) for both 6-hour and 12-hour durations.
- Antecedent wet conditions due to a persistently unsettled season increased runoff and river responsiveness.
- Radar outage (Westland radar struck by lightning in September) limited real-time rainfall monitoring; the Council's rainfall network provided coverage but with spatial gaps.

Hydrological impacts:

- Rainfall across the Buller catchment was highly variable, ranging from approximately 100 mm in the lower reaches near Westport and Reefton to over 400 mm in the central Brunner Range area. The heaviest rainfall was concentrated in the mid-catchment, where orographic effects enhanced totals along the main divide. This pattern indicates strong inflow generation potential from the central ranges, with reduced rainfall contributions from peripheral lowland and eastern sub-catchments. Buller District flow sites remained mostly below mean annual flood levels, except Inangahua at Blacks Point, which reached a 4.6-year ARI.
- Grey River (Dobson) peaked at 4198 m³/s, ARI ~3.2 years with flows recorded at Ahaura and Waipuna Rivers both exceeding 5-year ARIs. Rainfall in these catchments were characterised by short, intense rainfall bursts, strongly influenced by orographic uplift and local convective enhancement. While the total rainfall over the event was moderate compared to historic extreme events, it was consistent through the valley. The concentration of rainfall in upper sub catchments drove significant localised flooding, particularly in Ahaura and Waipuna. The hydrological signature of this event aligns with a classic northwest frontal system, producing dual rainfall maxima and fast-responding hydrographs across the mid-Grey District.
- Westland and Haast catchments experienced low-to-moderate effects, with rivers peaking well below flood thresholds.

Surface flooding occurred in parts of Greymouth, SH7, and Stillwater, leading to temporary road closures.

Overall, while rainfall intensities were locally high, the event's short duration and localized nature limited widespread flooding, though hydrological responses were amplified by wet antecedent conditions.

Event summary

Orange Heavy Rain Warnings were issued by MetService for the Westland, Grey, and Buller districts on 09 October 2025. The rainfall event progressed across the West Coast on 10 October, with peak intensities arriving earlier and moving more rapidly than forecast, resulting in a rapid rate of rise at both Ahaura and Waipuna, triggering a precautionary self-evacuation at the Ahaura school.

A short-duration, intense rainfall event was observed in the Grey District, particularly affecting the back catchments. Observed rainfall gauges indicate that most of the peak rainfall intensities occurred within a 6-12 hr window, with rainfall concentrated near the Ahaura and Waipuna water level sites. The Waipuna rain gauge recorded totals exceeding the 5-year return period at both the 6- and 12-hour durations. Comparison of the 24-hour totals against the full event duration in the Grey District suggests that most of the rainfall was largely confined to a single day, with minimal additional accumulation beyond the primary 24-hour period.

River levels and flows in the Grey District were elevated more than usual during the event due to frequent unsettled weather this season. The Grey River peaked on 10/10/2025 19:00 local time with a recorded flow at 4198 m³/s, an estimated ARI of 3.2 years, while the Ahaura and Waipuna rivers exceeded their 5-year return periods. In contrast, most rivers in Buller and Westland remained below their mean annual flood levels.

Rainfall forecasting in the Region was limited by the lack of radar coverage, as the Westland MetService rain radar was damaged during a lightning storm in September. The region's hydrometric network of rainfall gauges was used as an alternative data source; however, spatial coverage was limited compared to radar, reducing the accuracy of rainfall predictions and limiting the ability to monitor conditions in real time.

Extensive surface flooding occurred, with floodwaters covering sections of SH7, particularly between Stillwater and Greymouth, resulting in temporary road closures.

Antecedent Conditions:

River levels and flows were already elevated above median flow conditions due to frequent unsettled weather patterns since early September. The resulting wetter ground conditions in the catchments contributed to a faster catchment response and greater runoff volumes during the event.

Table 1: Minimum and maximum rainfall totals and hour intensities observed per catchment.

Catchment	Rainfall intensity				Total rainfall (mm)	
	30 minute (mm/0.5hr)		Hourly (mm/hr)			
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Karamea	4.5	17.7	6.5	29.6	84	427
Mokihinui	13	19.6	20.5	28.1	320	382
Buller	3.1	16.4	5.5	19.6	56	255
Grey	6	11.8	11.1	22.2	74	207
Taramakau / Hokitika	6.8	25	13.6	40.5	90	436
Whataroa	6.9	11	13.8	21	74	142
Waiho / Mahitahi	5.1	15.5	18.5	26.5	81	164
Haast	6.5	14.5	10.1	27	87	198

Table 2: Peak level and flow and annual return interval observed per river monitoring station.

River / Location of main gauge	Date and time of peak	Peak level (mm)	Peak flow (m3/s)	Estimated return period (years)	Record (years)
Karamea River / Gorge	12/10/2025 11:05	4584	1818	1.5	48
Mokihinui River / Welcome Bay	10/10/2025 14:15	5517	1528	1.3	34
Buller River / Te Kuha	10/10/2025 23:25	8283	3803	1.2	62
Grey River / Dobson	10/10/2025 19:00	5333	4198	3.2	56
Hokitika River / Gorge	10/10/2025 05:35	3960	1226	<1.1	28
Whataroa River / SH Bridge	10/10/2025 05:20	3742	1454	NA	NA
Waiho River / SH Bridge*	10/10/2025 04:30	7478	NA	NA	10
Haast River / Roaring Billy	10/10/2025 06:15	3647	1366	<1	54

1. Buller River Catchment



Figure 1: Location of Buller River Hydrometric Monitoring Locations

Three of the ten rainfall gauges in the Buller District recorded totals exceeding their 2-year ARI between the 6- and 24-hour durations. All three exceeded the 2-year ARI at the 12-hour peak intensity duration, and one gauge (Springs Junction) surpassed the 5-year ARI. This gauge is the farthest inland rainfall site WCRC operates and indicates rainfall was significant in the back lowland catchments, not just on the ranges. It also effectively borders the back of the Waipuna Catchment and is suggestive of the significance of rainfall that fell in the Grey District.

All river level sites, where ARI could be calculated in the Buller District recorded flows above 1 ARI but below the mean annual flood (2.33 year¹), with the exception of Blacks Point which surpassed its mean annual flood.

¹ The Average Recurrence Interval (ARI) for a mean annual event is 2.33 years, not 1 year, because of the statistical distinction between how the "mean annual flood" is defined (the average of the annual maximum flows) and the theoretical definition of the recurrence interval for frequent events.

The gauges recording the higher return periods were located in proximity to the Blacks Point Township water level site, reflecting localised intensity in the Inangahua back catchment area.

Table 3: Peak river flows and levels recorded in the Buller River Catchment.

Monitoring site	Date and time of peak	Peak water level (mm)	Peak flow (m3/s)	Return period	Record (years)
Buller Rv at Te Kuha	10/10/2025 23:25	8283	3803	1.2	62
Buller Rv at Woolfs	10/10/2025 22:35	5184	2286	1.3	61
Buller Rv at Longford	11/10/2025 02:40	3775	NA	NA	NA
Matakitaki at Horse Terrace Bridge	10/10/2025 13:40	2215	NA	NA	NA
Orikaka Rv at Gorge	10/10/2025 10:45	3625	497	~1.6	5
Inangahua Rv at Landing	10/10/2025 13:35	4317	1126	<1.3	62
Inangahua Rv at Blacks Pt	10/10/2025 12:35	3533	514	4.6	48
Maruia Rv at Lower Maruia Br*	10/10/2025 15:25	7763	964	NA	<5

Table 4: Rainfall intensities and totals recorded in the Buller River Catchment

Site	Record (years)	Maximum rainfall (mm)								
		30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Total
PlateauStm	HIRDS	13.4	19.6	30.5	60	109	172.8	202.5	255.5	255
Westport (NIWA)		5.1	10.2	18	26.4	35.4	54.4	70.4	82.6	83
BaldHill		12.3	15.7	24	34.5	53	79	107.9	123.5	123
ThreeChannel		10	13.2	22	44.2	70.7	111	132.2	156	156
Matakitaki (TDC)		7.5	11.5	18	33.5	58	95.5	125	152.5	152
BrunnerRange	6	16.4	19.4	29.7	54.7	92.1	150	178.9	217	217
Landing	HIRDS	9.2	15.6	28.2	67.2	102	126	147	172.7	173
Reefton		3.1	5.5	9.9	26.9	40.2	44.5	49.1	56.5	56
SpringsJunction		8.9	14.6	21.7	54.9	83.9	90	95.3	115.5	116

* HIRDS V4 stats used in flood manual, last update was 2016.

ARI (years)	2.0 / 2.33	5	10	20	50	100	200+
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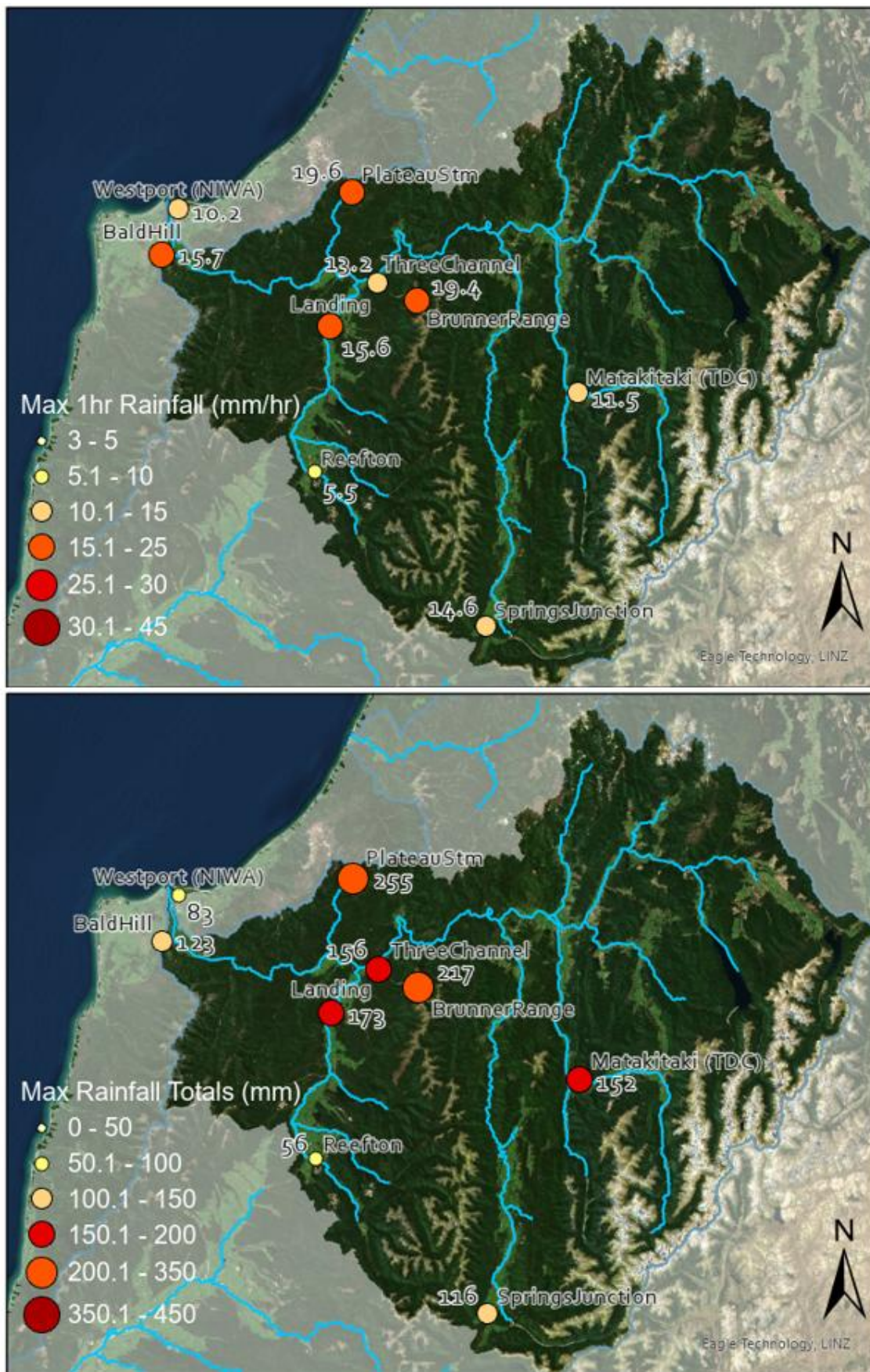


Figure 2: Rainfall intensities and totals observed over the WCRC Hydrometric Monitoring Network for Buller.

Figure 3 shows the rainfall totals presented in Figure 2 spatially with respect to the main trunk of the Buller River. Tise interpolated rainfall surface illustrates a distinct rainfall gradient across the Buller catchment, reflecting the interaction between frontal rainfall systems and orographic enhancement from the Paparoa and Victoria Ranges.

Totals ranged from <100 mm near the coast (Westport, Reefton) to 250 to 300 mm in central headwaters around Plateau Stream, Brunner Range, and Three Channel Flat. This pattern indicates a strong inland intensification driven by moist westerlies lifting over the ranges.

The 200 mm isohyet defines the central rainfall core zone. This overlaps with the headwaters of the Inangahua, Orikaka, and Upper Buller Rivers, which aligns with the locations where the highest river responses were observed during the event.

In contrast, Inangahua at Blacks Point exceeded its mean annual flood (4.6-year ARI) — reflecting the intensified local rainfall cell (200–250 mm zone) around the Brunner Range and Inangahua tributaries. Downstream attenuation reduced flow magnitude despite upstream rainfall concentration, showing the catchment’s flood storage capacity and spatial rainfall offset between sub catchments.

This event for the Buller demonstrates a short-duration, high-intensity rainfall pattern concentrated over the inland orographic belt, driving localized flood peaks rather than a synchronized whole-catchment flood. The steep gradients and flash-response tributaries (Inangahua, Orikaka) produced sharp rises, while the main Buller stem moderated the overall response.

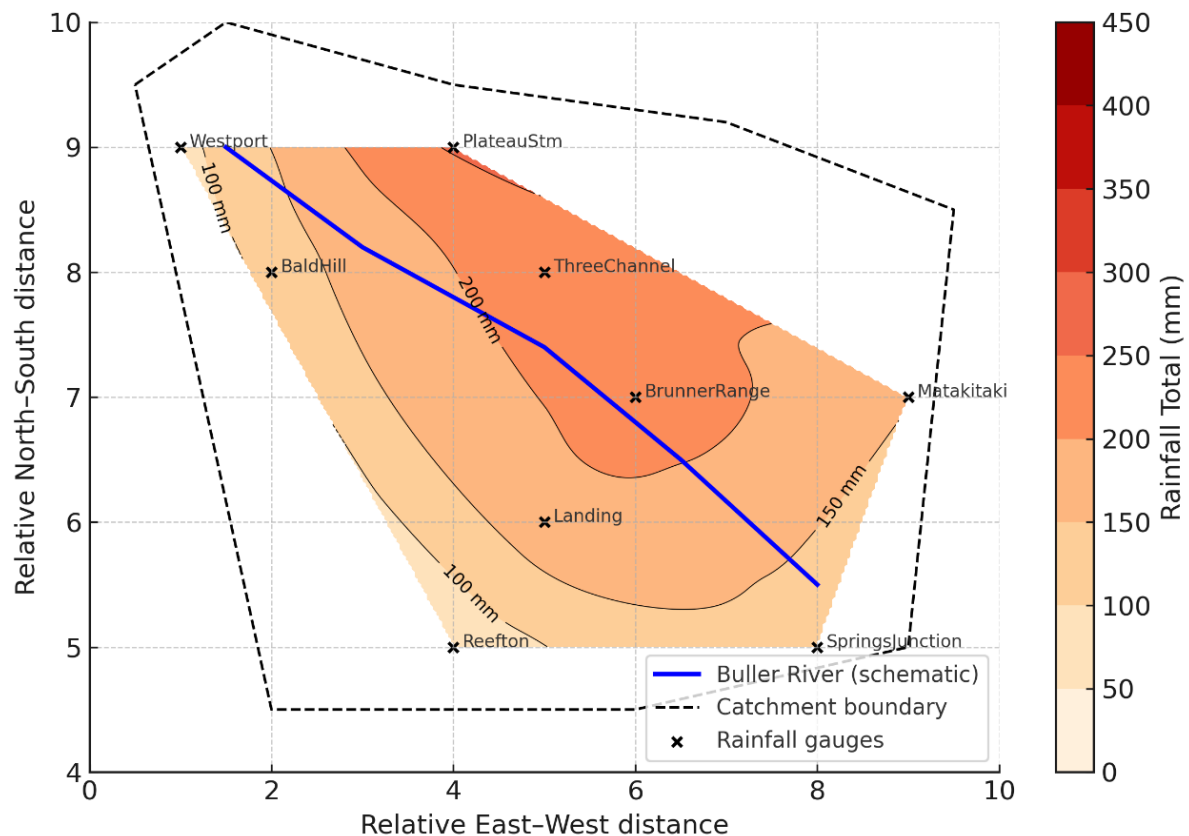


Figure 3: Interpolated rainfall totals for the Buller Catchment for the 9 to 11 October 2025 rainfall event.

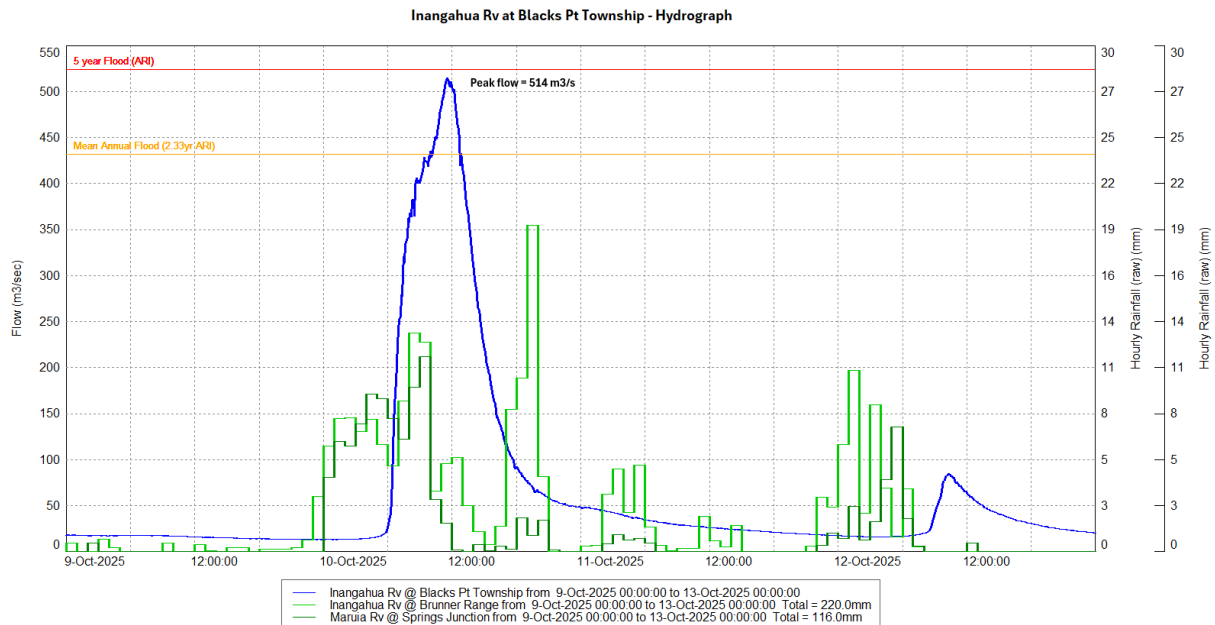


Figure 4: Figure 2: Comparison of event hydrograph at Inangahua at Blacks Point Township and associated rainfall site hyetographs.

The event hydrograph for Blacks Point Township recorder site shows a peak flow of 514 m³/s, occurring late morning on 10 October 2025. This flow exceeded the Mean Annual Flood (2.33-year ARI) but remained below the 5-year ARI threshold. The rate of rise was sharp, with flows increased rapidly between midnight and midday on 10 October, corresponding to intense rainfall over the preceding 6 to 12 hours (the catchments TOC).

Following the peak, the hydrograph shows a gradual recession, with flow returning near base flow levels by 12 October. The event represents a moderate but well-defined flood pulse, typical of short-duration high-intensity rainfall events in the Inangahua catchment.

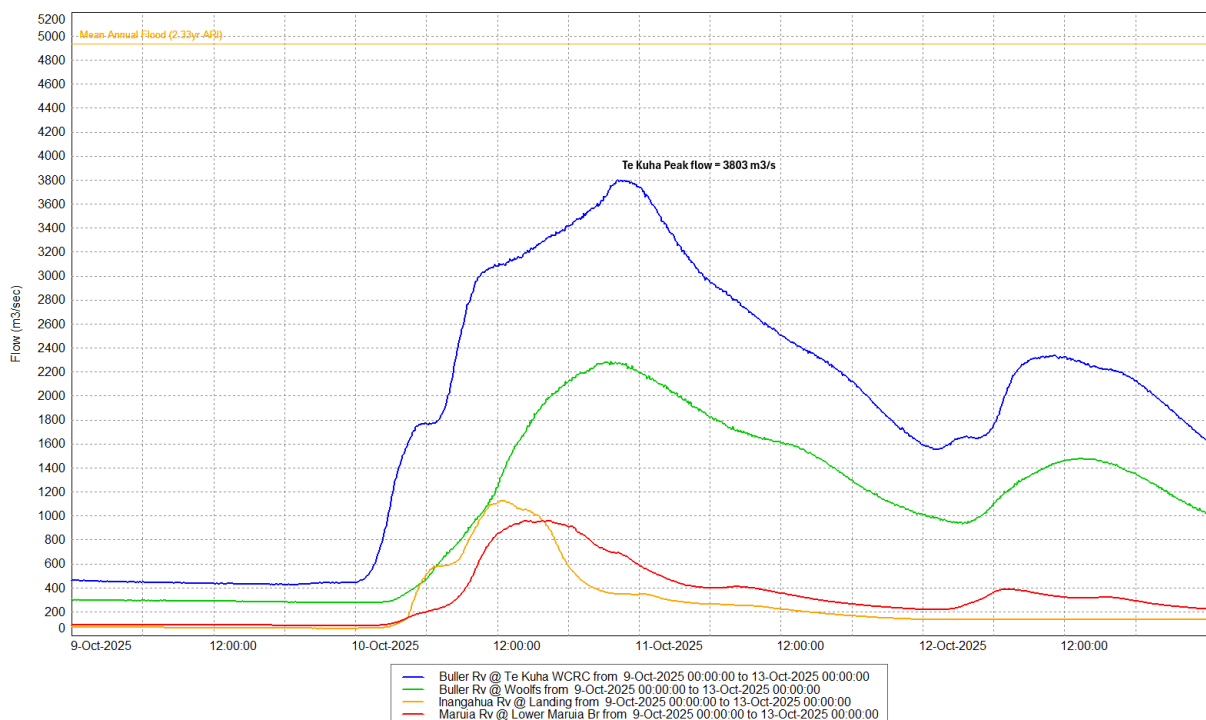


Figure 5: Event hydrographs for key flow sites on the Buller River main stem.

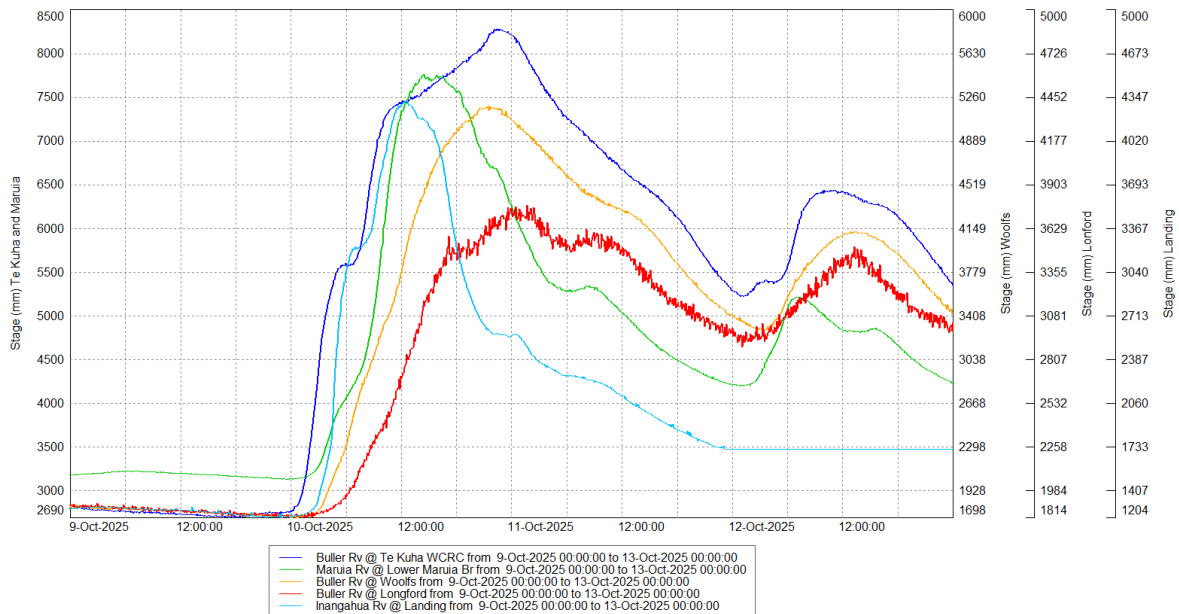
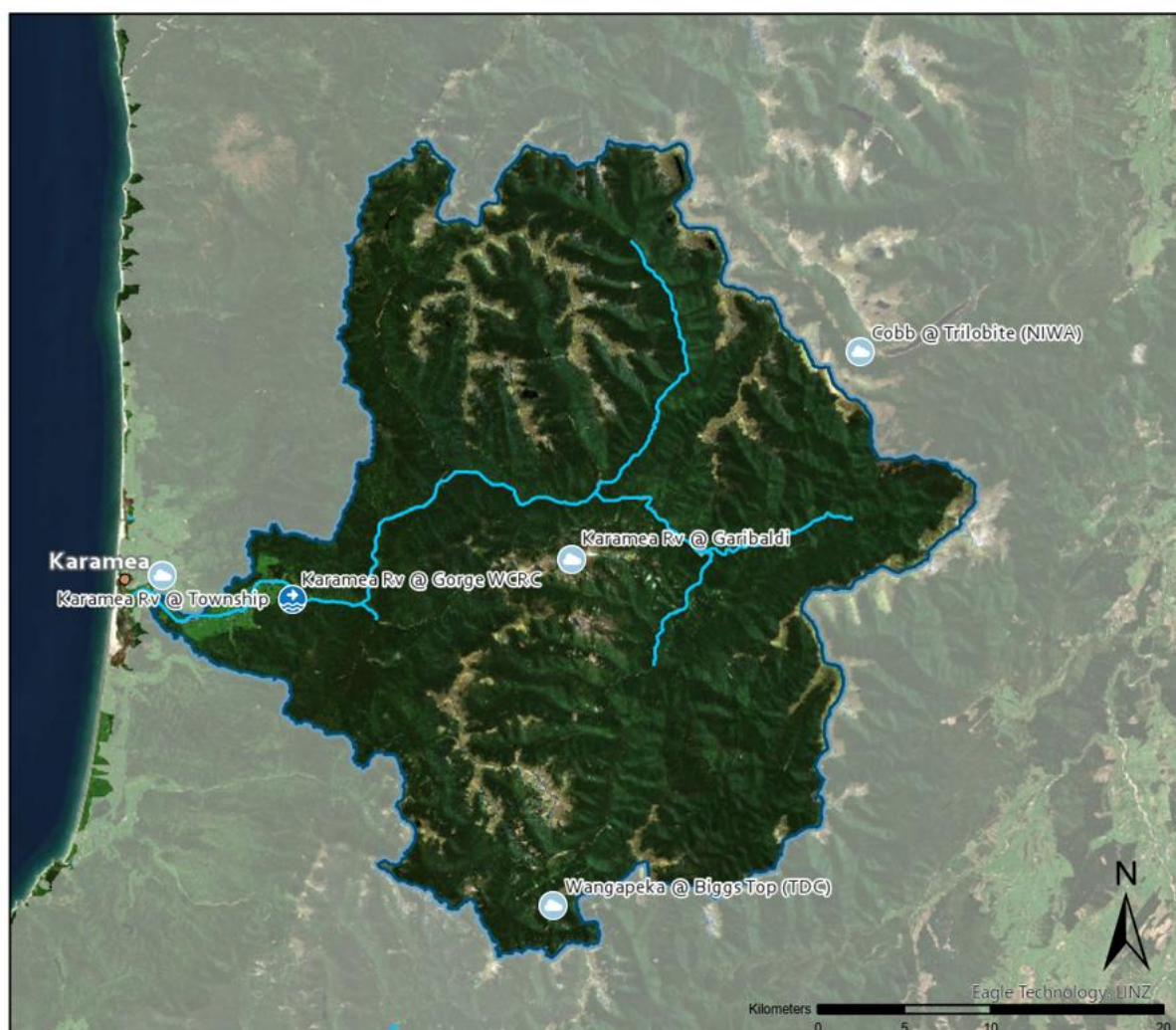


Figure 6: Stage hydrographs for key flow sites on the Buller River main stem

Figures 5 and 6 for a series of flow sites in the Buller River over the flood show a well-synchronised hydrological response across the Buller catchment, with Te Kuha reaching approximately 3800 m³/s. Tributary peaks from the Maruia and Inangahua rivers contributed to the mainstem rise, though their flows receded quickly. The second pulse indicates continuing rainfall or delayed tributary inflows.

The event shows a clear nested catchment response, where tributary peaks feed into the main Buller system with lag and attenuation downstream. Rapid rises followed by slower recessions reflect high-intensity rainfall followed by gradual catchment drainage.

2.2. Karamea River Catchment



2.2.1. River flows and levels

Table 5: Peak River flows and levels recorded in the Karamea River Catchment

Monitoring site	Date and time of peak	Peak water level (mm)	Peak flow (m3/s)	Return period	Record (years)
Karamea Rv at Gorge	12/10/2025 11:05	4584	1818	1.5	48

Table 6: Rainfall intensities and totals recorded in the Karamea River Catchment

Site	Record (years)	Maximum rainfall (mm)								
		30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Total
PerrySaddle (TDC)	HIRDS	6.2	11.2	17.7	38.5	53.2	71.8	127.2	152	152
Cobb (NIWA)	HIRDS	4.5	6.5	11	19.5	33.5	44.5	66	84.5	84
Garibaldi	14 yrs	17.7	29.6	47.5	109.1	168.5	221.9	324	427	427
Karamea	HIRDS	11.2	17.2	30.5	46.5	57.8	99.5	139.9	174	174
Wangapeka (TDC)	HIRDS	13	20.5	36	87	159.5	232	297	381.5	382

ARI (years)	2.0 / 2.33	5	10	20	50	100	200+
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Table 6 shows Garibaldi recorded the highest rainfall totals across all durations, with a Peak 1-hour intensity of 29.6 mm/hr and a total rainfall depth over the event of 427 mm.

The 12-hour and 24-hour totals (168.5 mm, 221.9 mm) exceed the 10-to-20-year ARI thresholds. With Wangapeka recorded the second-highest rainfall (382 mm total) recording up to 232 mm in 24 hours, consistent with a 20-year ARI event.

Karamea Township saw moderate rainfall (174 mm total), mainly between the 6-to-24-hour duration, within the 5-year ARI range. Perry Saddle and Cobb experienced lower totals (152 mm and 84.5 mm), representing 2-year ARI or less.

The data illustrates a strong inland intensification, with rainfall totals increasing from east to west, corresponding to uplift along the ranges with Garibaldi and Wangapeka—both high-altitude inland stations—captured the core rainfall zone. Coastal and low-elevation sites (Karamea Township received less intense but steady rainfall.

As a result, the Karamea River at Gorge peaked at 1818 m³/s (1.5-year ARI), consistent with the moderate regional rainfall pattern over the wider event but below the return periods observed inland. The localised high-intensity bursts at Garibaldi and Wangapeka suggest sub-catchment variability, with potential for flash runoff and elevated tributary inflows, though the mainstem response was tempered by the lower coastal rainfall.

2.3. Mokihinui River



Table 7: Peak River flows and levels recorded in the Mokihinui River Catchment

Monitoring site	Date and time of peak	Peak water level (mm)	Peak flow (m3/s)	Return period	Record (years)
Mokihinui Rv at Welcome Bay	10/10/2025 14:15	5517	1528	1.3	34

Table 8: Rainfall intensities and totals in the Mokihinui River Catchment

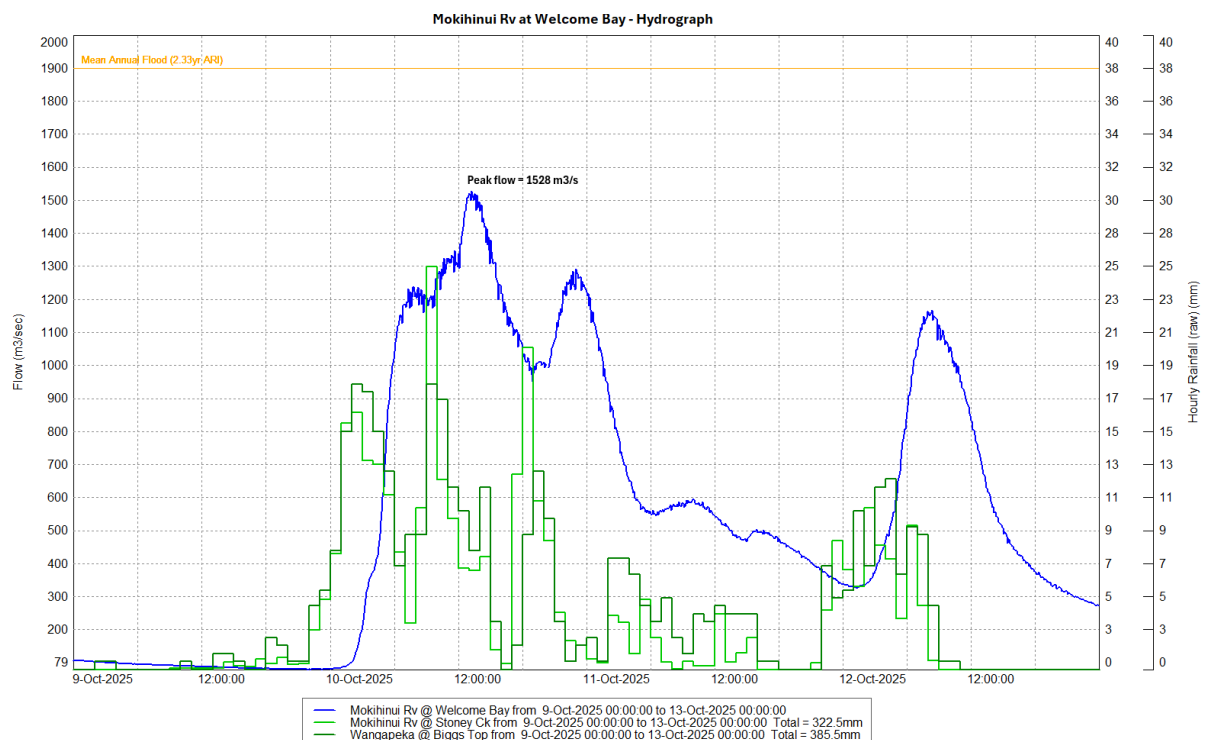
Site	Record (years)	Maximum rainfall (mm)								
		30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Total
Wangapeka (TDC)	HIRDS	13	20.5	36	87	159.5	232	297	381.5	382
Mokihinui	9 yrs	19.6	28.1	40.6	76.6	144.2	227.7	260.1	320.5	320

ARI (years)	2.0 / 2.33	5	10	20	50	100	200+
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The Mokihinui River catchment experienced a moderate rainfall and flow event during this event, with the Mokihinui River at Welcome Bay peaking at 5517 mm and 1528 m³/s at 14:15 on 10 October. This corresponds to an estimated 1.3-year return period, indicating a moderate but well-defined flood response.

Rainfall intensities across the catchment were elevated, with the Mokihinui gauge recording a total of 320 mm and the Wangapeka gauge 382 mm. Both sites recorded high short-duration intensities, with 12- hour totals of 144–160 mm and 24-hour accumulations exceeding 225 mm, consistent with 10 - 20-year ARI magnitudes. Rainfall was concentrated within a 6 - 24-hour window, producing a rapid rise in river levels on 10 October. The spatial rainfall distribution shows stronger intensities over the inland ranges, with orographic enhancement at Wangapeka and progressively lower totals toward the coast.

Despite the high localized rainfall, the event's short duration and offset rainfall peaks between tributaries moderated downstream flood severity. Overall, the Mokihinui catchment displayed a fast but limited hydrological response typical of the intense but short-lived frontal rainfall events commonly observed.



2. Grey



Current Event: October 10

The Grey River at Dobson reached a peak level of 5.3m and a peak flow of 4198 m³/s at 19:00, which has a return period of 3.2 years, just above the mean annual flood. Both Ahaura and Waipuna experienced higher flows relative to their water level records - with both exceeding their 5-year return periods.

The rate of rise was notable in both catchments, possibly due to the high intensity rainfall between 6- and 12-hours duration and already saturated catchments.

Table 9: Peak river flows and levels recorded in the Grey River Catchment

Monitoring site	Date and time of peak	Peak water level (mm)	Peak flow (m ³ /s)	Return period	Record (years)
Grey Rv at Dobson	10/10/2025 19:00	5333	4198	3.2	56
Ahaura Rv @ Gorge WCRC	10/10/2025 13:10	6515	2158	6.7	56
Grey Rv @ Waipuna	10/10/2025 11:05	5979	1586	>5	26
Arnold Rv at Moana / Moana at Jetty	12/10/2025 15:07	3361	165	1.3	52
Mawheraiti Rv @ Atarau Br	10/10/2025 12:25	4726	476	NA	<10

Most of the peak rainfall intensities occurred within a 6- to 12-hour window. Six out of 11 rainfall gauges in the district recorded totals exceeding their 2-year return period, particularly over the 6- and 24-hour durations. Rainfall was concentrated relatively near the Ahaura and Waipuna water level sites in the back catchment. The Waipuna rain gauge recorded totals exceeding the 5-year return period at both the 6- and 12-hour durations.

Analysis of the 24-hour totals compared to the full event duration suggests that most of the peak intensities was largely confined to a single day, with minor additional accumulation beyond the primary 24-hour period. This short, high-intensity event combined with elevated flows and moisture levels likely contributed to the rapid hydrological response observed in the catchments.

Site	Record (years)	Maximum rainfall (mm)								
		30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Total
SirdarCk	HIRDS	11.3	18.8	35.3	83.5	124.8	143.6	159.6	207	207
ConicalHill	HIRDS	6.3	11.1	19	44.1	61	65.5	76	91	91
Mawheraiti	HIRDS	6	11.2	18.3	41.9	56.6	61.5	65	79	79
Waipuna	HIRDS	9.4	17.3	26.6	58.7	78.1	82.5	88.3	111.5	112
Ahaura	HIRDS	8.9	14.3	23.5	55.6	85.9	89.1	94.2	116	116
Hauptiri	HIRDS	8.7	15	29.3	61.8	94.1	101.5	105.5	130	130
Ngahere	HIRDS	9.1	11.7	19.3	49.5	70	79.6	84	108.5	109
Moana WWTP*	<1 yr	10	17.2	27.1	57.5	90.9	99	104.5	122	122
Greymouth (NIWA)	HIRDS	10.5	21	24.6	32.8	56.4	63	65.8	74.2	74
WCRCOffice	HIRDS	11.8	18.4	25.2	36.3	67.6	78	83.5	97	97
Pigeon (NIWA)	HIRDS	11.2	22.2	41.2	100.6	143.6	159.4	172.2	200.4	200

* New rainfall site in Moana, no ARI data available to compare against.

ARI (years)	2.0 / 2.33	5	10	20	50	100	200+
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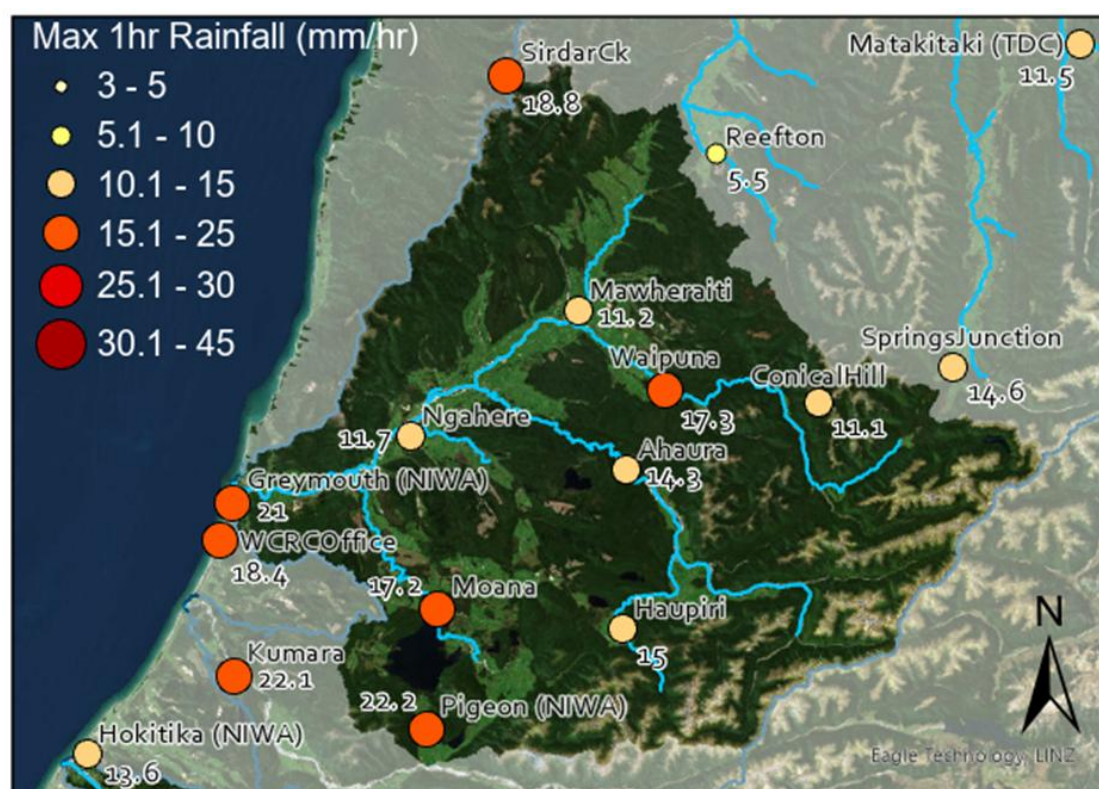


Figure 7: Rainfall intensities recorded over the Grey Catchment

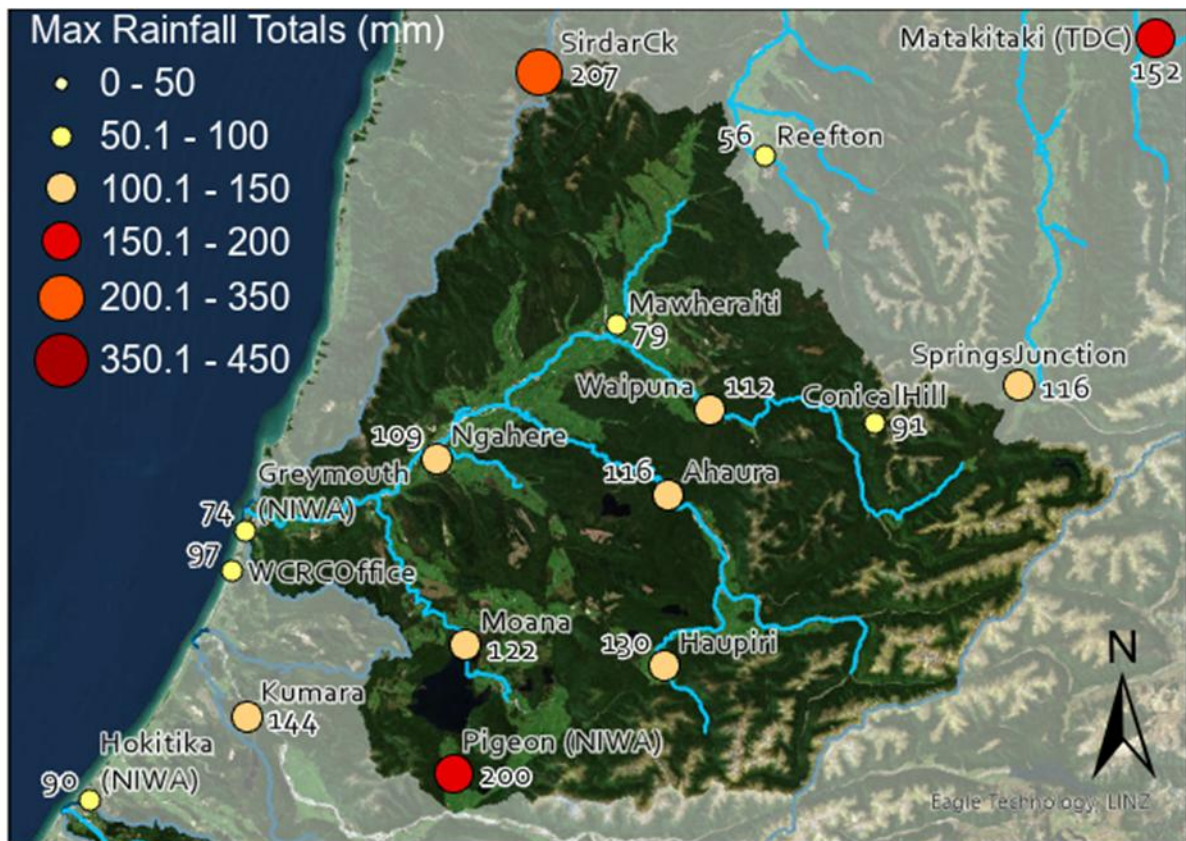


Figure 8: Rainfall totals recorded over the Grey Catchment.

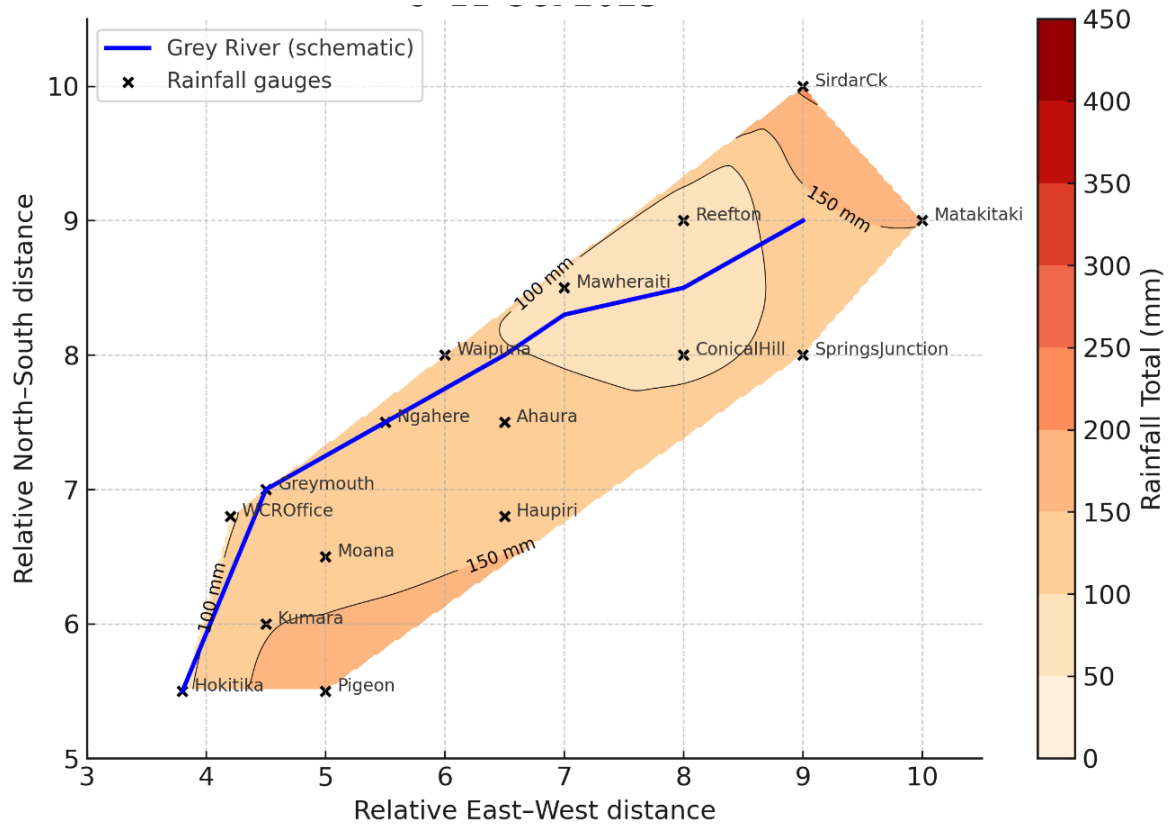


Figure 9: Interpolated rainfall totals for the Grey Catchment for the 9 to 11 October 2025 rainfall event

Between 9 and 11 October 2025, a widespread rainfall event delivered between 100 and 150 mm of rain across the Grey River catchment, with the heaviest totals occurring over the inland ranges near the Ahaura and Waipuna headwaters. The rainfall produced a rapid hydrological response, with steep rising limbs and short lag times across all gauges. The Ahaura River at Gorge peaked at 2,157 m³/s (approximately a 5-year ARI), while the Grey River at Waipuna reached 1,586 m³/s (around a 10-year ARI), both peaking late on 10 October. Downstream, the Grey River at Dobson recorded a peak of 4,198 m³/s, exceeding the mean annual flood, as the combined runoff from the upper catchment synchronised with mid-catchment inflows.

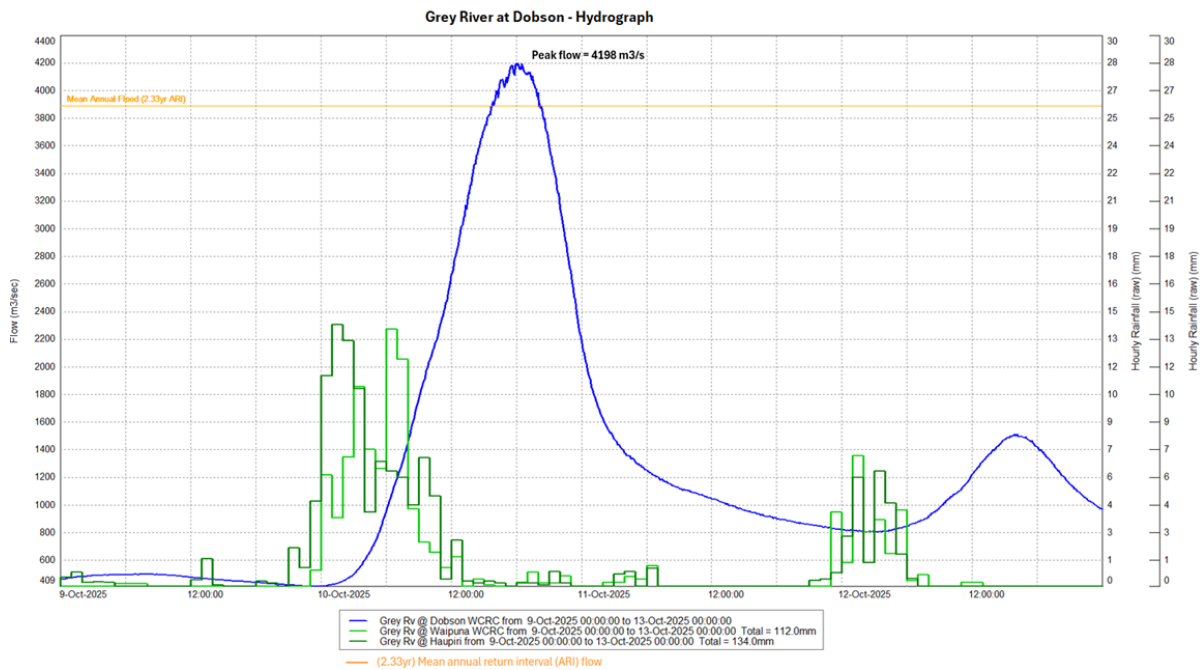


Figure 10: Flow hydrograph for Grey River at Dobson, and associated rain gauge hyetographs.

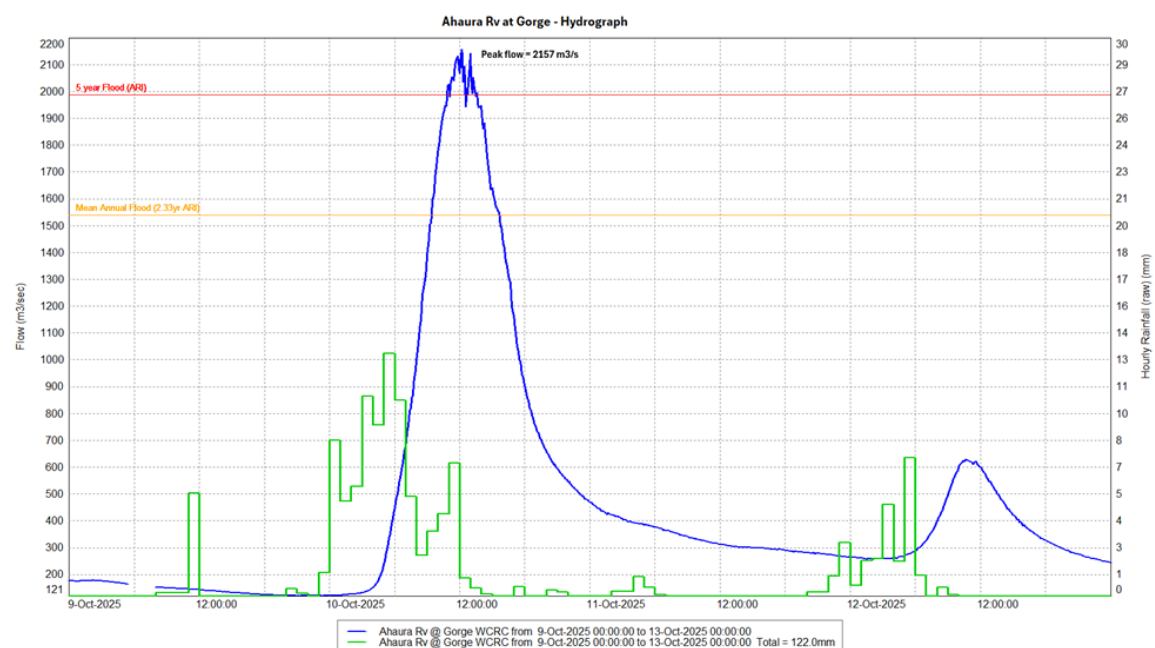


Figure 11: Flow hydrograph for Ahaura River at Gorge, and associated rain gauge hyetographs.

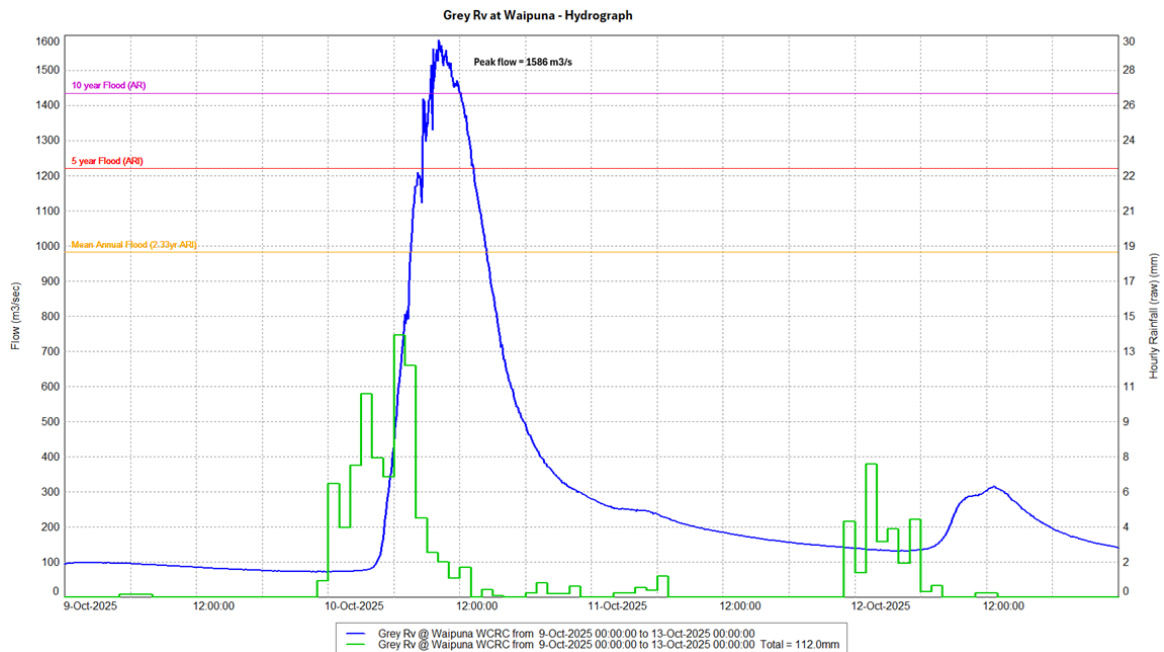
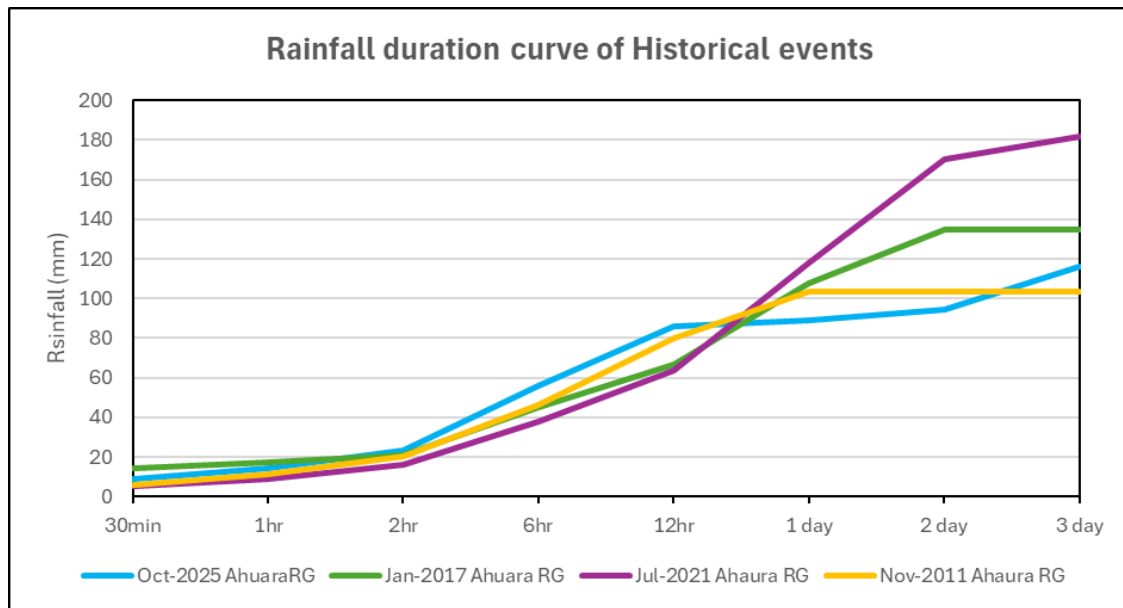


Figure 12: Flow hydrograph for Grey River at Waipuna, and associated rain gauge hyetographs.

Historical Context:

- July 17 2021:** This flood event in the Grey got overshadowed by the Westport flood but still produced some local impacts. This event had a higher peak flow of 4616 m³/s with a return period of 5.1 years. Localised flooding occurred in areas along SH7, particularly at the Stillwater underpass, resulting in road closures
- January 19 2017:** A larger event than July 2021, with a Grey River peak flow of 5010 m³/s (8.8-year ARI). Substantial flows were also recorded at Ahaura (2540 m³/s) and Waipuna (1538 m³/s), both exceeding 10-year return periods.
- November 21 2011:** Most significant flood event in the last 15 years, second biggest flood recorded after the September 1997 event since records began for the Grey River. Peak flow reached 5890 m³/s (39.4 ARI). Flood barriers were erected with significant surface flooding and cattle needing to be rescued from low lying areas.



Appendix

A. Rainfall summary table

Catchment	Rainfall Site	Maximum rainfall intensity		Total rainfall
		mm/30min	mm/1hr	(mm)
Karamea	Aorere Rv @ Perry Saddle (TDC)	6.2	11.2	152
	Cobb @ Trilobite (NIWA)	4.5	6.5	84
	Karamea Rv @ Garibaldi	17.7	29.6	427
	Karamea Rv @ Township	11.2	17.2	174
Mokihinui	Wangapeka @ Biggs Top (TDC)	13	20.5	382
	Mokihinui Rv @ Stoney Ck	19.6	28.1	320
Buller	Orikaka Rv @ Plateau Stm	13.4	19.6	255
	Westport EWS (NIWA)	5.1	10.2	83
	Ohikanui Rv @ Buckland Peaks	NA	NA	NA
	Buller Rv @ Bald Hill	12.3	15.7	123
	Buller Rv @ Three Channel Flat	10	13.2	156
	Matakitaki @ Horse Terrace Br (TDC)	7.5	11.5	152
	Inangahua Rv @ Brunner Range	16.4	19.4	217
	Inangahua Rv @ Landing	9.2	15.6	173
	Reefton @ Township	3.1	5.5	56
	Maruia Rv @ Springs Junction	8.9	14.6	116
Grey	Sirdar Ck @ Paparoa	11.3	18.8	207
	Grey Rv @ Conical Hill	6.3	11.1	91
	Mawheraiti Rv @ Atarau Br	6	11.2	79
	Grey Rv @ Waipuna	9.4	17.3	112
	Ahaura Rv @ Gorge	8.9	14.3	116
	Grey Rv @ Haupiri	8.7	15	130
	Grey Rv @ Ngahere	9.1	11.7	109
	Arnold Rv @ Moana WWTP	10	17.2	122
	Greymouth Aero EWS (NIWA)	10.5	21	74
	Grey Rv @ WCRC Office	11.8	18.4	97
	Pigeon Creek CWS (NIWA)	11.2	22.2	200
Taramakau / Hokitika	Kumara @ School	13.9	22.1	144
	Hokitika EWS (NIWA)	6.8	13.6	90
	Butchers Ck @ Butchers Gully (NIWA)	13.5	20	166
	Styx Rv @ Mt Browning	18.5	26.3	317
	Hokitika Rv @ Gorge	15.9	28.5	253
	Hokitika Rv @ Colliers Ck	13	25.3	255
	Ross @ Township	13.7	18.3	103
	Cropp Rv @ Base	NA	NA	NA
	Cropp Rv @ Waterfall (NIWA)	25	40.5	436
	Tuke Rv @ Tuke Hut (NIWA)	19.5	37.5	350
	Ivory Rv @ Ripplerock (NIWA)	10.5	20	222
Whataroa	Harihari at School	9.9	18.3	116

	Whataroa Rv @ SH6 (NIWA)	11	21	142
	Okarito EWS (NIWA)	6.9	13.8	74
Waiho / Mahitahi	Waiho Rv @ SH6	13.3	24.7	143
	Waiho Rv @ Douglas Hut (NIWA)	15.5	26.5	164
	Mahitahi Rv @ Bruce Bay	11.8	18.5	81
Haast	Haast Rv @ Deelaw	6.9	10.1	87
	Haast Rv @ Cron Ck (NIWA)	14.5	27	198
	Haast Rv @ Roaring Billy	7.2	11.6	125
	Haast Rv @ Roaring Billy (NIWA)	NA	NA	NA
	Haast Rv @ Moa Ck (NIWA)	6.5	11	116

B. Flood observations (photos and extra notes)

C. MetService warnings



Flood Event Report

20–25 October 2025

West Coast Regional Council Hydrology
November 2025

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Contents

Executive Summary.....	7
Event summary	8
Antecedent Conditions:	8
Climate and Atmospheric Drivers	8
Catchment Impacts and Observations.....	9
Karamea	9
Mokihinui	9
Buller	9
Grey.....	9
Westland	10
Waiho / Whataroa	10
Karamea River	14
Rainfall	14
River Response.....	16
Historical Comparisons:	17
2.3. Mokihinui River	20
Rainfall	20
River Response.....	22
First Flood Event – 21 October 2025.....	22
Second Flood Event – 23 October 2025.....	22
Buller	24
Rainfall	24
River Response.....	27
First Flood Event – 21 October 2025.....	27
Second Flood Event – 23–24 October 2025.....	27
Hydrological Characteristics.....	27
Upper Catchment Response – Inangahua River at Blacks Point Township.	29
First Flood Event – 21 October 2025.....	29
Second Flood Event – 24 October 2025.....	29
Grey.....	31
Rainfall	31
River Response.....	33
First Flood Event – 21 October 2025.....	33
Second Flood Event – 23- 24 October 2025.....	34

Comparison against October 10 event:	36
Historical context:	36
Haast River	38
Rainfall	38
River Response.....	40
Hokitika River	43
Rainfall	43
River Response.....	45
Appendix	48
A. Rainfall summary table	48
B. MetService warnings	50
C. Flood Frequency Analysis.....	55

Executive Summary

Between 20 and 25 October 2025, two significant rainfall events affected the West Coast, occurring against a backdrop of already elevated river levels and saturated catchments following persistent wet weather throughout October. The first event on 20–21 October delivered widespread, moderate-to-high rainfall across Westland, Grey, and Buller, closely aligning with MetService Orange Warnings. The second event on 23 October produced lower overall totals but generated renewed rises due to high antecedent flows, with Westland receiving the most intense rainfall during this later system.

Rainfall intensities were strongest across alpine zones, particularly in the Karamea and Westland ranges, where several gauges recorded short- to medium-duration intensities exceeding 5–50 year return periods. In contrast, most coastal and lowland gauges remained below their mean annual thresholds. These spatial patterns drove rapid hydrological responses, with steep, short-duration catchments responding most sharply to the 6–24 hour rainfall bursts.

Rivers across the region peaked predominantly on 21 October, except in Westland, where the highest flows occurred on 23 October. The most significant river responses included the Karamea River ($3007 \text{ m}^3/\text{s}$; >10-year ARI), Grey River at Waipuna ($1711 \text{ m}^3/\text{s}$; 20–50-year ARI), and Buller River at Te Kuha ($5398 \text{ m}^3/\text{s}$; >2-year ARI). Inangahua at Blacks Point exceeded its 10-year ARI, while most Buller tributaries recorded rapid rises consistent with strong inland rainfall. The Mokihinui and Hokitika catchments, despite high rainfall intensities at alpine gauges, remained below their mean annual flood magnitudes. The Haast River was the only Westland river to exceed its mean annual flood, peaking at $4355 \text{ m}^3/\text{s}$ on 23 October. The Waiho River exceeded its first alarm threshold, reaching 8.3 m on 23 October.

Across all catchments, high antecedent river levels, saturated soils, and limited infiltration contributed significantly to runoff efficiency and flood magnitude. Atmospheric drivers—including a predominantly negative Southern Annular Mode influenced by a September stratospheric warming event—supported frequent westerly flows and repeated frontal systems throughout October.

Overall, the October 20–25 period was characterised by widespread but spatially variable rainfall, rapid river responses, and moderate to locally significant flooding in several catchments. The alignment of intense alpine rainfall with already elevated baseflows amplified the hydrological impacts of both events, highlighting the sensitivity of West Coast catchments to multi-day storm sequences and antecedent wet conditions.

Event summary

Two significant rainfall events occurred between 20–25 October following an already wet period on 18–19 October, keeping river levels above median flows across the region. The first event (20–21 October) followed MetService Orange Warnings for Westland, Grey, and Buller, with forecast totals largely aligning with observed rainfall. Grey and Buller experienced shorter-duration, moderate totals, while Westland was exposed to longer-duration rainfall with maxima near 300 mm in alpine areas.

The second event (23 October) produced lower rainfall totals but generated renewed river responses due to elevated antecedent flows. Westland experienced stronger intensities during this later event, resulting in its highest river peaks on 23 October, while Grey and Buller catchments had already peaked on 21 October. Across the week, the most significant rainfall and river responses occurred in the Karamaea, Westland, and alpine regions. Saturated catchments and high baseflows contributed to rapid hydrological responses during both events.

Antecedent Conditions:

Persistent rainfall since September left rivers across the West Coast elevated well above median flows prior to both events. This reduced infiltration capacity and increased runoff efficiency, contributing to the rapid and energetic hydrological responses observed on 21 and 23 October.

Climate and Atmospheric Drivers

A predominantly negative Southern Annular Mode (SAM) in October, influenced by a September stratospheric warming event, favoured frequent westerlies and recurrent frontal systems. This pattern aligned with the sustained wet conditions observed throughout the region

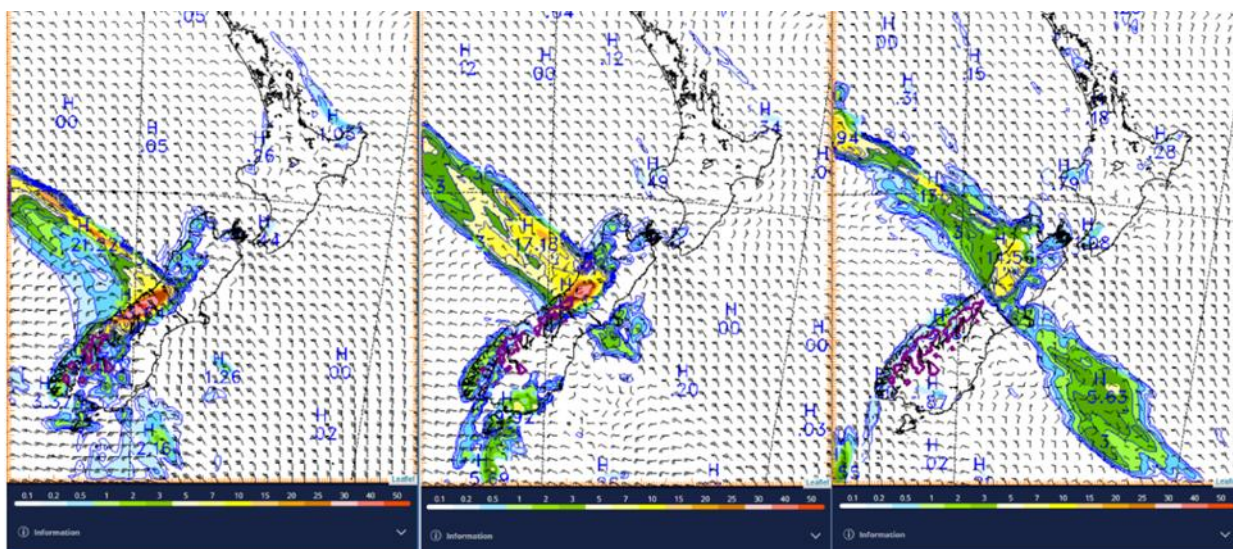


Figure 1: Metservice Rainfall Forecast for Saturday, the rainfall event before the 21st and 23rd Events. This kept river flows above median flows before the 21st.

Catchment Impacts and Observations

Karamea

Rainfall intensities in the Karamea ranges were higher than forecast, with Garibaldi recording extreme 6–12 hr ARIs (50–100+ year). The river peaked at 3007 m³/s on 21 October (>10-year ARI), the highest since 2013. The concentration of rainfall around the alpine zone, rather than coastal areas, likely constrained downstream flooding.

Mokihinui

Mokihinui peaked at 1691 m³/s on 21 October, below its Mean Annual Flood (2.33-year ARI). High intensities at Stoney Creek (6 hr >10-year ARI; 12 hr >20-year ARI) contributed to a sharp early response despite the moderate peak magnitude.

Buller

Most Buller tributaries peaked on 21 October except the Orikaka, which peaked again on 23 October. Rainfall intensities were strongest in the 6–24 hr durations, driving fast rises across small and mid-sized tributaries. Inangahua Landing peaked just below its 5-year ARI, while Blacks Point exceeded the 10-year ARI. The Buller mainstem exceeded its Mean Annual Flood at both Te Kuha and Woolfs.

Grey

Grey catchment rivers recorded moderate to high flows on 21 October, with Waipuna reaching a 20–50-year ARI. Rainfall was generally below Mean Annual thresholds except at a few alpine gauges (e.g., Sirdar Creek), where short-duration bursts reached up to 5-year ARIs. Higher river peaks relative to the 10 October event were primarily due to higher antecedent baseflows.

Westland

Westland had more spatially concentrated intensities during the second event, producing notable river peaks on 23 October. Only the Haast River exceeded its Mean Annual Flood, peaking at 4355 m³/s (3–3.4-year ARI). Despite strong short-duration rainfall at Cropp and Hokitika Gorge, most rivers remained below 2.33-year ARIs.

Waiho / Whataroa

Waiho exceeded its first alarm threshold on 23 October (8307 mm). Only Waiho SH6 and Douglas exceeded their 2.33-year ARI at 12 hours, with Douglas also surpassing the 5-year ARI for 6–12 hours.

Table 1: minimum and maximum rainfall totals and hour intensities per catchment.

Catchment	Rainfall intensity				Total rainfall (mm)	
	30 minute (mm/0.5hr)		Hourly (mm/hr)		Minimum	Maximum
	Minimum	Maximum	Minimum	Maximum		
Karamea	3.7	20.9	4.5	35.4	46	411
Mokihinui	14.3	17	26.7	30.5	307	385
Buller	2.4	13	4.8	24	47	218
Grey	6.1	19.7	10.5	36.8	106	282
Taramakau / Hokitika	4.7	38	9.4	62.5	107	734
Whataroa	7.6	17	15.2	33.5	180	310
Waiho / Mahitahi	2.4	23.5	25.2	40	314	502
Haast	17	34.3	27.5	64.1	346	504

Table 2: peak level and flow and annual return interval per river monitoring station.

River / Location of main gauge	Date and time of peak	Peak level (mm)	Peak flow (m ³ /s)	Estimated return period (years)	Record (years)
Karamea River / Gorge	21/10/2025 14:25	5867	3007	>10 to <20	48
Mokihinui River / Welcome Bay	21/10/2025 13:35	5837	1691	>1.5 to <1.6	34
Buller River / Te Kuha	21/10/2025 19:25	9922	5398	>2.9 to <3.3	62
Grey River / Dobson	21/10/2025 17:40	5751	4740	>5.9 to <6.7	56
Hokitika River / Gorge	23/10/2025 12:55	4774	1918	>1.2 to <1.4	28
Whataroa River / SH Bridge	23/10/2025 12:35	4560	2078	<1.3	38
Waiho River / SH Bridge*	23/10/2025 12:30	8307	NA	NA	10
Haast River / Roaring Billy	23/10/2025 12:15	6393	4355	>3.0 to <3.4	54

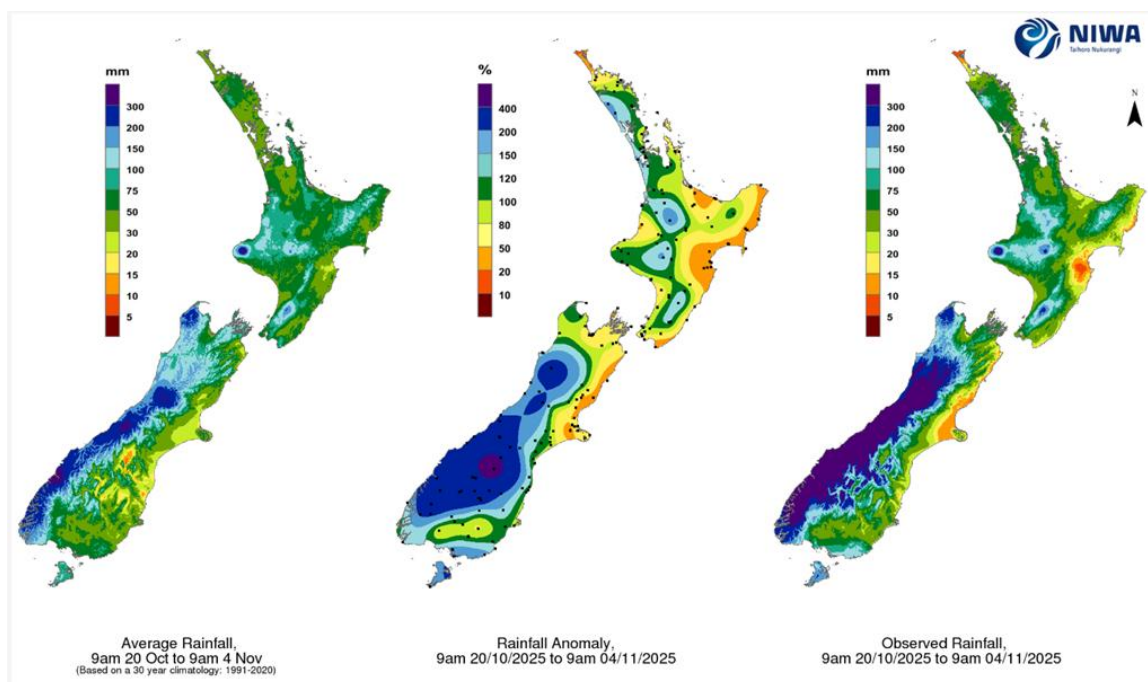


Figure 2: Average accumulation for the region from 20th October to 4th November 2025. Highlighting a wet west coast region. Graph obtained From Earth Science NZ, ESNZ, (formerly known as NIWA) website (https://shiny.niwa.co.nz/drought-forecast/?_gl=1*17o62he*_ga)

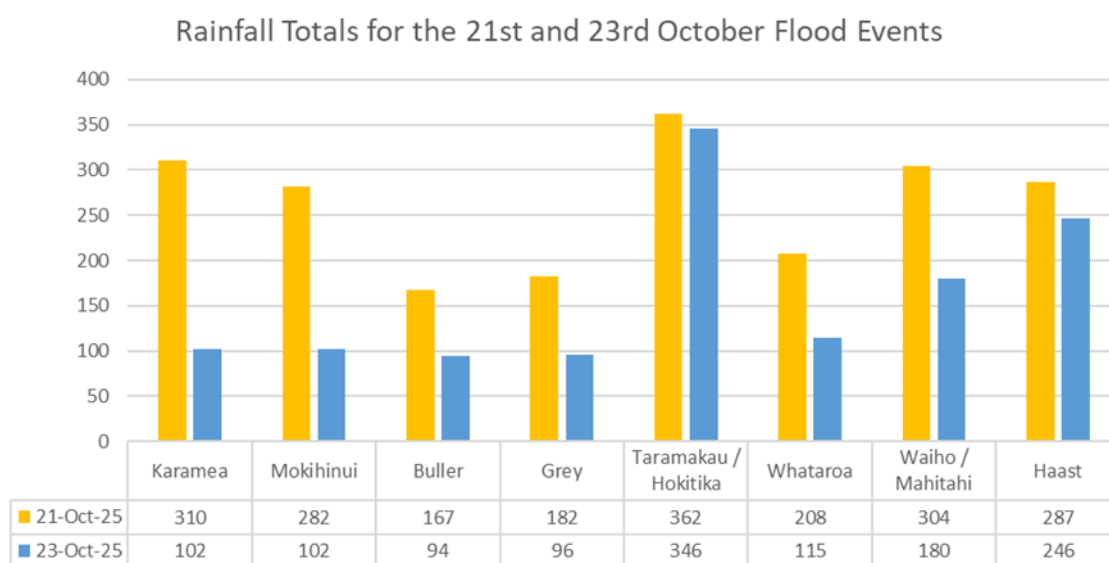


Figure 3: Summary of Maximum Rainfall totals recorded by a gauge in each catchment during the flood events on the 21st and 23rd October 2025.

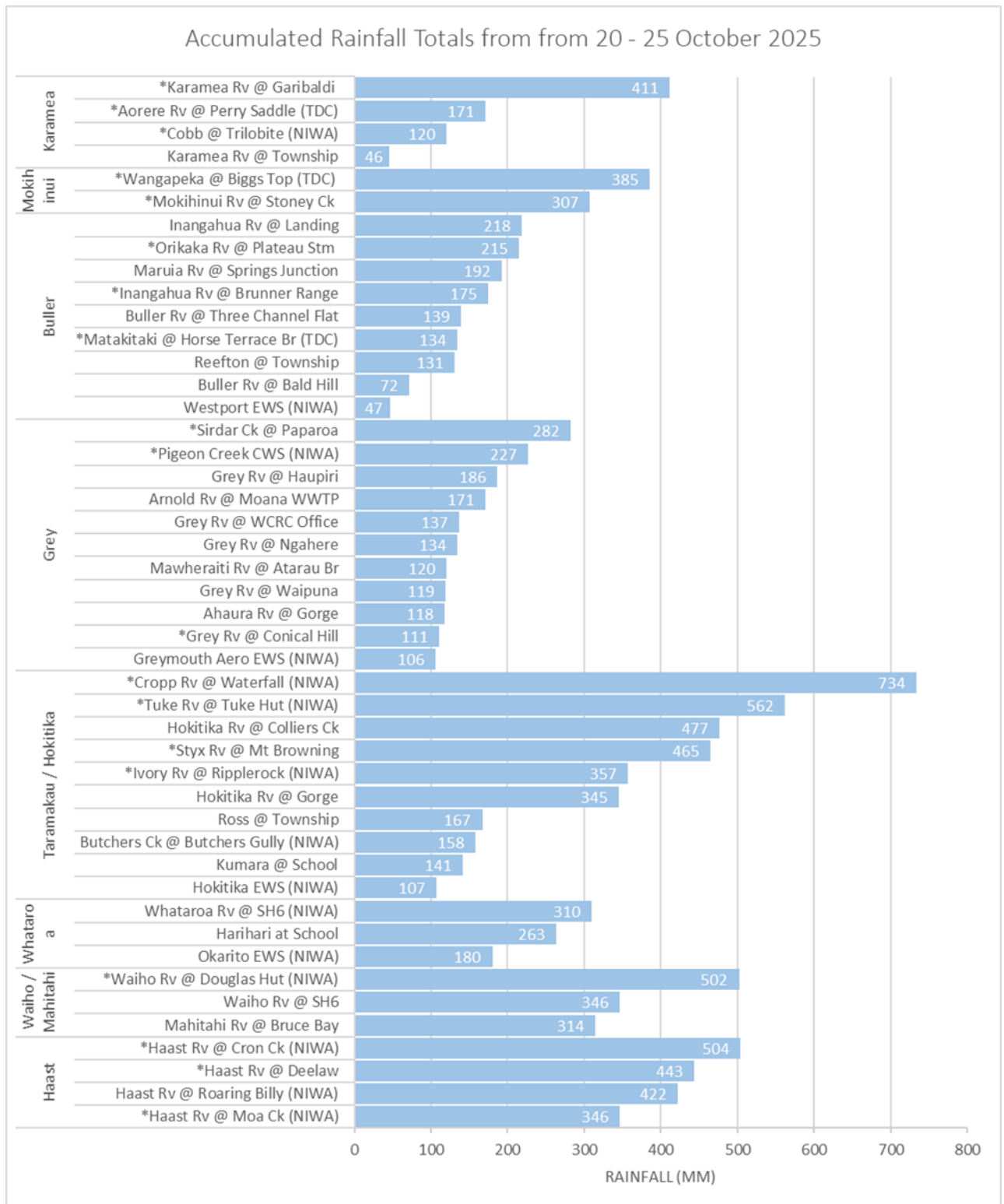


Figure 4: Bar graph of overall Rainfall totals from 20th to 25th October. Alpine sites are marked as *, as these sites generally have higher Rainfall totals than coastal/low land sites.

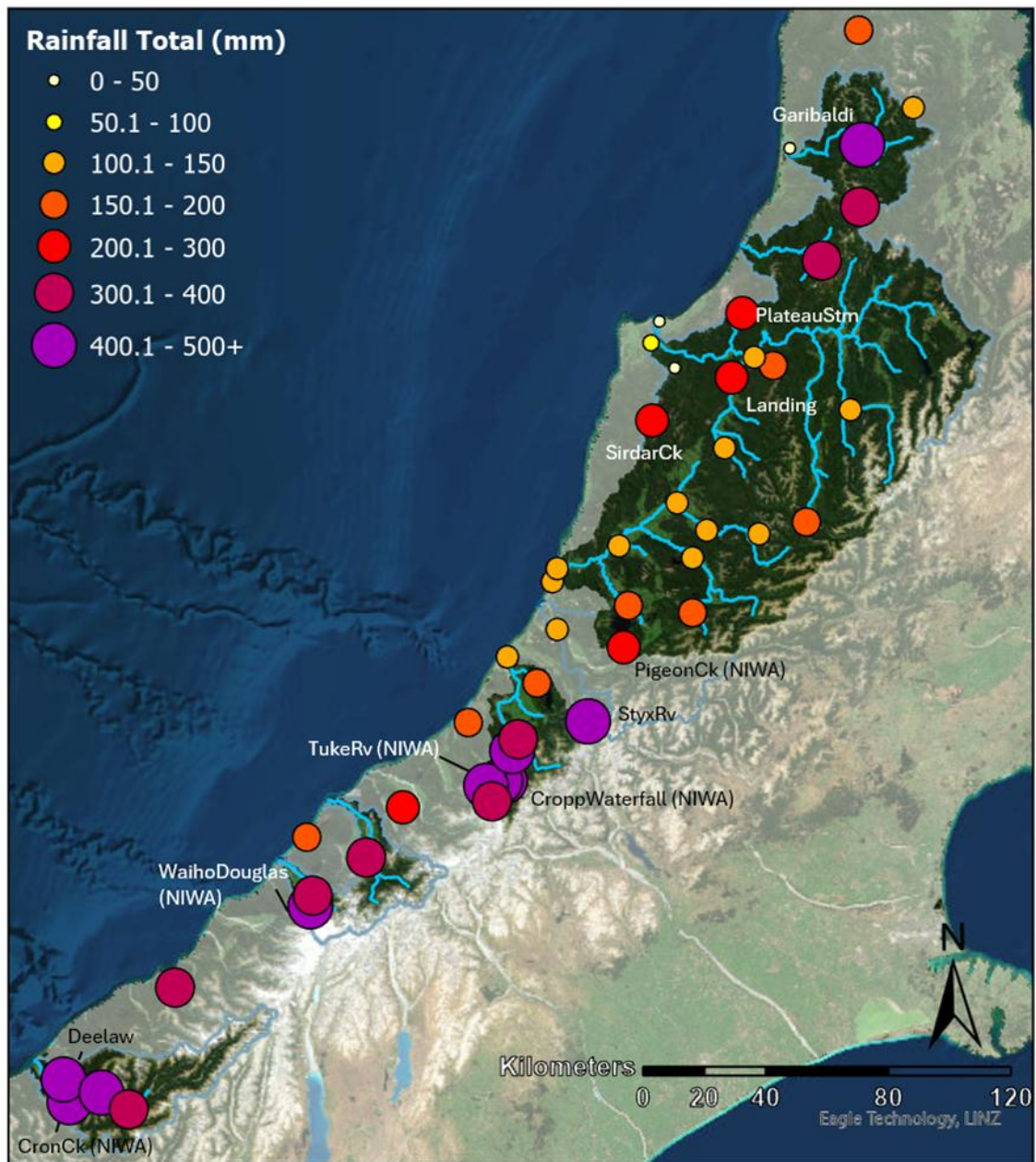


Figure 5: Map of total rainfall accumulation for the period from 20th to 25th October in the West Coast.

Karamea River

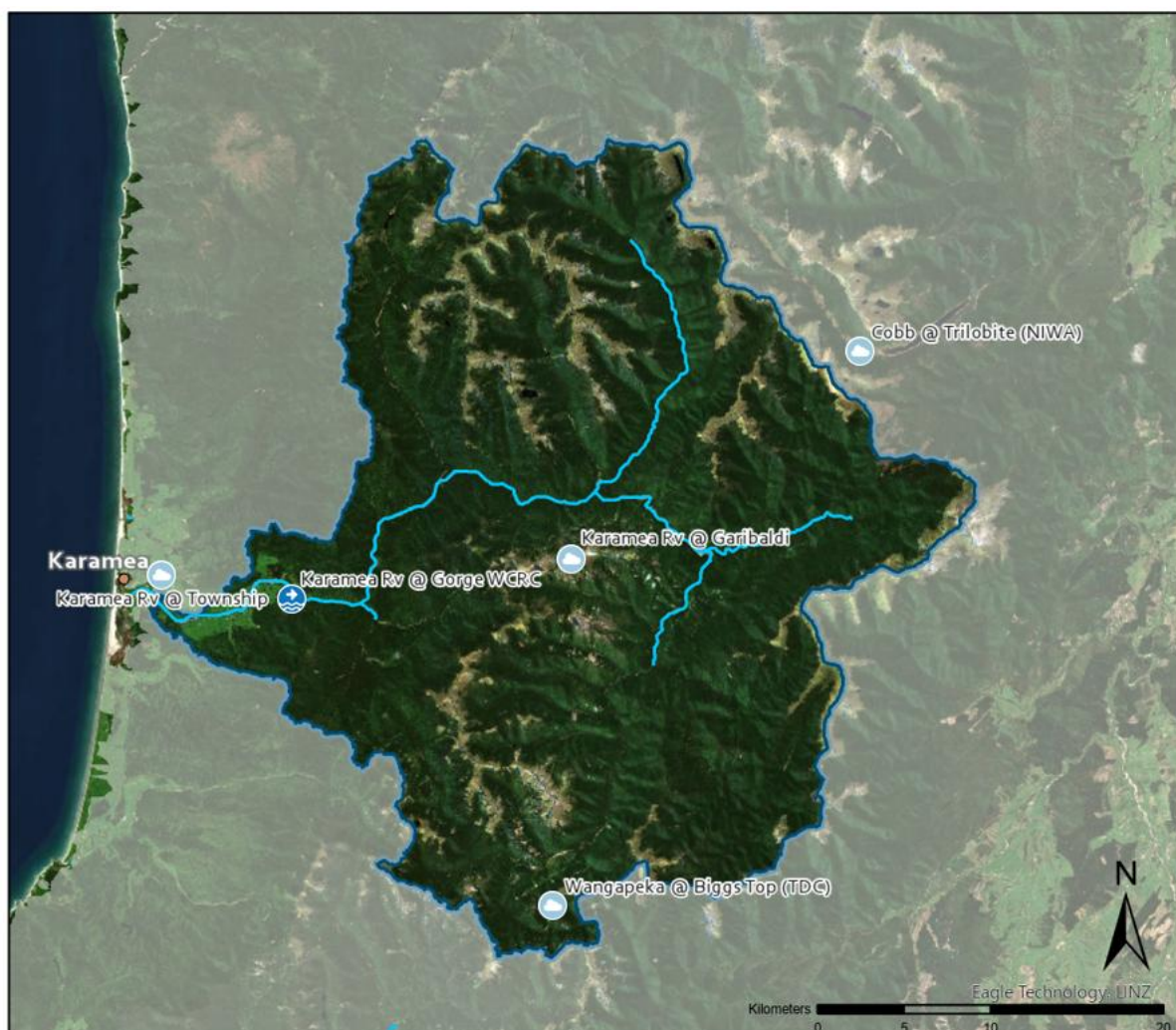


Figure 6: Map of Karamea River catchments with Hydrometric network locations

Rainfall

Higher-than-forecast rainfall intensities were observed in the Karamea catchment, particularly at the Karamea River at Garibaldi alpine gauge and Wangapeka at Biggs Tops (TDC site). The Garibaldi gauge recorded notably high intensities over multiple durations, including:

- 2-hour duration: > 10-year ARI
- 6-hour duration: > 50-year ARI
- 12-hour duration: > 100-year ARI

The minimum ARI recorded at Garibaldi during this event was 5 years.

At Wangapeka at Biggs Tops, the 12-hour duration exceeded the 20-year ARI, with most durations ranging from 2.3 to <10-year ARI.

In contrast, Karamaea at Township did not exceed its Mean Annual ARI, consistent with other lower Buller and coastal sites, which also remained below their Mean Annual thresholds.

With the heaviest rainfall occurring around the ranges rather than coastal areas the river discharge was likely helped, possibly reducing the potential for severe flooding downstream as was the case with the Ocotber 2013 event.

Table 3: Rainfall intensities and totals recorded in the Karamaea catchment and their annual return intervals (ARI).

Site	Record (years)	Maximum rainfall (mm)								
		30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Tot
PerrySaddle (TDC)	HIRDS	12.8	20.4	33.1	70.9	122.3	133	133	171	1
Cobb (NIWA)	HIRDS	10.5	17	24.5	49	85.5	93	93	120.5	12
Garibaldi	HIRDS	20.9	35.4	68	170.3	274.8	309.1	310.6	405.3	4
KaramaeaTownship	HIRDS	3.7	4.5	7.2	14.7	23.5	32	33	45.5	4
Wangapeka (TDC)	HIRDS	17	30.5	59	139	254.5	282.5	283.5	382.5	38

ARI (years)	2.0	5	10	20	50	100	250
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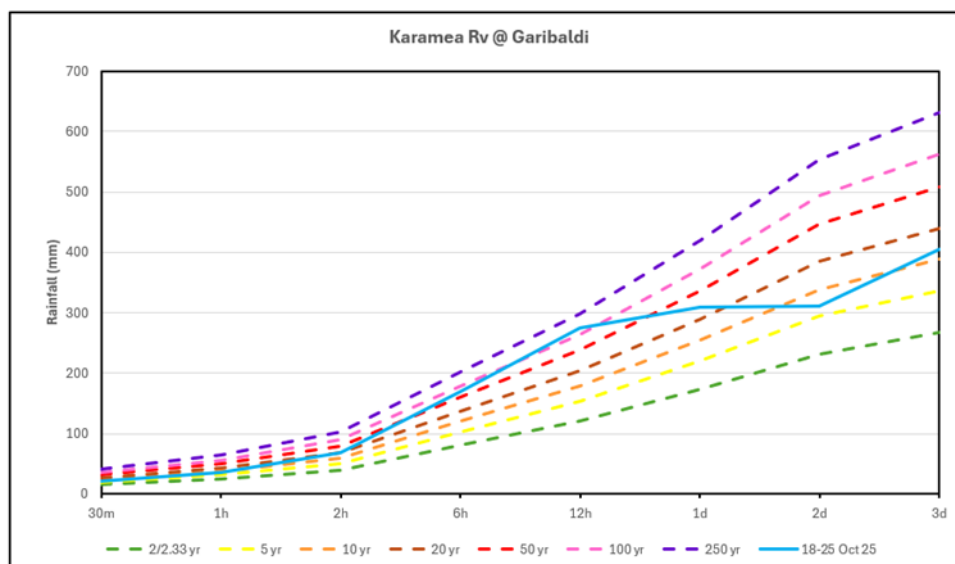


Figure 7: Graph of rainfall duration curves (max intensities for each duration) recorded at the Karamaea Rv at Garibaldi gauge from 20th - 25th October 2025.

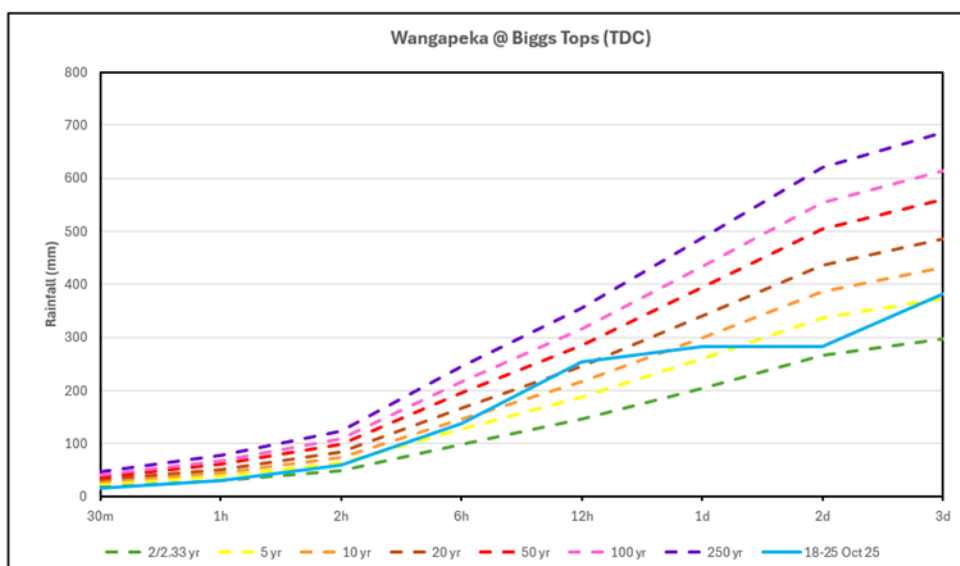


Figure 8: Graph of rainfall duration curves (max intensities for each duration) recorded at the Wangapeka at Biggs Tops (TDC) gauge from 20th - 25th October 2025.

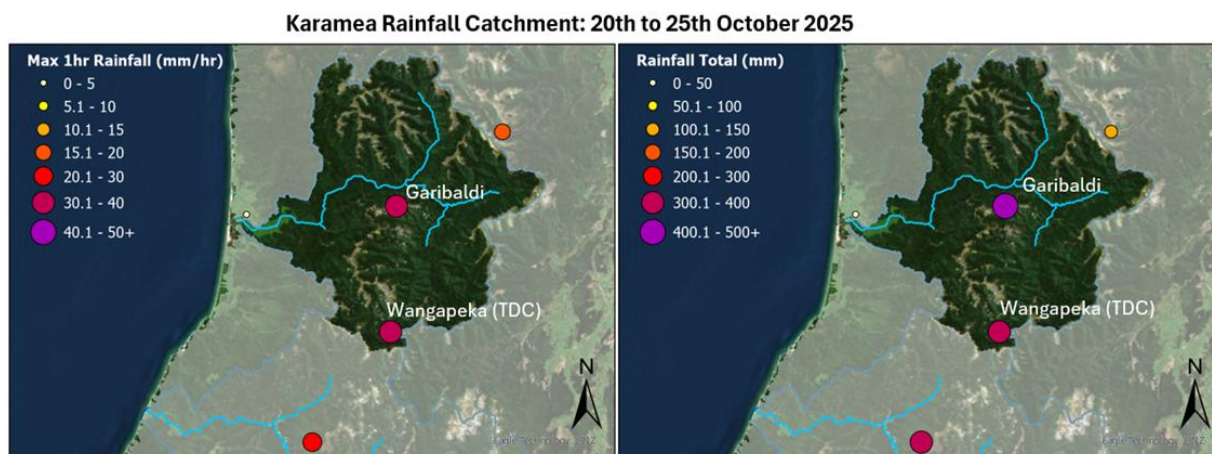


Figure 9: Distribution of peak rainfall intensities and totals across the Karamaea River Catchment rain gauge network

River Response

The Karamaea River recorded a peak level and flow on 21 October, reaching 5867 mm and 3007 m³/s, exceeding the 10-year return period for flow. The last comparable event occurred on 14 October 2013, when the river peaked at 3280 m³/s, exceeding the 20-year return period.

Table 4: Peak river flows and levels recorded in the Karamaea river catchment

Monitoring site	Date and time of peak	Peak water level (mm)	Peak flow (m ³ /s)	Return period	Record (years)
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Karamea Rv at Gorge	21/10/2025 14:25	5867	3007	>10 to <20	48
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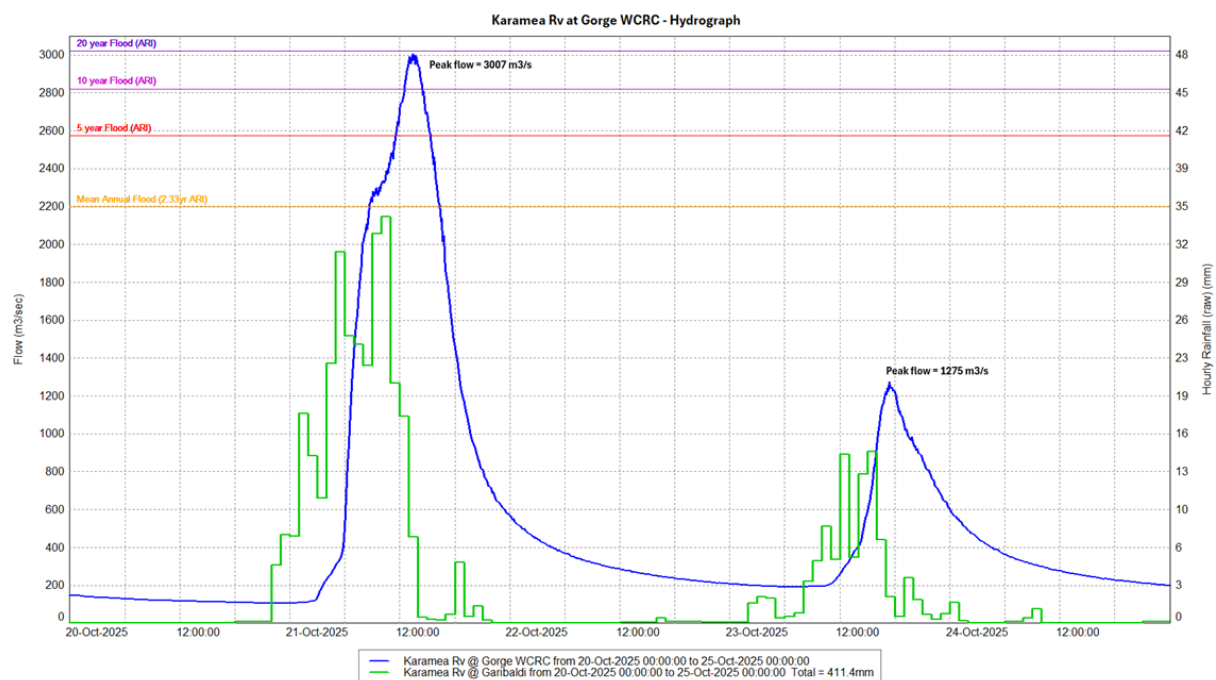


Figure 10: Flow hydrograph of the Karamea river at Gorge with hourly rainfall intensities from Karamea river at Garibaldi rain gauge.

Historical Comparisons:

Both October 2013 and October 2025 recorded above-median flows for the Karamea River, driven by a series of rainfall events that elevated baseflows throughout the month. Prior to the 14 October 2013 event, river levels were higher than they were at the start of the 21 October 2025 event.

Rainfall totals and intensities were lower in the October 2013 event compared with October 2025. However, the historical comparison indicates that the lead-up to the 14 October 2013 event included a longer and more recent period of rainfall, whereas the preceding rainfall before the October 2025 event was shorter in duration and occurred further in advance (**Error! Reference source not found.**).

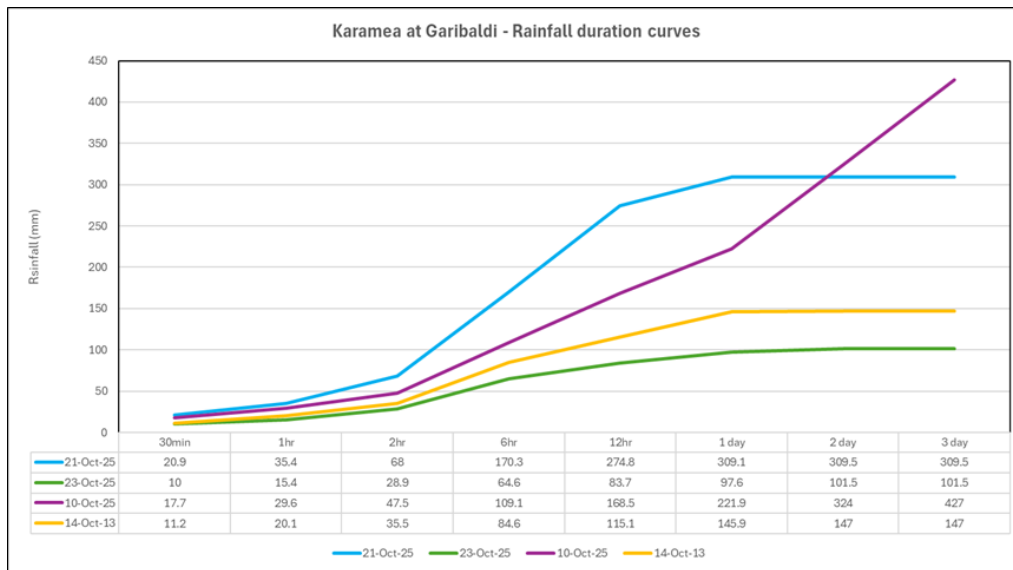


Figure 11: Rainfall duration curves for Karamea river at Garibaldi for the October 10, 21 and 23 events compared to the historical October 14th, 2013 event. Includes a table with max totals for each duration period.

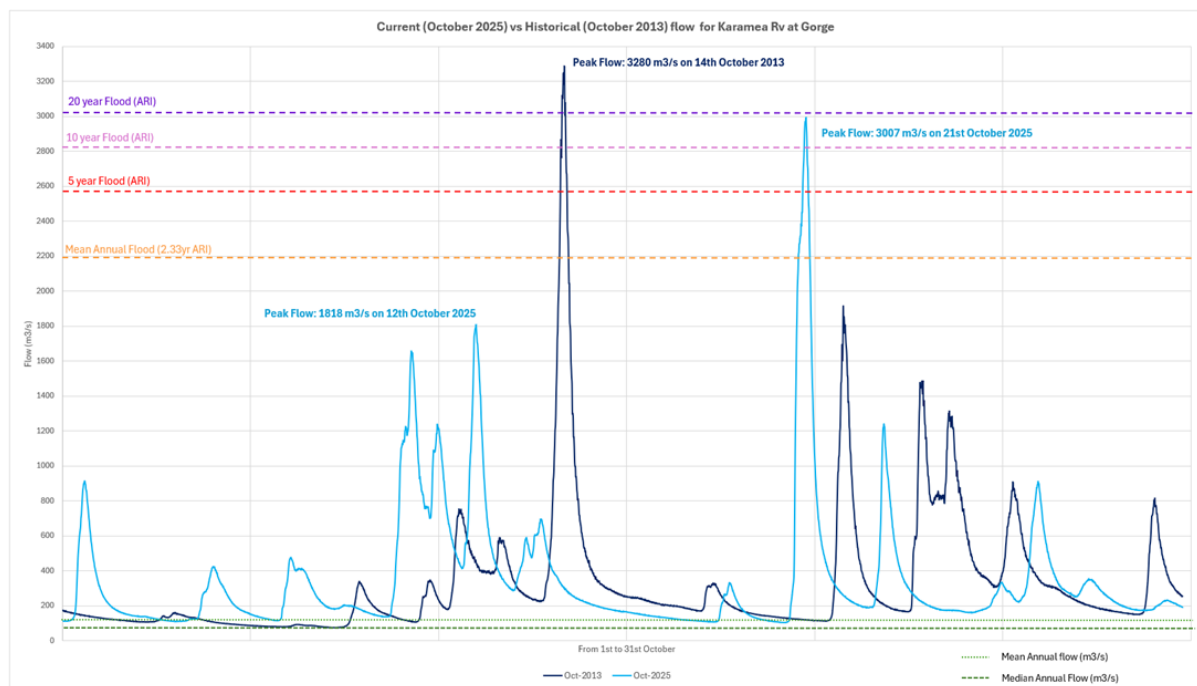


Figure 12: Flow Hydrographs for the Karamea river at Gorge comparing flows in October 2025 and October 2013 with ARI, Mean and Median thresholds included.

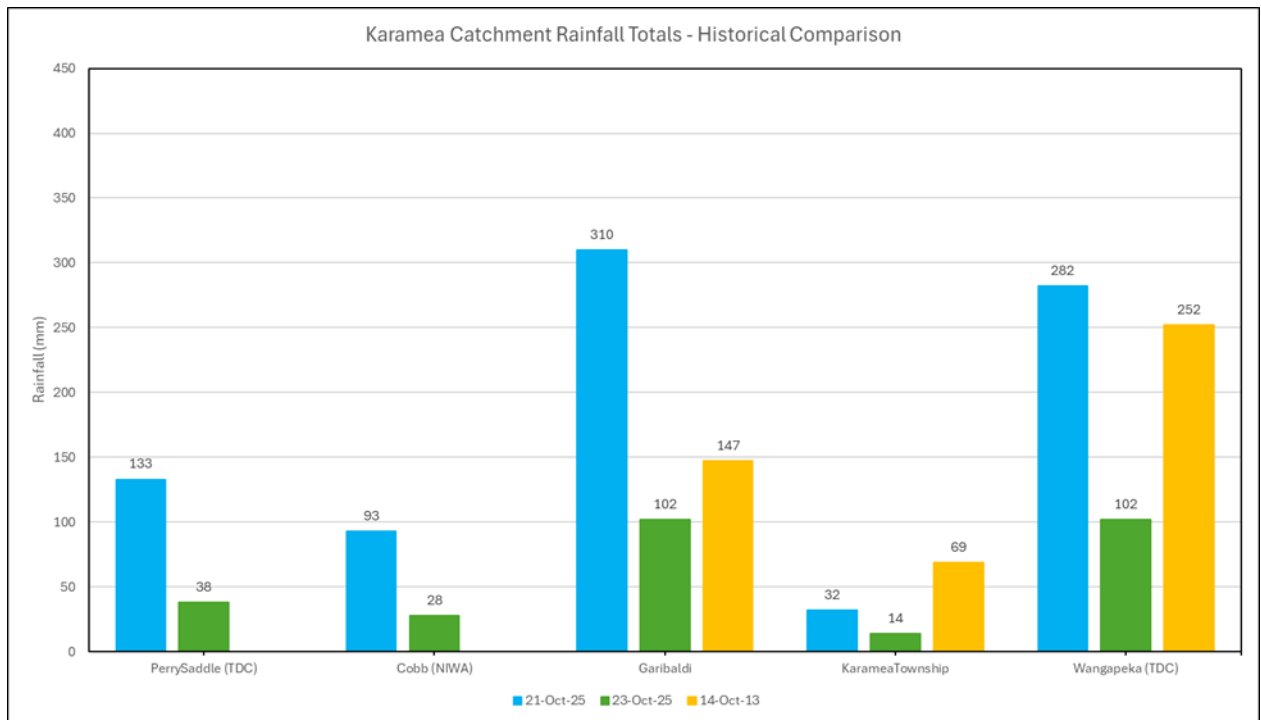


Figure 13: Rainfall totals for Karamea river at Garibaldi for the October 21 and 23 events compared to the historical October 14th, 2013, event.

2.3. Mokihinui River



Figure 14: Map of Mokihinui River catchments with Hydrometric network locations

Rainfall

High rainfall intensities were also observed in the Mokihnui river catchment. The Stoney Ck gauge recorded notably high intensities over a couple of durations:

- 6-hour duration: > 10-year ARI
- 12-hour duration: > 20-year ARI

At Wangapeka at Biggs Tops, the 12-hour duration exceeded the 20-year ARI, with most durations ranging from 2.3 to <10-year ARI.

Table 5: Rainfall intensities and totals recorded in the Karamea catchment and their annual return intervals (ARI).

Site		Maximum rainfall (mm)
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	Record (years)	30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Total
Wangapeka (TDC)	HIRDS	17	30.5	59	139	254.5	282.5	283.5	382.5	385
MokihinuiStoney	9 yrs	14.3	26.7	51.6	128.2	206	216.3	218.5	305	307

ARI (years)	2.0 / 2.33	5	10	20	50	100	≥ 200
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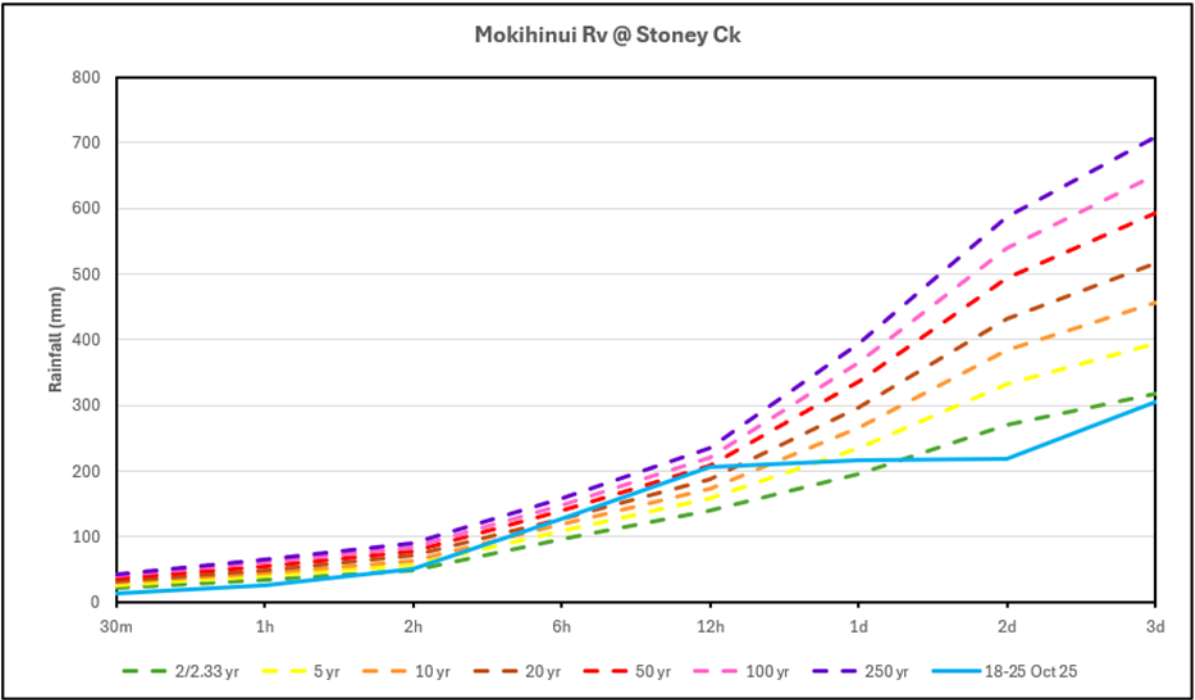


Figure 15: Graph of rainfall duration curves (max intensities for each duration) recorded at the Mokihinui Rv at Stoney Ck gauge from 20th – 25th October 2025.

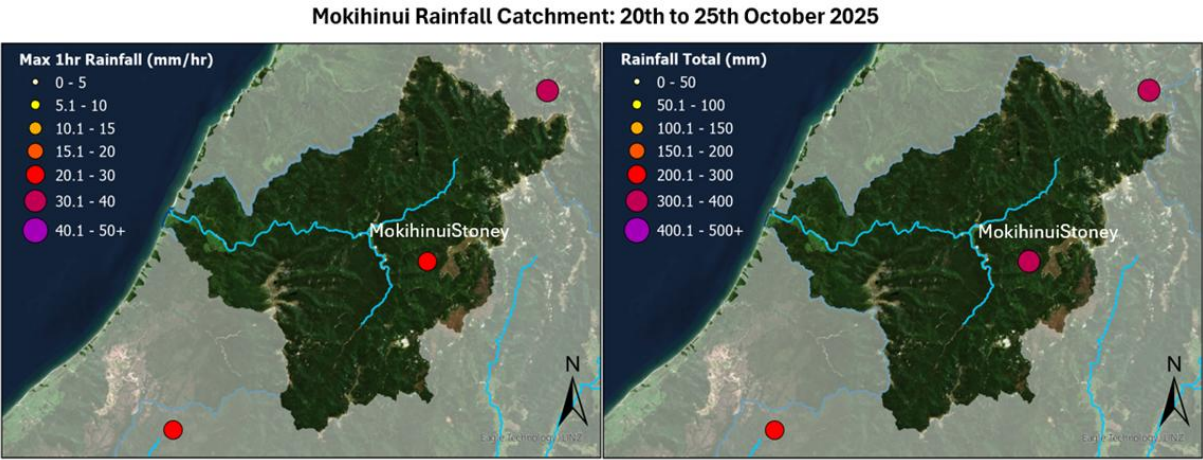


Figure 16: Distribution of peak rainfall intensities and totals across the Mokihinui River Catchment rain gauge network

River Response

First Flood Event – 21 October 2025

The Mokihinui River hydrograph shows two distinct flood responses to successive rainfall events, both characterised by rapid rises and sharp, well-defined peaks typical of a steep, responsive catchment. The first event on 21 October produced the larger peak, reaching 1,691 m³/s following a concentrated burst of rainfall at Stoney Creek. The hydrograph displays an exceptionally steep rising limb, with flows increasing from base levels to peak discharge within several hours, indicating highly efficient runoff generation and limited catchment storage. The equally rapid recession that follows reflects fast drainage pathways and minimal attenuation, consistent with the Mokihinui's rugged topography.

Second Flood Event – 23 October 2025

The second event on 23 October generated a smaller peak of 1,216 m³/s but followed a similar hydrological pattern. Despite lower rainfall totals, the river responded quickly due to elevated antecedent moisture from the earlier event, with the rising limb again closely aligned with the timing of the heaviest rainfall. The catchment's rapid rise and fall during both events highlight its flashy behaviour, where intense but short-duration rainfall quickly translates to significant flow increases. Overall, the hydrograph demonstrates that the Mokihinui is highly sensitive to rainfall intensity and antecedent conditions, with limited floodplain storage and rapid runoff routing driving pronounced peaks during multi-day storm sequences.

Table 6: Peak river flows and levels recorded in the Mokihinui river catchment

Monitoring site	Date and time of peak	Peak water level (mm)	Peak flow (m ³ /s)	Return period	Record (years)
Mokihinui Rv at Welcome Bay	21/10/2025 13:35	5837	1691	>1.5 to <1.6	34

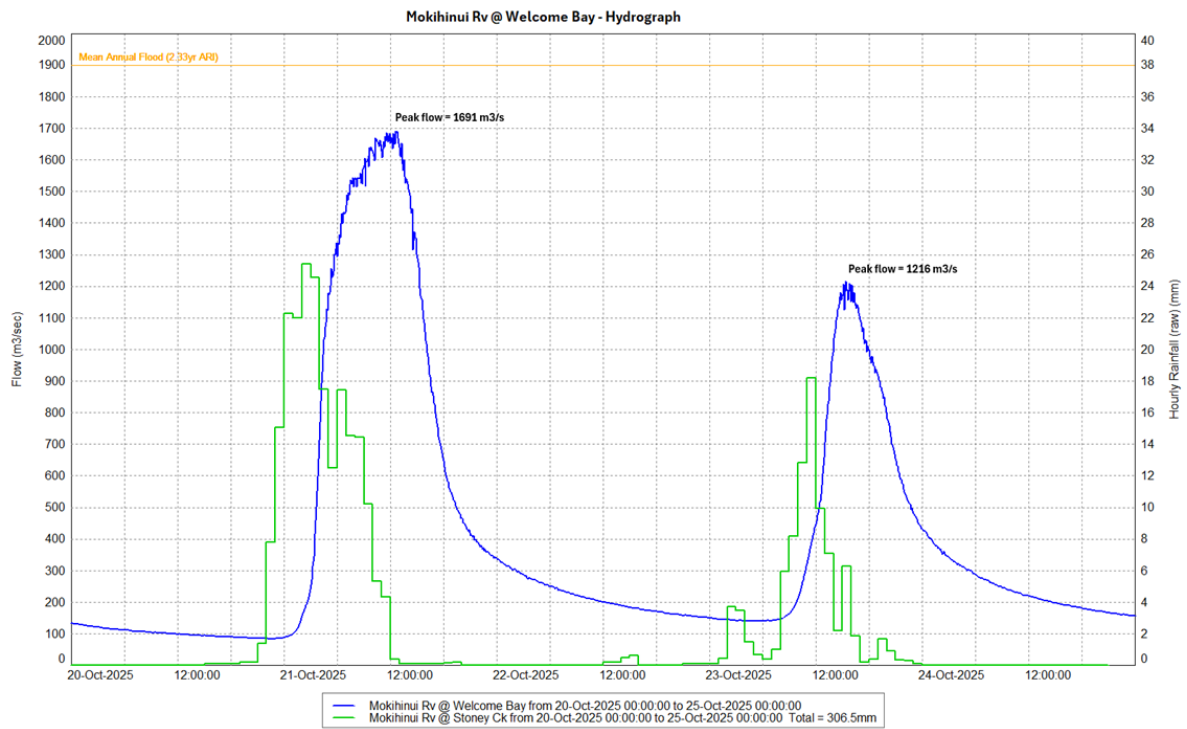


Figure 17: Flow hydrograph of the Mokihinui Rv at Welcome Bay with hourly rainfall intensities from Mokihinui Rv at Stoney Ck rain gauge.

Buller



Figure 18: Map of Buller River catchments with Hydrometric network locations.

Rainfall

Significant rainfall intensities were recorded at the 6-hour and 12-hour durations across most rain gauges in the Buller catchment. Notably, Inangahua River at Landing recorded a 12-hour intensity exceeding its 20-year return period. Coastal sites further from the ranges did not exceed their Mean Annual Flood Return Period (≈ 2.3 -year ARI).

Both the summary table and rainfall duration curves show that the highest rainfall intensities occurred over the 6–24-hour durations. This likely contributed to a relatively rapid river response, particularly in smaller rivers and tributaries, which rose quickly during the event.

Table 7: Peak River flows and levels recorded in the Buller river catchment.

Monitoring site		Date and time of peak	Peak water level (mm)	Peak flow (m ³ /s)	Return period	Record (years)
Buller Rv at Te Kuha		21/10/2025 19:25	9922	5398	>2.9 to <3.3	62
	Buller Rv at Woolfs	21/10/2025 18:05	6705	3542	>3.8 to <4	61
	Buller Rv at Longford	21/10/2025 15:30	5864	N/A	NA	NA
	Matakitaki at Horse Terrace Bridge	21/10/2025 13:20	2547	N/A	NA	NA
	Orikaka Rv at Gorge	23/10/2025 13:45	3247	372	NA	5
	Inangahua Rv at Landing	21/10/2025 12:50	5416	1793	>4 to 4.3	62
	Inangahua Rv at Blacks Pt	21/10/2025 10:45	3949	612	>10 to <12.6	48
	Maruia Rv at Lower Maruia Br*	21/10/2025 15:30	10201	1748	NA	<5

Table 8: Rainfall intensities and totals recorded in the Buller catchment and their annual return intervals (ARI).

Site	Record (years)	Maximum rainfall (mm)								
		30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Total
PlateauStm	HIRDS	13	20.3	32.3	67.1	107.7	119.5	121.5	212.6	215
Westport (NIWA)	HIRDS	2.4	4.8	8.2	13.4	20.2	24.8	25.4	44.6	47
*Buckland	NA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BaldHill	HIRDS	4.9	7.2	12.1	19.4	30.8	37	38.5	69	72
ThreeChannel	HIRDS	7.5	11.6	18.9	49.6	91.9	94.5	95	137.5	139
Matakitaki (TDC)	HIRDS	7.5	13	22	43.5	82.5	85	85	132	134
BrunnerRange	HIRDS	9	15.1	22.9	62.7	108.8	113.5	116	167.3	175
Landing	HIRDS	13	24	40.6	104.1	164.4	167	167.5	216	218
Reefton	HIRDS	9.8	15.5	26.9	47.8	67.3	69.5	71	128.5	131
SpringsJunction	HIRDS	9.6	15.8	27.1	64.9	104.3	110.6	116.5	185.3	192

* No data available for Bucklands as gauge was offline during event.

ARI (years)	2.0	5	10	20	50	100	250
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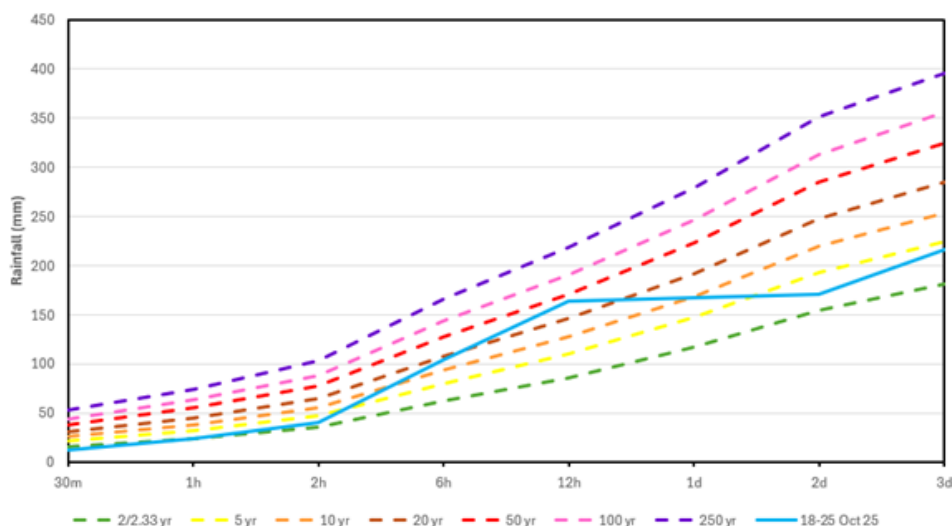


Figure 19: Graph of rainfall duration curves (max intensities for each duration) recorded at the Inangahua Rv at Landing gauge from 20th - 25th October 2025.

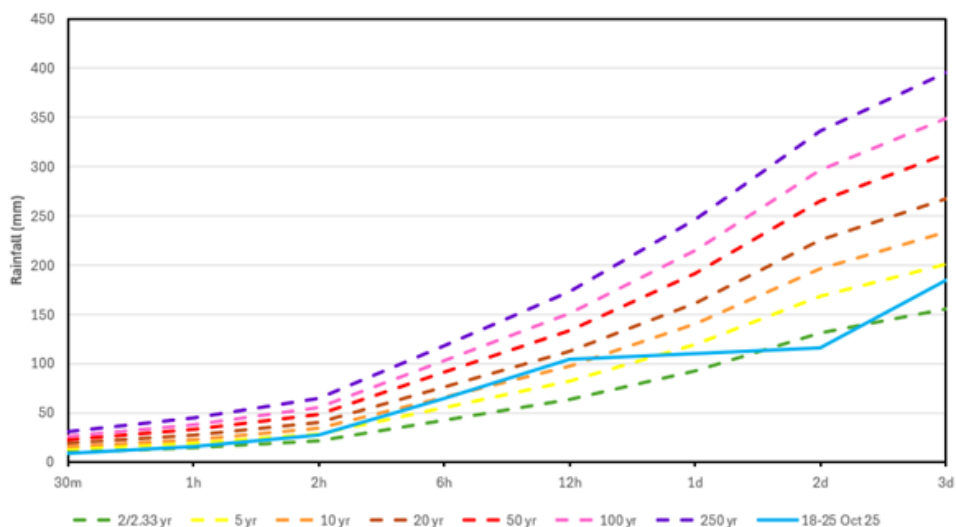


Figure 20: Graph of rainfall duration curves (max intensities for each duration) recorded at the Maruia Rv at Springs Junction gauge from 20th - 25th October 2025.

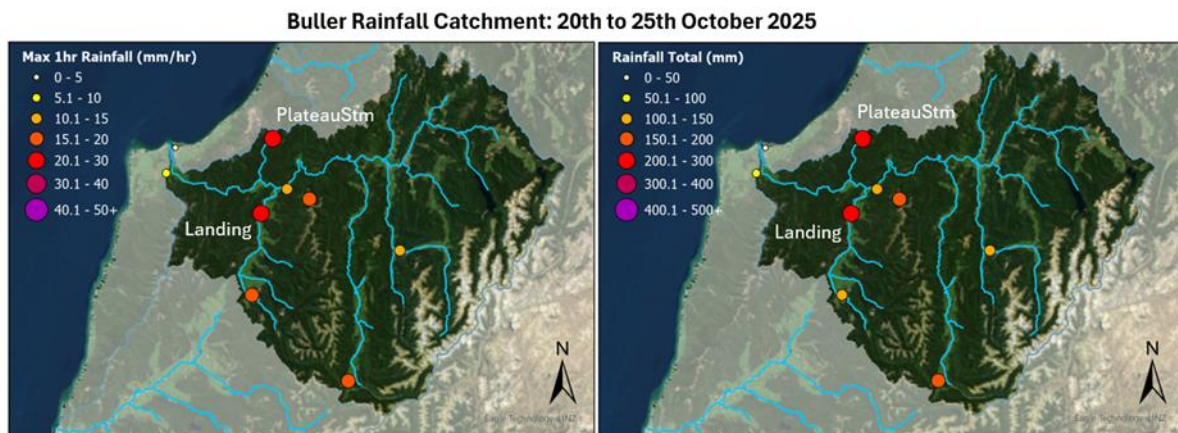


Figure 21: Distribution of peak rainfall intensities and totals across the Buller River Catchment rain gauge network

River Response

First Flood Event – 21 October 2025

The hydrographs for the Buller River shows a coherent catchment response—each tributary peaking within a few hours of one another, driving a sharp, single-peaked flood wave at Te Kuha.

Rapid rises and short lag times indicate antecedently wet soils and steep tributary inflows, consistent with the heavy rainfall recorded on 20–21 October.

Second Flood Event – 23–24 October 2025

This second event likely reflects a secondary front passing over already saturated catchments.

Although rainfall totals were lower, the catchment's reduced infiltration capacity and high antecedent flow levels produced another substantial but lower-magnitude flood pulse.

Hydrological Characteristics

- Both floods exhibit short response times (12–18 hours from onset to peak) and rapid recessions, typical of the Buller system under moist northwest storm patterns.
- The near-simultaneous tributary peaks demonstrate a highly integrated hydrological network, with limited flood attenuation between upper and lower catchments.
- The first event's peak (Te Kuha: 5398 m³/s) places it among moderate regional floods, comparable to ~3-year recurrence interval magnitudes.
- The second flood's lower but quick response confirms persistent catchment wetness and multiple frontal systems during this period.

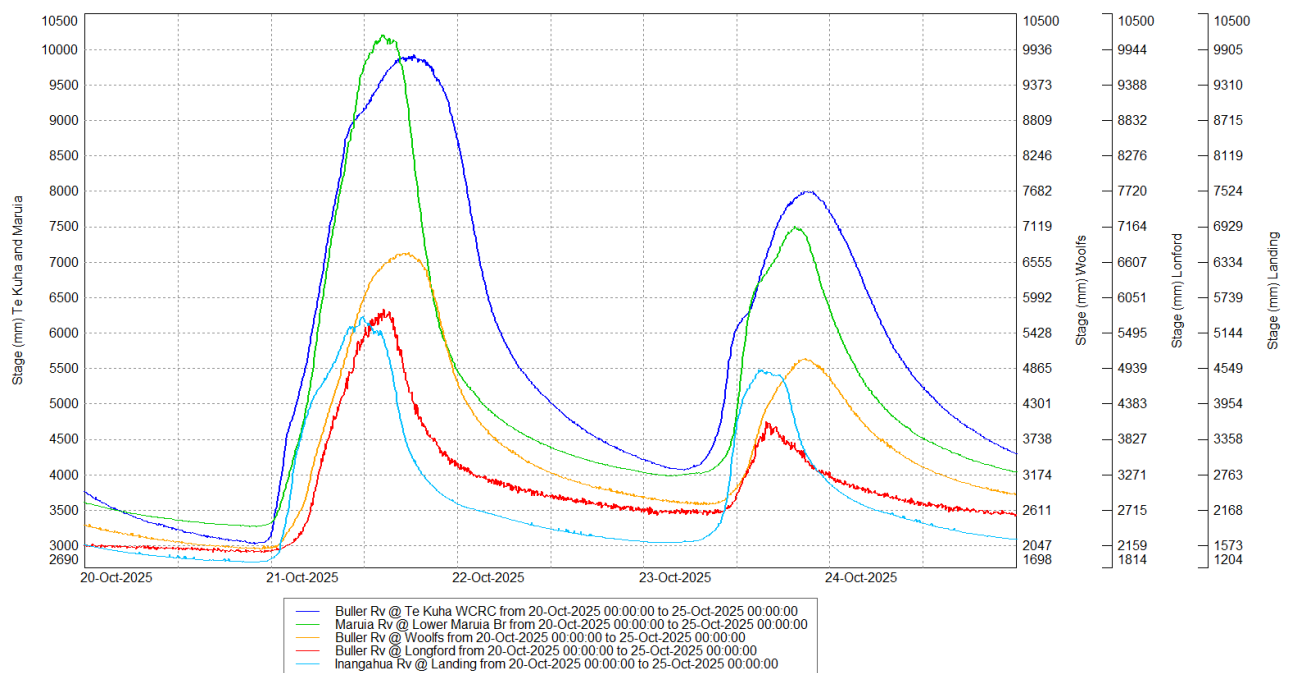
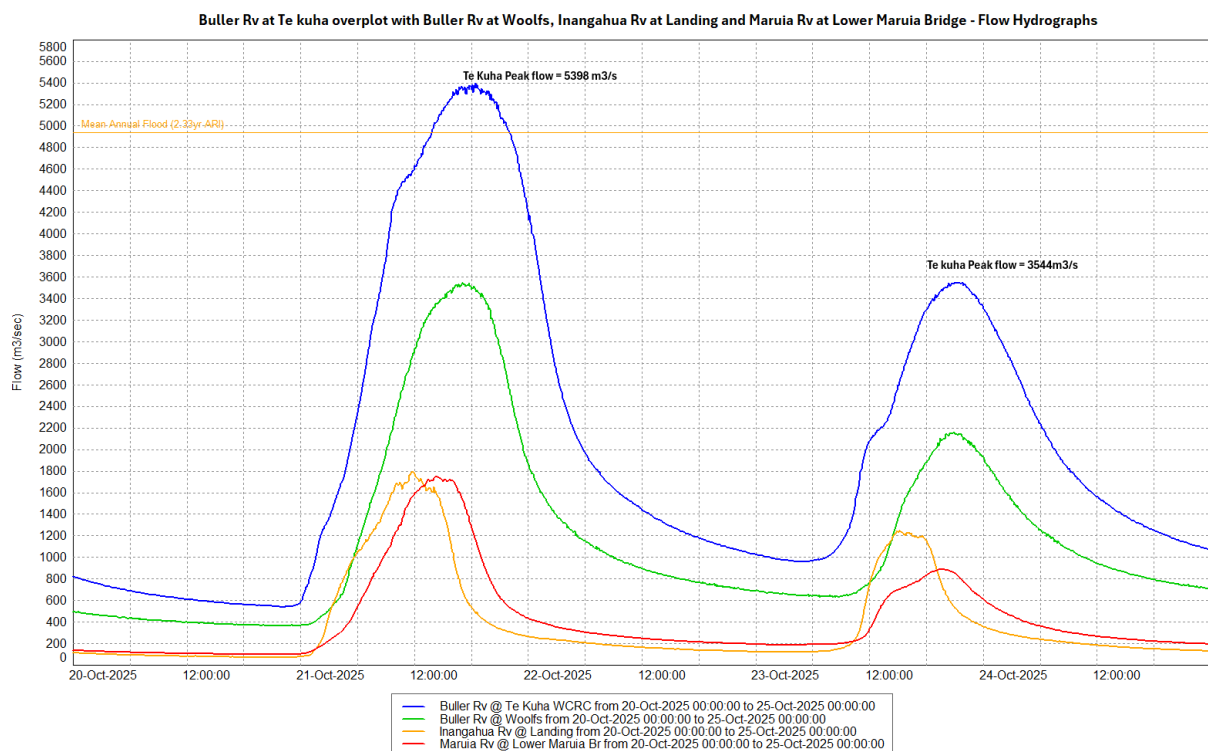


Figure 22: Stage Hydrographs for key flow sites on the main stem of the Buller River.



Upper Catchment Response – Inangahua River at Blacks Point Township.

First Flood Event – 21 October 2025

The first flood event on 21 October 2025 reached a peak flow of $612 \text{ m}^3/\text{s}$, corresponding to an estimated 10-year ARI. The main rainfall burst occurred overnight on 20 – 21 October, with hourly intensities exceeding 25 – 30 mm/hr at Brunner Range and Springs Junction. The hydrograph shows an extremely sharp rise, with flows increasing from under $50 \text{ m}^3/\text{s}$ to over $600 \text{ m}^3/\text{s}$ within approximately 8–10 hours. The peak coincided closely with the end of the heaviest rainfall, indicating a fast, efficient runoff response typical of the steep Inangahua catchment. A rapid recession over the subsequent 12 hours further reflects short storage times and well-drained catchment conditions.

Second Flood Event – 24 October 2025

This event was characterised by short-duration, high-intensity rainfall that generated rapid runoff and localised flooding, aligning with widespread regional peaks recorded across the Buller and Grey catchments on the same date. The river reached a peak flow of $464 \text{ m}^3/\text{s}$, equivalent to a ~5-year ARI flood, following 90–120 mm of rainfall between 23–24 October, primarily over the Brunner and Maruia sub catchments. The hydrograph displays a broader rising limb than the first event, indicating lower intensity but more sustained rainfall. Despite the lower totals, the catchment's antecedent wetness enabled efficient runoff, producing a relatively high peak flow even under more moderate rainfall conditions.

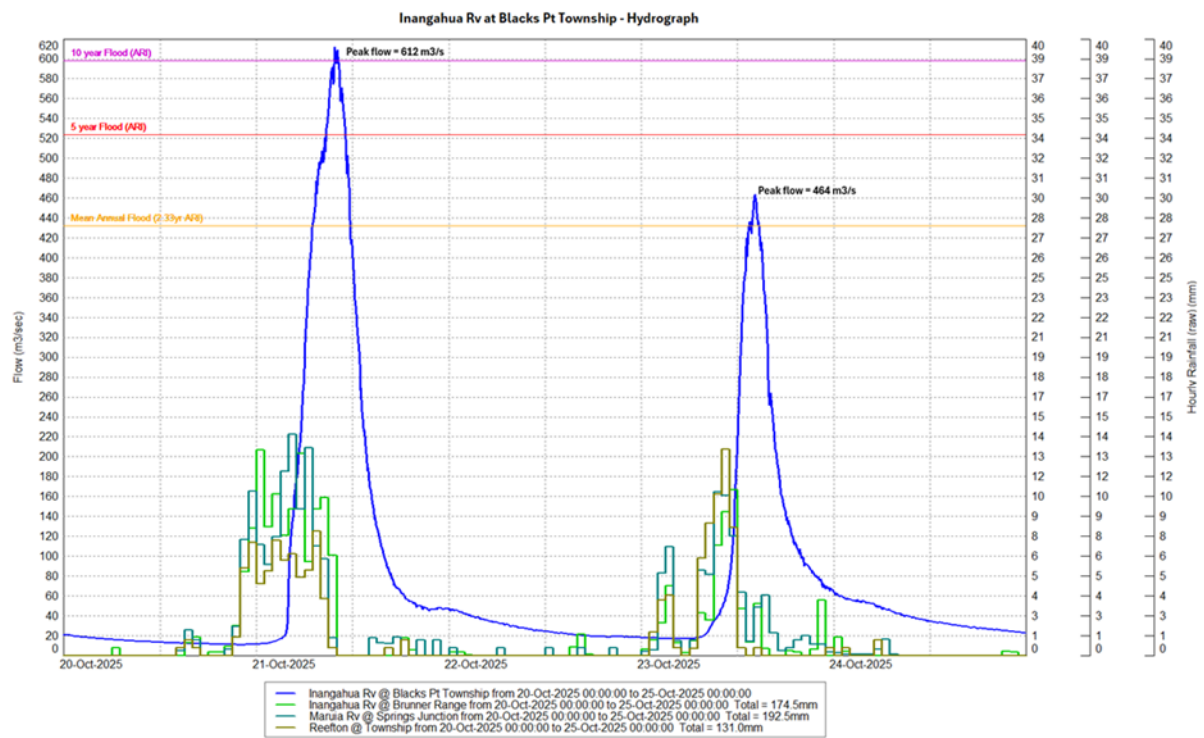


Figure 23: Flow hydrograph of the Inangahua river at Blacks Point with hourly rainfall intensities of relevant rain gauges

Grey



Figure 24: Map of Grey River catchments with Hydrometric network locations

Rainfall

Across the Grey catchment, rainfall intensities were generally modest, with most gauges remaining below their Mean Annual (~2.33-year) ARI for all duration windows. Only a small number of sites reached Mean Annual thresholds for short-to medium-duration bursts, indicating that rainfall was not especially extreme or prolonged across much of the district. Sirdar Creek showed the highest intensities, reaching Mean Annual levels at the 30-minute and 12-hour durations and up to a 5-year ARI for the 1- to 6-hour periods—a reflection of its alpine location and exposure to strong orographic enhancement during westerly flows.

Other sites showed more muted responses. Mawheraiti and Moana reached Mean Annual levels only for the 6- and 12-hour durations, while Waipuna achieved Mean Annual thresholds from 1 to 12 hours. All remaining gauges stayed below Mean Annual levels entirely, confirming that while some localised pockets of elevated rainfall occurred, the event was not characterised by widespread high-intensity rainfall across the Grey catchment.

Table 9: Rainfall intensities and totals recorded in the Grey catchment and their annual return intervals (ARI).

Site	Record (years)	Maximum rainfall (mm)								
		30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Total
SirdarCk	HIRDS	19.7	36.8	61.7	111.7	163.8	176.8	187.7	267.2	282
ConicalHill	HIRDS	7.5	11.7	19.1	35.1	57.5	61	66.9	105	111
Mawheraiti	HIRDS	10.8	15.4	22.1	47.1	70	74	76.5	116	120
Waipuna	HIRDS	10.1	17.9	30	44	58.4	64.5	68	112.4	119
Ahaura	HIRDS	6.1	10.5	16.1	37.7	50	55.7	65	110.9	118
Haupiri	HIRDS	10.4	15.6	23	57.6	79.8	90	104	172.1	186
Ngahere	HIRDS	10.9	15.8	27.2	48.6	65.9	77	82.5	126	134
Moana WWTP*	HIRDS	10.3	20	33.1	66.6	87	98	107.2	156.4	171
Greymouth (NIWA)	HIRDS	6.9	13.8	18	39.6	52.8	57.6	62.6	98.4	106
WCRCOffice	HIRDS	10.3	15.8	25.4	49.9	63.5	70.1	77	126.7	137
Pigeon (NIWA)	HIRDS	16.6	22.8	39.2	85.4	103.6	119.6	134.8	201.6	227

* New rainfall site in Moana, no ARI data available to compare against.

ARI (years)	2.0	5	10	20	50	100	250
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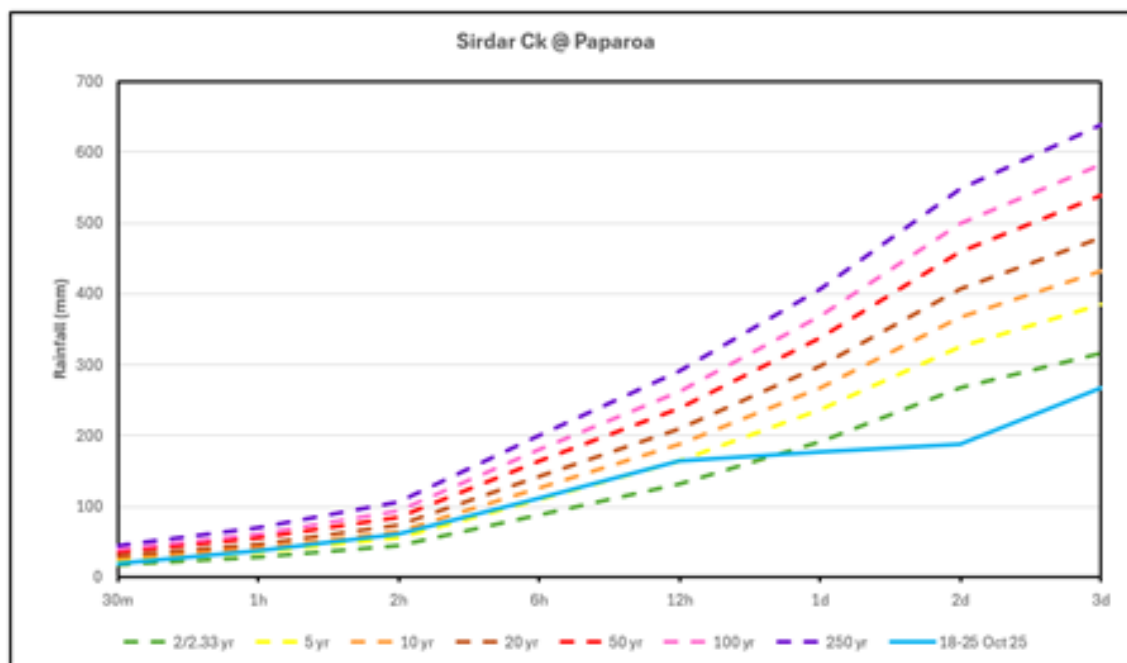


Figure 25: Graph of rainfall duration curves (max intensities for each duration) recorded at the Sirdar Ck at Paparoa gauge from 20th - 25th October 2025.

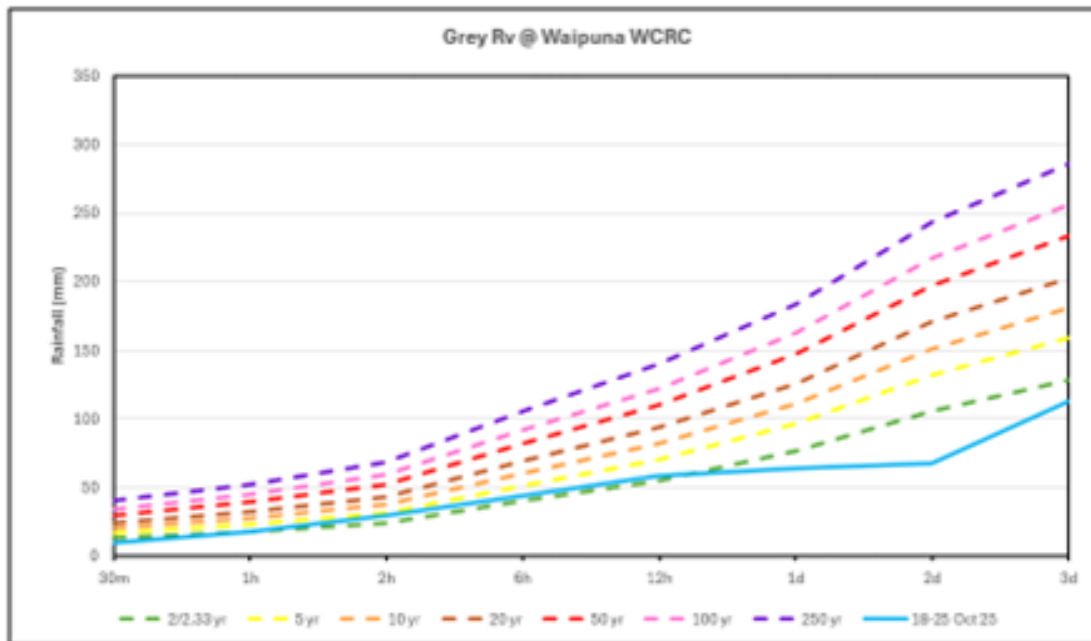


Figure 26: Graph of rainfall duration curves (max intensities for each duration) recorded at the Grey Rv at Waipuna WCRC gauge from 20th - 25th October 2025.

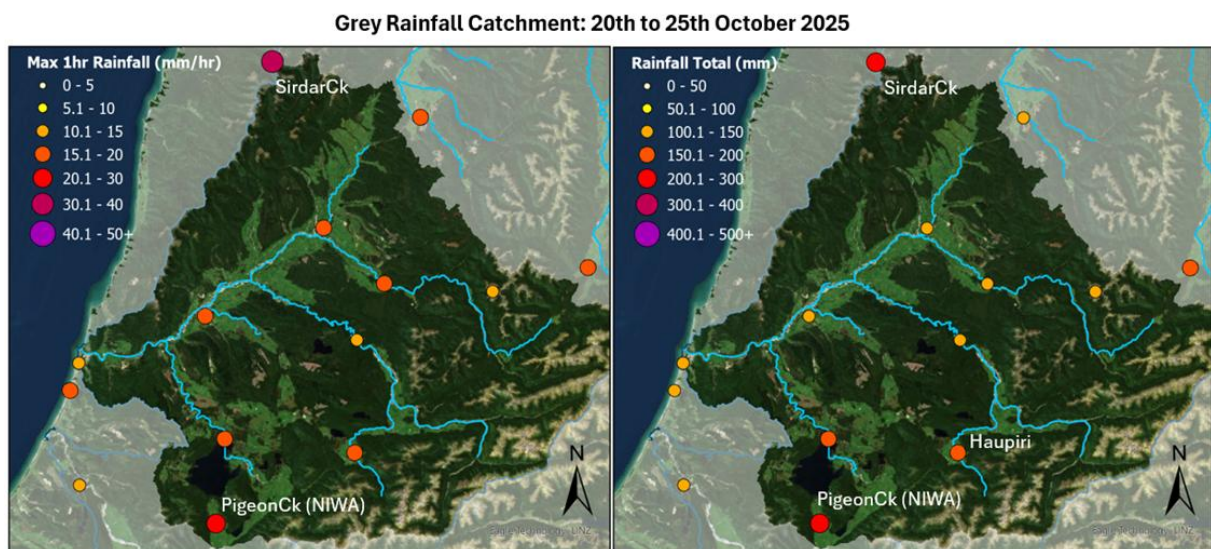


Figure 27: : Distribution of peak rainfall intensities and totals across the Grey River Catchment rain gauge network

River Response

First Flood Event – 21 October 2025

The hydrographs show a highly coherent and rapid catchment response across the Grey River system during the 21 October event, with all major tributaries peaking within a short time window before contributing to a sharp, pronounced flood peak at Dobson. The Grey River at Dobson reached 4,740 m³/s (a ~6–7-year ARI), driven by strong inflows from both the Ahaura River—peaking earlier at 2,265 m³/s (~7–9-year ARI)—and the Waipuna River, which recorded the most

significant relative response of the event with a 1,711 m³/s peak corresponding to a 20–50-year ARI. The synchronised timing of these tributary peaks compressed the flood wave, producing a steep rising limb and relatively limited attenuation through the mainstem. The Mawheraiti River also peaked on 21 October, contributing additional—but smaller—flows, although its return period cannot be confidently determined due to short record length.

Second Flood Event – 23– 24 October 2025

The second event on 23–24 October generated a smaller but still notable response, with the Grey River at Dobson peaking again at 3,210 m³/s. While rainfall intensities were generally lower than the 21 October event, catchment saturation and elevated baseflows enabled an efficient runoff response. This was particularly evident in the delayed peak on the Arnold River at Moana, which rose on 24 October (~3.7-year ARI) and contributed to the secondary rise in the mainstem. Overall, the hydrograph highlights a highly responsive hydrological system, with synchronised tributary peaks, short lag times, and rapid recessions characteristic of the Grey catchment. The Waipuna subcatchment stands out as the most sensitive during this sequence, producing the largest relative event on record for its 26-year gauge history.

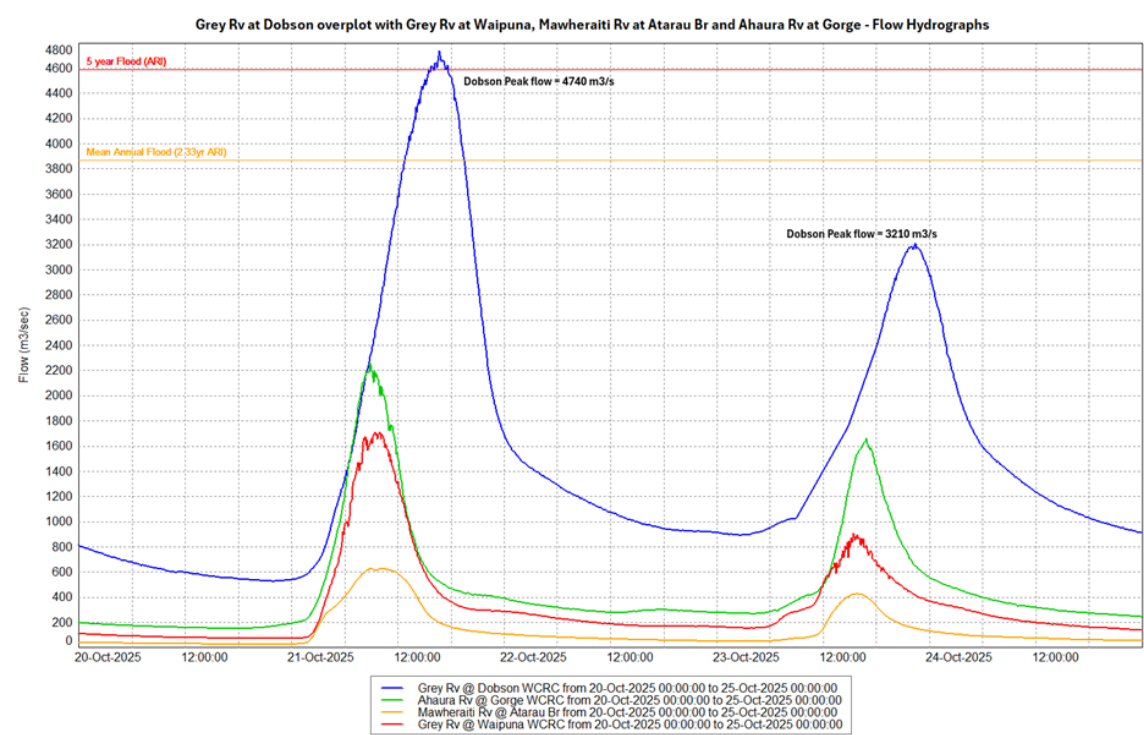


Table 10: Peak river flows and levels recorded in the Grey river catchment

Monitoring site					
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	Date and time of peak	Peak water level (mm)	Peak flow (m ³ /s)	Return period	Record (years)
Grey Rv at Dobson	21/10/2025 17:40	5751	4740	>5.9 to <6.7	56
Ahaura Rv @ Gorge WCRC	21/10/2025 09:50	6674	2265	>6.7 to <9.2	56
Grey Rv @ Waipuna	21/10/2025 10:25	6149	1711	>20 to <50	26
Arnold Rv at Moana / Moana at Jetty	24/10/2025 00:37	3894	234	3.7	52
Mawheraiti Rv @ Atarau Br	21/10/2025 10:10	5618	635	NA	<10

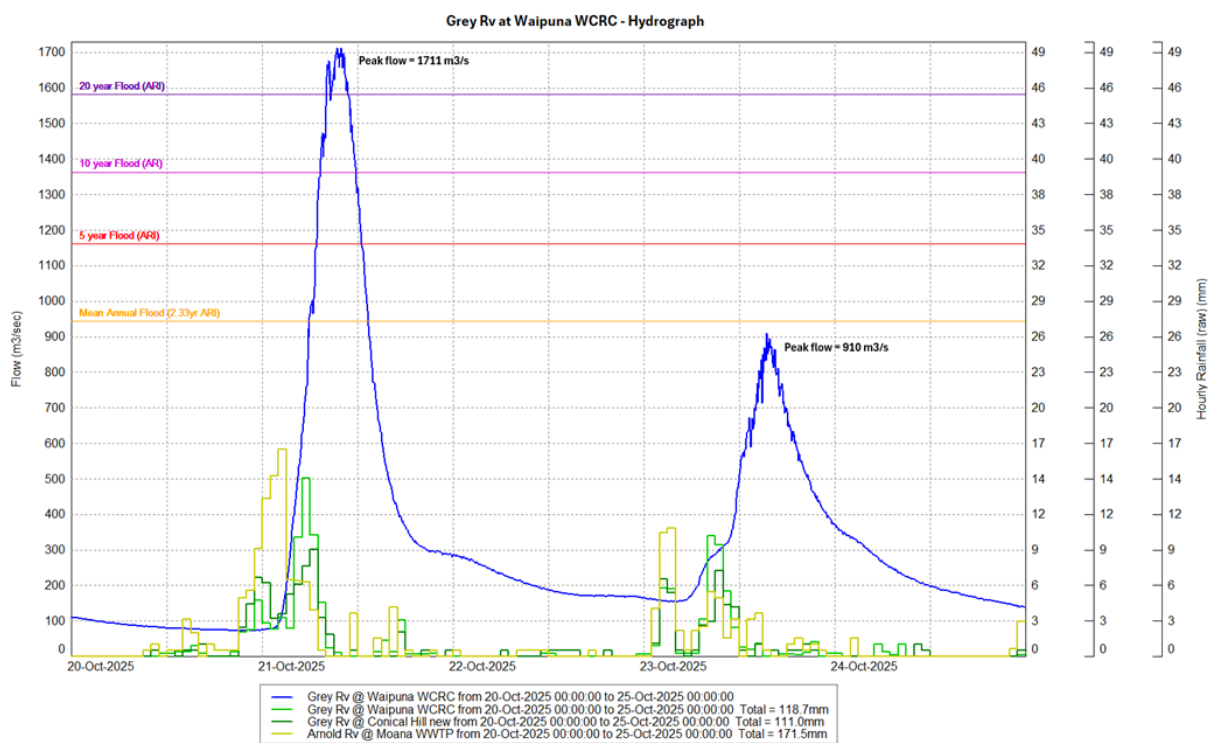


Figure 28: Flow hydrograph of the Grey Rv at Waipuna with hourly rainfall intensities from relevant rain gauges.

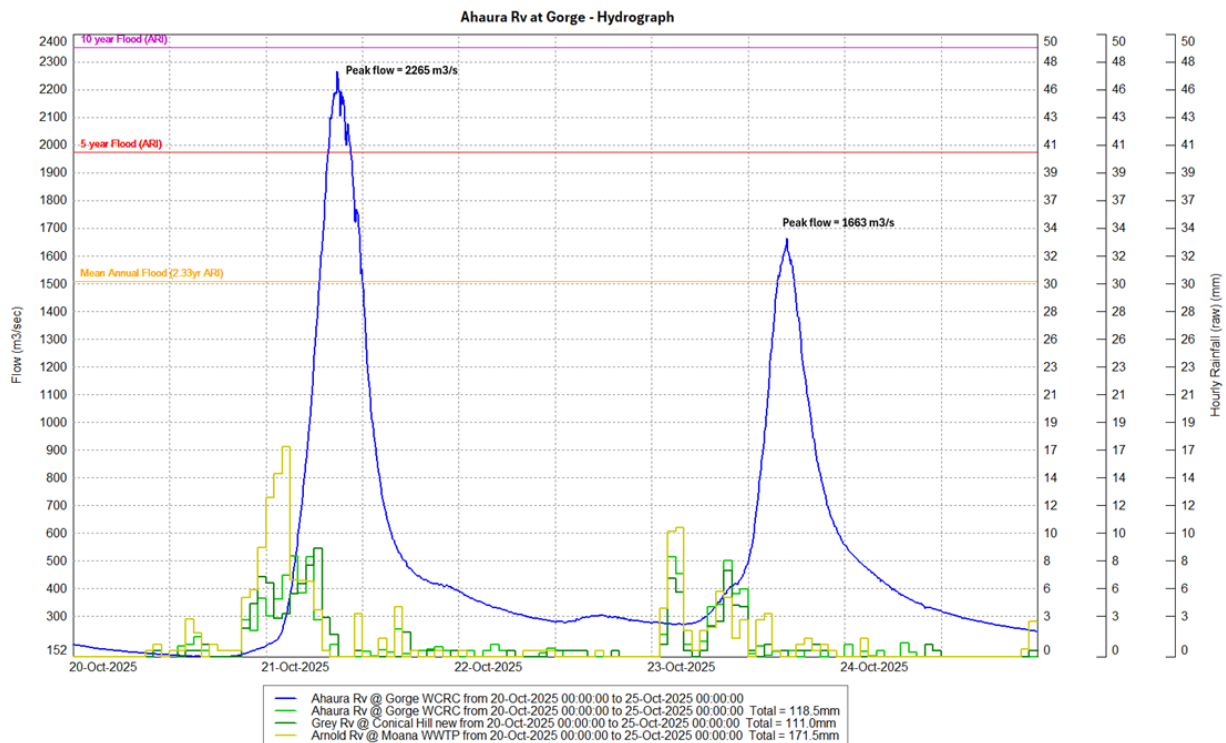


Figure 29: Flow hydrograph of the Ahaura river at Gorge with hourly rainfall intensities from relevant rain gauges

Comparison against October 10 event:

Though Rainfall intensities seemed to be higher for the October 10th event, the base flow preceding the event was lower than the base flow preceding October 21st event. Which is likely the reason why river flows in the Grey catchment record higher peaks than the event on October 10 (**Error! Reference source not found., Error! Reference source not found., and Error! Reference source not found.**).

Historical context:

- **July 17 2021:** got overshadowed by the Westport flood but still produced some local impacts. This event had a had a higher peak flow of 4616 m³/s with a return period of 5.1 years. Localised flooding occurred in areas along SH7, particularly at the Stillwater underpass, resulting in road closures
- **January 19 2017:** A larger event than July 2021, with a Grey River peak flow of 5,010 m³/s (8.8-year ARI). Substantial flows were also recorded at Ahaura (2,540 m³/s) and Waipuna (1,538 m³/s), both exceeding 10-year return periods.
- **November 21 2011:** Most significant flood event in the last 15 years, second biggest flood recorded after the September 1997 event since records began for the Grey River. Peak flow reached 5890 m³/s (39.4 ARI). Flood

barriers were erected with significant surface flooding and cattle needing rescued from low lying areas.

Haast River



Figure 30: Map of Haast River catchments with Hydrometric network locations

Rainfall

Most of the alpine gauges have exceeded their mean annual return period for some durations. The catchment has also observed some high intensities for the following sites:

- Haast at Deelaw:
 - 12hr duration = exceeded Mean annual (~2.33 year AR)
 - 30 min and 6 hour durations = exceeded 5 year ARI
 - 1 hour to 2 hour duration = exceeded 10 year ARI
- Moa Ck (NIWA):
 - 30min and 72 hour = exceeded Mean annual (~2.33 year AR)
 - 1 hour and 12 hour durations = exceeded 5 year ARI
 - 2hour to 6 hour = exceeded 10 year ARI

Site	Record (years)	Maximum rainfall (mm)								
		30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Total
Deelaw	HIRDS	34.3	64.1	107.1	182	234.9	243.6	265.7	383.3	443

CronCk (NIWA)	HIRDS	17	32	59	142	216.5	265.5	292.5	409.5	504
Haast	HIRDS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Haast(NIWA)	HIRDS	17	27.5	48	103.5	159	194	221.5	344	422
MoaCk (NIWA)	HIRDS	17.5	33	53.5	108	143.5	148.5	176.5	284	346

ARI (years)	2.0	5	10	20	50	100	250
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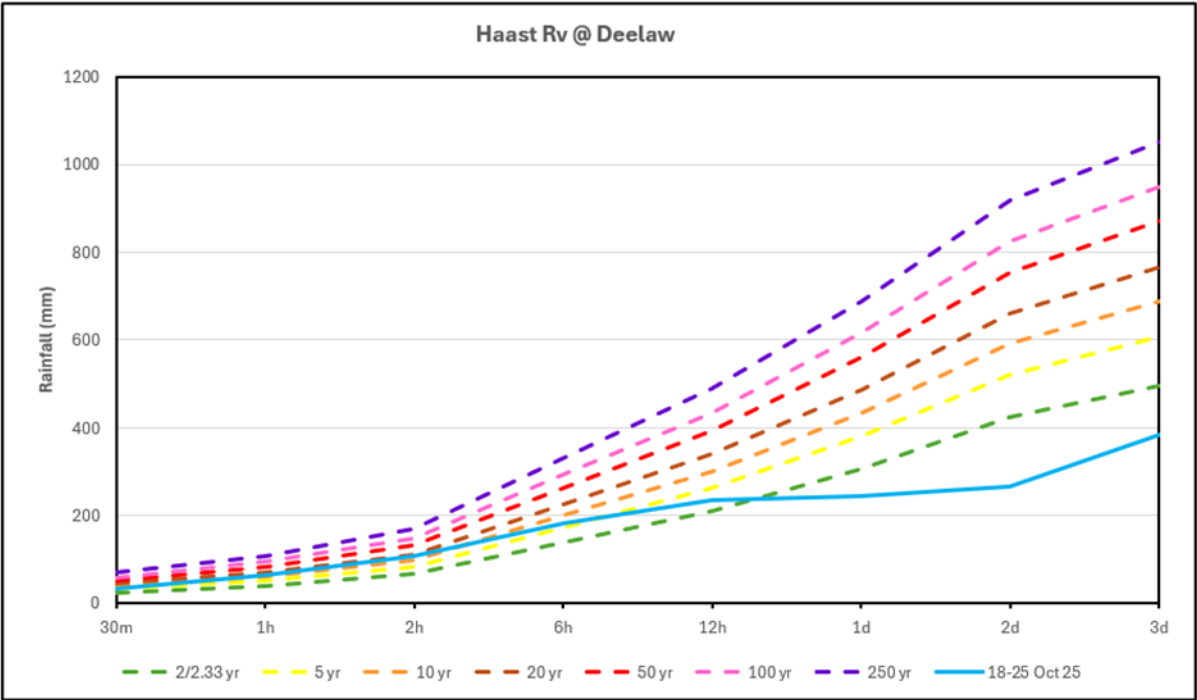


Figure 31: Graph of rainfall duration curves (max intensities for each duration) recorded at the Haast Rv at Deelaw gauge from 20th - 25th October 2025.

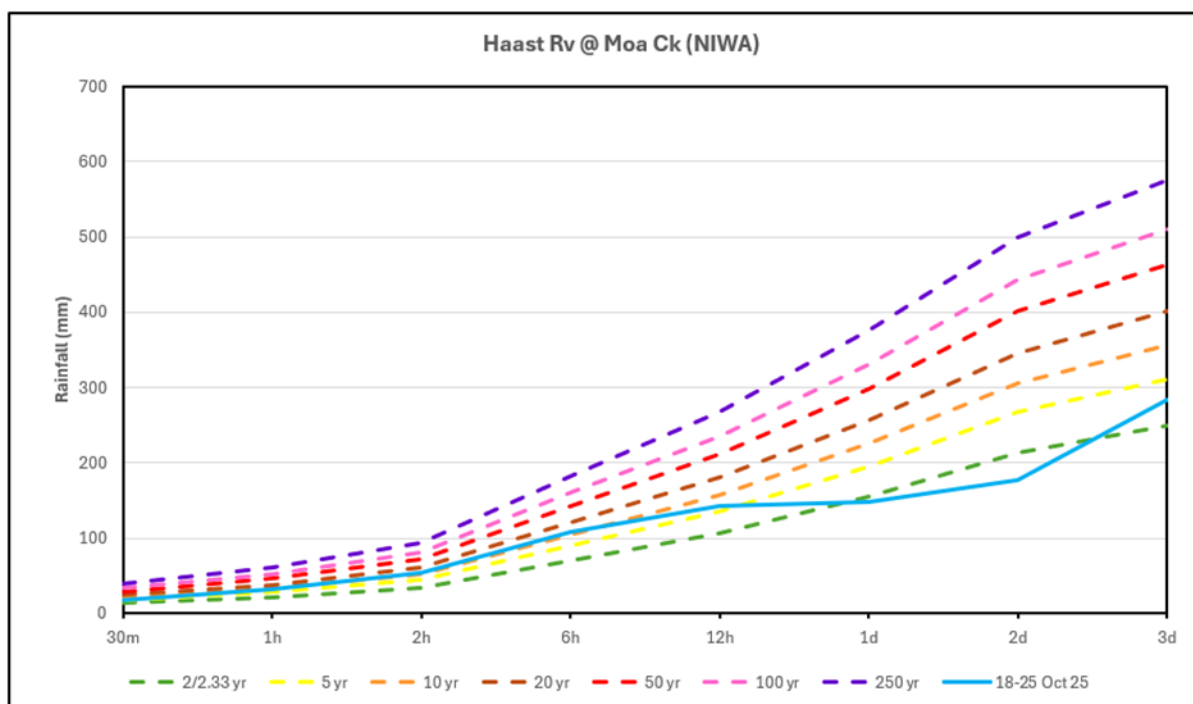


Figure 32: Graph of rainfall duration curves (max intensities for each duration) recorded at the Haast Rv @ Moa Ck (NIWA) gauge from 20th - 25th October 2025.

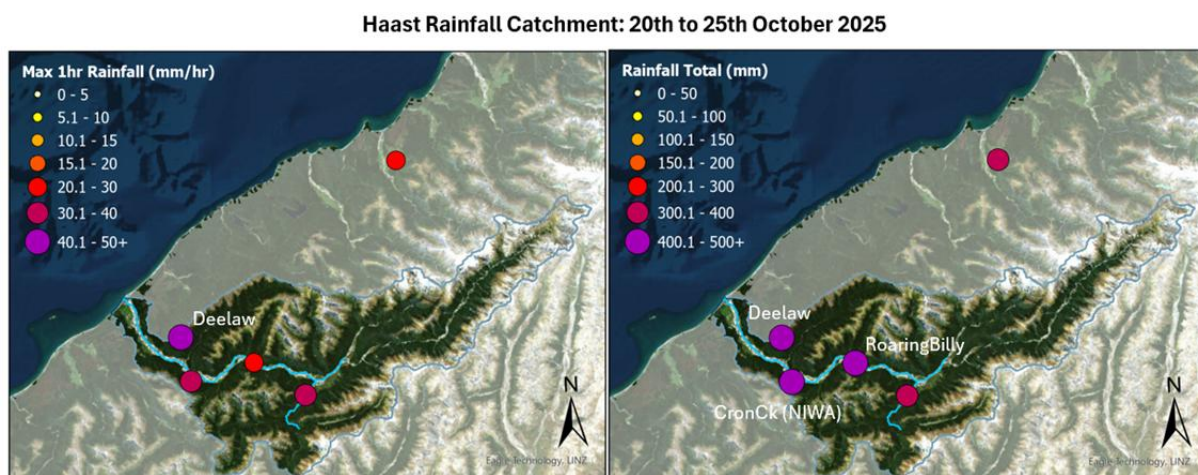


Figure 33: Distribution of peak rainfall intensities and totals across the Haast River Catchment rain gauge network

River Response

The hydrograph for the Haast River at Roaring Billy shows two distinct flood responses during the event sequence, with the most significant peak occurring on 23 October. During this later event, the river rose extremely rapidly to a peak flow of $4,355 \text{ m}^3/\text{s}$ —corresponding to a 3–3.4-year return period—driven by intense short- to medium-duration rainfall recorded at several alpine gauges, including Deelaw and Moa Creek. The steep rising limb and narrow peak indicate highly efficient runoff generation in this steep, mountainous catchment, where rainfall is

quickly converted to streamflow with minimal storage or attenuation. The subsequent rapid recession reflects fast-draining channel systems and limited floodplain buffering typical of the Haast valley.

The first event on 21 October produced a much smaller peak of around 1,464 m³/s but followed a similar hydrological pattern, with quick rises closely linked to rainfall timing. The Arawhata River also responded strongly on 23 October, reaching 2,890 m³/s shortly after the Haast peak, although its return period cannot be reliably estimated due to the provisional rating curve. Overall, the hydrograph illustrates the sensitivity of South Westland alpine rivers to high-intensity rainfall and highlights how back-to-back storms over saturated catchments can rapidly escalate flows, culminating in the pronounced 23 October flood peak.

Table 11: Peak river flows and levels recorded in the Haast river catchment

Monitoring site	Date and time of peak	Peak water level (mm)	Peak flow (m ³ /s)	Return period	Record (years)
Haast Rv at Roaring Billy	23/10/2025 12:15	6393	4355	>3.0 to <3.4	54
Arawhata Rv at County Br	23/10/2025 13:10	5528	2890	NA	27

** Provisional rating, not suitable to calculate ARI for site re-established in 2024.*

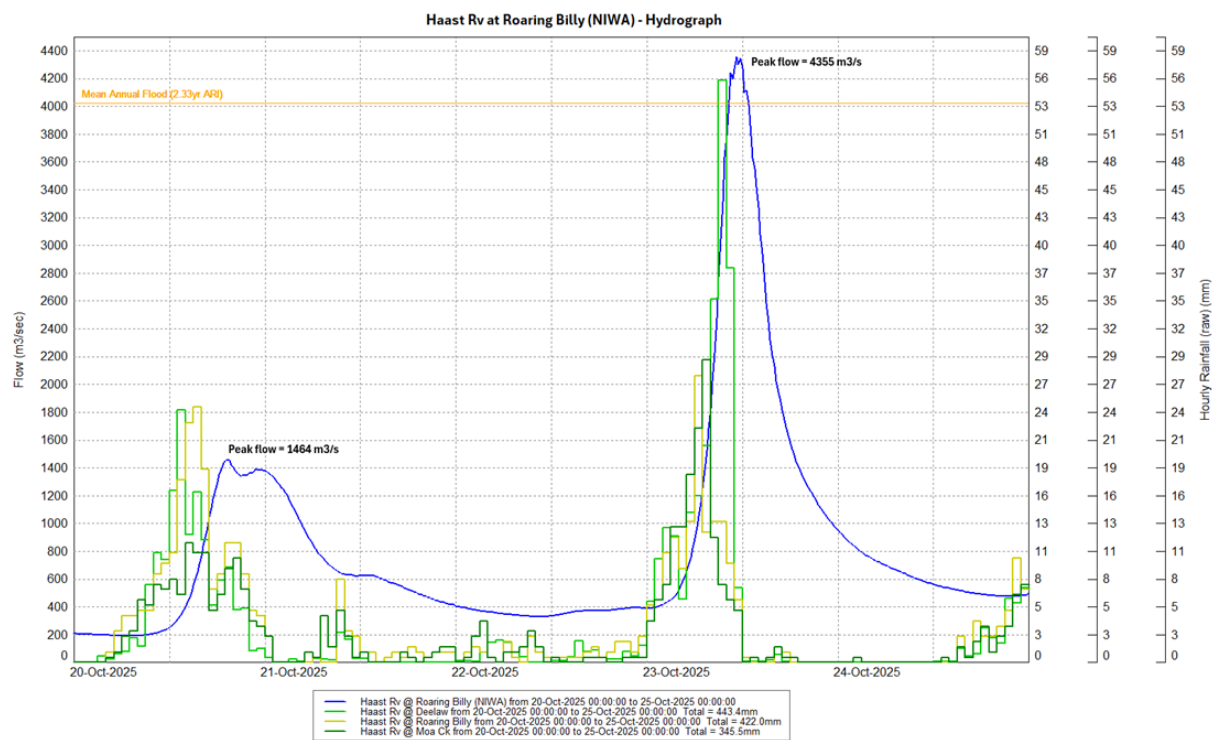


Figure 34: Flow hydrograph of the Haast river at Roaring Billy (NIWA) with hourly rainfall intensities from relevant rain gauges

Hokitika River

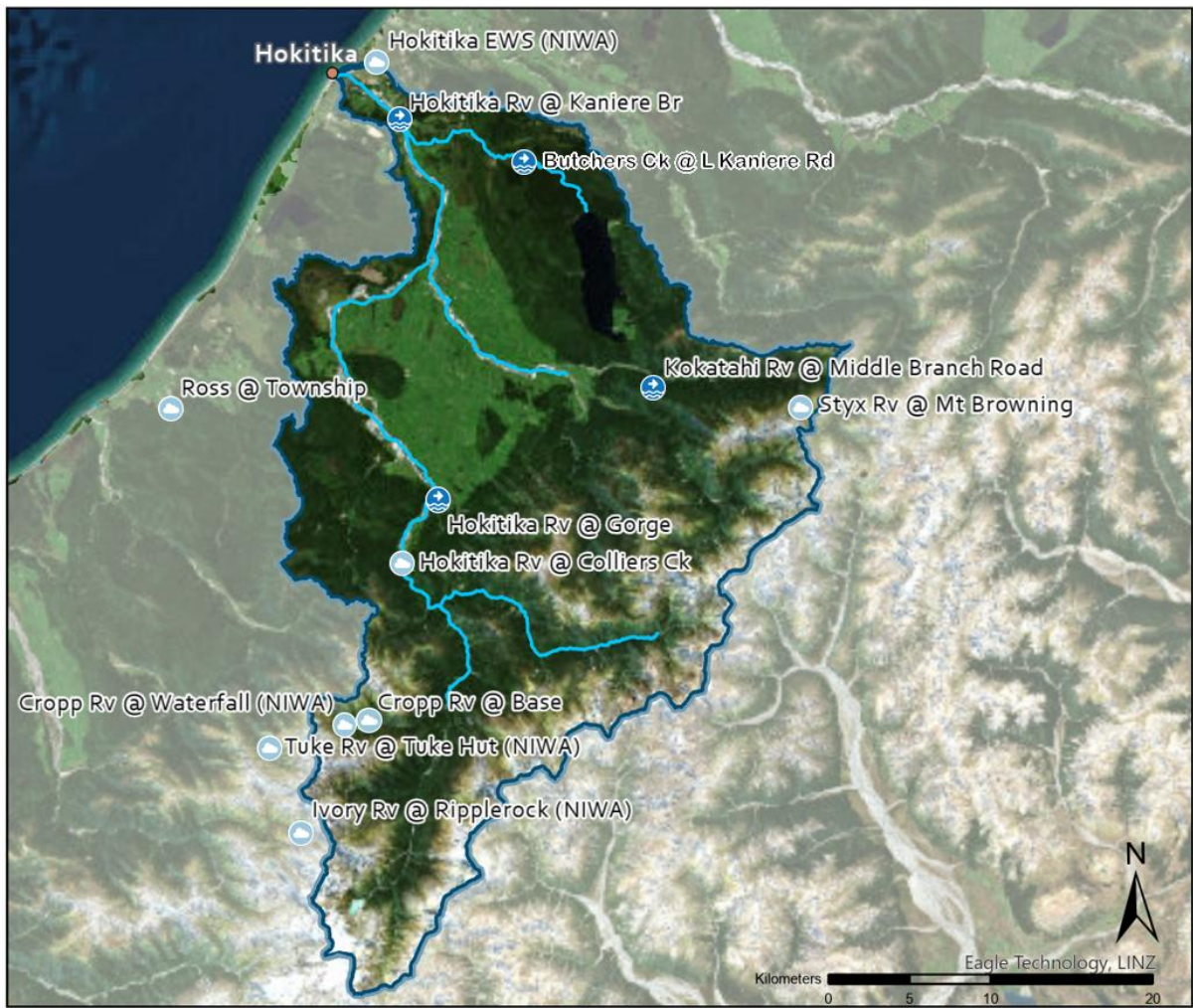


Figure 35: Map of Hokitika River catchments with Hydrometric network locations

Rainfall

Some rain gauges in the catchment exceeded their Mean Annual Return Period, most notably Hokitika Gorge, which surpassed its 10-year ARI for the 12-hour intensity. However, the majority of gauges, particularly those away from the ranges, remained below their mean annual flood thresholds.

Of particular interest, a maximum 1-hour intensity of 62.5 mm/hr was recorded at the Cropp River at Waterfall (NIWA) alpine gauge. Cropp is well known for high rainfall, and while this was a significant short-duration burst, it only exceeded the site’s mean annual flood return period.

Table 12: Rainfall intensities and totals recorded in the Hokitika catchment and their annual return intervals (ARI).

Site	Record (years)	Maximum rainfall (mm)								
		30min	1hr	2hr	6hr	12hr	24hr	48hr	72hr	Total

Kumara	<1 yr	11.4	14.5	25.8	41.8	55.8	68.5	76.6	129.4	141
Hokitika (NIWA)	HIRDS	4.7	9.4	18	31.8	43.6	49.8	54	96.6	107
ButchersGully (NIWA)	HIRDS	9	13	21.5	43	65.5	73.5	85.5	152.5	158
StyxRv	HIRDS	21.1	39.3	68.8	133.8	189.8	221.6	252.8	438.2	465
HokitikaGorge***	HIRDS	16.1	27.4	47.1	107.6	176.6	202.5	213.8	329.8	345
ColliersCk	HIRDS	20.8	33.9	62	153.8	245	278	295.9	459.1	477
Ross	HIRDS	8.8	15.5	25.3	49.9	78.8	97	103	161.4	167
**CroppWCRC	NA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CroppRv (NIWA)	HIRDS	38	62.5	93	212	287.5	332	368.5	654	734
TukeRv (NIWA)	HIRDS	21	38.5	66.5	146	224.5	268.5	309	487.5	562
IvoryRv (NIWA)	HIRDS	12.5	23	42	114	171.5	184.5	193.5	341.5	357

*New site, no ARI stats to compare.

** Comms down during event, no observed rainfall data available.

*** HIRDS stats generated from location, not historical data.

ARI (years)	2.0	5	10	20	50	100	250
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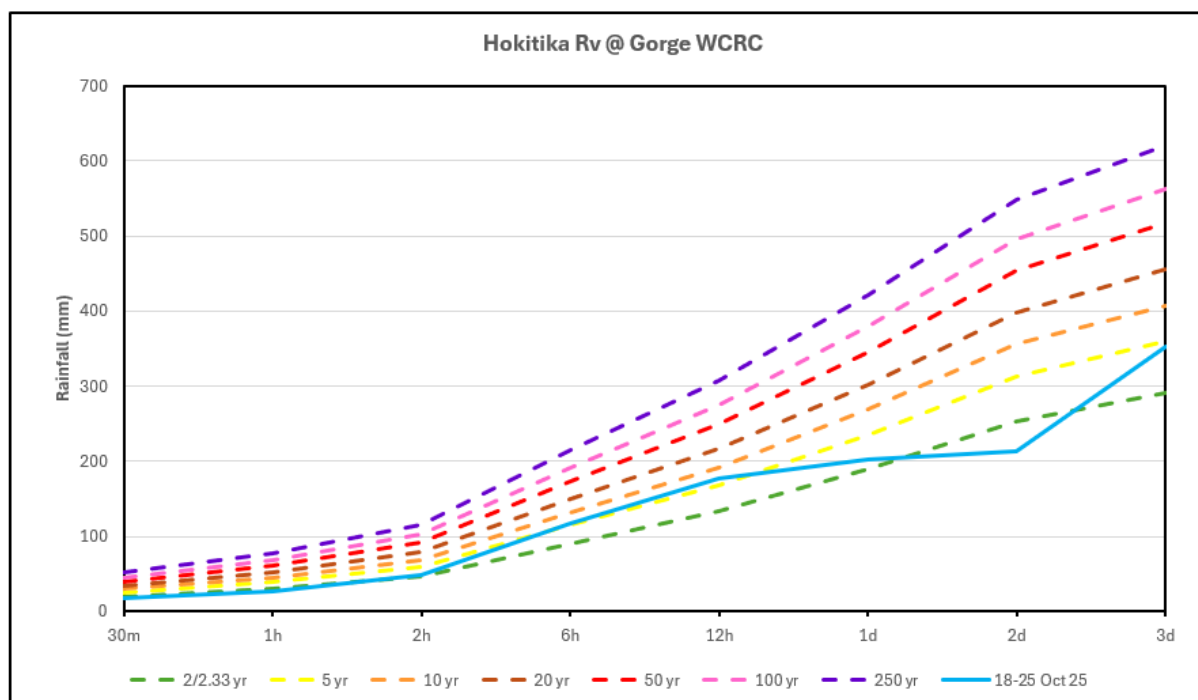


Figure 36: Graph of rainfall duration curves (max intensities for each duration) recorded at the Hokitika Rv at Gorge WCRC gauge from 20th - 25th October 2025.

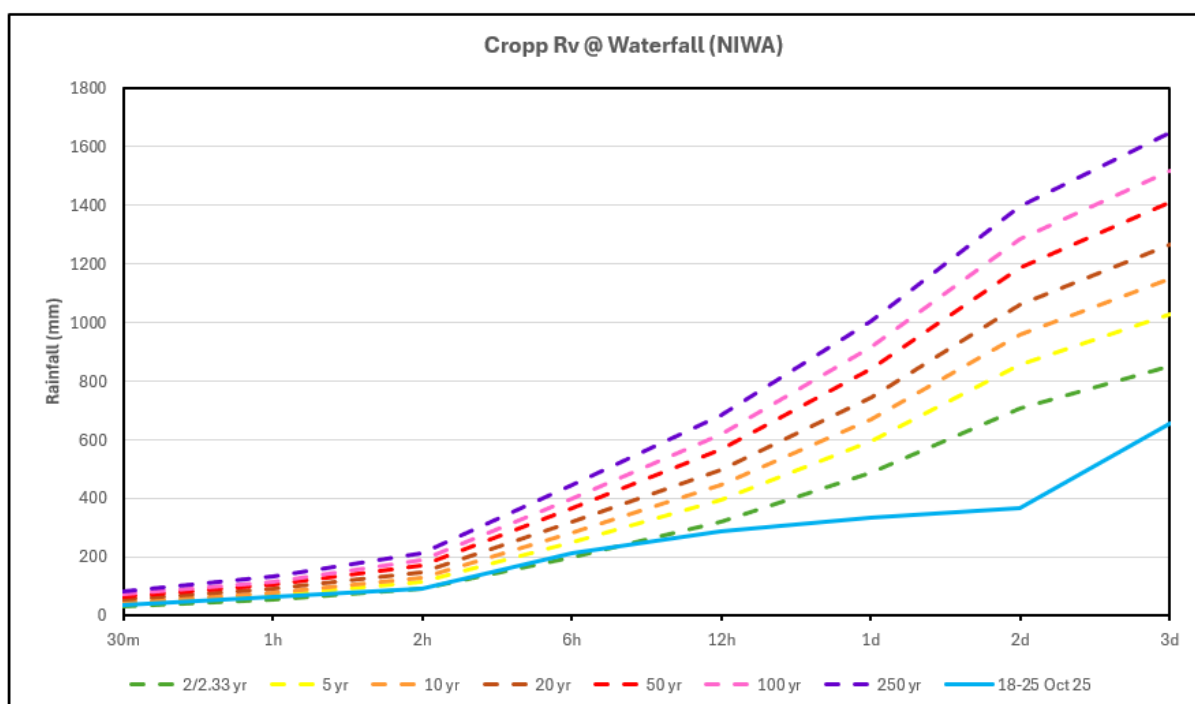


Figure 37: Graph of rainfall duration curves (max intensities for each duration) recorded at the Cropp Rv at Waterfall (NIWA) gauge from 20th - 25th October 2025.

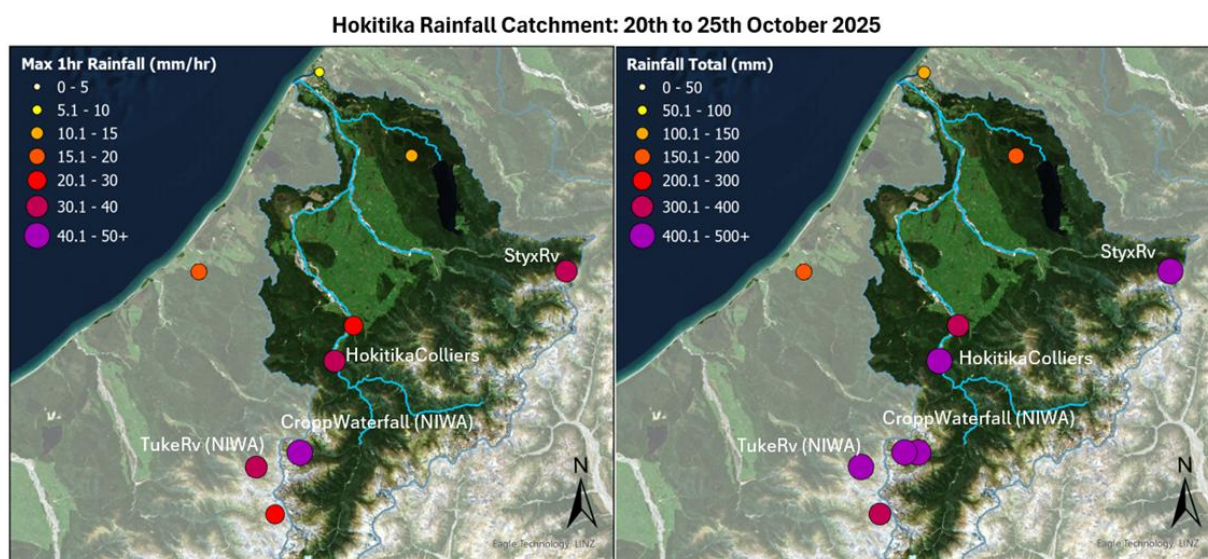


Figure 38: Distribution of peak rainfall intensities and totals across the Hokitika River Catchment rain gauge network

River Response

The hydrograph for the Hokitika River at the Gorge shows two distinct flood responses, with the larger peak occurring on 23 October. During this second event, the river rose sharply to 1,918 m³/s at 12:55 pm, a flow well below the site's Mean Annual Flood and corresponding to a modest return period of approximately 1.2–

1.4 years. This peak aligns closely with a concentrated burst of high-intensity rainfall recorded at several alpine gauges—particularly Cropp Waterfall and Colliers Creek—which show steep spikes in hourly rainfall in the hours immediately preceding the peak. The rapid rise and equally quick recession of the hydrograph reflect the steep, highly responsive nature of the Hokitika catchment, where rainfall in the upper alpine zones translates quickly into downstream flow increases.

The first event on 21 October generated a smaller and more prolonged peak of around 1,513 m³/s, with flows increasing gradually in response to earlier and more distributed rainfall. In contrast, the 23 October peak was sharper and more synchronised with rainfall onset, consistent with the intense short-duration bursts indicated in the hyetograph. Most rivers in Westland, including the Hokitika, reached their maximum flows on the 23rd as the later system delivered higher intensities to the region’s headwaters. Exceptions such as the Kokatahi and Kanieri sites peaked earlier on the 21st, reflecting their localised rainfall patterns and smaller catchment scales. Overall, the hydrograph illustrates the Hokitika’s sensitivity to alpine rainfall and the strong influence of timing and intensity of precipitation on flood magnitude within this steep Westland system.

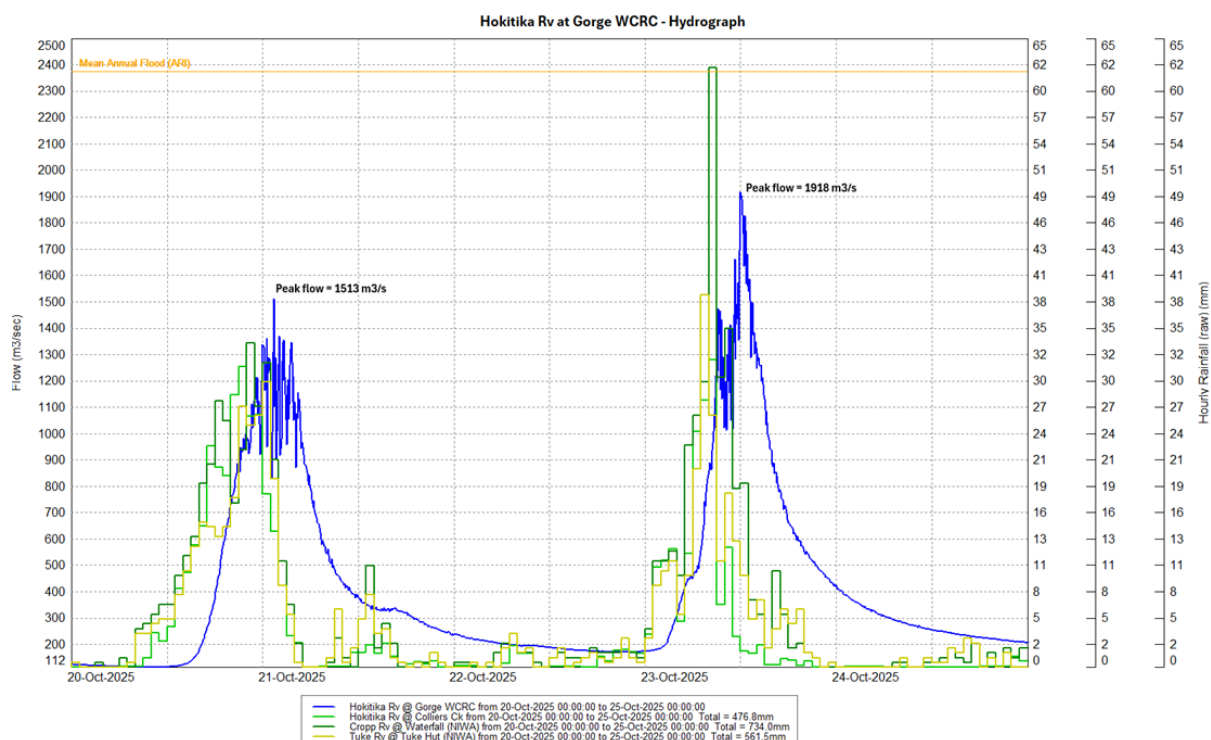


Figure 39: Flow hydrograph of the Hokitika river at Gorge WCRC with hourly rainfall intensities from relevant rain gauges

Appendix

A. Rainfall summary table

Catchment	Rainfall Site	Maximum rainfall intensity		Total rainfall
		mm/30min	mm/1hr	(mm)
Karamea	Aorere Rv @ Perry Saddle (TDC)	12.8	20.4	171
	Cobb @ Trilobite (NIWA)	10.5	17	120
	Karamea Rv @ Garibaldi	20.9	35.4	411
	Karamea Rv @ Township	3.7	4.5	46
Mokihinui	Wangapeka @ Biggs Top (TDC)	17	30.5	385
	Mokihinui Rv @ Stoney Ck	14.3	26.7	307
Buller	Orikaka Rv @ Plateau Stm	13	20.3	215
	Westport EWS (NIWA)	2.4	4.8	47
	Ohikanui Rv @ Buckland Peaks	N/A	N/A	N/A
	Buller Rv @ Bald Hill	4.9	7.2	72
	Buller Rv @ Three Channel Flat	7.5	11.6	139
	Matakitaki @ Horse Terrace Br (TDC)	7.5	13	134
	Inangahua Rv @ Brunner Range	9	15.1	175
	Inangahua Rv @ Landing	13	24	218
	Reefton @ Township	9.8	15.5	131
	Maruia Rv @ Springs Junction	9.6	15.8	192
Grey	Sirdar Ck @ Paparoa	19.7	36.8	282
	Grey Rv @ Conical Hill	7.5	11.7	111
	Mawheraiti Rv @ Atarau Br	10.8	15.4	120
	Grey Rv @ Waipuna	10.1	17.9	119
	Ahaura Rv @ Gorge	6.1	10.5	118
	Grey Rv @ Haupiri	10.4	15.6	186
	Grey Rv @ Ngahere	10.9	15.8	134
	Arnold Rv @ Moana WWTP	10.3	20	171
	Greymouth Aero EWS (NIWA)	6.9	13.8	106
	Grey Rv @ WCRC Office	10.3	15.8	137
	Pigeon Creek CWS (NIWA)	16.6	22.8	227
Taramakau / Hokitika	Kumara @ School	11.4	14.5	141
	Hokitika EWS (NIWA)	4.7	9.4	107
	Butchers Ck @ Butchers Gully (NIWA)	9	13	158

	Styx Rv @ Mt Browning	21.1	39.3	465
	Hokitika Rv @ Gorge	16.1	27.4	345
	Hokitika Rv @ Colliers Ck	20.8	33.9	477
	Ross @ Township	8.8	15.5	167
	Cropp Rv @ Base	N/A	N/A	N/A
	Cropp Rv @ Waterfall (NIWA)	38	62.5	734
	Tuke Rv @ Tuke Hut (NIWA)	21	38.5	562
	Ivory Rv @ Ripplerock (NIWA)	12.5	23	357
Whataroa	Harihari at School	15.2	26.1	263
	Whataroa Rv @ SH6 (NIWA)	17	33.5	310
	Okarito EWS (NIWA)	7.6	15.2	180
Waiho / Mahitahi	Waiho Rv @ SH6	19.7	30.5	346
	Waiho Rv @ Douglas Hut (NIWA)	23.5	40	502
	Mahitahi Rv @ Bruce Bay	15.1	25.2	314
Haast	Haast Rv @ Deelaw	34.3	64.1	443
	Haast Rv @ Cron Ck (NIWA)	17	32	504
	Haast Rv @ Roaring Billy	N/A	N/A	N/A
	Haast Rv @ Roaring Billy (NIWA)	17	27.5	422
	Haast Rv @ Moa Ck (NIWA)	17.5	33	346

B. MetService warnings

Sunday 19th October 2025 10:39 am:

Situation

A front preceded by a strong and humid northwest flow moves over New Zealand during Monday and Tuesday. Warnings and Watches for heavy rain and severe gales are now in force. Please stay up to date with the latest forecast.

Heavy Rain Warning - Orange

Area: Grey, Buller and Tasman district west of Takaka, also Nelson Lakes National Park and the Spenser and St Arnaud Ranges of Marlborough

Period: 16hrs from 10:00pm Mon to 2:00pm Tue

Forecast: Expect 90 to 140 mm of rain, especially about the ranges. Peak rates of 15 to 25 mm/h.
Minimal chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 10:39am Sun 19 October

Next Update: 9:00pm Sun 19 October

Heavy Rain Warning - Orange

Area: The ranges of Westland

Period: 18hrs from 10:00am Mon to 4:00am Tue

Forecast: Expect 150 to 250 mm of rain. Peak rates of 20 to 30 mm/h.

Low chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 10:39am Sun 19 October

Next Update: 9:00pm Sun 19 October

Sunday 19th October 2025 8:24 pm

Situation

A front preceded by a strong and humid northwest flow moves over New Zealand during Monday and Tuesday. Warnings and Watches for heavy rain and severe gales are in force. Please stay up to date with the latest forecast.

Heavy Rain Warning - Orange

Area: Grey, Buller, Tasman District west of Takaka, Nelson Lakes National Park, Spenser Mountains and St Arnaud Range

Period: 15hrs from 10:00pm Mon to 1:00pm Tue

Forecast: Expect 90 to 140 mm of rain, especially about the ranges. Peak rates of 15 to 25 mm/h.

Minimal chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 8:24pm Sun 19 October

Next Update: 10:00am Mon 20 October

Heavy Rain Warning - Orange

Area: The ranges of Westland

Period: 21hrs from 9:00am Mon to 6:00am Tue

Forecast: Expect 150 to 250 mm of rain, but up to 300 mm possible about and north of the glaciers. Peak rates of 20 to 30 mm/h.

Low chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 8:24pm Sun 19 October

Next Update: 10:00am Mon 20 October

Monday 20th October 2025 9:57 am

Situation

A front preceded by a strong and humid northwest flow moves over New Zealand during Monday and Tuesday. Warnings and Watches for heavy rain and severe gales are in force. Please note: Another system brings heavy rain and strong winds to similar areas during Thursday, and is likely to be significant and impactful. Please stay up to date with the latest forecast.

Heavy Rain Warning - Orange

Area: Grey, Buller, Tasman District west of Takaka, Nelson Lakes National Park, Spenser Mountains and St Arnaud Range

Period: 16hrs from 9:00pm Mon to 1:00pm Tue

Forecast: Expect 90 to 140 mm of rain, especially about the ranges. Peak rates of 15 to 25 mm/h.

Minimal chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 9:57am Mon 20 October

Next Update: 9:00pm Mon 20 October

Heavy Rain Warning - Orange

Area: The ranges of Westland

Period: 21hrs from 9:00am Mon to 6:00am Tue

Forecast: Expect 200 to 250 mm of rain, but up to 300 mm possible about and north of the glaciers. Peak rates of 20 to 30 mm/h.

Rain easing from the south Tuesday morning.

Low chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 9:57am Mon 20 October

Next Update: 9:00pm Mon 20 October

Monday 20th October 2025 4:41pm

Situation

A front preceded by a strong and humid northwest flow moves over New Zealand during Monday and Tuesday. Warnings and Watches for heavy rain and severe gales are in force. The wind Warnings for Southland and Otago for Monday have expired and have been replaced with wind Watches for Tuesday. Please note: Another system brings heavy rain and strong winds to similar areas during Thursday, and is likely to be significant and impactful. Please stay up to date with the latest forecast.

Heavy Rain Warning - Orange

Area: Grey, Buller, Tasman District west of Takaka, Nelson Lakes National Park, Spenser Mountains and St Arnaud Range

Period: 16hrs from 9:00pm Mon to 1:00pm Tue

Forecast: Expect 90 to 140 mm of rain, especially about the ranges. Peak rates of 15 to 25 mm/h.

Minimal chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 9:57am Mon 20 October

Next Update: 9:00pm Mon 20 October

Heavy Rain Warning - Orange

Area: The ranges of Westland

Period: 14hrs from 4:00pm Mon to 6:00am Tue

Forecast: Expect a further 150 to 200 mm of rain on top of what has already fallen, but up to 250 mm possible about and north of the glaciers. Peak rates of 20 to 30 mm/h. Rain easing from the south Tuesday morning.

Low chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 4:41pm Mon 20 October

Next Update: 9:00pm Mon 20 October

Monday 20th October 2025 8:26pm

Situation

A front preceded by a strong and humid northwest flow moves over New Zealand during Monday and Tuesday. Warnings and Watches for heavy rain and severe gales are in force. Please note: Another system brings heavy rain and strong winds to similar areas during Thursday, and is likely to be significant and impactful. Please stay up to date with the latest forecast.

Heavy Rain Warning - Orange

Area: Grey, Buller, Tasman District west of Takaka, Nelson Lakes National Park, Spenser Mountains and St Arnaud Range

Period: 16hrs from 9:00pm Mon to 1:00pm Tue

Forecast: Expect 90 to 140 mm of rain, especially about the ranges. Peak rates of 15 to 25 mm/h.

Minimal chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 8:36pm Mon 20 October

Next Update: 10:00am Tue 21 October

Heavy Rain Warning - Orange

Area: The ranges of Westland

Period: 10hrs from 8:00pm Mon to 6:00am Tue

Forecast: Expect a further 100 to 160 mm of rain on top of what has already fallen, but up to 200 mm possible about and north of the glaciers. Peak rates of 20 to 30 mm/h. Rain easing from the south Tuesday morning.

Low chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 8:36pm Mon 20 October

Next Update: 10:00am Tue 21 October

Tuesday 21st October 2025 am

Situation

A front preceded by a very strong and humid northwest flow moves over central New Zealand today. Another front, also preceded by a very strong and humid northwest flow moves over southern and central New Zealand during Thursday. Warnings and Watches for heavy rain and severe gales are in force. Please stay up to date with forecasts.

Heavy Rain Warning - Orange

Area: Buller, Tasman District west of Takaka, Nelson Lakes National Park, Spenser Mountains and St Arnaud Range

Period: 5hrs from 9:00am Tue to 2:00pm Tue

Forecast: Expect 40 to 60 mm of rain in addition to what has already fallen, especially about the ranges. Peak rates of 15 to 25 mm/h. Thunderstorms possible.

Note, another period of heavy rain is likely on Thursday, and another Warning or Watch may be issued closer to the time.

Minimal chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 9:30am Tue 21 October

Next Update: 9:00pm Tue 21 October

Heavy Rain Warning - Orange

Area: The ranges of Westland

Period: 17hrs from 12:00am Thu to 5:00pm Thu

Forecast: Heavy rain that fell yesterday and this morning has eased, but another period of heavy rain is forecast on Thursday.

Expect 200 to 250 mm of rain. Peak rates of 30 to 40 mm/h. Thunderstorms possible.

Low chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 9:30am Tue 21 October

Next Update: 9:00pm Tue 21 October

Cancellations

Heavy Rain Warning for Grey - Orange

Wednesday 22nd October pm

Situation

An active front, associated with a significant deep low to the south, moves over southern and central New Zealand on Thursday. Significant impacts are expected, and there is a possibility that Orange Warnings may be upgraded to Red Warnings. Please stay up to date with forecasts.

Heavy Rain Warning - Orange

Area: The ranges of Westland

Period: 14hrs from 1:00am Thu to 3:00pm Thu

Forecast: Expect 200 to 250 mm of rain. Peak rates of 30 to 40 mm/h Thursday morning. Thunderstorms expected.

Low chance of upgrading to a Red Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 8:57pm Wed 22 October

Next Update: 10:00am Thu 23 October

Situation

An active front, associated with a significant deep low to the south, moves over southern and central New Zealand on Thursday. Significant impacts are expected, and there is a possibility that Orange Warnings may be upgraded to Red Warnings. Please stay up to date with forecasts.

Heavy Rain Watch - Yellow

Area: Buller and Grey Districts, Nelson Lakes National Park, Spenser Mountains and St Arnaud Range

Period: 10hrs from 8:00am Thu to 6:00pm Thu

Forecast: A period of heavy rain, with thunderstorms expected. Amounts may approach warning criteria.

High chance of upgrading to a Warning.

Impact: Streams and rivers may rise rapidly. Surface flooding, slips, and difficult driving conditions possible.

Action: Clear your drains and gutters to prepare for heavy rain. Avoid low-lying areas and drive cautiously.

Issued: 8:57pm Wed 22 October

Next Update: 10:00am Thu 23 October

Strong Wind Watch - Yellow

Area: Grey, Buller and Nelson/Tasman districts

Period: 8hrs from 9:00am Thu to 5:00pm Thu

Forecast: Northwest winds may approach severe gale in exposed places.

Moderate chance of upgrading to a Warning.

Issued: 8:57pm Wed 22 October

Next Update: 10:00am Thu 23 October

Heavy Rain Watch - Yellow

Area: Westland away from the ranges

Period: 13hrs from 2:00am Thu to 3:00pm Thu

Forecast: Periods of heavy rain, with thunderstorms expected. Rainfall amounts may approach warning criteria.

Moderate chance of upgrading to a Warning.

C. Flood Frequency Analysis

8.5 West Coast Region Waterway Health and Quality State Report

Author	Jonny Horrox, Principal Scientist; Fergus McCallum, Environmental Monitoring Officer; Emma Perrin-Smith, Environmental Science Coordinator
Authoriser	Shanti Morgan, Group Manager Environmental Science
Public Excluded	No

Report Purpose

To present the West Coast Regional Council's 2024 State of the Environment (SoE) technical report on river water quality and ecosystem health, and to outline key implications for future freshwater management, including NPS-FM implementation and partnership with Poutini Ngāi Tahu.

Report Summary

This cover report introduces the fifth comprehensive surface water quality technical report for the region's rivers. The technical report collates long-term monitoring results, primarily from the regional river network and NIWA's National River Water Quality Network, and assesses the state of key water quality and ecosystem health attributes against the National Policy Statement for Freshwater Management 2020 (NPS-FM).

Overall, the results confirm that many West Coast rivers remain in good condition, particularly catchments with predominantly natural landcover. However, the report also identifies areas where nutrients, suspended sediment, dissolved oxygen and faecal contamination are affecting ecosystem health and human recreation values, particularly in catchments with higher proportions of anthropogenic land use and in some low-gradient, highly modified streams.

The findings will inform freshwater target setting, limits, and monitoring priorities under the NPS-FM, and support ongoing work with Poutini Ngāi Tahu and communities to protect and improve the mauri of wai across Te Tai Poutini.

Recommendation

It is recommended that the Committee resolve to:

1. *Receive the report "State of the Environment – River Water Quality and Ecosystem Health (2024)" and its accompanying technical report.*

2. *Note that the report confirms generally good water quality in largely natural catchments and identifies degraded or at-risk sites linked to more intensive or historic land uses.*
3. *Note that the findings will inform National Environment Standard implementation, partnership with Poutini Ngāi Tahu, and prioritisation of future monitoring and management responses.*
4. *Endorse the Planning, Catchment Coordination and Science teams working together to develop and implement targeted responses where water quality attributes are at or below national bottom lines.*

Issues and Discussion

Background

The West Coast Regional Council has monitored surface water quality since the mid-1990s, with a focus on rivers and streams that represent a range of land uses, pressures, and environmental settings. The programme has evolved over time from quarterly to monthly sampling, and now includes discrete sampling, continuous monitoring at selected sites, and targeted primary contact (recreational) monitoring.

The 2024 technical report is the fifth comprehensive synthesis of river water quality and ecosystem health information. It combines Council's monitoring data with NIWA's National River Water Quality Network data and assesses a suite of physical, chemical, and biological attributes (e.g. temperature, clarity, turbidity, dissolved oxygen, nutrients, E. coli, macroinvertebrates, periphyton) against national frameworks, principally the NPS-FM 2020.

The report also explicitly recognises the values and expectations of Poutini Ngāi Tahu as mana whenua, including the importance of mauri, ki uta ki tai, and Te Mana o te Wai, and the obligation to pass healthy water on to future generations. The findings provide an evidence base for upcoming freshwater planning decisions and for discussions with partners and stakeholders.

Current situation

Key points from the technical report are:

1. Landcover and pressures:
 - Catchments with predominantly natural landcover (indigenous forest, scrub, tussock) generally have good water quality and ecosystem health, with most attributes in the A or B bands.
 - As the proportion of anthropogenic landcover (pasture, exotic forestry, urban and other modified land) increases, there is a corresponding increase in

nutrients, faecal indicators, and in some cases suspended sediment and reduced dissolved oxygen.

2. Temperature and dissolved oxygen

- While the West Coast has a cool, wet climate overall, some smaller, low-gradient and/or poorly shaded streams periodically reach temperatures that can stress sensitive aquatic species.
- Dissolved oxygen regimes are generally acceptable, but a small number of sites are below the national bottom line (D band), typically where elevated nutrients, warm conditions, high plant/algal biomass and low velocities coincide.

3. Clarity, turbidity and suspended sediment

- Most monitored sites have good clarity and low turbidity.
- Exceptions include streams affected by legacy or current mining activities, large slips (e.g. in the Orowaiti catchment), or low-gradient, intensively farmed catchments lacking spring recharge.
- Five sites are below the national bottom line for suspended fine sediment, indicating significant ecological impacts and loss of sensitive species.

4. Nutrients (nitrate and ammonia, dissolved reactive phosphorus)

- Nitrate and ammonia concentrations across the network are within the A or B bands for toxicity, so acute toxicity risk to aquatic life is low.
- However, nitrate and dissolved reactive phosphorus (DRP) increase with anthropogenic landcover, and in catchments with >40% modified land there is a higher risk that nutrient concentrations will promote nuisance periphyton and macrophyte growth when other conditions are favourable.
- Around 15% of sites are below the National Bottom Line for DRP (D band), indicating a high risk of eutrophication and ecological change if left unmanaged.

5. Microbial water quality and human contact

- Many sites score poorly under the NPS-FM E. coli criteria for human contact. Anthropogenic sources (human and ruminant) are key contributors, alongside birds, high rainfall, and statistical treatment of the data.
- Recreational water quality (primary contact suitability) is generally best at lakes, followed by coastal beaches, with rivers and estuaries more variable and sometimes unsuitable following rainfall.

6. Macroinvertebrates and ecosystem health

- Macroinvertebrate communities are generally healthy in catchments with predominantly natural landcover, reflecting good habitat and water quality.

- Communities are degraded where multiple stressors converge (e.g. elevated nutrients, fine sediment, low dissolved oxygen, high temperatures, low gradient and low velocities, and legacy activities such as mining or drainage of wetlands).
- The programme design and methods described in the technical report ensure that data collection and analysis meet recognised quality standards and are suitable for informing regional planning, reporting, and communication with stakeholders.

Considerations

Implications/risks

1. Regulatory and policy risk – NPS-FM implementation

- *Issue:* Some attributes (e.g. dissolved oxygen, suspended fine sediment, DRP, E. coli) are at or below national bottom lines in a subset of sites, creating a clear need to respond through freshwater planning instruments and implementation programmes.
- *Implications:*
 - Failure to respond adequately could expose Council to legal and reputational risk, including challenges through freshwater planning processes and non-compliance with national direction.
- *Mitigation / Response:*
 - Planning staff have been provided this information and will use the technical report as a core evidence base for setting environmental outcomes, targets and limits in the freshwater planning process.
 - Science staff will work with the regulatory and policy group and Council's catchment coordination team to prioritise at-risk catchments for more detailed investigation and management responses (e.g. targeted mitigation, farm planning, consent reviews where appropriate).

2. Partnership and iwi relationship risk

- *Issue:* The report confirms that in some locations the mauri of water and the ability to provide safe mahinga kai and recreation are compromised by contaminants associated with land use and historic activities.
- *Implications:*
 - If Council does not transparently acknowledge these issues and commit to action, this may undermine trust with Poutini Ngāi Tahu and communities.
- *Mitigation / Response:*
 - Staff will continue to work in partnership with Poutini Ngāi Tahu on interpreting the findings through a Te Mana o te Wai lens and jointly developing priorities for action.
 - Staff will use the report as a shared evidence base to inform co-designed monitoring, restoration, and policy responses.

3. Programme resourcing risk

- *Issue:* Maintaining and improving the SoE monitoring network (e.g. continuous sensors, lab analysis, data management and reporting) requires ongoing investment.
- *Implications:*
 - Insufficient resourcing may limit Council's ability to track trends, evaluate the effectiveness of interventions, or meet national reporting requirements.
- *Mitigation / Response:*
 - Staff will align future LTP and annual plan budgets with the monitoring and analysis effort required under NPS-FM and for ongoing SoE reporting.
 - Staff will continue to refine the network and methods to ensure monitoring remains targeted, efficient, and fit-for-purpose. Additionally, a full independent network review is scheduled for the financial year which will identify gaps, risks and issues.

Significance and Engagement Policy assessment

There are no issues within this report which trigger matters in this Policy.

Mana whenua views

Staff are not aware of any issues within this report which would impact mana whenua.

Views of affected parties

Staff are not aware of any views of affected parties which impact on matters discussed in this report.

Financial implications

Monitoring of the regionals river water quality state sits within Council Annual Plan budgets.

Future implications

Not applicable

Legal implications

Not applicable

Attachments

Attachment 1: WCRC State of the environment monitoring waterway health and quality state report



WEST COAST
REGIONAL COUNCIL

State of the environment monitoring
Waterway health and quality
State

September 2025



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Disclaimer

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Table of Contents

SUMMARY	1
Statement of data verification and liability	2
1. INTRODUCTION	3
2. METHODS	4
2.1. Program design	4
2.2. Program components	5
2.3. Thresholds and assessment criteria	5
2.3.1. The National Policy Statement for Freshwater Management: Target attribute states	5
2.3.2. Human contact vs. primary contact in freshwater environments	6
2.3.3. Primary contact in marine environments	6
2.3.4. Other attributes	6
2.3.5. Catchment landcover	7
3. RESULTS AND DISCUSSION	7
3.1. REC	Error! Bookmark not defined.
3.2. Water quality attributes	8
3.2.1. Temperature	8
3.2.2. Clarity	12
3.2.3. Turbidity	15
1.1.1. Dissolved oxygen	18
3.2.4. pH	22
3.2.5. Ammonia and nitrate	24

3.2.6.	Dissolved reactive phosphorus	29
3.2.7.	E. coli: human contact.	32
3.2.8.	Macroinvertebrates	35
3.2.9.	Periphyton cover	39
3.2.10.	Primary human contact	41
4.	REFERENCES	43
APPENDIX A – INDIVIDUAL SITE DATA FOR PRIMARY CONTACT RECREATION MONITORING		45



Summary

All water is important and valued by Poutini Ngāi Tahu, whether it is groundwater, coastal water or water flowing in rivers or drains. It is very important to Poutini Ngāi Tahu that the mauri - the life-giving essence - of water is maintained. If water is degraded, it affects mana, as it reduces the ability for hapū to collect and provide safe mahinga kai. Poutini Ngāi Tahu, as mana whenua and kaitiaki, have an inherited responsibility to pass healthy water onto future generations.

The West Coast is renowned for its natural and physical attributes, including its lakes, rivers, and coastal areas. Our water resources provide a range of benefits supporting agriculture, industry, tourism, and the health and well-being of people and communities. Reduced water quality increases risks to public health and affects our ability to use freshwater environments for recreational and commercial purposes. Natural factors, such as climate, geology, and topography help determine how human pressures affect the state of water quality and ecosystem health in a particular waterbody. The types of pressures vary, for example, faecal contamination versus nutrients versus sediment discharges, which will impact on a waterbody's values in different ways.

Council's main water quality focus is on the West Coast's network of waterways, with other significant programs covering lakes, and coastal primary contact recreation locations. Council's first and foremost duty is to measure and report on what is the highest priority for Poutini Ngāi Tahu and the local community. Council also has a responsibility to obey national regulations that dictate what should be monitored and how. The National Policy Statement for Freshwater Management 2020 (NPSFM), has a dominant role in directing what we measure and more critically, the thresholds we apply to determine what is adequate in terms of water quality and ecosystem health.

The proportion of anthropogenic landcover was used to compare to a range of water quality and aquatic health attributes. Sites with less anthropogenic landcover were likely to have better dissolved oxygen regimes, lower nutrients, less faecal contamination, and better macroinvertebrate health.

The West Coast generally has a cool, wet climate but thermal stress can occur periodically in some streams ($CRI > 22^{\circ}\text{C}$), at which point sensitive species are at risk. Risk factors include: reduced riparian shade; small size and a lack of cool sources like springs or forested hill country; and climatic extremes.

Suspended sediment was assessed using measures of clarity (as per the NPSFM 2020), and turbidity. The majority of monitoring sites had good clarity. Naturally occurring dissolved organic matter can reduce clarity in some waterways and care is needed to avoid attributing clarity reductions from this on suspended sediment. There was not a strong relationship between anthropogenic landcover and clarity suggesting that individual activities and natural factors play a significant role.

Dissolved oxygen can vary widely over the course of a day and assessment requires continuous datasets eg every 15 minutes not every month. Plant and algal proliferations were likely to be a common cause of low dissolved oxygen when nutrients, light, warmth, and stable flows encouraged high biomass.



A suite of intrinsic factors can exacerbate real or perceived reductions in water quality. Low gradient, slow flowing waterways tend to be warmer, have less oxygen, more aquatic plants and poorer macroinvertebrate health. Dissolved organic matter, known for its brown colouration, can reduce pH and clarity significantly in absence of any suspended sediment.

Nutrient levels in West Coast waterways were not toxic but could reach concentrations high enough to promote plant and algal proliferations. This was most likely in the warmer months, supported by oxygen fluctuations measured Nov-March, but less likely outside of these times as suggested from monthly periphyton/algal biomass assessments.

A large number of sites scored poorly under the NPSFM E. coli criteria for human contact. Anthropogenic sources (human and ruminant) are causing problems, but birds, high rainfall, and statistical methodology are also contributing to these poor results. Suitability for primary contact (swimming) was also impacted by the same causal factors, but was safe at most sites most of the time. Lakes were the cleanest, followed by ocean beaches, then rivers and estuaries last.

Macroinvertebrate communities can be affected by a wide range of factors. A range of different anthropogenic causes are likely to reduce macroinvertebrate community health, and these could be exacerbated by intrinsic factors such as those previously mentioned.

Statement of data verification and liability

The West Coast Regional Council recognizes the importance of good quality data. This fifth comprehensive surface water quality technical report provides interpretation of results from the West Coast Regional Council Surface Water Quality Monitoring Program and is a summary of relevant information available at the time the report was produced.

Data collection and management systems follow systematic quality control procedures. International Accreditation New Zealand laboratories carried out sample analysis, excluding field analysis. When possible expert staff have been involved in each stage of the monitoring process.

While every attempt has been made to ensure the accuracy of the data and information presented, the West Coast Regional Council does not accept any liability for the accuracy of the information. It is the responsibility of the user to ensure the appropriate use of any data or information from the text, tables or figures. Not all available data or information is presented in the report. Only information considered reliable, of good quality, and of most importance to the readers has been included.



1. Introduction

West Coasters have strong connections to water across Te Tai Poutini, and our freshwater environments hold immense significance for Poutini Ngāi Tahu. Water is highly valued, providing us with drinking water, farming and mining, recreation and wellbeing and habitat for a diverse range of native plants and animals. Improving and sustaining water resources and the health of our freshwater ecosystems is therefore of great importance.

Aims of the West Coast monitoring program are:

- To determine the health of surface waters in the West Coast region in reference to accepted standards (for public health, recreational, and ecological values).
- To identify short and long-term trends in water quality.
- To assess potential for environmental effects and compare to relevant guidelines and standards.
- To understand the nature of surface water quality problems/issues in order to provide information that enables defensible management responses to be enacted. Such responses include seeking reviews to Regional Council resource management plans, regulations, and resource consent conditions.

The National Policy Statement for Freshwater Management 2020 (NPSFM), provides a national framework for how freshwater is to be managed across the country. It applies to all freshwater (including groundwater) and, to the extent they are affected by freshwater, to receiving environments such as estuaries and the coastal marine area. The NPSFM (2020) includes a framework for assessing many key attributes associated with water quality and ecosystem health.

Water is a taonga (treasure) to Poutini Ngāi Tahu and having the ability to exercise tino rangatiratanga over water within their takiwā is of utmost importance to them. The Ngāi Tahu ki uta ki tai (from the mountains to the sea) practice, supported also in the NPSFM (2020), recognises the connections between land, groundwater, surface water and coastal water. It is very important to Poutini Ngāi Tahu that the mauri - the life-giving essence - of water is maintained. If water is degraded, it impacts mana as it reduces the ability for hapū to collect and provide safe mahinga kai so they can manaaki their visitors. Poutini Ngāi Tahu, as mana whenua and kaitiaki, have an inherited responsibility to pass healthy water onto future generations.

Te Mana o te Wai is a concept underpinned by the NPSFM (2020) that refers to the fundamental importance of water and recognises that protecting the health of freshwater protects the health and well-being of the wider environment. It protects the mauri of the wai. Te Mana o te Wai is about restoring and preserving the balance between the water, the wider environment, and the community.

The West Coast's land cover profile is characterised by a predominance of natural landcover types. Of this, the bulk is made up of forest cover (about two thirds of land area), of which most is indigenous forest (LCDB 2020). Other types include: A substantial area of grassland/other herbaceous vegetation cover (17% of land area), of which more than half



is tussock grassland; scrub/shrubland cover, predominantly comprised of indigenous scrub/shrubland; and a relatively substantial area of natural bare/lightly vegetated surfaces (e.g. gravel or rock, permanent snow and ice, etc.).

Only a relatively small proportion of West Coast landcover is anthropogenic or influenced significantly by human activity. Approximately 12% of the region has landscapes significantly modified by human activity, which includes: Exotic grassland (7%), exotic forest (2%), exotic scrub/shrubland (1%), cropping/horticulture (<1%), artificial bare surfaces (<1%), and urban area (<1%)(Land Cover Database version 6.0).

2. Methods

2.1. Program design

The monitoring program must work within a number of constraints. Given the limited resources available, quarterly sampling was the norm until autumn 2016. Since then, sampling frequency has increased among sites to monthly, which is the sampling frequency for all sites in the program as of 2025.

Sampling protocols have also changed alongside an increase in sampling frequency. Previously, sampling only occurred at median flow so very little was known about water quality following rain or flood events. Sampling currently occurs on a recurring schedule so that sites are sampled at the same time each month irrespective of weather and flows.

The monitoring program targets areas where the most significant human pressures are while maintaining a subset of sites in low impact and pristine areas for reference. Sites in the program were chosen to try to achieve a balance within and between the following criteria:

- (a) Geographical spread throughout the West Coast region;
- (b) Range of waterway sizes represented (from large main-stem rivers to small creeks);
- (c) Range of different environmental pressures represented at different sites;
- (d) In areas with high human use (such as for recreation or drinking) or significant ecological values.

In order to address its aims while working within the constraints mentioned above, design of the monitoring program involved choosing attributes that were informative for assessing health and quality for a range of values. These values have been dictated by the local community and via central government environmental standards and policy statements.



2.2. Program components

The Surface Water Quality Monitoring Program has involved the collection of data from rivers, lakes and the ocean since the mid-nineties. The overall program contains many individual components (*Figure 1*).

Table 1: Components of the surface water quality monitoring program as of 2024. An asterisk denotes those components that are covered in this report.

Monitoring area	Attribute	Timing
Waterways	E. coli, physical and chemical attributes *	Monthly
Waterways	Periphyton *	Monthly
Waterways	Macroinvertebrates *	Annual
Waterways	Habitat	Annual
Waterways	Continuous pH, oxygen, turbidity, conductivity *	November-March, >7 days@ 15-minute interval
Waterways	Continuous temperature *	Permanent, 15-minute interval
Contact recreation – rivers, lakes, and coastal	E. coli or Enterococci *	November-March, weekly
Lakes	E. coli, physical and chemical attributes	Lake Brunner – monthly Other lakes – annual
Lakes	Submerged plant assessment	3-5 years

The majority of effort has been and continues to be invested in sampling a range of streams and rivers across the region. The National Institute of Water and Atmospheric Research's (NIWA) National River Water Quality Network has four sites within the West Coast region that have been sampled monthly since 1989, and data from this program is incorporated into analysis presented in this report.

Lake Brunner is a particular area of focus where monitoring has been conducted at a range of sites in the lake and its tributaries as part of the monitoring program. Tributaries of Lake Brunner are included here, but synthesis of sampling in the lake itself is covered in a separate report.

2.3. Thresholds and assessment criteria

2.3.1. The National Policy Statement for Freshwater Management: Target attribute states

The NPSFM has target attribute states for a range of attributes e.g. ammonia, clarity, and dissolved oxygen. Each attribute has four bands ranging from A to D. Human contact is the one exception with five E. coli bands. The precise definition of these bands varies among attributes, but to generalize, A is good and D is poor. We have used these bands as a reference for a range of attributes measured by the WCRC.



In 2014, the New Zealand Government produced the National Policy Statement for Freshwater Management (NPSFM), which was later amended in 2017 and 2020 (MfE, 2017 & 2020). The NPSFM provides direction on how local and regional authorities, including the WCRC, should carry out their responsibilities under the Resource Management Act 1991 for managing freshwater.

2.3.2. Human contact vs. primary contact in freshwater environments

Human health for recreation is listed in the NPSFM as a compulsory national value of freshwater. Fecal bacteria are indicators for the presence of pathogens that can harm people when they come into contact with water. The NPSFM has two separate tables in the National Objectives Framework (NOF) that list thresholds (attribute states) for bacterial health. The first is for human contact, for all freshwaters, which we have applied to our monthly river sampling network data.

The second table provides specific thresholds for primary contact sites e.g. swimming. These thresholds are very similar to the single sample criteria provided by the Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas (MfE 2003), which we have used for our primary contact reference threshold. This data comes from WCRC's primary contact water quality program that tests some of the West Coasts well-used bathing sites. The program involves the weekly collection of water quality samples between November and March.

2.3.3. Primary contact in marine environments

As the NPSFM covers freshwater, both the human contact and primary contact NOF tables use *E. coli* bacteria as the attribute. For marine primary contact we have followed the Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas (MfE 2003), using the bacteria *Enterococci* and thresholds that recommends. *E. coli* has been used for monitoring in brackish estuaries as all the estuarine sites in the program tend more to the riverine freshwater end of the spectrum.

2.3.4. Other attributes

The NPSFM (2020) stipulates a range of attributes that should be measured, along with thresholds to assess them and determine whether the various values associated with freshwater are supported. There are other attributes and thresholds, not included in the NPSFM (2020), that are applicable. This includes temperature and the percentage saturation of dissolved oxygen.

Potential for a temperature NOF was investigated by the government but this was not implemented. The Cox-Rutherford Index (CRI) was proposed to evaluate the suitability of stream temperature regimes on aquatic health (Davies-Colley et al. 2013). The CRI is calculated using the 5 hottest days in a year. Many of the WCRC's monitoring sites have multiple years of continuous data (15-minute intervals), thus a spread of annual CRI's can be presented. The thresholds for Maritime Climates (18°C, 20°C, 24°C), have been used.

Both the Macroinvertebrate Community Index (MCI) and Quantitative Macroinvertebrate Community Index (QMCI) are part of the NPSFM NOF for freshwater monitoring and are complementary tools for assessing stream health. It should be noted that for the calculation of QMCI scores, some older SQMCI categorical data has been used for certain sites.



This is due to a shift in sorting protocols from P1 coded abundance to P2 200 Fixed Count + Scan for Rare Taxa (Stark et al. 2001).

2.3.5. Catchment landcover

Landcover is derived from the New Zealand Land Cover Database. The New Zealand LCDB (2020) is a classification of the country's land cover derived from satellite imagery, with 33 mainland land cover classes. We have designated these classes as either natural or anthropogenic and summed the proportion of these two groups in each of the catchments where monitoring is undertaken. This allows us to examine the relationship between our sampling data and the extent of human activity upstream of that sampling.

3. Results and discussion

3.1. River Environment Classification

The 2005 Regional Council SoE report covered Regional Council data records up until 2004–2005, conducting analysis under the River Environment Classification (REC) framework (Snelder et al. 2010). The REC system groups rivers with similar physical and biological characteristics for management and research purposes. This GIS-based classification uses factors like climate, topography, geology, and land cover to define a nested hierarchy of river segments. It provides a framework for resource management by allowing different river classes to be treated as similar to one another.

The REC was used to group sites by climate, source of flow, geology, land cover, and stream order. Relationships between these REC classes and water quality were investigated. It is worth mentioning this work as it is useful for describing some fundamental characteristics of West Coast waterways.

Many significant differences in physical, chemical, and biological water quality attributes were observed between the REC classes of: source of flow, geology, land cover, and stream order. Patterns observed for these attributes amongst REC classes suggested that streams could be characterised as:

- Streams with a hill source of flow; hard sedimentary or plutonic geology; often incorporating larger rivers; with higher, less variable water quality; brown trout more abundant.
- Lowland streams (low elevation source of flow); higher turbidity, nutrients, and temperature (which may not solely have been a response of human activity); smaller, more variable and susceptible to impact; potentially higher fish and invertebrate diversity.
- Streams draining predominantly agricultural catchments (sub-set of lowland streams); comparatively poorer water quality with fewer sensitive macroinvertebrate taxa.
- Stream catchments with soft sedimentary geology; higher turbidity; distinctive physically and chemically from other geology classes; smaller size; lower source of flow



3.2. Water quality attributes

Freshwater quality attributes are measurable physical, chemical, and biological properties used to determine the health of an aquatic ecosystem and its suitability for uses like drinking, swimming, or supporting aquatic life. The WCRC measures a broad range of key attributes that can be used to assess how well various values are catered for. As an example, faecal bacteria like *E. coli* and Enterococci indicate pathogen risk to people and livestock should they swim or consume the water. Suspended sediment impacts on amenity (unsightly, unsafe to swim), and ecology (abrasion of gills, difficulty finding prey, reduced productivity).

3.2.1. Temperature

Temperature strongly influences water composition, because it affects the equilibrium point (e.g. equilibrium solubility of dissolved oxygen) and the rates of physico-chemical and biochemical reactions (e.g. the rate of dissolved oxygen consumption by bacterial respiration). Temperature profoundly affects aquatic ecosystems because, besides the effects on oxygen and other chemical constituents (e.g., ammonia), growth of most organisms is a function of temperature. There is an optimum temperature for growth rate, below which growth falls slowly. Our main concern, though, is for temperatures above the growth optimum, because such temperatures impose thermal stress on organisms, and lethal temperatures can be reached only slightly higher than (perhaps 5°C above) the growth optimum (Davies-Colley et al. 2013). Temperatures higher than the optimum become increasingly stressful because of effects on cellular function with enzymes becoming denatured.

Under the REC, all West Coast waterways are defined climatically as cool/wet or cool/extremely wet. While this may appear reassuring, temperatures high enough to cause thermal stress in aquatic organisms do occur. Fundamentally, a closer proximity to the ocean lowers temperatures in summer and increases them in winter (Figure 1). Conditions are typically warmer and drier to the north and further inland (at low altitudes), but as altitude increases temperatures decrease (Macara 2016). A range of smaller scale site specific factors come into play like stream size, shading, brown colouration, flow rate, and spring recharge. Climatic variability plays a key role, where normally cool and wet weather can deviate to dry and hot over summer. It is usually during these periods that the highest CRI's are observed. CRI essentially indicates the maximum temperatures observed in a waterway reach.

The majority of continuous temperature monitoring sites are in the Grey River catchment (Arnold and Grey, *Figure 2*). Sites within this catchment show a wide range of CRI scores as the sites vary greatly in size, source of flow, shading, and distance from the sea. The Orangipuku River is one of the coolest rivers in summer due to a dominant spring fed supply. This strong groundwater derived source leads to relatively warm temperatures in winter. Sawyers Ck is a third order stream near Greymouth, which has two monitoring sites – one in the town, near a tidal lagoon, and the other in forested hill country. While these sites are less than 4 km apart, the effect of reduced riparian shade is significant on this smaller, slow flowing waterway, with respective median CRI's of 16.4°C and 21.7°C. Maximum CRI's for these sites are further apart 17.4°C and 22.9°C (Table 2).

The Hohonu River (4th order) is a similar example further inland in the Grey River catchment. There are two sites on this river, 9 km apart, one at the base of steep, forest clad hill country and the other downstream in flatter country with reduced riparian cover. As well as the effect of reduced riparian shade, additions of dark dissolved organic matter



(DOM) and slower water velocities exacerbate downstream temperature increases (Williamson et al. 2015). Upstream to downstream respective median CRI's are 16.5°C and 23.4°C, with maximum CRI's for these sites at 17.2°C and 25.9°C respectively. The lower site consistently has CRI's that will cause some stress on occasions, forcing out sensitive species. While rarer, there are hot periods every few years that will cause significant thermal stress and loss of ecological integrity.

In the regions north, in the Buller catchment and Karamea area, summer maximums were the highest (Figure 2). None of these sites have significant recharge but do have notable colouring from DOM. The four warmest waterways were smaller 3rd order streams with slower water velocities and reduced riparian shading. These occasionally had significant thermal stress. The coolest waterway was a small, hill fed stream with an indigenous forest catchment. Two sites were located on the large (5-6 order) Inangahua River. While the main channel moving to the downstream site has little riparian shade, the majority of the catchment is clad in indigenous forest. Both locations in the Inangahua River typically reached summer maximums of ~21.5°C. All sites in the Buller catchment and Karamea area consistently reached maximums that would cause some stress on occasions that will eliminate sensitive species. While they varied in terms of size, velocity, distance from the coast they were all in areas with a warmer climate.

Westland sites had lower summer maximums due to significant spring recharge from groundwater. The exception, regarding source, is Okutua Stream, but its entire catchment is covered with indigenous lowland forest. These sites are also located the farthest south.

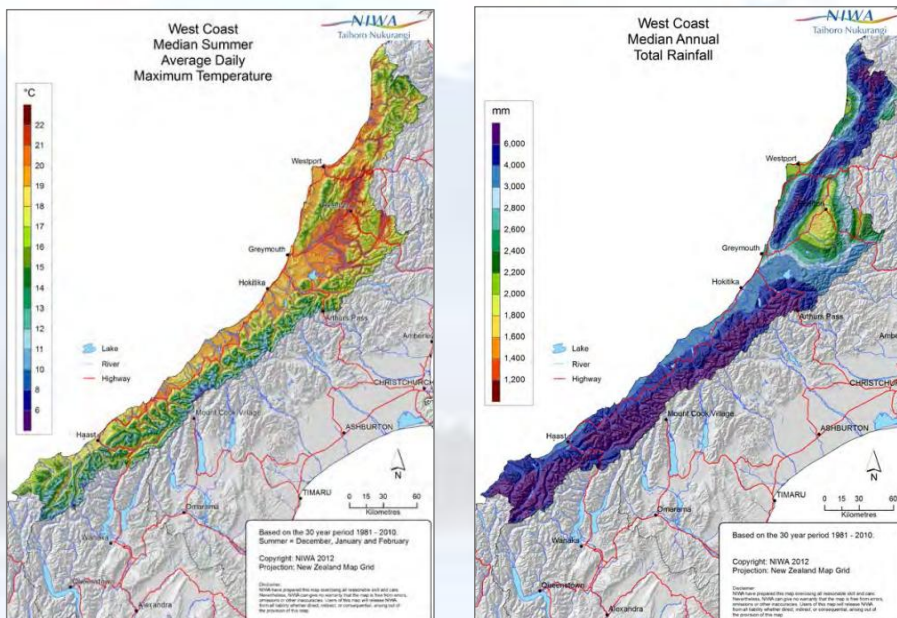


Figure 1: Left: West Coast median summer (December, January and February) average daily maximum temperature. Right: West Coast median annual total rainfall, 1981–2010. From Macara (2016).

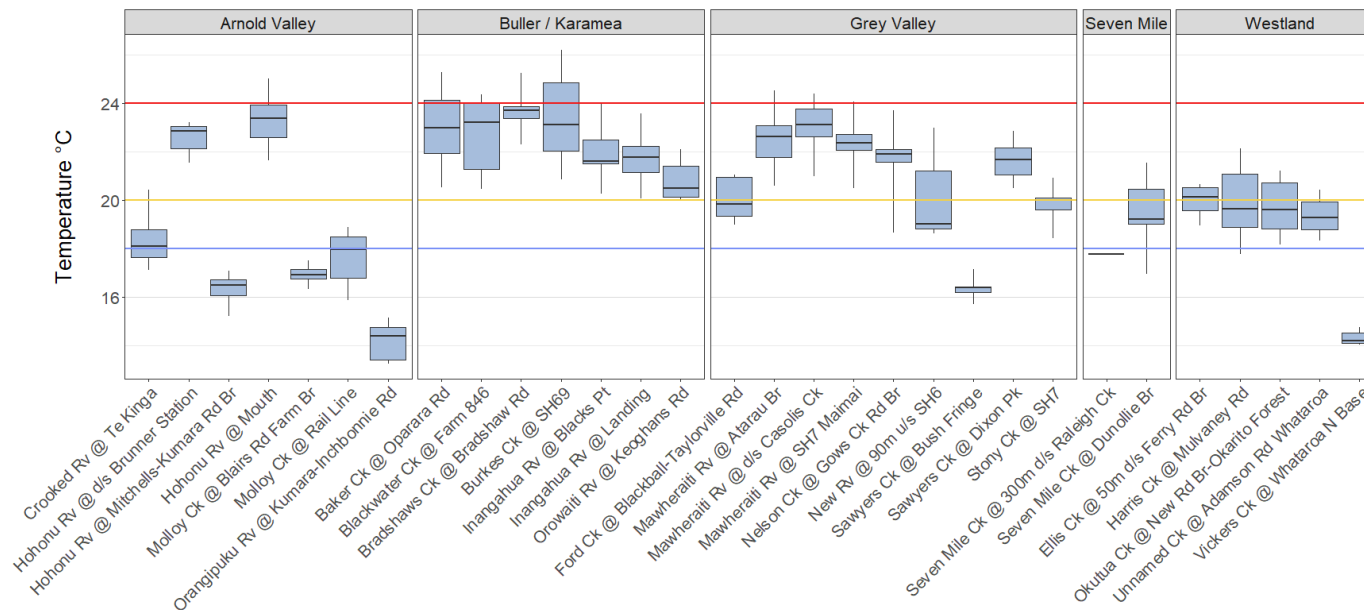


Figure 2. Box and whisker graph showing the spread of water temperature data based on CRI, calculated on the 5 hottest days in summer for individual Council monitoring program sites where there is continuous data available. Sites are grouped into geographical areas.



Table 2: Cox Rutherford Limit (CRI) categories. Dark green, No stress; Light green, Minor stress; Orange, Some stress on occasions that will eliminate sensitive species; Red, Significant thermal stress, loss of ecological integrity.

Site	Number of years	Temperature C			Area
		Median of annual CRI's	Min CRI	Max CRI	
Vickers Ck @ Whataroa N Base	3	14.2	14.0	14.8	Westland
Orangipuku Rv @ Kumara-Inchbonnie Rd	12	14.4	13.2	15.5	Arnold Valley
Sawyers Ck @ Bush Fringe	6	16.4	15.6	17.4	Grey Valley
Hohonu Rv @ Mitchells-Kumara Rd Br	4	16.5	15.0	17.2	Arnold Valley
Molloy Ck @ Blairs Rd Farm Br	7	16.9	16.2	17.6	Arnold Valley
Seven Mile Ck @ 300m d/s Raleigh Ck	1	17.8	17.8	17.8	Seven Mile
Molloy Ck @ Rail Line	3	18.0	15.6	19.0	Arnold Valley
Crooked Rv @ Te Kinga	13	18.1	16.9	20.6	Arnold Valley
New Rv @ 90m u/s SH6	3	19.0	18.6	23.4	Grey Valley
Seven Mile Ck @ Dunollie Br	7	19.2	16.1	21.8	Seven Mile
Unnamed Ck @ Adamson Rd Whataroa	8	19.3	18.2	20.6	Westland
Okutua Ck @ New Rd Br-Okarito Forest	6	19.6	18.0	21.3	Westland
Harris Ck @ Mulvaney Rd	10	19.6	17.4	22.7	Westland
Ford Ck @ Blackball-Taylorville Rd	5	19.9	18.9	21.1	Grey Valley
Stony Ck @ SH7	9	20.0	17.8	21.4	Grey Valley
Ellis Ck @ 50m d/s Ferry Rd Br	4	20.2	18.8	20.7	Westland
Orowaiti Rv @ Keoghans Rd	5	20.5	20.0	22.3	Buller / Karamea
Inangahua Rv @ Blacks Pt	9	21.6	19.5	25.0	Buller / Karamea
Sawyers Ck @ Dixon Pk	10	21.7	20.2	22.9	Grey Valley
Inangahua Rv @ Landing	9	21.8	19.7	24.4	Buller / Karamea
Nelson Ck @ Gows Ck Rd Br	9	21.9	16.9	24.4	Grey Valley
Mawheraiti Rv @ SH7 Maimai	12	22.4	20.3	25.1	Grey Valley
Mawheraiti Rv @ Atarau Br	7	22.6	20.4	25.0	Grey Valley
Hohonu Rv @ d/s Brunner Station	3	22.8	21.4	23.3	Arnold Valley
Baker Ck @ Oparara Rd	7	23.0	20.1	25.6	Buller / Karamea
Burkes Ck @ SH69	10	23.1	20.6	26.6	Buller / Karamea
Mawheraiti Rv @ d/s Casolis Ck	10	23.1	20.8	24.7	Grey Valley
Blackwater Ck @ Farm 846	7	23.2	20.4	24.4	Buller / Karamea
Hohonu Rv @ Mouth	11	23.4	21.4	25.9	Arnold Valley
Bradshaws Ck @ Bradshaw Rd	7	23.7	21.9	25.8	Buller / Karamea



3.2.2. Clarity

Water clarity is a measure of how transparent water is, or how far light can penetrate through it. It indicates the optical quality of water, which is important for aquatic ecosystems, visual amenity, and photosynthesis. The WCRC measures clarity using a horizontal black disk or clarity tube.

The two main factors reducing clarity in West Coast waterways are suspended sediment and dissolved organic matter (DOM), also known as 'tea stain'. Both of these affect clarity measurements, but only suspended sediment affects turbidity readings, which don't detect dissolved substances like DOM. Regardless, the NPSFM selected clarity rather than turbidity as a surrogate measure for suspended sediment levels. We have used the clarity as the attribute unit for assessing Suspended fine sediment, as per NOF Table 8 in the NPSFM. This table also adjusts assessment based on dominant catchment geology.

While streams with very high DOM can be problematic, clarity for the most part works well as a surrogate for suspended sediment. West Coast waterways often have suspended sediment levels that are lower than the detection limits of turbidity meters and conventional gravimetric methods like total suspended solids. However, the WCRC does also measure turbidity as it can be complimentary when suspended sediment concentrations are high.

In catchments with anthropogenic landcover there was no clear relationship between the amount of anthropogenic landcover, median clarity, or NOF attribute state. Waterways with no anthropogenic landcover were in the A band although there were exceptions. Okutua Stream had reduced clarity due to very high concentrations of DOM. The Orowaiti River sites were affected by a large slip in the headwaters that occurred during 2021. The Buller River @ Te Kuha and Grey River @ Dobson are very large river sites (7th order). Despite the relative lack of anthropogenic landcover, given their large catchments, it is difficult to know what human activities could be affecting clarity at these locations.

Even sites with a high proportion of anthropogenic landcover could have high clarity. Sites with 80-100% anthropogenic cover were all spring fed creeks in Westland's flat alluvial plains. Despite being surrounded by intensive agriculture these streams retained high clarity and low suspended sediment levels. Good clarity was observed for most spring fed streams in the region.

Overall, the majority of monitoring sites had good clarity. Twenty percent of sites were classified as having 'Moderate to high impact of suspended sediment on instream biota. Sensitive fish species may be lost.' These exceptions related to high DOM, current and historic mining, natural slips, and other unknown activities. Five sites have clarities below the national bottom line, which describes condition as 'High impact of suspended sediment on instream biota. Ecological communities are significantly altered and sensitive fish and macroinvertebrate species are lost or at high risk of being lost'. These were all surrounded by intensive agriculture but lacked the significant spring recharge that buffered other farmland streams. Several of these sites drained low gradient, swampy land, predisposed to erosion and turbidity. The remainder were small waterways, in catchments where ongoing land disturbance and/or mining has clearly increased suspended sediment levels (Table 3).

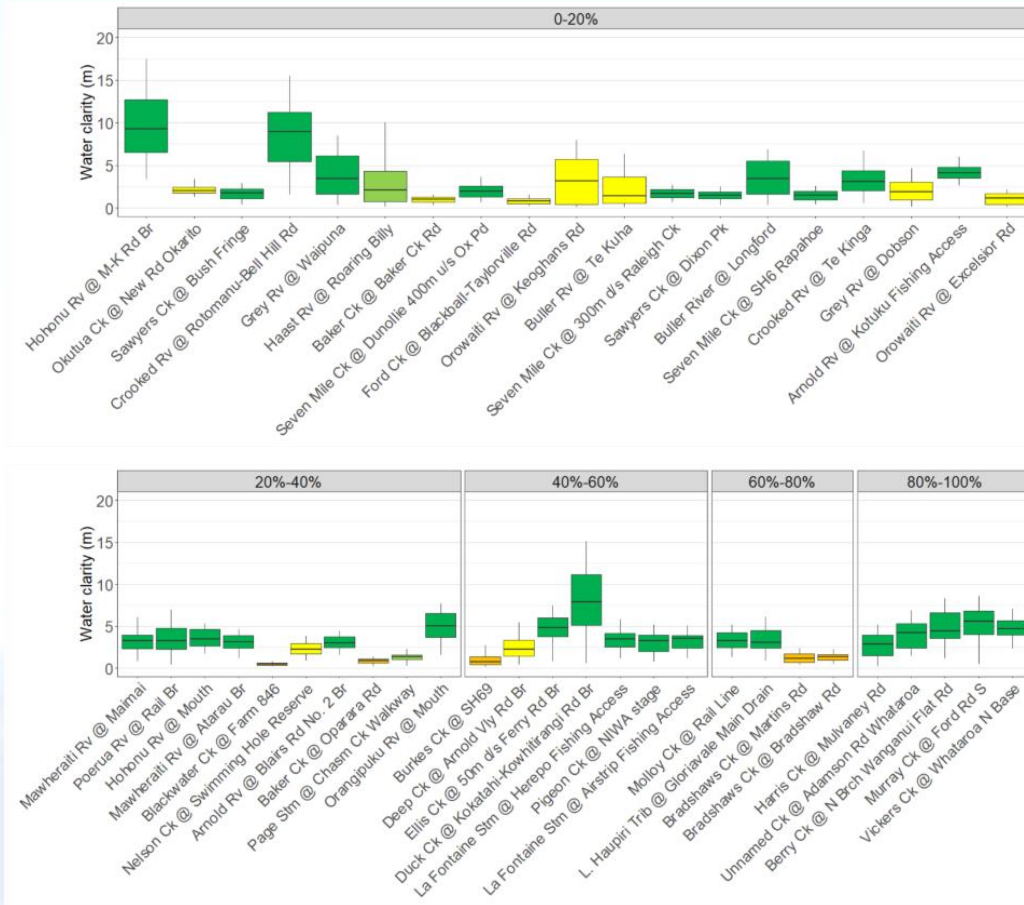


Figure 3. Clarity (black disc and clarity tube combined). Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. Box colors represent NPSFM (2020) NOF categories: Green = A, Minimal impact of suspended sediment on instream biota. Ecological communities are similar to those observed in natural reference conditions; Light green = B, Low to moderate impact of suspended sediment on instream biota. Abundance of sensitive fish species may be reduced; Yellow = C, Moderate to high impact of suspended sediment on instream biota. Sensitive fish species may be lost; Orange = D, High impact of suspended sediment on instream biota. Ecological communities are significantly altered and sensitive fish and macroinvertebrate species are lost or at high risk of being lost.



Table 3 Suspended fine sediment NOF grades for Regional Council monitoring program sites. Calculated as 5 yearly medians, year ending 2023. Box colors represent NPSFM (2020) NOF categories: Green = A, Minimal impact of suspended sediment on instream biota. Ecological communities are similar to those observed in natural reference conditions; Light green = B, Low to moderate impact of suspended sediment on instream biota. Abundance of sensitive fish species may be reduced; Yellow = C, Moderate to high impact of suspended sediment on instream biota. Sensitive fish species may be lost.; Orange = D, High impact of suspended sediment on instream biota. Ecological communities are significantly altered and sensitive fish and macroinvertebrate species are lost or at high risk of being lost.

Site Name	Overall NOF 2023	Site Name	Overall NOF 2023
Arnold Rv @ Blairs Rd No. 2 Br	A	L. Haupiri Trib @ Gloriavale Main Drain	A
Arnold Rv @ Kotuku Fishing Access	A	La Fontaine Stm @ Airstrip Fishing Access	A
Baker Ck @ Baker Ck Rd	D	La Fontaine Stm @ Herepo Fishing Access	A
Baker Ck @ Oparara Rd	D	Mawheraiti Rv @ Atarau Br	A
Berry Ck @ N Brch Wanganui Flat Rd	A	Mawheraiti Rv @ SH7 Maimai	A
Blackwater Ck @ Farm 846	D	Molloy Ck @ Rail Line	A
Bradshaws Ck @ Bradshaw Rd	D	Murray Ck @ Ford Rd S	A
Bradshaws Ck @ Martins Rd	D	Nelson Ck @ Swimming Hole Reserve	C
Buller River @ Longford	A	Okutua Ck @ New Rd Br-Okarito Forest	D
Buller Rv @ Te Kuha	C	Orangipuku Rv @ Mouth	A
Burkes Ck @ SH69	D	Orowaiti Rv @ Excelsior Rd	D
Crooked Rv @ Rotomanu-Bell Hill Rd	A	Orowaiti Rv @ Keoghans Rd	D
Crooked Rv @ Te Kinga	A	Page Stm @ Chasm Ck Walkway	B
Deep Ck @ Arnold Vly Rd Br	C	Pigeon Ck @ NIWA stage	A
Duck Ck @ Kokatahi-Kowhitirangi Rd Br	A	Poerua Rv @ Rail Br	A
Ellis Ck @ 50m d/s Ferry Rd Br	A	Sawyers Ck @ Bush Fringe	A
Ford Ck @ Blackball-Taylorville Rd	D	Sawyers Ck @ Dixon Pk	A
Grey Rv @ Dobson	C	Seven Mile Ck @ 300m d/s Raleigh Ck	A
Grey Rv @ Waipuna	A	Seven Mile Ck @ Dunollie 400m u/s Ox Pd	A
Haast Rv @ Roaring Billy	C	Seven Mile Ck @ SH6 Rapahoe	A
Harris Ck @ Mulvaney Rd	A	Unnamed Ck @ Adamson Rd Whataroa	A
Hohonu Rv @ Mitchells-Kumara Rd Br	A	Vickers Ck @ Whataroa N Base	A
Hohonu Rv @ Mouth	A		



3.2.3. Turbidity

Turbidity is a measure of the cloudiness or haziness of a liquid, like water, caused by suspended particles such as silt, clay, algae, and organic matter. It quantifies how much light is scattered by these particles. Higher turbidity means more suspended particles, resulting in a cloudier liquid that scatters more light. Turbidity is not a direct count by weight of particles (like total suspended solids), but an optical measurement of how much light is scattered by them.

There was no obvious relationship between the amount of anthropogenic landcover in a catchment and median turbidity. However, turbidity ranges were smaller in catchments with little or no anthropogenic landcover (Figure 4). It should be noted that the typical duration of data collection was 2 weeks with 15-minute sampling frequencies, so heavy rainfall and other perturbations may or may not have occurred in that time period.

The three sites with the poorest turbidity results were all unusual in their circumstances (Figure 5). Ford Creek receives acid mine drainage (AMD) from the historic Blackball mine. The mine provides a constant supply of dissolved iron from underground that promptly precipitates into a fine sediment (iron oxide). The lower reaches of Blackwater Creek are fed by a large drainage network constructed to drain what was a swamp and is now grazing. The Orowaiti River, particularly the upper reaches, traditionally has had low turbidity but a very large slip in the headwaters during 2021 led to a large increase from 2020 to 2021 (annual means of 0.7 FNU to 69 FNU, respectively).

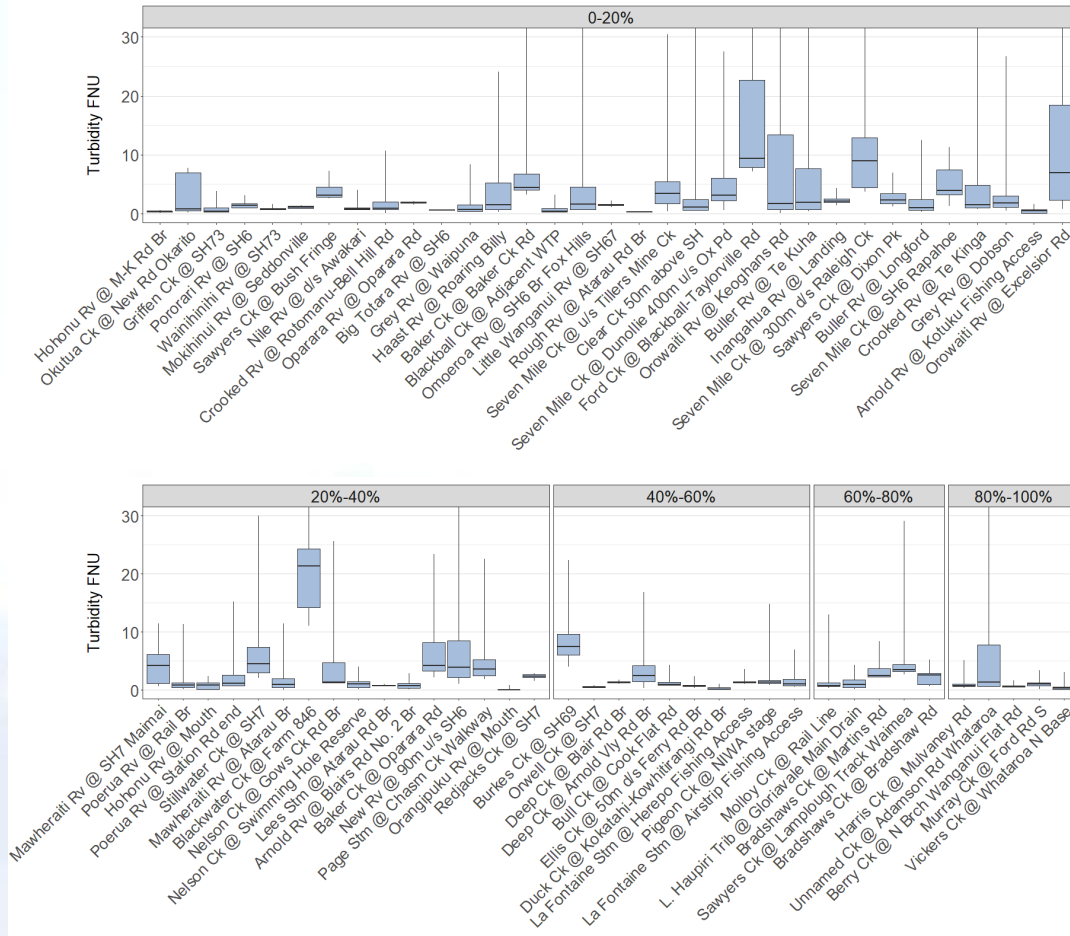


Figure 4. Turbidity data for sites where there is continuous data available (minimums and maximums excluded). Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. The Y-axis limit has been limited to 30 FNU in order to provide greater resolution at lower turbidities.

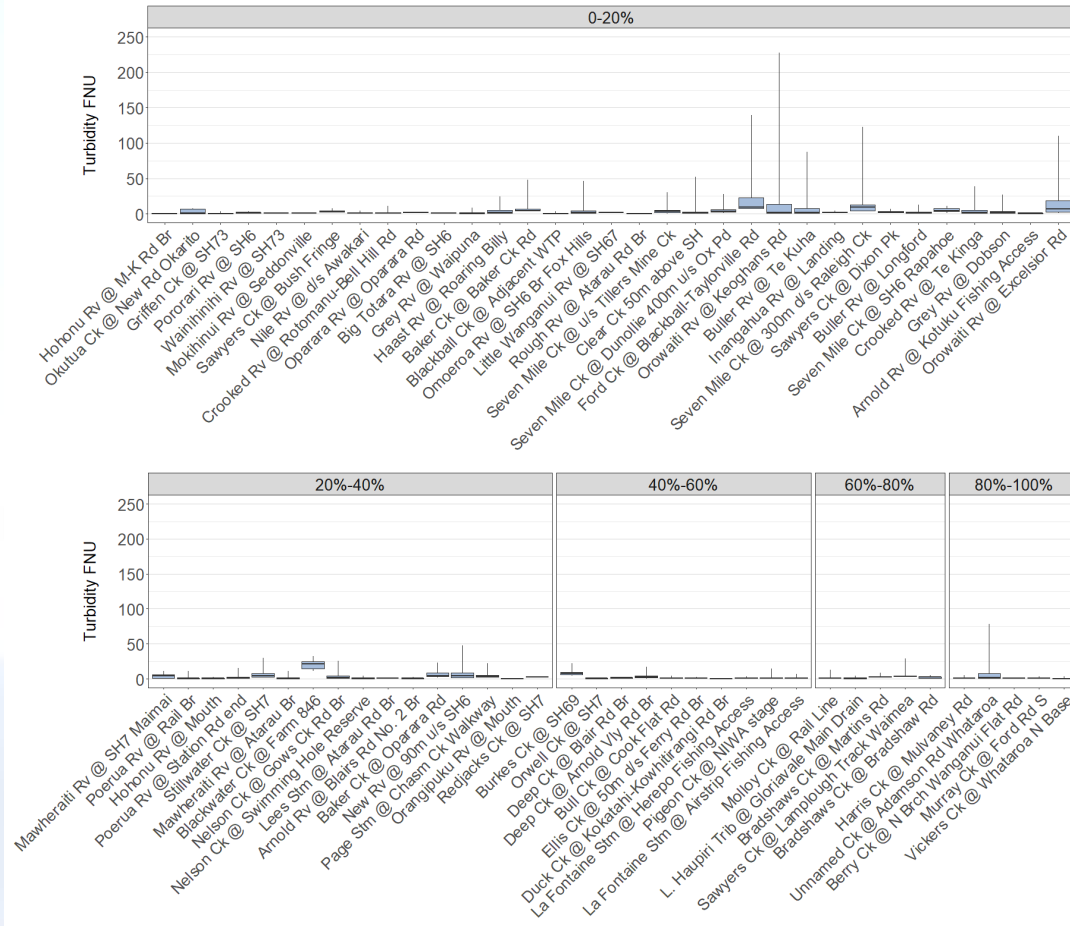


Figure 5. Turbidity data for sites where there is continuous data available (minimums and maximums excluded). Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. The Y-axis limit has been extended to 260 FNU in order to show the 95% percentile range of all sites.



1.1.1. Dissolved oxygen

The WCRC measures dissolved oxygen (DO) in streams in both milligrams per litre (mg/L) and percent saturation. Milligrams per litre is an absolute measure of how much oxygen is present whereas percent saturation indicates how much oxygen is present relative to the atmosphere (100%) at a given temperature. Warmer water holds less oxygen so 100% saturation at 25°C has less oxygen than 100% saturation at 10°C, which is 8.26 mg/L and 11.3 mg/L, respectively. If saturation is less than 100%, then there is less oxygen in the water than what would be expected in ideal environmental conditions. Super saturation can occur when significant photosynthesis boosts oxygen saturation to levels above what would be possible in air at that temperature. A clear and open stream, filled with aquatic plants, on a sunny afternoon, would be a candidate for supersaturation.

DO is important because it is necessary for the survival of aquatic life, like fish and other organisms that require it for respiration. A lack of DO can stress or kill aquatic organisms. High levels indicate a healthy environment, but this does not include our example with high plant biomass and photosynthesis – while DO is high in the afternoon, this will drop to much lower levels on dark when photosynthesis ceases and there is only respiration (oxygen use). Monitoring of DO occurs from November to March.

Sites with less anthropogenic landcover were likely to have better dissolved oxygen regimes (Figure 6) (Table 4). A broad range of factors can reduce DO: Increased nutrients and less riparian shading increases plant/algal growth and subsequent consumption of oxygen at night by plants; less riparian shading directly reduces water temperatures, warmer water having a lower oxygen carrying capacity; low gradient streams with little in the way of turbulence and reoxygenation from the atmosphere; oxidation of organic material by bacteria in the water column; a significant contribution to the stream from low DO groundwater (Abell and Doucet, 2024). A favourable DO regime included a median of 9-10 mg/L, but importantly, also had limited variation around this mark. It is the lack of variation rather than the median that is most indicative of healthy conditions. A small DO range indicates that many of the negative aforementioned drivers of low DO are not having a significant effect.

Four sites were in the D attribute state, below the national bottom line. At this level there can be significant, persistent stress on a range of aquatic organisms caused by dissolved oxygen exceeding tolerance levels. Likelihood of local extinctions of keystone species and loss of ecological integrity. Contributing factors included: high nutrients, stable flows and a lack of shade leading to plant proliferations and early morning DO troughs; low gradients/velocities exacerbating warming and a lack of reoxygenation from the atmosphere; warm climate and intrinsically warm water (with the exception of Murray Creek), that promotes plant/algal growth and holds less oxygen.

Patterns in percent oxygen saturation largely mimicked absolute quantities of oxygen (mg/L) (Figure 7). Exceptions included some strongly spring fed streams that had reduced saturation as a result of low oxygen levels in the groundwaters feeding them (Duck Creek). Duck Creek has high clarity and oxygen deficits associated partly with nighttime plant respiration, but a lack of midday oxygen peaks some suggests suppression from low DO groundwater sources. Others showed signs of instream respiration associated with non-photosynthetic organisms like bacteria (Blackwater Creek), where turbidity and organic loadings are high, and velocities are very low.



Dissolved oxygen was acceptable at most sites either posing no chance of stress or occasional minor stress on sensitive organisms caused by short periods (a few hours each day) of lower dissolved oxygen. Risk of reduced abundance of sensitive fish and macroinvertebrate species.

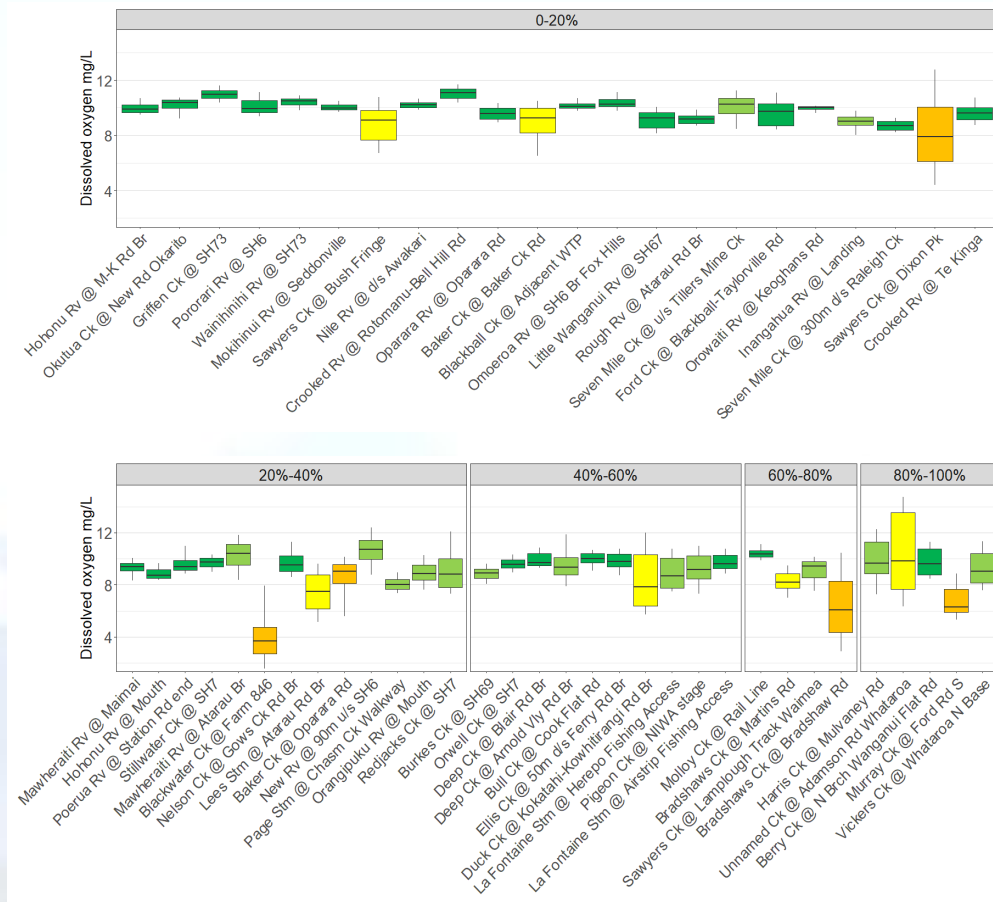


Figure 6. Dissolved oxygen (mg/L) for sites that have continuous data available (minimums and maximums excluded). Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. Box colors represent NPSFM (2020) NOF categories: Green = A, No stress caused by low dissolved oxygen on any aquatic organisms that are present at matched reference (near-pristine) sites; Light green = B, Occasional minor stress on sensitive organisms caused by short periods (a few hours each day) of lower dissolved oxygen. Risk of reduced abundance of sensitive fish and macroinvertebrate species; Yellow = C, Moderate stress on a number of aquatic organisms caused by dissolved oxygen levels exceeding preference levels for periods of several hours each day. Risk of sensitive fish and macroinvertebrate species being lost; Orange = D, Significant, persistent stress on a range of aquatic organisms caused by dissolved oxygen exceeding tolerance levels. Likelihood of local extinctions of keystone species and loss of ecological integrity.

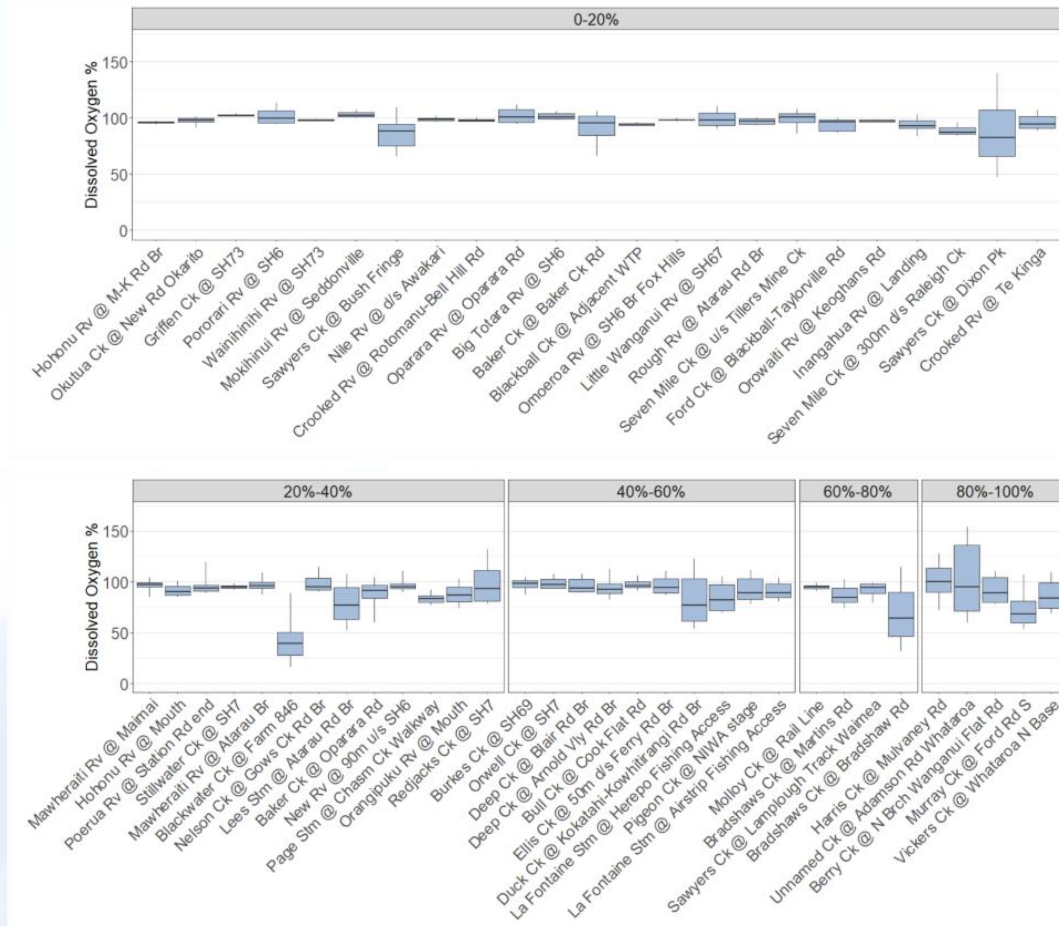


Figure 7. Dissolved oxygen (percent saturation) for sites that have continuous data. Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right.



Table 4: NOF categories for dissolved oxygen (mg/L), 2014-2024. Box colors represent NPSFM (2020) NOF categories: Green = A, No stress caused by low dissolved oxygen on any aquatic organisms that are present at matched reference (near-pristine) sites; Light green = B, Occasional minor stress on sensitive organisms caused by short periods (a few hours each day) of lower dissolved oxygen. Risk of reduced abundance of sensitive fish and macroinvertebrate species; Yellow = C, Moderate stress on a number of aquatic organisms caused by dissolved oxygen levels exceeding preference levels for periods of several hours each day. Risk of sensitive fish and macroinvertebrate species being lost; Orange = D, Significant, persistent stress on a range of aquatic organisms caused by dissolved oxygen exceeding tolerance levels. Likelihood of local extinctions of keystone species and loss of ecological integrity.

Site	1 day min	7-day	Overall	Site	1 day min	7-day	Overall
Baker Ck @ Baker Ck Rd	B	C	C	Mawheraiti Rv @ Atarau Br	B	B	B
Baker Ck @ Oparara Rd	D	C	D	Mawheraiti Rv @ SH7 Maimai	A	A	A
Berry Ck @ N Brch Wanganui Flat Rd	A	A	A	Mokihinui Rv @ Seddonville	A	A	A
Big Totara Rv @ SH6	A	A	A	Molloy Ck @ Rail Line	A	A	A
Blackball Ck @ Adjacent WTP	A	A	A	Murray Ck @ Ford Rd S	D	D	D
Blackwater Ck @ Farm 846	D	D	D	Nelson Ck @ Gows Ck Rd Br	A	A	A
Bradshaws Ck @ Bradshaw Rd	D	D	D	New Rv @ 90m u/s SH6	B	B	B
Bradshaws Ck @ Martins Rd	B	C	C	Nile Rv @ d/s Awakari	A	A	A
Bull Ck @ Cook Flat Rd	A	A	A	Okutua Ck @ New Rd Br-Okarito Forest	A	A	A
Burkes Ck @ SH69	A	B	B	Omoeroa Rv @ SH6 Br Fox Hills	A	A	A
Crooked Rv @ Rotomanu-Bell Hill Rd	A	A	A	Oparara Rv @ Oparara Rd	A	A	A
Crooked Rv @ Te Kinga	A	A	A	Orangipuku Rv @ Mouth	B	B	B
Deep Ck @ Arnold Vly Rd Br	B	B	B	Orowaiti Rv @ Keoghans Rd	A	A	A
Deep Ck @ Blair Rd Br	A	A	A	Orwell Ck @ SH7	A	A	A
Duck Ck @ Kokatahi-Kowhitirangi Rd Br	B	C	C	Page Stm @ Chasm Ck Walkway	B	B	B
Ellis Ck @ 50m d/s Ferry Rd Br	A	A	A	Pigeon Ck @ NIWA stage	B	B	B
Ford Ck @ Blackball-Taylorville Rd	A	A	A	Poerua Rv @ Station Rd end	A	A	A
Griffen Ck @ SH73	A	A	A	Pororari Rv @ SH6	A	A	A
Harris Ck @ Mulvaney Rd	B	B	B	Redjacks Ck @ SH7	B	B	B
Hohonu Rv @ Mitchells-Kumara Rd Br	A	A	A	Rough Rv @ Atarau Rd Br	A	A	A
Hohonu Rv @ Mouth	A	A	A	Sawyers Ck @ Bush Fringe	B	C	C
Inangahua Rv @ Landing	B	B	B	Sawyers Ck @ Dixon Pk	D	D	D
La Fontaine Stm @ Airstrip Fishing Access	A	A	A	Sawyers Ck @ Lamplough Track Waimea	B	B	B
La Fontaine Stm @ Herepo Fishing Access	B	B	B	Seven Mile Ck @ 300m d/s Raleigh Ck	A	A	A
Lees Stm @ Atarau Rd Br	C	C	C	Seven Mile Ck @ u/s Tillers Mine Ck	B	B	B
Little Wanganui Rv @ SH67	A	A	A	Stillwater Ck @ SH7	A	A	A



3.2.4. pH

The geology and source of a water often determine its pH. The pH is an important 'master variable' because it affects other variables and is often needed to interpret other variables (Davies-Colley 2012). Ammonia toxicity is affected by pH because the proportion of the toxic un-ionised form, NH_3 , of total ammoniacal nitrogen is primarily controlled by pH and temperature.

Maxima in pH and dissolved oxygen occur in the late afternoon when photosynthesis dominates whereas minima occur in early morning when respiration is dominant (Wilcock and Chapra 2005). During periods of base flow, in many streams with abundant plant biomass (macrophytes, phytoplankton or periphyton), strong daily cycles of dissolved oxygen and pH coincide. This is due to carbonic acid, a small proportion of which comes from carbon dioxide. When significant photosynthesis occurs carbon dioxide is consumed and oxygen produced, hence there is less carbonic acid and a lower pH. The opposite occurs at night.

On the West Coast, low pH can occur in streams for several other reasons other than photosynthesis and carbonic acid concentrations, including organic and inorganic acids (McDiffett 1996). Many West Coast waterways have low pH's due to high rainfall leaching organic acids from wetlands and native forests (Collier and Winterbourn 1990). Acid mine drainage (AMD) is a factor affecting some sites in the WCRC monitoring program. AMD results from the oxidation of pyrite in rocks that accompany Brunner coal measures and is characterized by low pH, sometimes as low as 2-4, and elevated concentrations of dissolved metals such as iron, aluminium and zinc.

The study concluded that the range of pH encountered in New Zealand lowland streams was unlikely to have a major impact on the distribution of most native freshwater fish (West et al. 1997).

Consideration for a pH NOF was made by MfE (Davies-Colley 2013) but not incorporated into the NPSFM. We have used this framework for pH levels over 7 but not for those under 7 due to the regions often naturally low pH's.

Most streams in the WCRC monitoring program have a pH below 8. Examples where it consistently gets higher occur in spring fed streams dominated with submerged plant cover (e.g. Unnamed Creek @ Adamson Road). Alternatively, catchments with significant quantities of limestone geology have elevated pH as the calcium carbonate neutralises hydrogen ions (e.g. Porarari River). AMD was a causal factor in lowering pH at Page Stream, while organic acids created low pH levels in Okutua Stream. Okutua Stream is in the lowland Okarito Forest, and while logging has occurred in parts of this forest historically, significant regeneration has occurred with a catchment of ~100% indigenous forest.

There was no relationship between landcover type and median pH levels but the greatest pH variation was observed in streams with significant anthropogenic activity. This could be due to a lack of riparian shade combined with increased nutrients, leading to increased plant/algal growth and carbon dioxide (carbonic acid) fluctuations.

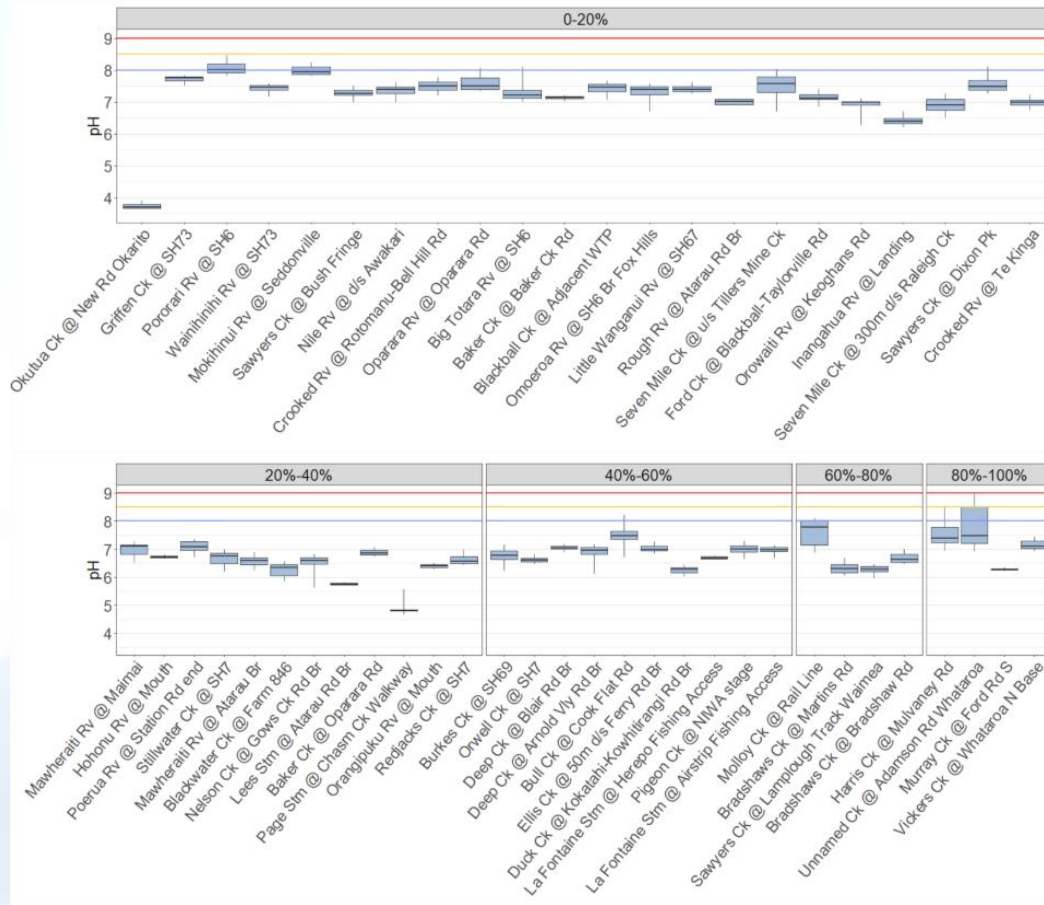


Figure 8. pH levels for a range of WCRC monitoring sites. Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right.



3.2.5. Ammonia and nitrate

Nitrogen is an essential nutrient required for plant growth. Total nitrogen consists of all nitrogen forms found in waterways. Nitrate and ammonia are highly soluble components of total nitrogen and are readily used by plants and algae to help them grow. They can leach from land to rivers, particularly when conditions are wet. Too much nitrogen can cause excessive algal growth or be toxic. In agricultural catchments, nitrate generally comes from nitrogen fertilizer and livestock urine, while ammonia comes more from point-sources such as discharges from sewerage treatment plants, farm dairy effluent, and industrial operations.

Ammonia levels at all West Coast monitoring sites were predominantly in the A attribute band, which provides a '99% species protection level: No observed effect on any species tested' (Table 5 and Figure 9). The remainder of sites were in the B band: '95% species protection level: Starts impacting occasionally on the 5% most sensitive species'. Three sites with elevated median ammonia were directly downstream of municipal sewerage oxidation pond discharges. The remainder of sites with higher ammonia were in catchment containing intensive farmland, and often this combined with peaty soils where swampy areas had been converted to pasture (e.g. Blackwater Creek). No sites were in the C or D band for ammonia or nitrate, thus no sites were below the NPSFM national bottom line for these attributes.

Nitrate levels have been low in West Coast waterways when using the NPSFM nitrate NOF framework for a benchmark (Figure 10 and Table 6). Nitrate is highly soluble and in the West Coast's wet or extremely wet climate is readily leached to surface waters via groundwater pathways. A pattern can be observed between anthropogenic landcover of 20% or less, 20%-40%, and over 40%, where nitrate is clearly increasing with anthropogenic landcover. Nitrate toxicity for aquatic fauna is unlikely anywhere on the West Coast.

Elevated nitrate may promote unwanted algal and plant growth at concentrations well below toxicity thresholds set by the NPSFM (2020). A range of studies in Aotearoa have considered what appropriate levels of dissolved inorganic nitrogen (DIN) are for managing nuisance algal growth. DIN is nitrate and ammonia combined. As the vast majority of DIN in West Coast streams consists of nitrate, we can apply these DIN thresholds to West Coast nitrate data. Matheson et al. (2012) proposed <0.05 mg/L for DIN as the most stringent, low risk safeguard, up to <0.3 mg/L as a more lenient high risk threshold. Following on from this Matheson et al. (2016) proposed the same <0.05 mg/L for DIN as the most stringent, low risk safeguard, and up to <0.2 mg/L as a more lenient high-risk threshold. Storey et al. (2017) suggested a slightly higher low risk DIN threshold of to <0.09 mg/L for the Ruamahanga River – a warmer, drier catchment compared to anything on the West Coast.

West Coast monitoring sites at locations with anthropogenic landcover of 20% or less typically met all the above thresholds. At 20%-40% anthropogenic landcover, a mixture of median nitrate levels were observed, some close to low-risk thresholds and some at or above those designated as high risk. From 40% and over, nitrate levels were typically around high-risk DIN thresholds, or above. This could indicate that nitrate is likely to exacerbate algal growth in West Coast waterways when anthropogenic landcover is over 40% of the catchment, and other factors are conducive (e.g. adequate light, warmth, phosphorus, and stable flow regimes).

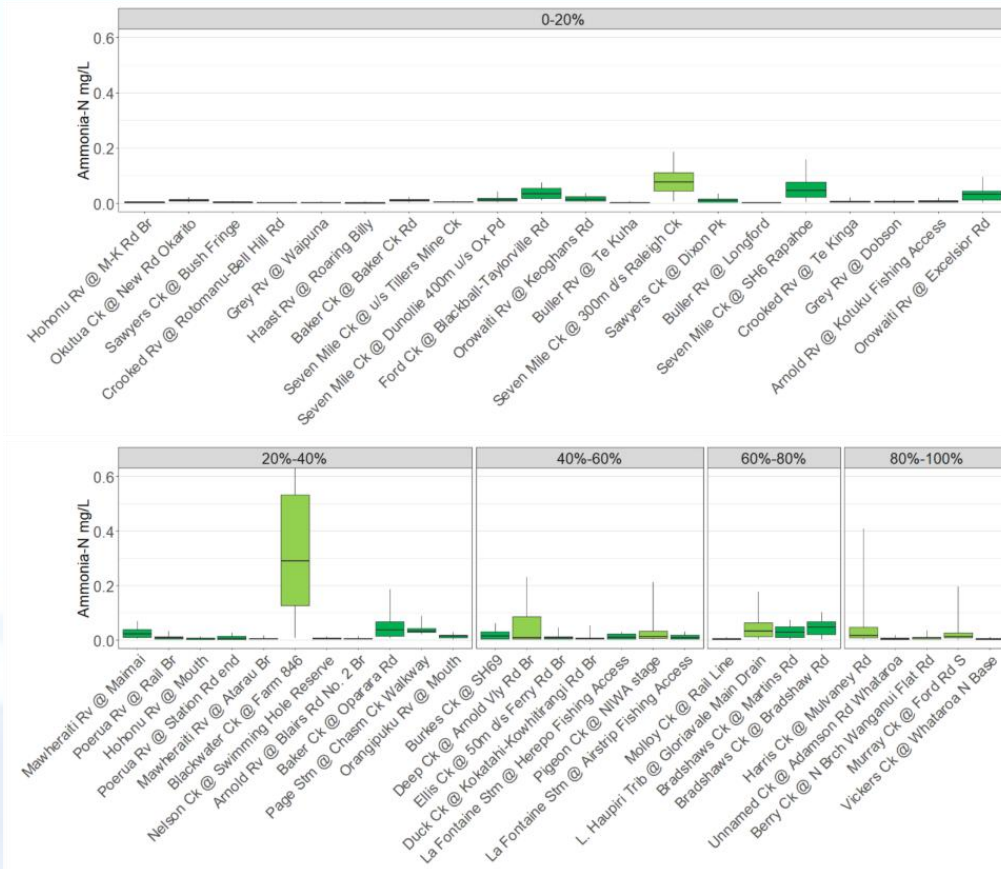


Figure 9. Ammonical nitrogen. Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. Box colors represent NPSFM (2020) NOF categories: Green = A, 99% species protection level: No observed effect on any species tested.; Light green = B, 95% species protection level: Starts impacting occasionally on the 5% most sensitive species.



Table 5. Ammonical nitrogen NOF grades. Calculated as 5 yearly medians and maximums (year ending 2023).
 Box colors represent NPSFM (2020) NOF categories: Green = A, 99% species protection level: No observed effect on any species tested.; Light green = B, 95% species protection level: Starts impacting occasionally on the 5% most sensitive species.

Site name	Median	95%ile	Overall NOF	Site name	Median	95%ile	Overall NOF
Arnold Rv @ Blairs Rd No. 2 Br	A	A	A	L. Haupiri Trib @ Gloriavale Main Drain	A	B	B
Arnold Rv @ Kotuku Fishing Access	A	A	A	La Fontaine Stm @ Airstrip Fishing Access	A	A	A
Baker Ck @ Baker Ck Rd	A	A	A	La Fontaine Stm @ Herepo Fishing Access	A	A	A
Baker Ck @ Oparara Rd	A	A	A	Mawheraiti Rv @ Atarau Br	A	A	A
Berry Ck @ N Brch Wanganui Flat Rd	A	B	B	Mawheraiti Rv @ SH7 Maimai	A	A	A
Blackwater Ck @ Farm 846	B	B	B	Molloy Ck @ Rail Line	A	A	A
Bradshaws Ck @ Bradshaw Rd	A	A	A	Murray Ck @ Ford Rd S	A	B	B
Bradshaws Ck @ Martins Rd	A	A	A	Nelson Ck @ Swimming Hole Reserve	A	A	A
Buller River @ Longford	A	A	A	Okutua Ck @ New Rd Br-Okarito Forest	A	A	A
Buller Rv @ Te Kuha	A	A	A	Orangipuku Rv @ Mouth	A	A	A
Burkes Ck @ SH69	A	A	A	Orowaiti Rv @ Excelsior Rd	A	A	A
Crooked Rv @ Rotomanu-Bell Hill Rd	A	A	A	Orowaiti Rv @ Keoghans Rd	A	A	A
Crooked Rv @ Te Kinga	A	A	A	Page Stm @ Chasm Ck Walkway	A	A	A
Deep Ck @ Arnold Vly Rd Br	A	B	B	Pigeon Ck @ NIWA stage	A	B	B
Duck Ck @ Kokatahi-Kowhitirangi Rd Br	A	A	A	Poerua Rv @ Rail Br	A	A	A
Ellis Ck @ 50m d/s Ferry Rd Br	A	A	A	Sawyers Ck @ Bush Fringe	A	A	A
Ford Ck @ Blackball-Taylorville Rd	A	A	A	Sawyers Ck @ Dixon Pk	A	A	A
Grey Rv @ Dobson	A	A	A	Seven Mile Ck @ 300m d/s Raleigh Ck	A	B	B
Grey Rv @ Waipuna	A	A	A	Seven Mile Ck @ Dunollie 400m u/s Ox Pd	A	A	A
Haast Rv @ Roaring Billy	A	A	A	Seven Mile Ck @ SH6 Rapahoe	A	A	A
Harris Ck @ Mulvaney Rd	A	B	B	Seven Mile Ck @ u/s Tillers Mine Ck	A	A	A
Hohonu Rv @ Mitchells-Kumara Rd Br	A	A	A	Unnamed Ck @ Adamson Rd Whataroa	A	A	A
Hohonu Rv @ Mouth	A	A	A	Vickers Ck @ Whataroa N Base	A	A	A

Commented [SS1]: Rerun the R script and fix the y axis limit problem, just need update the two graphs.

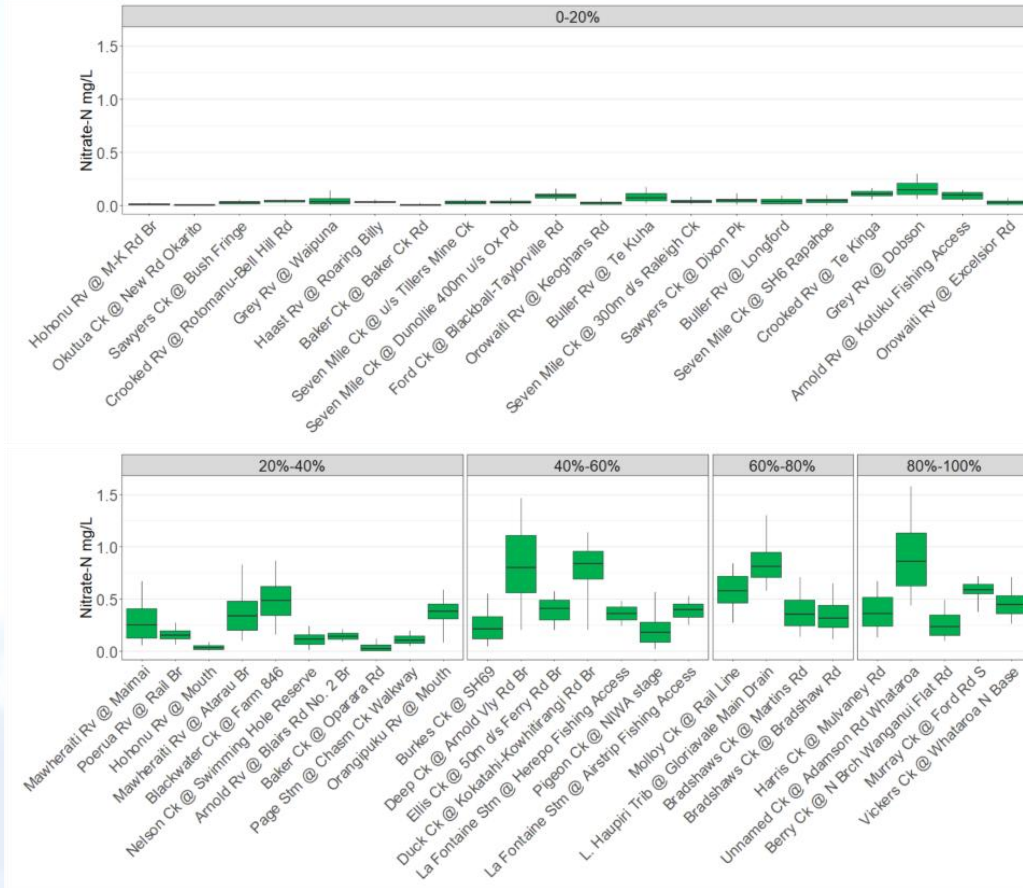


Figure 10. Box and whisker graph showing the spread of Nitrate nitrogen data for individual Regional Council monitoring program sites where there is discrete data available. (minimums and maximums excluded). Graph group sites based on the proportion of anthropogenic land cover, box colors represent NOF categories: A. Green = A state.



Table 6 Nitrate NOF grades for individual Regional Council monitoring program sites, calculated as a 5 yearly median and 95th percentile (displayed as year ending of 5 year block of data, year ending 2023).

Site name	Median	95 th percentile	Site name	Median	95 th percentile
Arnold Rv @ Blairs Rd No. 2 Br	A	A	L. Haupiri Trib @ Gloriavale Main Drain	A	A
Arnold Rv @ Kotuku Fishing Access	A	A	La Fontaine Stm @ Airstrip Fishing Access	A	A
Baker Ck @ Baker Ck Rd	A	A	La Fontaine Stm @ Herepo Fishing Access	A	A
Baker Ck @ Oparara Rd	A	A	Mawheraiti Rv @ Atarau Br	A	A
Berry Ck @ N Brch Wanganui Flat Rd	A	A	Mawheraiti Rv @ SH7 Maimai	A	A
Blackwater Ck @ Farm 846	A	A	Molloy Ck @ Rail Line	A	A
Bradshaws Ck @ Bradshaw Rd	A	A	Murray Ck @ Ford Rd S	A	A
Bradshaws Ck @ Martins Rd	A	A	Nelson Ck @ Swimming Hole Reserve	A	A
Burkes Ck @ SH69	A	A	Okutua Ck @ New Rd Br-Okarito Forest	A	A
Crooked Rv @ Rotomanu-Bell Hill Rd	A	A	Orangipuku Rv @ Mouth	A	A
Crooked Rv @ Te Kinga	A	A	Orowaiti Rv @ Excelsior Rd	A	A
Deep Ck @ Arnold Vly Rd Br	A	A	Orowaiti Rv @ Keoghans Rd	A	A
Duck Ck @ Kokatahi-Kowhitirangi Rd Br	A	A	Page Stm @ Chasm Ck Walkway	A	A
Ellis Ck @ 50m d/s Ferry Rd Br	A	A	Pigeon Ck @ NIWA stage	A	A
Ford Ck @ Blackball-Taylorville Rd	A	A	Poerua Rv @ Rail Br	A	A
Harris Ck @ Mulvaney Rd	A	A	Sawyers Ck @ Bush Fringe	A	A
Hohonu Rv @ Mitchells-Kumara Rd Br	A	A	Sawyers Ck @ Dixon Pk	A	A
Hohonu Rv @ Mouth	A	A			



3.2.6. Dissolved reactive phosphorus

Nutrient supply is a controlling factor in the proliferation of aquatic macrophytes and algae associated with eutrophication of streams and rivers. Bioavailability of either nitrogen (N) or phosphorus (P) often limits macrophyte and algal growth rates.

Phosphorus is an essential nutrient for plants and is a natural component of healthy rivers when at low concentrations. Agricultural and urban land use can add phosphorus to waterways, which may cause excessive algal growth and have a negative effect on river habitats. Council monitors both total phosphorus and dissolved reactive phosphorus. Dissolved reactive phosphorus (DRP) is the form of phosphorus immediately available to support plant and algae growth.

The NPSFM (2020) provides a NOF for DRP in waterways, to protect against nuisance algal growth, and which has been applied to the DRP data collected at Council monitoring sites (Table 7 and Figure 11. ***Dissolved reactive phosphorus. Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. Box colors represent NPSFM (2020) NOF categories: Green = A, Ecological communities and ecosystem processes are similar to those of natural reference conditions. No adverse effects attributable to dissolved reactive phosphorus (DRP) enrichment are expected; Light green = B.*** A similar pattern as nitrate, albeit less pronounced, can be observed between anthropogenic landcover of 20% or less, 20%-40%, and over 40%, where phosphorus increases with anthropogenic landcover. At 20% or less anthropogenic landcover the majority of sites are in the A or B band, with one in the C band. Above 20% a greater number of sites are in the C and D bands. Sites in the C band risk having ecological communities impacted by moderate DRP elevation above natural reference conditions. If other conditions also favour eutrophication, DRP enrichment may cause increased algal and plant growth, loss of sensitive macro-invertebrate and fish taxa, and high rates of respiration and decay. A total of 15% of monitor sites were below the National Bottom Line for DRP, in the D band. At this point 'ecological communities are impacted by substantial DRP elevation above natural reference conditions. In combination with other conditions favouring eutrophication, DRP enrichment drives excessive primary production and significant changes in macroinvertebrate and fish communities, as taxa sensitive to hypoxia are lost'.

The Redfield ratio (Redfield et al. 1963), is considered to be the optimum ratio of N and P for plant growth, which is a molar ratio of N:P of 16:1. Around 76% of waterways monitored by South Island Regional Councils were found to be phosphorus limited, with a higher figure likely for the West Coast (Mcdowell et al. 2009). Given the likelihood of P limitation in most West Coast waterways, many stream reaches with over 40% of anthropogenic landcover were likely to have P concentrations above thresholds that could contribute to aquatic plant and algal proliferations.

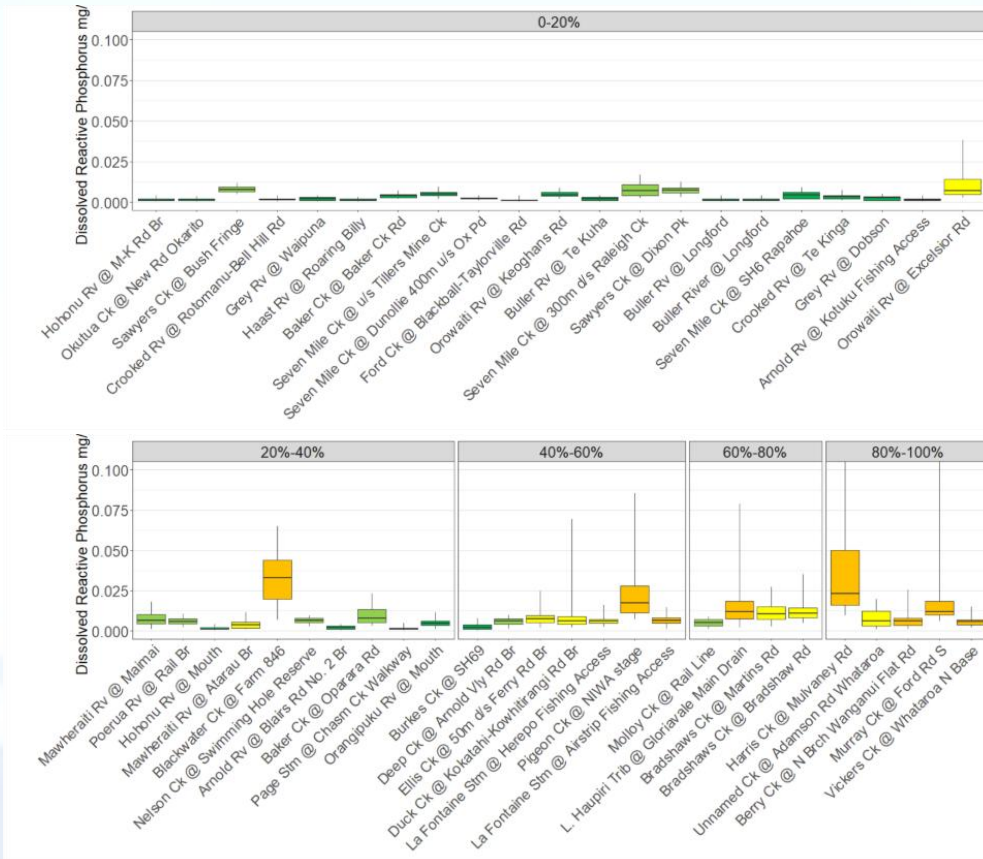


Figure 11. Dissolved reactive phosphorus. Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. Box colors represent NPSFM (2020) NOF categories: Green = A, Ecological communities and ecosystem processes are similar to those of natural reference conditions. No adverse effects attributable to dissolved reactive phosphorus (DRP) enrichment are expected; Light green = B, Ecological communities are slightly impacted by minor DRP elevation above natural reference conditions. If other conditions also favour eutrophication, sensitive ecosystems may experience additional algal and plant growth, loss of sensitive macroinvertebrate taxa, and higher respiration and decay rates; Yellow = C, Ecological communities are impacted by moderate DRP elevation above natural reference conditions. If other conditions also favour eutrophication, DRP enrichment may cause increased algal and plant growth, loss of sensitive macro-invertebrate and fish taxa, and high rates of respiration and decay; Orange = D, Ecological communities impacted by substantial DRP elevation above natural reference conditions. In combination with other conditions favouring eutrophication, DRP enrichment drives excessive primary production and significant changes in macroinvertebrate and fish communities, as taxa sensitive to hypoxia are lost.



Table 7 Dissolved reactive phosphorus NOF grades for individual Regional Council monitoring program sites, calculated as a 5 yearly median and 95th percentile (displayed as year ending of 5 year block of data, year ending 2023). Refer Figure 11 for NOF category descriptions.

Site Name	Median	95thile	Overall NOF
Arnold Rv @ Blairs Rd No. 2 Br	A	A	A
Arnold Rv @ Kotuku Fishing Access	A	A	A
Baker Ck @ Baker Ck Rd	A	A	A
Baker Ck @ Oparara Rd	B	A	B
Berry Ck @ N Brch Wanganui Flat Rd	B	D	D
Blackwater Ck @ Farm 846	D	D	D
Bradshaws Ck @ Bradshaw Rd	C	C	C
Bradshaws Ck @ Martins Rd	C	C	C
Buller River @ Longford	A	A	A
Buller Rv @ Te Kuha	A	A	A
Burkes Ck @ SH69	A	A	A
Crooked Rv @ Rotomanu-Bell Hill Rd	A	A	A
Crooked Rv @ Te Kinga	A	A	A
Deep Ck @ Arnold Vly Rd Br	B	A	B
Duck Ck @ Kokatahi-Kowhitirangi Rd Br	B	C	C
Ellis Ck @ 50m d/s Ferry Rd Br	B	C	C
Ford Ck @ Blackball-Taylorville Rd	A	A	A
Grey Rv @ Dobson	A	A	A
Grey Rv @ Waipuna	A	A	A
Haast Rv @ Roaring Billy	A	A	A
Harris Ck @ Mulvaney Rd	D	D	D
Hohonu Rv @ Mitchells-Kumara Rd Br	A	A	A
Hohonu Rv @ Mouth	A	A	A
L. Haupiri Trib @ Gloriavale Main Drain	C	D	D
La Fontaine Stm @ Airstrip Fishing Access	B	D	D
La Fontaine Stm @ Herepo Fishing Access	B	C	C
Mawheraiti Rv @ Atarau Br	B	C	C
Mawheraiti Rv @ SH7 Maimai	B	A	B
Molloy Ck @ Rail Line	B	A	B
Murray Ck @ Ford Rd S	C	D	D
Nelson Ck @ Swimming Hole Reserve	B	A	B
Okutua Ck @ New Rd Br-Okarito Forest	A	A	A
Orangipuku Rv @ Mouth	A	A	A
Orowaiti Rv @ Excelsior Rd	B	C	C
Orowaiti Rv @ Keoghans Rd	A	A	A
Page Stm @ Chasm Ck Walkway	A	A	A
Pigeon Ck @ NIWA stage	C	D	D
Poerua Rv @ Rail Br	B	A	B
Sawyers Ck @ Bush Fringe	B	A	B
Sawyers Ck @ Dixon Pk	B	A	B
Seven Mile Ck @ 300m d/s Raleigh Ck	B	A	B
Seven Mile Ck @ Dunollie 400m u/s Ox Pd	A	A	A
Seven Mile Ck @ SH6 Rapahoe	A	A	A
Seven Mile Ck @ u/s Tillers Mine Ck	A	A	A
Unnamed Ck @ Adamson Rd Whataroa	B	C	C
Vickers Ck @ Whataroa N Base	B	D	D



3.2.7. E. coli: human contact.

Water contaminated with faeces from warm blooded animals can be a risk for people and stock that are drinking or coming into contact with it. The presence of E. coli in water indicates contamination from faecal matter. Concentrations of E. coli are used to estimate the risk of disease-causing organisms like campylobacter, in freshwaters.

The purpose of the E. coli target attribute states in the National Objectives Framework (NOF) under the NPSFM for *human contact* is to provide a compulsory attribute for assessing freshwater suitability for activities involving direct human contact, such as swimming, kayaking, and other recreation. To reiterate, this *differs* from the NOF for *primary contact*, which applies to primary contact recreation sampling sites surveyed weekly from November to March each year.

Unlike the other NOF compulsory attributes, the NOF for human contact has 5, not 4, attribute bands for E. coli, ranging from A to E. There is no National Bottom Line, but there is an expectation under the legislation that a site will be improved to a point where it moves up at least one attribute band.

Site where there was little of no anthropogenic landcover had E. coli levels in the A band. This changed rapidly with the introduction of human activity (Figure 12), with most sites sitting in the E band once past 10% anthropogenic landcover, and all sites in E band after 40%. The E band describes infection risk as ‘for more than 30% of the time the estimated risk is ≥ 50 in 1,000 ($>5\%$ risk). The predicted average infection risk is $>7\%$ ’.

The NOF for human contact criteria for determining attributes states uses four statistical categories, and the one generating the poorest score is used for the final attribute state score. One of these categories uses the 95th percentile and another a median (Table 8). Not only does the 95th percentile consistently score a much poorer band than other measures like the median, but it is often puts a site into the E band when the median scores as an A. The West Coast has a wet to very wet climate and the high rainfall is conducive to regular event with significant surface run-off into waterways. Climate projections are for the West Coast to get wetter and receive more heavy rainfall events (MfE 2018). Sites with an A for the median and an E for the 95th percentile suggested that while E. coli performance was often favourable, as few as 1 in 20 high results would be enough to trigger this. A significant rain event, sufficient to generate surface run-off could cause this.

The obvious sources of faecal contamination in catchments with at least a little anthropogenic landcover are ruminants and people, both of which are consistently detected when the source of the E. coli is determined using eDNA testing in areas with significant contamination. However, avian markers are also often present. These birds are wild and largely beyond our ability to manage, and many common, more adaptable species of waterfowl maybe more abundant in lowland areas that coincide with human activity (Wang et al. 2021).

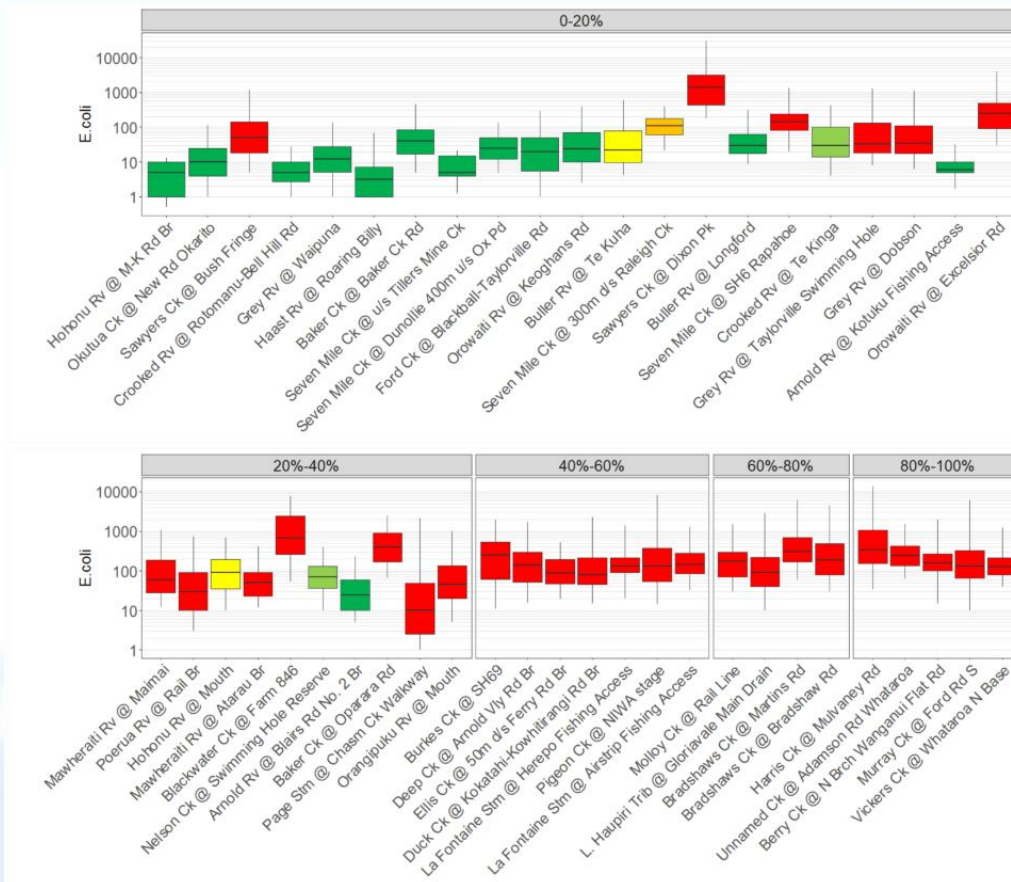


Figure 12. *E. coli* (minimums and maximums excluded). Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. Box colors represent NPSFM (2020) NOF categories: Green = A, For at least half the time, the estimated risk is <1 in 1,000 (0.1% risk). The predicted average infection risk is 1%; Light green = B, For at least half the time, the estimated risk is <1 in 1,000 (0.1% risk). The predicted average infection risk is 2%; Yellow = C For at least half the time, the estimated risk is <1 in 1,000 (0.1% risk). The predicted average infection risk is 3%; Orange = D, 20-30% of the time the estimated risk is ≥50 in 1,000 (>5% risk). The predicted average infection risk is >3%; Red = E, For more than 30% of the time the estimated risk is ≥50 in 1,000 (>5% risk). The predicted average infection risk is >7%.



Table 8 E. coli 5 yearly NOF grades for individual monitoring program sites 2019 – 2023 (displayed as year ending of 5 year block of data). Refer to Figure 12 for NOF categories.

Site Name	Median	95%ile	% >260	% >540	Overall NOF
Arnold Rv @ Blairs Rd No. 2 Br	A	A	A	A	A
Arnold Rv @ Kotuku Fishing Access	A	A	A	A	A
Baker Ck @ Baker Ck Rd	A	A	A	A	A
Baker Ck @ Oparara Rd	E	E	E	E	E
Berry Ck @ N Brch Wanganui Flat Rd	D	E	B	C	E
Blackwater Ck @ Farm 846	E	E	E	E	E
Bradshaws Ck @ Bradshaw Rd	E	E	D	D	E
Bradshaws Ck @ Martins Rd	E	E	E	E	E
Buller River @ Longford	A	A	A	A	A
Buller Rv @ Te Kuha	A	B	B	C	C
Burkes Ck @ SH69	D	E	D	D	E
Crooked Rv @ Rotomanu-Bell Hill Rd	A	A	A	A	A
Crooked Rv @ Te Kinga	A	B	A	B	B
Deep Ck @ Arnold Vly Rd Br	D	E	D	D	E
Duck Ck @ Kokatahi-Kowhitirangi Rd Br	A	E	B	D	E
Ellis Ck @ 50m d/s Ferry Rd Br	A	E	B	B	E
Ford Ck @ Blackball-Taylorville Rd	A	A	A	A	A
Grey Rv @ Dobson	A	E	B	C	E
Grey Rv @ Taylorville Swimming Hole	A	E	A	C	E
Haast Rv @ Roaring Billy	A	A	A	A	A
Harris Ck @ Mulvaney Rd	E	E	E	E	E
Hohonu Rv @ Mitchells-Kumara Rd Br	A	A	A	A	A
Hohonu Rv @ Mouth	A	C	A	C	C
L. Haupiri Trib @ Gloriavale Main Drain	A	E	B	D	E
La Fontaine Stm @ Airstrip Fishing Access	D	E	D	D	E
La Fontaine Stm @ Herepo Fishing Access	D	E	C	C	E
Mawheraiti Rv @ Atarau Br	A	B	E	E	E
Mawheraiti Rv @ SH7 Maimai	A	E	B	C	E
Molloy Ck @ Rail Line	D	E	B	C	E
Murray Ck @ Ford Rd S	D	E	C	D	E
Nelson Ck @ Swimming Hole Reserve	A	B	A	B	B
Okutua Ck @ New Rd Br-Okarito Forest	A	A	A	A	A
Orangipuku Rv @ Mouth	A	E	B	C	E
Orowaiti Rv @ Excelsior Rd	E	E	D	D	E
Orowaiti Rv @ Keoghans Rd	A	A	A	A	A
Page Stm @ Chasm Ck Walkway	A	E	B	C	E
Pigeon Ck @ NIWA stage	D	E	D	C	E
Poerua Rv @ Rail Br	A	E	A	C	E
Sawyers Ck @ Bush Fringe	A	E	A	C	E
Sawyers Ck @ Dixon Pk	E	E	E	E	E
Seven Mile Ck @ 300m d/s Raleigh Ck	D	A	A	A	D
Seven Mile Ck @ Dunollie 400m u/s Ox Pd	A	A	A	A	A
Seven Mile Ck @ SH6 Rapahoe	D	E	B	C	E
Seven Mile Ck @ u/s Tillers Mine Ck	A	A	A	A	A
Unnamed Ck @ Adamson Rd Whataroa	E	E	E	E	E
Vickers Ck @ Whataroa N Base	D	E	D	D	E



3.2.8. Macroinvertebrates

Freshwater invertebrates include organisms such as crustaceans, molluscs, worms, and freshwater insects. Invertebrates perform important ecosystem services, become food for native fish and birds, and some become food for people. They are affected by impacts on water and habitat quality; therefore, they are useful indicators of stream health. The MCI and QMCI are part of the NPSFM NOF for freshwater monitoring. Both indices use the same scores for taxa, which are allocated a number 1 to 10, depending on their pollution tolerance. However, while the MCI only uses presence/absence data for taxa, the QMCI also utilizes the abundance of each taxa. Smaller numbers equal poorer quality.

While not always the case, it was typical for QMCI scores to be poorer than MCI scores (

Table 9. MCI and QMCI grades for individual Regional Council monitoring program sites, calculated as a 5 yearly median (displayed as year ending of 5 year block of data, year ending 2023).). Both the MCI and QMCI showed a similar overall declining trend with an increase in anthropogenic landcover, but there were individual exceptions (Figure 13). Additionally, the difference between high and lower quality sites was often much greater for QMCI versus MCI scores. The reason for this is that not only did many of the poorer quality sites have a higher occurrence of low scoring taxa, but that these low scoring taxa were more numerous, leading to more profound differentiation between good and poor sites.

Macroinvertebrate community structure can be affected by many factors. These can work collectively, and it is often hard to tease them apart. Changes in community structure are often attributed to 'water quality' but this should be defined more carefully. Contaminants in the water like dissolved metals, ammonia and nitrate toxicity, and organic pollution are not normally high enough in West Coast waterways to have direct effect on most macroinvertebrate taxa. However, increased nutrients may assist with algal growth that affects habitats and oxygen regimes. Increases in deposited and suspended fine sediment reduce habitat and food quality for more sensitive (aka high scoring) taxa. Water that is warmer and slower flowing is less suitable for sensitive species. Hence differences in habitat rather than water quality per se is what regulates community structure the most.

Spatially, the origin of what has influence on macroinvertebrates, at the location they are sampled, could be at a reach or catchment scale. Examples of reach scale would be: riparian shade adjacent to the sampling point, limiting algal growth and improving habitat; or adjacent bank erosion smothering the sampling point in fine sediment (cobbles are preferable to sand and silt). Catchment scale examples include: accumulating nutrient enrichment and fine sediment from multiple upstream sources; rising water temperatures resulting from a collective lack of riparian shade. The overall downward gradient of MCI and QMCI scores in response to increasing anthropogenic landcover suggests the importance of catchment scale factors.

It is important to note the role of intrinsic characteristics, which are beyond the control of people, which can exacerbate impact from human activity. Examples are: soft, erodible geology prone to erosion and generation of fine sediment



(e.g. Sawyers Ck @ Bush Fringe); small lowland streams that have limited assistance from cool mountain headwater supply or spring recharge (e.g. Burke Ck and Baker Ck @ Oparara); low gradient streams with low water velocities (desirable macroinvertebrates like high velocities to get enough oxygen), that are prone to aquatic plant proliferations (e.g. Bradshaws and Blackwater Creeks). Such characteristics can exacerbate or ameliorate the impact from anthropogenic activities. A large number of WCRC sampling sites have relatively small amounts of anthropogenic cover in the catchment. Such sites are normally in the A or B attribute bands. Despite a largely pristine catchment, some form of human influence can't be ruled out for those that are not in the A band but intrinsic factors may also push scores below the A band. As few WCRC monitoring sites have zero anthropogenic landcover, this is hard to test, but two such sites were in the B band for MCI. The B band designates quality as a 'macroinvertebrate community indicative of mild organic pollution or nutrient enrichment. Largely composed of taxa sensitive to organic pollution/nutrient enrichment.'

Four sites in the 0-20% anthropogenic cover group scored particularly poorly. Sawyers Ck @ Dixon Park is in a highly developed urban area. Sewerage overflows are common, combined with stormwater inputs, earthworks, and other sources of contaminants. The other three sites are on large rivers, and monitored by NIWA. These sites, the Grey River @ Waipuna in particular, have good water quality and it must be a habitat feature that is causing poor scores. For Waipuna in particular, the nature of habitat at the sampling location maybe responsible for these low scores. For the remaining sites below the National Bottom Line (D band), that are in catchments with over 20% anthropogenic landcover, it is predominantly human activities like fine sediment inputs from earthworks, significant loss of inorganic nutrients, lack of riparian protection, and instream habitat alteration, that are likely to impact on macroinvertebrate communities.

Table 9. MCI and QMCI grades for individual Regional Council monitoring program sites, calculated as a 5 yearly median (displayed as year ending of 5 year block of data, year ending 2023).

Site name	MCI median	QMCI median	Site name	MCI median	QMCI median
Baker Ck @ Baker Ck Rd	B	B	La Fontaine Stm @ Airstrip Fishing Access	C	C
Baker Ck @ Oparara Rd	C	D	La Fontaine Stm @ Herepo Fishing Access	C	C
Berry Ck @ N Brch Wanganui Flat Rd	C	C	Mawheraiti Rv @ Atarau Br	B	A
Bradshaws Ck @ Bradshaw Rd	D	D	Mawheraiti Rv @ SH7 Maimai	B	B
Buller Rv @ Longford	C	D	Molloy Ck @ Rail Line	B	B
Buller Rv @ Te Kuha	C	D	Murray Ck @ Ford Rd S	C	B
Burkes Ck @ SH69	C	D	Nelson Ck @ Swimming Hole Reserve	B	A
Crooked Rv @ Rotomanu-Bell Hill Rd	B	A	Okutua Ck @ New Rd Br-Okarito Forest	B	A
Crooked Rv @ Te Kinga	B	A	Orangipuku Rv @ Mouth	B	A
Deep Ck @ Arnold Vly Rd Br	B	B	Orowaiti Rv @ Keoghans Rd	B	B
Duck Ck @ Kokatahi-Kowhitirangi Rd Br	B	A	Page Stm @ Chasm Ck Walkway	C	D
Ellis Ck @ 50m d/s Ferry Rd Br	B	B	Poerua Rv @ Rail Br	B	A
Ford Ck @ Blackball-Taylorville Rd	B	B	Sawyers Ck @ Bush Fringe	B	A
Grey Rv @ Dobson	C	D	Sawyers Ck @ Dixon Pk	C	D
Grey Rv @ Waipuna	B	D	Seven Mile Ck @ 300m d/s Raleigh Ck	B	C



Haast Rv @ Roaring Billy	C	B	Seven Mile Ck @ Dunollie 400m u/s Ox Pd	B	A
Harris Ck @ Mulvaney Rd	C	C	Seven Mile Ck @ u/s Tillers Mine Ck	A	A
Hohonu Rv @ Mitchells-Kumara Rd Br	A	A	Unnamed Ck @ Adamson Rd Whataroa	D	D
Hohonu Rv @ Mouth	B	A	Vickers Ck @ Whataroa N Base	C	C

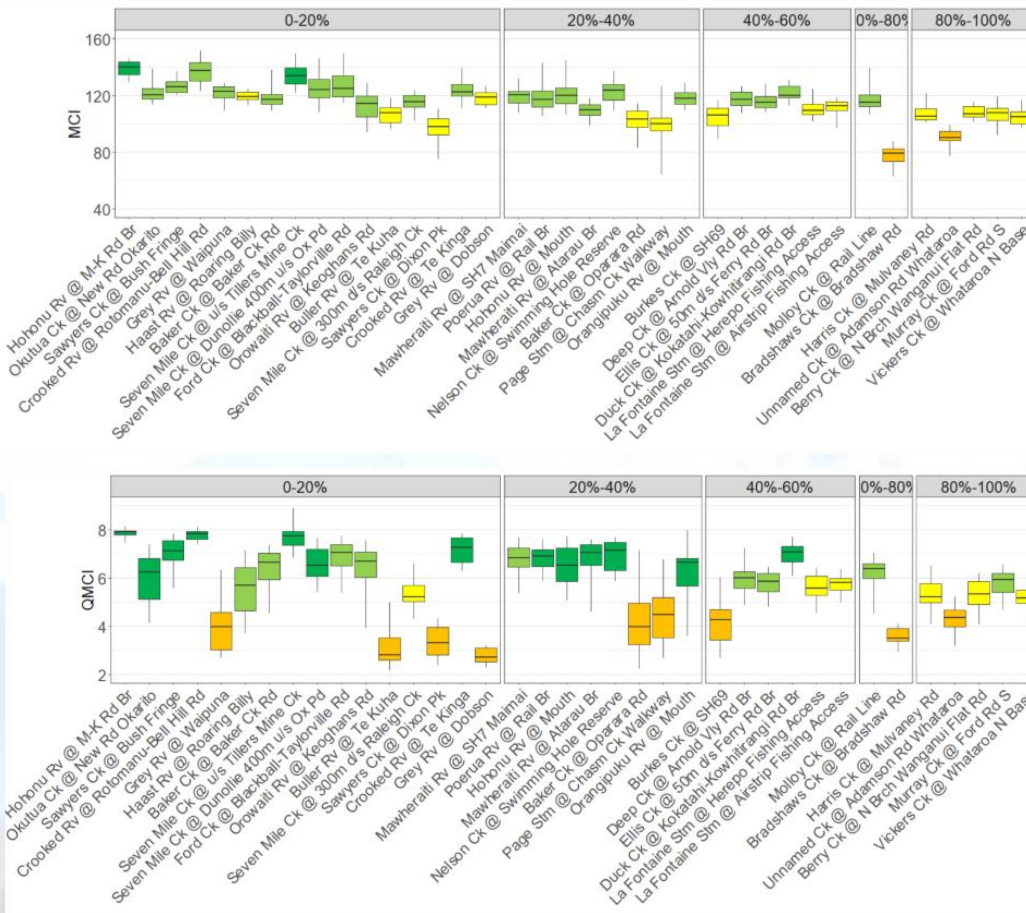


Figure 13 (MCI) and (QMCI). Data for monitoring program sites (minimums and maximums excluded). Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. Box colors represent NPSFM (2020) NOF categories: Green = A Macroinvertebrate community, indicative of pristine conditions with almost no organic pollution or nutrient enrichment; Light green = B, Macroinvertebrate community indicative of mild organic pollution or nutrient enrichment. Largely composed of taxa sensitive to organic pollution/nutrient enrichment; Yellow = C, Macroinvertebrate community indicative of moderate organic pollution or nutrient enrichment. There is a mix of taxa sensitive and insensitive



to organic pollution/nutrient enrichment; and Orange = D, Macroinvertebrate community indicative of severe organic pollution or nutrient enrichment. Communities are largely composed of taxa insensitive to inorganic pollution/nutrient enrichment.



3.2.9. Periphyton cover

The NPSFM (2020) has a NOF and attribute bands for periphyton. Periphyton is a community of algae, bacteria, fungi, and detritus attached to submerged surfaces in streams, rivers, and lakes. Algae are the mainstay of measurable bulk periphyton biomass in West Coast waterways and the driver of excessive quantities. Hence the weight of chlorophyll *a* on a known area of streambed is used to estimate the biomass of periphyton.

Periphyton forms a slimy or filamentous layers on rocks, wood, and plants in the stream. It is a primary producer in freshwater ecosystems, providing an important food source for many macroinvertebrates, and subsequently the food chain. However, too much periphyton: negatively alters habitat for many aquatic fauna; reduced oxygen at night; and reduces amenity value.

Periphyton biomass is assessed via measuring the weight of chlorophyll *a* removed from a known area of river stones. A subset of our monitoring sites are assessed monthly, when stream flows are low enough to allow access. Okutua Stream is a reference site with no human activity upstream. Its waters are cool and low in nutrients. The channel at the sampling site and across the whole catchment is well shaded by tall mature trees. As a result, periphyton concentrations are negligible (Figure 14). Most sites were in the A or B band, indicating rare or occasional algal blooms. There were two exceptions (Table 10).

Sawyers Creek, despite its forested headwaters, lacks riparian shade at the sampling site and upstream as it winds through urban Greymouth. It is small and slow flowing in its lower reaches, receiving nutrients from sewerage overflows and farming. While not excessively warm (median CRI ~22°C), mild, coastal temperatures are suitable for faster algal growth and greater biomass.

Unnamed Ck @ Adamsons Rd is a small spring fed stream with no significant riparian shade, high nutrient concentrations, stable flows with minimum scouring and bed movement, and narrow annual temperature range.

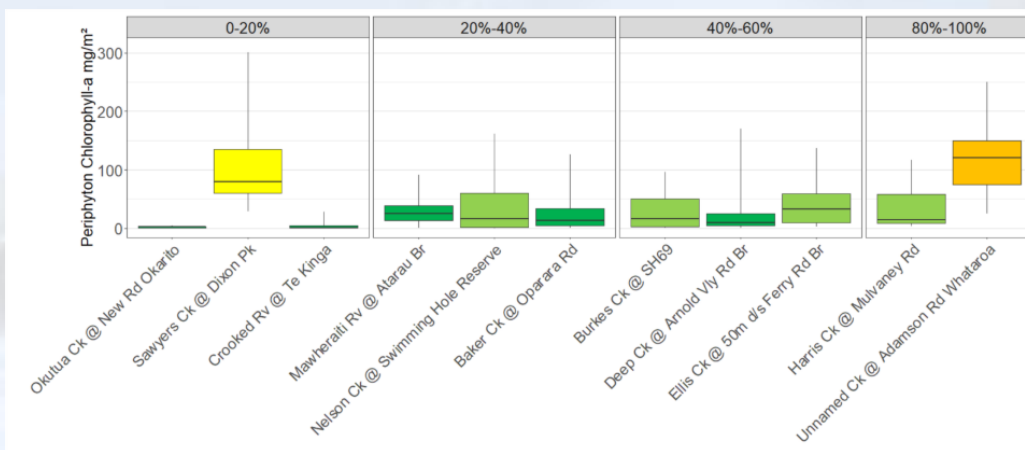




Figure 14. Periphyton (minimums and maximums excluded). Sites grouped according to proportion of anthropogenic land cover, with the proportion increasing from left to right. Green = A, Rare blooms reflecting negligible nutrient enrichment and/or alteration of the natural flow regime or habitat.; Light green = B, Occasional blooms reflecting low nutrient enrichment and/or alteration of the natural flow regime or habitat; Yellow = C, Periodic short-duration nuisance blooms reflecting moderate nutrient enrichment and/or moderate alteration of the natural flow regime or habitat; Orange = D, Regular and/or extended-duration nuisance blooms reflecting high nutrient enrichment and/or significant alteration of the natural flow regime or habitat.

Table 10 Periphyton NOF grades for individual Regional Council monitoring program sites, calculated as a 3 yearly 92% percentile (displayed as year ending of 3 year block of data, year ending 2023).

Site Name	NOF
Baker Ck @ Oparara Rd	A
Burkes Ck @ SH69	B
Crooked Rv @ Te Kinga	A
Deep Ck @ Arnold Vly Rd Br	A
Ellis Ck @ 50m d/s Ferry Rd Br	B
Harris Ck @ Mulvaney Rd	B
Nelson Ck @ Swimming Hole Reserve	B
Okutua Ck @ New Rd Br-Okarito Forest	A
Sawyers Ck @ Dixon Pk	C
Unnamed Ck @ Adamson Rd Whataroa	D
Mawheraiti Rv @ Atarau Br	A



3.2.10. Primary human contact

Water contaminated with faeces from warm-blooded animals can be a risk for people and stock that are drinking or coming into contact with it. The presence in water of faecal bacteria like *E. coli* and Enterococci indicates contamination from faecal matter. Concentrations of these bacteria are used to estimate the risk of disease-causing organisms like campylobacter.

From November to March, Council monitors *E. coli* and Enterococci at rivers, lakes, and coastal beaches used for swimming. Council applies criteria from the Ministry for the Environment (MfE) microbiological water quality guidelines for marine and freshwater recreational areas to this data, which is similar to the NPSFM NOF for primary contact.

Rivers and estuaries were more frequently unsuitable for swimming (Figure 15), particularly during, and shortly after, rain events compared to lakes and ocean beaches. Lakes had the highest quality and lowest pathogen risk. (Figure 15). Results for individual sites have been provided in Appendix A.

All river and lagoon sites are located in places that are downstream of a large number of potential pathogen sources. Faecal source tracking using DNA markers for *E. coli* animal origin, undertaken by Council to investigate potential sources of contamination, have identified bovine, human and avian sources of contamination at all sites tested, at some point in time e.g. the Orowaiti Lagoon. Some sources maybe more prevalent, with a higher occurrence or stronger signal within a sample. Shingle Beach samples were dominated by human and bovine. Bovine was most prevalent at Marrs beach, but avian was often present as well. These tests are predominantly presence/absence with some ability to roughly estimate the strength of the source within a sample. Sewerage and septage discharges, and agricultural run-off are likely sources, particularly when weather has been wet. It is then that overflows and surface run-off are likely to occur – swimming in rivers and estuaries during and shortly after rain events always presents a higher pathogen risk. While shellfish are seldom tested for faecal bacteria or viruses, these results are a form of proxy indicator for shellfish palatability. Thorough cooking will kill faecal pathogens, but there maybe a risk of illness if shellfish are not cooked in locations with higher bacterial levels.

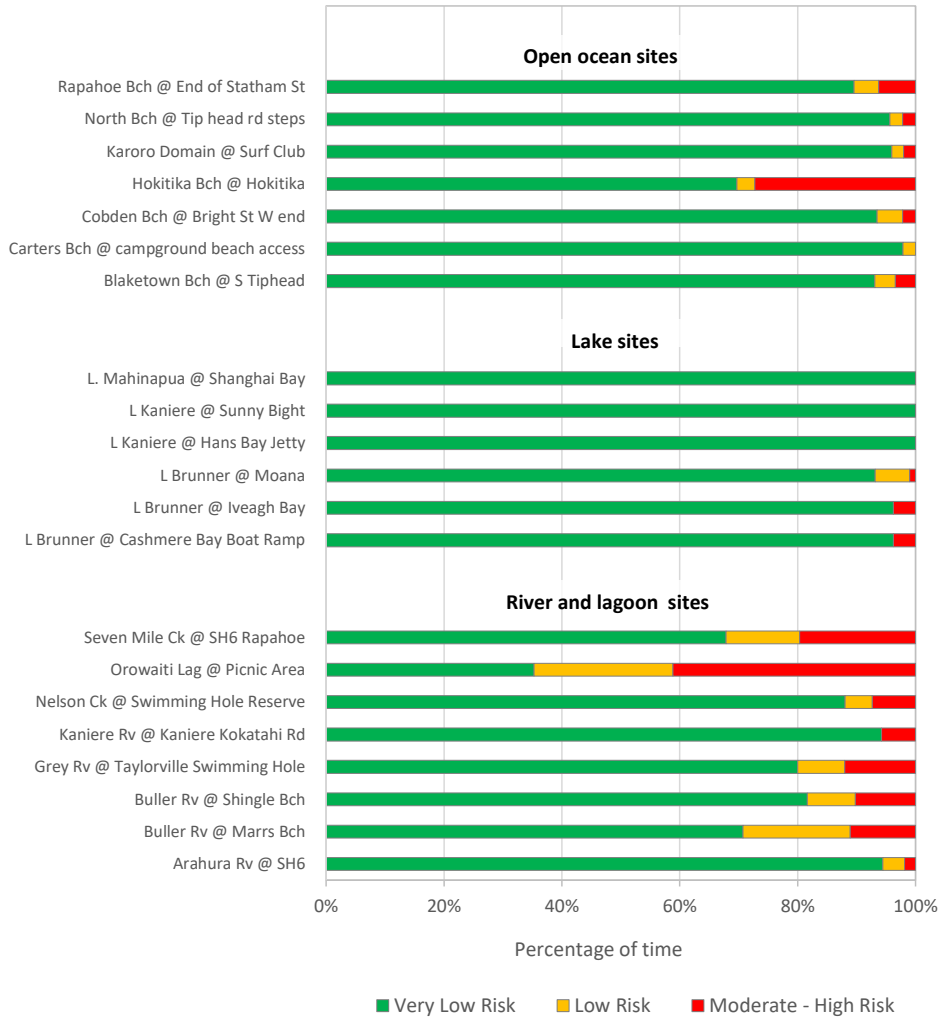


Figure 15: Contact recreation monitoring data from 2020-2025. The number of samples in each of the three swimmability categories is presented as a percentage of the total number of samples collected over the 5 year period. Some sites have 10 samples per season (50 samples total) and other sites 20 samples (100 samples total).

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Appendix A – Individual site data for primary contact recreation monitoring

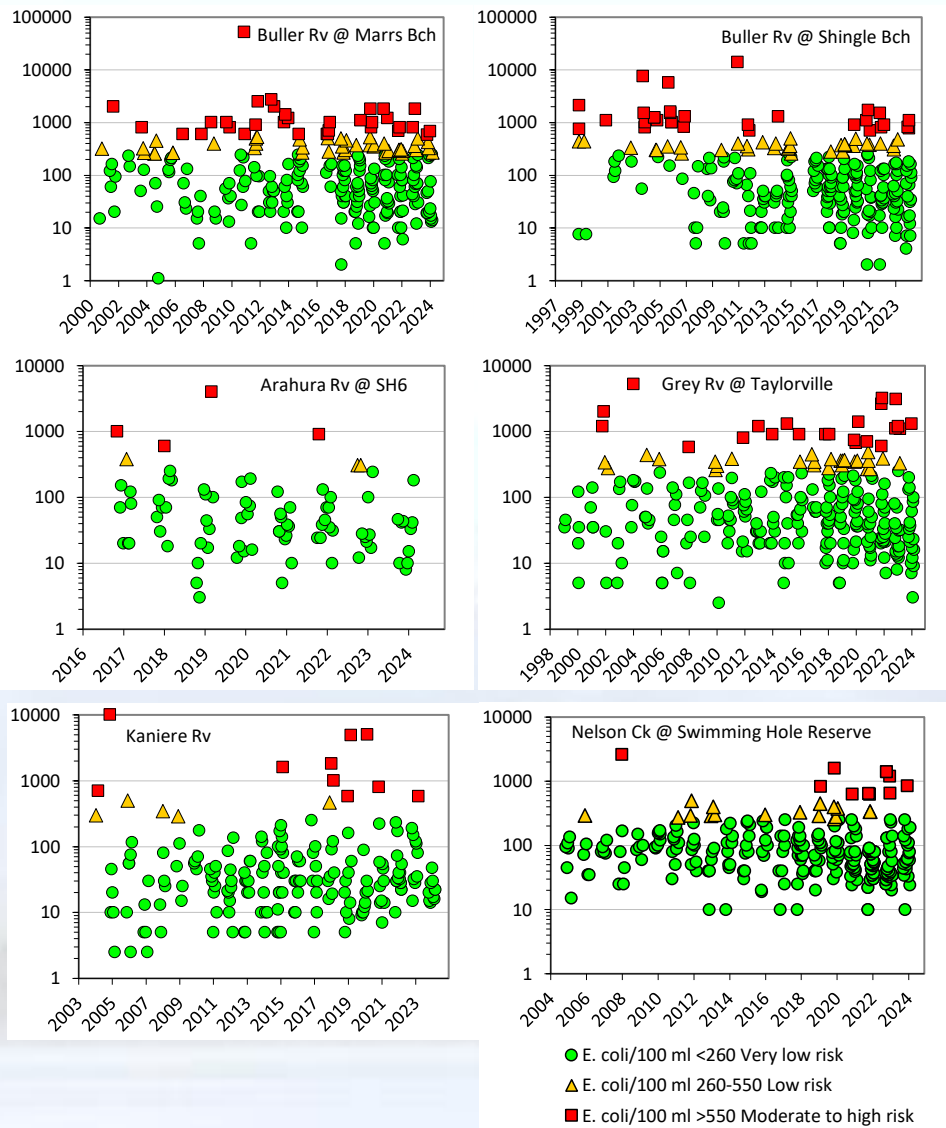


Figure 16: Contact recreation monitoring data for **river sites**, full record. Units are E. coli/100 ml, logarithmic scale.

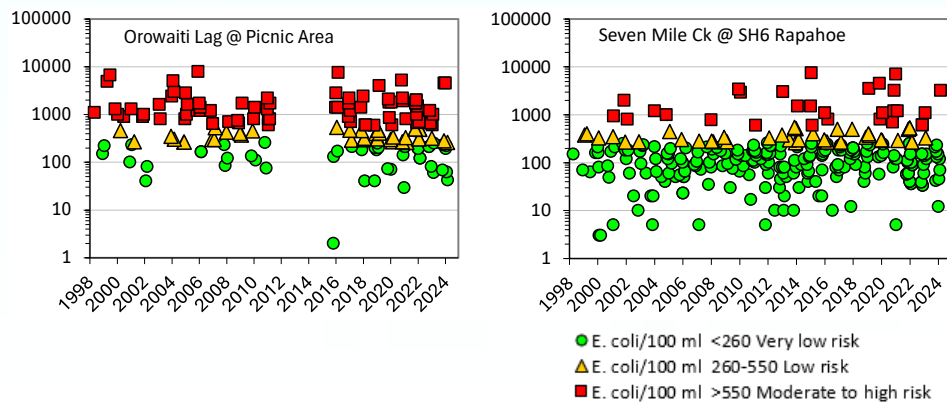


Figure 17: Contact recreation monitoring data for lagoon sites, full record. Units are *E. coli*/100 ml, logarithmic scale.

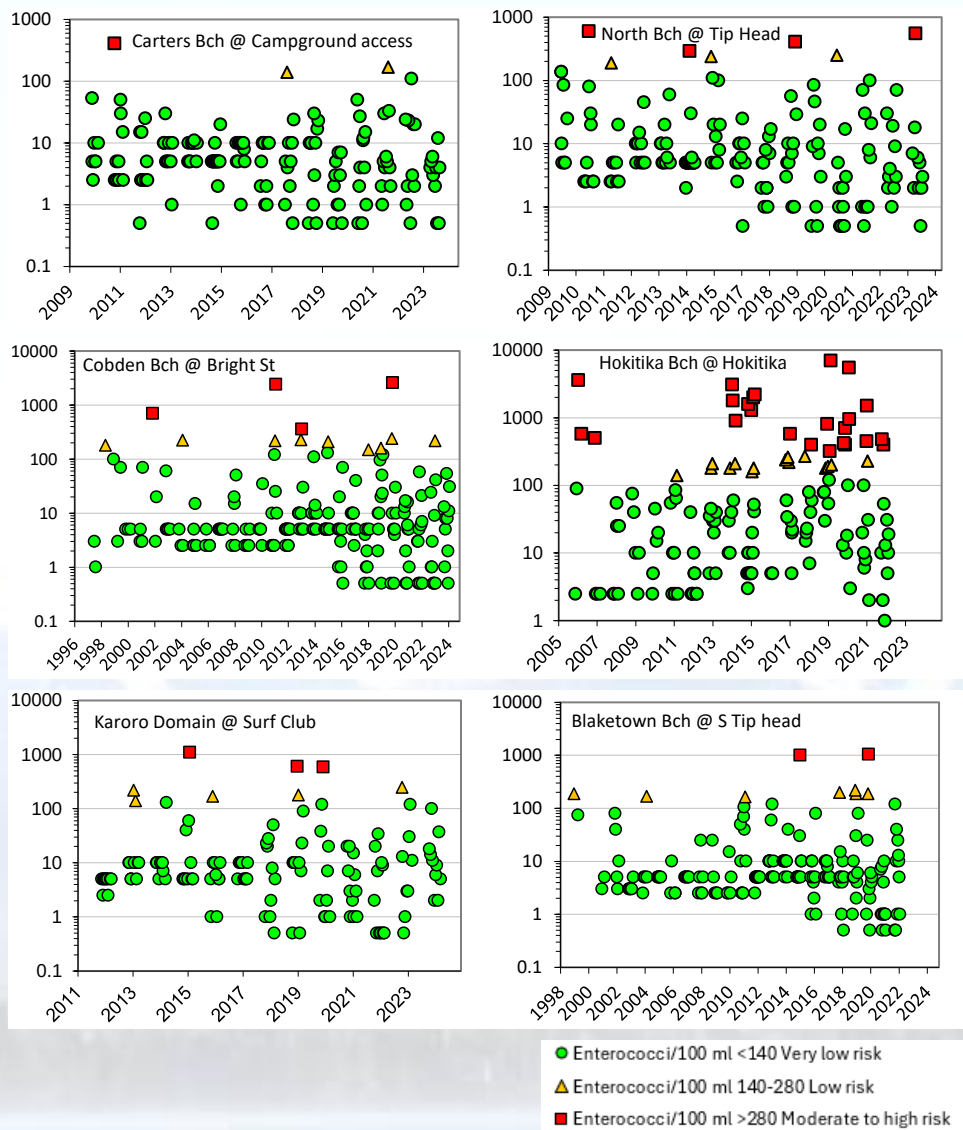


Figure 18: Contact recreation monitoring data for coastal beach sites, full record. Units are Enterococci/100 ml, logarithmic scale.

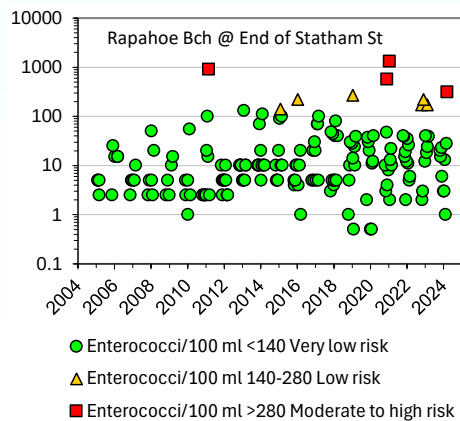
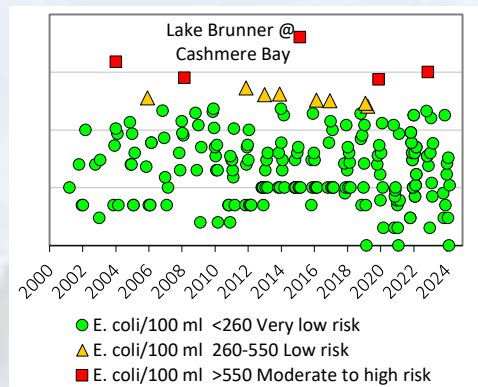
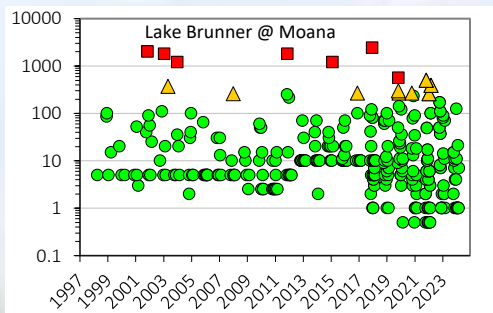
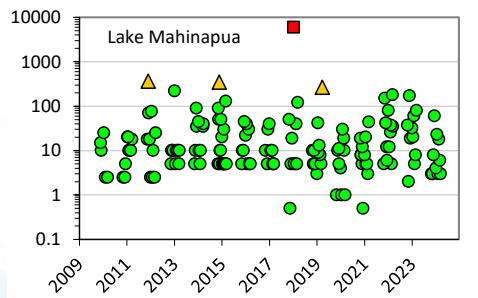
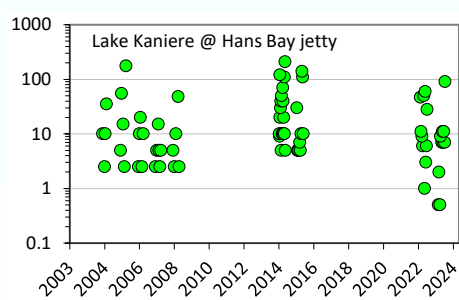
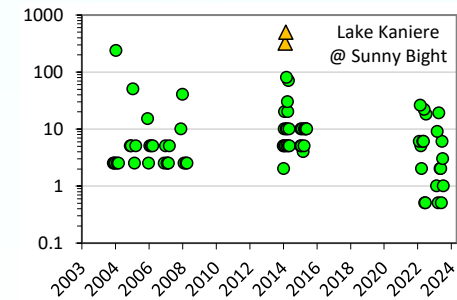


Figure 19: Contact recreation monitoring data for coastal beach sites, full record, continued. Units are Enterococci/100 ml, logarithmic scale.



- E. coli/100 ml <260 Very low risk
- ▲ E. coli/100 ml 260-550 Low risk
- E. coli/100 ml >550 Moderate to high risk



8.6 Planning and TTPP Report**Author** Lillie Sadler, Senior Planner; Marianne Bimont, Planner**Authoriser** Matt Smith, Group Manager, Regulatory and Policy**Public Excluded** No**Report Purpose**

This report provides an update on the Policy and Planning work programme, upcoming RMA reforms, and other matters.

Report Summary

This report provides an update on the Policy and Planning team's current workflows. The key areas of focus are:

- Fast-Track Approvals Amendment Bill
- TTPP Decisions on Council Submission
- Transport
- TTPP

The Fast-Track Approvals Amendment Bill proposes to speed up infrastructure and development projects by shortening processes and removing steps, but Te Uru Kahika has raised concerns about reduced Council involvement, weaker Treaty provisions, risks of incomplete advice reaching Ministers and panels.

Staff have reviewed the Te Tai o Poutini Plan decisions, with several key Council submission points accepted. Rejected points are not expected to have significant impacts.

In transport, the new Total Mobility digital system is already improving data quality, and the Regional Transport Committee meets on 4 December 2025 to begin work on the new Regional Land Transport Plan.

Regarding TTPP, the decisions Version of the TTPP was notified in October, and the appeal period has been extended by 10 working days until 8 December 2025.

Recommendation

It is recommended that the Committee resolve to:

1. *Receive the report.*

Issues and Discussion

Planning

Fast-Track Approvals Amendment Bill

The Fast-Track Approvals Amendment Bill was introduced to Parliament on 6 November 2025 and released for submissions on 7 November 2025. The part of the Bill relevant to Council's functions seeks to amend the Fast-Track Approvals Act 2024 to make it more efficient and accelerate infrastructure and development projects that deliver significant regional and national economic benefits, mainly by shortening process times and removing or reducing process steps.

The regional Council sector organisation, Te Uru Kahika (TUK), made a submission (*see Attachment 1*) raising the following concerns:

- Replacing the current requirement for applicants to consult Councils prior to lodging an application, with a limited notification and response process, will diminish Councils' role;
- Some of the Bill's provisions could lead to the Minister or panels making decisions with incomplete advice, and applications being declined or heavily conditioned due to unresolved issues that could have been addressed through early engagement with Councils;
- New provisions in the Bill weaken the Crown's ability to uphold Te Tiriti o Waitangi, with consultation requirements being reduced to written notification;
- Clear provisions for cost recovery must remain – not only is this fair but also enables Councils to contribute to sound and consistent decision-making, and reduces the burden on ratepayers;

Te Tai o Poutini Plan Decisions on Council submission

Staff have gone through the TTPP Decisions Reports to see whether the Council's submission and further submission points are accepted or rejected.

The following is a summary of key changes sought in Council's submission and further submission that were accepted or accepted in part:

- Permitted maximum height of four metres for (hydrology) environmental monitoring equipment is increased to seven metres in Natural Open Space (DOC land), and Open Space, Zones, and 10 metres in the Rural Zone;
- Replacement permitted rule for indigenous vegetation clearance outside an SNA and outside the coastal environment, to undertake maintenance and repair of existing lawfully established structures now includes environmental monitoring equipment and natural hazard mitigation structures;

- In the Rural and Natural Open Space (DOC land) Zones, biosecurity work undertaken by helicopters is added to the definition of “conservation activities”, and are now permitted activities;
- The permitted Noise Rule 12 for aircraft take off and landing is amended to include “conservation activities”. The VCS Manager has advised that the new condition for predator control aircraft movements of no more than 30 days in any 12 month period per site is workable;
- In the Rural Zone, the Highly Productive Land (HPL) Precinct maps will be amended to only cover land that has Land Use Classification (LUC) Class 1-3 soils (the most productive soils), and land that is not LUC Class 1-3 soils will be removed from the maps;
- The High Coastal Natural Character Overlay is removed from modified areas of the lower Karamaea and Mokihinui Rivers, riparian margins and adjoining land, which have Rating District flood protection structures, gravel extraction areas, farmland, a camping ground and residential properties.

Staff consider that the TTPP Decisions Reports’ reasons for rejecting some of Council’s submission are sound, and also note that these do not have significant consequences for Council. Existing land use activities are protected under the RMA, however, consents may be required for new activities, which may differ from pre TTPP requirements.

Transport

Total Mobility

The new digital system is already delivering reliable and comprehensive data. This improved visibility will enable staff to collate information more efficiently, supporting more consistent and insightful reporting in future. Overall, the system represents a positive step towards enhancing service monitoring and planning across the region.

Regional Transport Committee

The first Regional Transport Committee meeting is scheduled for 4 December 2025, signalling the start of the upcoming transport planning cycle. Work on the new Regional Land Transport Plan is now in its early stages, with initial preparation and engagement activities underway.

TTPP

The Decisions Version of the TTPP was notified on 10 October 2025. The Environment Court has since granted a waiver to extend the appeals period by 10 working days to 8 December 2025.

A staff report is due to the Environment Court by 16 February 2026, and mediation meetings will follow.

Considerations**Implications/Risks****Te Tai o Poutini Plan (TTPP) decisions and appeals**

Council's key submission points have largely been accepted, and staff consider the reasons for rejected points to be sound with no significant consequences for Council. The residual risk is that, by not lodging an appeal, Council will have limited ability to influence remaining matters through the Environment Court process. This risk is mitigated by having made a submission and so being privy to proceedings.

Transport – Total Mobility and Regional Land Transport Plan

The commencement of work on the new Regional Land Transport Plan involves discussion and strategy around funding availability and alignment with national priorities. Early planning and engagement through the Regional Transport Committee process will help to manage these risks and ensure West Coast transport needs are clearly articulated.

Significance and Engagement Policy Assessment

There are no issues within this report which trigger the Significance and Engagement policy.

Tangata Whenua views

Staff engage our Poutini Ngāi Tahu partners on the matters above as needed as part of our Mana Whakahono ā Rohe Agreement.

Views of affected parties

No parties will be affected by the subject matter of this report.

Financial implications

There are no current financial implications arising from items in this report.

Legal implications

There are no legal implications arising from items in this report.

Attachments

Attachment 1: Te Uru Kahika submission on Fast-Track Approvals Amendment Bill

Attachment 8.6.1: Te Uru Kahika submission on Fast-Track Approvals Amendment Bill



Regional and
Unitary Councils
Aotearoa

17 NOVEMBER 2025

ENVIRONMENT SELECT COMMITTEE
PARLIAMENT BUILDINGS
WELLINGTON

VIA EMAIL TO: EN.LEGISLATION@PARLIAMENT.GOV.T.NZ

Tēnā koutou katoa

1. Te Uru Kahika (Regional and Unitary Councils Aotearoa) thanks the Environment Select Committee (the Select Committee) for the opportunity to submit on the Fast-track Approvals Amendment Bill (the Bill).
2. Te Uru Kahika is the collective voice of New Zealand's 16 regional and unitary councils. It is underpinned by an extensive network of subject-matter experts. Together, we play a vital role in championing best practice, information sharing and collaboration across regional government. As implementation agents for New Zealand's resource management system, we also work with central government to deliver better outcomes for local people and their environment.
3. This submission draws on our collective expertise to present a perspective on behalf of regional government. Some regional and unitary councils will make individual submissions, reflecting their own local circumstances. Should our positions diverge on specific points, we respect the authority of councils to express their own views. Where differences arise between regions, we trust this supports you in understanding the complexity of the issues being considered.
4. Councils play a critical role to support the quality of the fast-track system, and support changes that will deliver better outcomes, faster and at reduced cost. We acknowledge aspects of the Bill will help achieve this, while others compromise these outcomes.
5. As objective testers of fast-track applications, Councils bring valuable experience and understanding to the process. They are also responsible for monitoring consents once granted, and their input is essential to the effective ongoing operation of the fast-track system. Replacing the current requirement for applicants to consult councils prior to lodging an application, with a limited notification and response process, will diminish this role.
6. Early consultation helps to deliver good consenting outcomes. It is particularly important because once an application is lodged, the compressed statutory timeframes leave little opportunity for expert panels to receive meaningful technical input from councils. We know from experience that pre-application engagement allows issues to be identified and resolved efficiently, supports higher-quality applications, generates cost and time-savings, and reduces the likelihood of dispute later in the process.
7. In practice, some of the Bill's provisions could lead to the Minister or panels making decisions with incomplete advice, and applications being declined or heavily conditioned due to unresolved issues that could have been addressed through early engagement. We believe panels will continue to want

to receive informed and practicable input from councils to help reduce the likelihood of these outcomes, particularly under tighter decision-making timeframes.

8. Te Uru Kahika and our member councils are clear on the importance of iwi and hapū participation in resource management decision-making. We are committed to Te Tiriti and to working in genuine partnership with mana whenua in our regions. We remain committed to working with the Government to ensure this legislation is workable and flexible and at the same time protects and enhances Māori rights and interests as guaranteed by Te Tiriti.
9. We observe that effective consultation with iwi hapū and leads to more enduring outcomes – it smooths the process for the applicant and enables issues to be worked through prior to lodgement, ultimately increasing certainty for applicants.
10. We are concerned that provisions in the Bill weaken the Crown’s ability to uphold Te Tiriti o Waitangi. Consultation requirements are largely procedural, and, in clause 6, have been reduced to written notification, limiting tangata whenua influence and constraining engagement through shortened timeframes. Notification alone does not guarantee participation and may result in lower-quality applications and decisions. The removal of the requirement to send draft reports to the Minister for Māori Crown Relations: Te Arawhiti, and the Minister for Māori Development in clause 10, reduces transparency and opportunities for early engagement. We remain concerned that expert panels are still not required to include Māori representation and have no statutory duty to consider kaitiakitanga, mātauranga Māori, cultural impact assessments or the protection of taonga species.
11. Overall, the existing timeframes are short, and the process provides Applicants with significant benefits, with appeals being limited to points of law and hearings usually avoided. Reducing the timeframes for comments and the overall timeframe for the panel’s decision, constrains the process too much and risks resulting in suboptimal decisions that create difficulties for the Applicant, councils and the community.
12. Finally, clear provisions for cost recovery must remain – not only is this fair but also enables councils to contribute at the level and pace needed to support sound and consistent decision-making and reduces the burden on ratepayers.
13. We welcome the opportunity to give feedback on the Bill to the Select Committee, and our contribution aims to ensure its provisions can be successfully implemented, and resource management system goals achieved.
14. Detailed comments on provisions are contained from page 3 onwards. On matters arising from this submission, contact in the first instance should be made with:

Al Cross

Director, Resource Management System

Te Uru Kahika

Al.Cross@teurukahika.govt.nz

027 201 3571

We wish to be heard in support of our submission.

Nāku iti noa, nā



Nigel Corry, Stefanie Rixecker and Jonathan Gibbard

ON BEHALF OF REGIONAL CHIEF EXECUTIVE OFFICERS

TE URU KAHIKA | REGIONAL AND UNITARY COUNCILS AOTEAROA

SUMMARY OF TE URU KAHIKA POSITIONS ON THE FAST-TRACK APPROVALS ACT AMENDMENT BILL

SUMMARY OF TE URU KAHIKA POSITIONS INCLUDING PROPOSED CHANGES	
Government Policy Statement	
Clauses 5 / s.10A Clause 12 / s.22 Clause 45 / s.81	Clause 5 provides for the Minister of Infrastructure to issue a Government Policy Statement for not only infrastructure but also development projects and for that to be considered in decisions on referral and substantive applications (under clauses 12 and 45). The clauses provide for a <i>Government</i> Policy Statement but only require consultation with the 'relevant portfolio Ministers'. The proposal provides for such projects that have regional or national benefits but does not include any process for how those benefits are determined. We do not support the proposed ability for a GPS to cover regional benefits. The benefits of different types of development projects will vary depending on the regional and local context. For example, in the Waikato region there are a large number of urban development projects proposing to utilise the fast-track process around the periphery of Hamilton, in addition to ongoing projects under the Resource Management Act 1991 (RMA). These collectively far exceed the demand for housing and business land identified in the relevant Housing and Business Capacity Assessments. This is a different context to localities or regions with a smaller number of fast-track development proposals or greater unmet demand for housing or business land. Given this, we consider that the regional benefits of projects are best assessed on an individual basis, so that proposals are considered within the relevant local context. Recommendation: If clauses 5, 12 and 45 are adopted, then they are amended to provide only for infrastructure with national benefits.
Referral Application	
Clauses 7(1) / s.13	We support clause 7(1) which adds the requirement to provide a description of the significance of the adverse effects on the environment.
Staging	
Clauses 19 / and 23 / s.43	We support changes to the FTAA to provide for listed projects to be considered in stages.
Consultation and Report on Treaty settlements and other obligations	
Clause 6 / s.11 Clause 10 / s.18	Clauses 6 and 14 seek to remove the requirement to undertake consultation with councils and tangata whenua prior to lodgement of a Fast-track application (referral or substantive applications).

SUMMARY OF TE URU KAHIKA POSITIONS INCLUDING PROPOSED CHANGES

Clause 14 / s.29

Clause 43 / s.72

Councils play a critical role as objective testers of applications, bringing valuable experience and understanding to the process. They are also responsible for administering consents once granted, and their input is essential to the effective ongoing operation of the fast-track system. Replacing the current requirement for applicants to consult councils prior to lodging an application with a limited notification and response process risks diminishing this role and its value to the process.

Early consultation is particularly important because once an application is lodged, the compressed statutory timeframes leave little opportunity for councils to provide meaningful technical input. Pre-application engagement allows issues to be identified and resolved efficiently, supports higher-quality applications, and reduces the likelihood of delay or dispute later in the process. Without it, and without clear provisions for cost recovery for technical review, councils may be unable to contribute at the level needed to support sound and consistent decision-making.

In practice, this could lead to perverse outcomes, such as applications being declined or heavily conditioned due to unresolved issues that could have been addressed through early engagement. It may also result in greater reliance on externally commissioned advice that lacks local context, institutional knowledge, and accountability and increases costs. Particularly under tighter decision-making timeframes, panels need to be able to rely on informed, timely, and practicable input from councils to ensure the system operates effectively and efficiently.

For example, urban development projects in the Waikato region on land that is currently zoned rural where little or no planning for urban development has been undertaken have benefited from consultation. Consultation with local authorities ensures that the applicant is aware of all the relevant matters that need addressing in their application and that they have the most up to date information that local authorities hold in relation to the property and the vicinity. An example is the recent acid sulphate soil mapping undertaken by WRC. Applicants are generally unaware of the existence of acid sulphate soils and the need to manage it carefully to prevent discharge of acidic runoff into water ways.

Furthermore, these are complex applications which ordinarily would have had to undergo a plan change process prior to applying for resource consent. Waikato Regional Council, together with Waipā and Waikato district and Hamilton city councils, have been working proactively with these applicants to ensure that substantive applications address all the relevant matters, are able to be serviced, and have a set of workable conditions of consent. Simply being notified in writing (which is unlikely to include sufficient detail to enable comment), would mean that a lot of this work is then pushed into the later substantive stage and has to be addressed within the set timeframes.

Under the Covid-19 Fast-track Consenting Act, the Whakatāne Commercial Boat Harbour was granted consent. Consultation prior to lodgement was lacking and it was identified that the site may contain PFAS which is a contaminant that is challenging to dispose of. Following consent, soil testing determined that PFAS was present which

SUMMARY OF TE URU KAHIKA POSITIONS INCLUDING PROPOSED CHANGES

	eventually led to the project not proceeding. Focused consultation prior to lodgement would have saved the Applicant time and cost. Sufficient consultation prior to lodgement also helps councils to identify key issues and supports the Panel convenor in their panel selection process in identifying relevant expertise. The proposed timeframe for appointing a panel will be challenging and retaining the consultation requirement will also allow councils to prepare nominations in advance. Likewise, consultation with tangata whenua prior to lodgement of an application makes the statutory timeframes more workable, allowing issues to be resolved or refined prior to lodgement and allowing the applicant to respond and potentially refine their application. Removing the consultation requirement will prevent such collaboration and potentially lead to more appeals on points of law. By further example, in the context of Canterbury, these proposals undermine commitments made by the Crown to Ngāi Tahu, under the Ngāi Tahu Settlement Act, including expression of rangatiratanga. Clause 10 removes the requirement for the draft Report on Treaty settlements and other obligations to be provided to the Minister of Māori Development and Te Arawhiti with ten working days for a response. Given the importance of upholding Treaty Settlements and other obligations, omitting this step may result in breaches of obligations and appeals. The changes proposed to s.72 do not address this issue due to the timing. The current requirement for a draft Report on Treaty settlements and other obligations to the Minister of Māori Development and Te Arawhiti, with the current timeframe for feedback, should be retained to provide the Applicant with certainty. Recommendation: Reject clauses 6, 10, 14 and 43
Clause 9 Section 17	Clause 9(1) amends S 17 to invite comments from Māori Crown Relations and Māori Development Ministers, a change supported by Te Uru Kahika. For clarity, we support the changes in clause 9(1) and oppose clause 10. Clause 9(4) seeks to reduce the working days for comment from 20 to 15. This, particularly when combined with the other changes such as the removal of the draft Report on Treaty settlements and other obligations and removal of the consultation requirement, could result in a lack of sufficient information and feedback in the Fast-track process. Recommendation: Adopt clause 9(1) Reject clause 9(4)

SUMMARY OF TE URU KAHIKA POSITIONS INCLUDING PROPOSED CHANGES

Conditions relating to Infrastructure

Clause 46

The proposed new section 84A reads:

The panel may set conditions to ensure that the infrastructure in the project area or other infrastructure the project will rely on is or will be made adequate to support—

(a) the project; or

(b) the stage of the project to which the application relates.

The intent of proposed section 84A is unclear. Developments frequently depend on connecting to existing council infrastructure or the provision of new infrastructure. For instance, urban developments may require access to council wastewater and water networks and electricity lines; however, if these networks are at full capacity, upgrades are necessary before connections can be made. The FTAA does not define infrastructure. The RMA defines infrastructure and does not specifically include flood protection assets but does include ‘a drainage or sewerage system’. Flood protection assets often include drainage networks with pump stations and stopbanks (with or without a drainage network). These provide important protections to people and property. Urban developments can add more stormwater to an area, necessitating drainage upgrades and increasing maintenance costs. Within the Bay of Plenty region, an urban development has been listed which may have an impact on an existing drainage scheme. Both the council and applicant have been working together to quantify the impact, and initial indications suggest significant increased maintenance costs post development. How this will be funded needs to be worked out in advance of lodging a substantive application.

We assume that section 84A is not intended to empower the panel to require parties other than the applicant—such as councils and ratepayers—to undertake or fund infrastructure works or upgrades. Such a requirement would raise significant natural justice concerns, as it would obligate one party to subsidise another’s development.

The panel already has the authority to condition applicants to provide suitable infrastructure. To avoid ambiguity and ensure fairness, we recommend amending proposed section 84A to explicitly state that only applicants may be required to undertake or fund necessary infrastructure works. For these reasons, we oppose clause 46 / proposed section 84A, in its current form.

Recommendation:

Reject clause 46

Comments on Projects

Clause 33 / s.53(4)

Clause 33 creates an additional step in the process which adds unnecessary complication in a process that is already under time pressure. Receiving comments from additional persons does not create a burden on the panel or the applicant. Given

SUMMARY OF TE URU KAHIKA POSITIONS INCLUDING PROPOSED CHANGES

	the powers of the panel, the proposed step in s 53(3) and 53(4) creates no material benefit additional to the existing section 53(3). Recommendation: Reject clause 33
Modifications to Projects	
Clause 42 / ss.68A and 68B	We support allowance for modifications to Fast-track projects during the process when the modification will reduce adverse effects on the environment or persons. However, we suggest that where modifications are determined to proceed, they are subject to parties being invited to comment within sufficient timeframes. Recommendation: Amend clause 42: - allowing for modifications to a Project that reduce or address issues and reduce adverse effects on persons and/or the environment; - ensuring any modification is subject to parties being invited to comment under section 53.
Timing of Panel Decisions	
Clause 44(1) / s.79	Clause 44 seeks to cap the timeframe for a panel to make a decision to 60 working days from receiving comments. Some Fast-track projects will be large scale and complex, requiring sufficient time to work through issues and ensure consistency with the novel legislation and suitable conditions of consent. For example, complex mining and geothermal proposals also have wide ranging environmental matters which need to be addressed. The Waihi North Fast-track application requires 84 regional consents. In this instance the applicant was supportive of a longer time period for the panel to make a decision. Further restricting the timeframe for the panel to issue a decision may result in unintended consequences such as declining the application due to unresolved matters; or imposing conditions that are challenging to comply with, monitor and enforce - and may lead to the need for the Applicant to seek variations to Fast-track consents after approval. The process already provides Applicants with significant benefits such as appeal rights limited to points of law, so further constraining the process is unnecessary. Recommendation: Reject clause 44(1)
Appeal Rights	
Clause 50	Clause 50 reduces appeal rights (on points of law) to exclude some persons such as directly adjoining neighbours and other affected persons. It retains the ability for councils and identified Māori groups to appeal on points of law. The appeal rights are

SUMMARY OF TE URU KAHIKA POSITIONS INCLUDING PROPOSED CHANGES

	already significantly constrained, and the proposed changes will further erode access to justice by placing additional limitations on who can challenge decisions, reducing accountability and further undermining confidence in the Fast-track system. Recommendation: Reject Clause 50
Cost Recovery	
Clause 53	The current framework already requires that fees and charges are reasonable and scrutiny can be applied to all costs. Clause 53 seeks to require fees and charges to be in accordance with Regulations which are not yet available. The Regulations would set: (i) upper limits, (ii) criteria for the quantification of costs, and (iii) exclusions for certain categories of costs from costs recovery. The scale and significance of different Fast-track projects is variable and technical assessments for each project will differ in complexity, time and cost. Regulations with upper limits or criteria will most likely not be able to provide for all scenarios and result in some costs falling on ratepayers. Local Government Minister Simon Watts has advised that Councils need to show they are wisely spending ratepayers' hard-earned money and that the Government is considering capping rates increases. Excluding some costs from cost recovery will result in costs being met by ratepayers rather than the applicant. Recommendation: Reject clause 53
Clause 56(2)	Clause 56(2) introduces a requirement for the EPA to notify the applicant and local authorities of the prospective panel members and allow them to raise issues with the proposed panel members. Panel members are carefully considered in regard to potential conflicts of interest, areas of expertise, capacity for the work and willingness to be on the panel. We see no reason for the proposed step given the processes already in place. The panels should be independent and so Applicants should not have influence over the panel members. Whilst many of the changes proposed in the Bill appear to have the intent of shortening the processing timeframe, clause 56(2) will add time and potential complication to the process with no benefit. Recommendation: Reject clause 56(2)

8.7 **Proposed Policy on Dangerous Dams, Earthquake-Prone Dams and Flood-prone Dams 2025– Hearing and Deliberations**

Author	Marianne Bimont, Planner; Max Dickens, Policy Manager
Authoriser	Matt Smith, Group Manager Regulatory and Policy
Public Excluded	No

Report Purpose

This report provides an overview of the proposed Policy on Dangerous, Earthquake-prone, and Flood-prone Dams 2025 (the Policy), summarises feedback received during consultation, and provides staff analysis and recommendations to the Environmental Management Committee (EMC) on potential updates or clarifications to the Policy.

Report Summary

The Council's current Policy on dangerous, earthquake-prone, and flood-prone dams has been reviewed, and a new version was publicly notified in July 2025. Consultation closed on 12 August 2025. Two parties provided feedback, with one requesting the opportunity to speak to their submission.

The Committee will review the feedback, hear from the submitter, and consider staff recommendations before finalising the Policy for approval by Council.

Recommendation

It is recommended that the Committee resolve to:

1. *Receive this report and its attachments.*
2. *Revoke the previous decision of the 1 July RMC meeting, if the Committee wishes to allow all Councillors to participate in the hearing and:*
 - a. *Hear from the submitter who wishes to provide input.*
3. *Note the staff analysis and recommendations on potential updates to the Policy.*
4. *Agree on any updates or clarifications to the Policy for final approval by Council, including:*
 - a. *Accept the Policy as currently drafted, or*
 - b. *Accept the Policy with amendments, or*
 - c. *Reject the Policy.*

Issues and Discussion

Background

The Council is updating the Policy to align with the Building (Dam Safety) Regulations 2022, which came into effect in May 2024.

This policy sets out what West Coast Regional Council (the Council) will do in relation to a dangerous, earthquake-prone or flood-prone dam in the West Coast region. It covers our regulatory and legislative responsibilities in relation to these dams under the Building Act 2004.

The policy has four key sections:

- What principles will apply.
- How Council will perform its legislative functions in relation to dangerous, earthquake-prone or flood-prone dams.
- Council priorities when performing these functions.
- How the policy will apply to heritage dams.

Consultation on the proposed Policy was carried out under the Local Government Act's special consultative procedures from 8 July to 12 August 2025. The proposed Policy is included as *Attachment 1*.

Current situation

Two submissions were received on the proposed Policy by the due date, from Fritz Fehling and New Zealand Transport Agency (*Attachment 2*). One submitter wishes to be heard in person.

Submissions analysis

The staff analysis of submissions and recommendations is in *Attachment 3*. Fritz Fehling is concerned that the growing number and height of dams is causing environmental and visual damage.

NZTA supports a policy requiring that lifeline utility providers be directly notified about any dangerous, earthquake-prone, or flood-prone dams whose failure could threaten the State Highway network or other essential infrastructure located within the corridor.

Hearing

A hearing for the submitter who wishes to speak will take place on 2 December 2025 as an item on the Environmental Management Committee agenda.

The Committee itself will conduct the hearing. The submitter will have five minutes to present their views, and committee members may ask questions to clarify any

points raised. Once the submitter has finished and there are no further questions, the Committee will close the hearing.

Deliberations

Following the close of the hearing, the Committee will deliberate. Guidelines on the deliberations process have been shared with committee members.

During deliberations, the Committee may recommend any changes it considers necessary to the Policy. Once the final wording is confirmed, the Policy will be forwarded to a Council meeting for approval.

Considerations

Implications/Risks

With only two submissions received, including one supporting the approach, risks and implications for this consultation process are low. The Policy itself remains important due to the safety issues associated with dams.

Significance and Engagement Policy Assessment

There are no issues within this report which trigger matters in this policy.

Tangata whenua views

Poutini Ngāi Tahu were invited to provide input to Regional Council staff before the proposed Policy was notified, or through the public consultation process. Feedback was received on 11 September 2024.

Views of affected parties

A list of parties who were consulted with in the notification of the Draft Policy is shown below. Stakeholders were identified based on either their interest in dam safety or because they own or operate dams within the region.

- | | |
|--|------------------------------|
| • Te Rūnanga o Ngāti Waewae | • Department of Conservation |
| • Te Rūnanga o Makaawhio | • Development West Coast |
| • Te Rūnanga o Ngāi Tahu | • Westpower |
| • Ministry of Business, Innovation and Employment (MBIE) | • Manawa Energy |
| • Grey District Council | • Kawatiri Energy Limited |
| • Westland District Council | • Bathurst Resources Ltd |
| • Buller District Council | • Minerals West Coast |
| • Environment Canterbury | • Oceana Gold |
| • Tasman District Council | • Environment Southland |
| • Otago Regional Council | • Federated Farmers |
| | • Westland Milk Products |

Financial implications

Current budget

There are no other budget implications that need to be addressed in this report.

Future implications

There are no other budget implications that need to be addressed in this report.

Legal implications

The policy review ensures WCRC meets its statutory requirement to review the policy every five years, noting that it has not been reviewed since its adoption in 2006.

Attachments

Attachment 1: Proposed Policy on dangerous dams, earthquake-prone dams and flood-prone dams 2025

Attachment 2: Public submissions

Attachment 3: Staff analysis of submissions



WEST COAST
REGIONAL COUNCIL

S161 Building Act 2004

**Policy on dangerous dams,
earthquake-prone dams and
flood-prone dams 2025**

Contents

1. Introduction	1
2. Application of this policy	1
3. Principles	2
4. Council's approach to performing these functions	3
4.1. Information on dam status	3
4.2. Working with dam owners	3
4.3. Directing and taking action	3
5. Council's priorities in performing these functions	5
6. Application to heritage dams	5

1. Introduction

This document sets out the policy on dangerous dams, earthquake-prone dams and flood-prone dams adopted by West Coast Regional Council (“the Council”) in accordance with sections 161 and section 162 of the Building Act 2004 (“the Act”).

This policy is a key component of the wider regulatory framework for protecting people, property, and the environment from the potential impacts of dam failure. It provides for the identification and management of dams of concern in the West Coast Region, and the measures the Council will take (with the dam owner) to reduce or remove danger.

The policy states the approach and priorities the Council will take in performing its functions in relation to dangerous dams, earthquake-prone dams and flood-prone dams in the West Coast region, and how the policy will apply to heritage dams, in accordance with section 161(2) of the Act.

This policy applies to dams defined in section 7 of the Act. This policy also applies to dangerous dams, earthquake prone dams, and flood-prone dams within the region, as defined in sections 153, 153A and 153AA of the Act.

The dam safety provisions in subpart 7 of part 2 of the Act, apply to:

1. Classifiable dams (defined in regulation 5 of the Building (Dam Safety) Regulations 2022 (“the Regulations”) to be 4 or more metres high and storing 20,000 cubic metres volume of water or other fluid)
2. Referable dams as defined in the Regulations¹
3. All dams but only for the purposes of section 133B² (height measurement of dams) and sections 157 and section 158 (measures by a regional authority to avoid immediate danger).

2. Application of this policy

This policy applies to dams everywhere in the West Coast region, irrespective of the age and intended life of the dam. Where required by the Act, parts of this policy apply specifically to classifiable dams, which also include “large dams” as defined in section 7 of the Act.

The terms ‘dangerous dam’, ‘earthquake-prone dam’ and ‘flood-prone dam’ have the same meaning as provided in section 153, section 153A and section 153AA of the Act³.

¹ Acknowledged by Ministry of Business, Innovation and Employment (MBIE) as not yet defined in Regulations (as of February 2025).

² When measuring the height of the dam under this section, the crest of the dam includes any freeboard – refer to section 133B of the Act for the definition.

³ This includes buildings in areas designated under subpart 6B as set out in section 153AA of the Act.

This policy must be read alongside the Building (Dam Safety) Regulations 2022 (“the Regulations”) which define terms used in the Act in relation to “dangerous dams”, “earthquake-prone dams” and “flood-prone dams”⁴.

The Regulations and the Act can be accessed at www.legislation.govt.nz⁵.

Under section 153AA of the Act, if a dangerous dam is located in an area that has been affected by an emergency (designated under Subpart 6B of the Act – Special provisions for buildings affected by emergency), this policy and other provisions of the Act continue to apply to the dam after the designation but only in relation to:

- a) an action taken in relation to the dam under section 154(1)(a) or (b) before the designation comes into force;
- b) a notice given in relation to the same under section 154(1)(c), or work carried out in accordance with the notice or under section 156 of the Act before the designation comes into force; or
- c) an action taken in relation to the dam under a warrant issued under section 157 of the Act.

This policy commences three weeks after the Council resolution is made to adopt the policy.

This policy will be reviewed every five years or earlier as required. The policy remains in effect even though it is due for review or being reviewed.

3. Principles

The Council will apply the following principles to the exercise of its dangerous dams, earthquake-prone dams and flood-prone dams functions under the Act.

1. Dam owners have the primary responsibility for identifying, monitoring and reporting on dangerous, earthquake-prone and flood-prone dams and for reducing or removing the risk of harm to people, property and the environment in a timely and effective manner.
2. An engineer engaged (by the owner) to provide a certificate for the purposes of sections 135(1)(b), 142(1)(b), or 150(2)(f) will notify Council and the owner of the dam, in writing and within 5 working days, if they believe that the dam is dangerous.
3. The state of all dangerous, earthquake-prone and flood-prone dams (as defined in the Act and the Regulations) must be known by dam owners (noting that other dam safety provisions in the Act apply to all dams) and this information, if known to the Council, will be made readily available by the Council, to all persons potentially affected by the safety risks of a dangerous, earthquake-prone or flood-prone dams.

⁴ Section 19 of the Regulations defines moderate earthquake, moderate flood, earthquake threshold event and flood threshold event.

⁵ The Regulations: legislation.govt.nz/regulation/public/2022/0133/latest/whole, and the Act: legislation.govt.nz/act/public/2004/0072/latest/whole

4. Council's approach to performing these functions

4.1. Information on dam status

The Council will keep a register of dams as required by section 151 of the Act recording the dangerous, earthquake-prone or flood-prone status of each classifiable dam on the register. The Council will develop a monitoring procedure to ensure information held in the register is up to date. This information will be provided to the Chief Executive and the relevant territorial authority to update property files and any relevant land information memorandum.

Should the Council receive information about a dangerous, earthquake-prone and flood-prone dam in its regional boundary, the Council will notify the relevant territorial authority and West Coast Emergency Management (West Coast Civil Defence and Emergency Management Group). West Coast Emergency Management will be requested to notify potentially affected lifeline utility providers.

4.2. Working with dam owners

Legislation requires owners of all classifiable dams to notify the Council of their dam classification and whether the dam is dangerous, and any changes, in a timely manner, to comply with the Act and the Regulations. The Act requires dam owners to notify the Council immediately if they have reasonable grounds for believing their dam is dangerous. This applies to dams that are either a high potential impact dam or a medium potential impact dam and are likely to fail in the ordinary course of events, or a in "moderate earthquake" or "moderate flood" (as defined in the Regulations).

The Act also requires an engineer (engaged by the owner) to provide documentation for the purposes of sections 135(1)(b), 142(1)(b), or 150(2)(f), to notify Council and the owner of the dam in writing and within 5 working days if they believe the dam is dangerous.

Owners of identified dangerous dams, earthquake-prone dams or flood-prone dams will develop an action plan (with timeframes) with the goals of increasing the safety of the dam and eliminating or reducing risks of the dam to people, property and the environment. It is not realistic to specify a timeframe in this policy for achieving this goal because timeframes will be dictated by the circumstances of each case. When setting a timeframe for action, the Council will consider the state of the dam, whether it is a dangerous dam, and the likelihood and consequences of dam failure.

4.3. Directing and taking action

The Council may intervene:

- For dangerous, earthquake-prone and flood-prone dams:
 - If the owner of any dam is not acting in accordance with an agreed action plan; or
 - Where there is no agreed action plan; or
 - Where it considers that the agreed action plan requires review or amendment; or
 - Where ownership is not known or is disputed.
- For all dams, where there is or likely to be a risk of immediate danger.

Before exercising any of its powers under sections 154 to section 159 of the Act the Council will, unless the circumstances dictate otherwise (such as where there is immediate danger to the safety of persons, property, or the environment), seek to discuss options for action with the owner of the dam, with a view to obtaining from the owner a mutually acceptable formal proposal for reducing or removing the danger. Acceptable actions by the owner may include but not be limited to, one or more of the following:

- Operational changes such as reducing the volume of impounded fluid or completely emptying the reservoir;
- Reconfiguring an existing spillway, or creating a new or supplementary spillway, so as to limit the maximum impounded volume and/or to safely route flood flows;
- Increased surveillance and monitoring;
- Development of emergency preparedness and response plans;
- Review of the dam safety assurance programme;
- Engaging a dam specialist to investigate and make recommendations on how risks to people, property or the environment may be mitigated, with any report provided to the Council at the earliest opportunity;
- Implementing measures to enable controlled, rapid emptying of the impounded fluid;
- Measures downstream of the dam to mitigate the impact of dam failure;
- Physical works including reconstruction or partial demolition of the dam;
- Decommissioning and/or removal of the dam.

The whole or part of any agreement between the Council and the dam owner may be formalised in a Notice to Fix issued under section 164 of the Act. If agreement cannot be reached between the Council and the dam owner, the Council may exercise any of its statutory powers in sections 154 to section 159 and section 164 of the Act.

If no action is taken by the owner to address the danger, or action is not being taken by the owner in a timely manner, the Council may exercise any of its statutory powers in sections 154 to section 159 and section 164 of the Act.

The Council will notify potentially affected communities downstream of a dangerous, earthquake-prone or flood-prone dam. The Council will do this by publishing information about any dangerous, earthquake-prone or flood-prone dam in the West Coast region. The Council will liaise with West Coast Emergency Management on any actions taken in response to a dangerous, earthquake-prone, or flood-prone dam.

The Council may at any time require the dam owner to review a dam safety assurance programme if the dam is an earthquake-prone or flood-prone dam.

In a situation where a dam is dangerous, the Council may:

- Erect a hoarding or fence to prevent people from approaching the dam nearer than is safe.
- Attach a notice on or near the dam (or affected downstream areas) that warns people not to approach.
- Give written notice to the owner requiring work to be carried out on the dam, within the time stated in the notice for the purposes of removing or reducing the danger.

Where the Council takes action in response to a dangerous, earthquake-prone or flood-prone dam, the Council will notify Poutini Ngai-Tahu where there is potential for the dam to affect any area of interest to the rūnanga.

If action is taken in response to a dangerous, earthquake-prone or flood-prone dam, the Council will notify the relevant local territorial authority in which the dam is located.

In a situation where the Chief Executive of the Council considers that, because of the state of the dam, immediate danger to the safety of persons, property, or the environment is likely then the Chief Executive of the Council may:

- Cause any action to be taken that is necessary to remove that danger.
- Recover the costs of taking any action from the dam owner.

5. Council's priorities in performing these functions

The dangerous dam provisions of the Act will be used by the Council as a mechanism to remedy an unsatisfactory situation that has developed in the West Coast region, rather than as a means of responding to "emergencies" that arise in the future. The Council's approach to dangerous dams is therefore tailored towards achieving a reduction in pre-existing risk whilst still being able to deal with risks that emerge in the future.

In performing these functions, dams will be prioritised by Council as follows, in which Priority 1 is the highest priority and Priority 4 is the lowest priority:

1. Responding to any dam posing a risk of immediate danger, regardless of the potential impact classification of the dam, or the status of any dam safety assurance programme for the dam.
2. Reducing risks posed by dangerous dams, with high potential impact classification dangerous dams considered the highest priority. Those without a dam safety assurance programme will be prioritised over those with an approved dam safety assurance programme.
3. Reducing risks posed by earthquake-prone or flood-prone dams with high potential impact classification. Those without a dam safety assurance programme will be prioritised over those with an approved dam safety assurance programme.
4. Reducing risks posed by earthquake-prone or flood-prone dams with medium potential impact classification. Those without a dam safety assurance programme will be prioritised over those with an approved dam safety assurance programme.

When reducing the risks posed by a dangerous dam, earthquake-prone dam or flood-prone dam, the Council will give precedence to the requirement to remove or reduce the danger to public safety, and having addressed this, will then have regard to the potential for damage or loss to property and the environment including heritage matters.

6. Application to heritage dams

Heritage dams as defined in section 7 of the Act means a dam that is included on:

- a) the New Zealand Heritage List/Rārangi Kōrero maintained under section 65 of the Heritage New Zealand Pouhere Taonga Act 2014; or
- b) the National Historic Landmarks/Ngā Manawhenua o Aotearoa me ōna Kōrero Tūturu list maintained under section 81 of the Heritage New Zealand Pouhere Taonga Act 2014.

Section 4(2)(l) of the Act recognises “the need to facilitate the preservation of buildings of significant cultural, historical, or heritage value”.⁶

The Council recognises the need to retain heritage values of the dam itself, but also the need to reduce or remove any risk posed by a heritage dam which has been classified as dangerous, flood-prone or earthquake-prone. When considering heritage dams under this policy, the Council will take into account the need to facilitate preservation of parts of the dams with significant heritage value.

When dealing with heritage dams, which are deemed dangerous, earthquake-prone, or flood-prone, or when taking action in response to any dangerous, earthquake-prone or flood-prone dam that is located near a site which is entered on the New Zealand Heritage List/Rārangi Kōrero (including historic places, historic areas, wāhi tapu or wāhi tūpuna areas), or is otherwise identified by iwi as a place of cultural significance, the Council will seek advice from Heritage New Zealand Pouhere Taonga before any actions are undertaken by the Council under sections 153 to section 160 of the Act.

The Council may also engage suitably qualified professionals with engineering expertise and heritage expertise to advise and recommend actions. When considering any recommendations, the Council will have regard to the priorities set out in clause 5 of this policy. Copies of all notices served for all heritage dams which are deemed dangerous, earthquake-prone or flood-prone will be provided to Heritage New Zealand Pouhere Taonga.

The Council will record the heritage listing of all dangerous, earthquake-prone and flood-prone dams it is made aware of in its register of dams and supply this information to the relevant territorial authority for inclusion on property files and any relevant land information memorandum.

⁶ Under the Heritage New Zealand Pouhere Taonga Act 2014 (HNZPTA), the permission of Heritage New Zealand Pouhere Taonga must be sought prior to the modification or destruction of any archaeological site, whether or not the site is recorded. An archaeological site is described in the HNZPTA as a place associated with pre-1900 human activity, which may provide evidence relating to the history of New Zealand. Works to pre-1900 structures, such as dams, or earthworks near pre-1900 structures may require an archaeological authority to be obtained prior to works commencing. Please contact Heritage New Zealand Pouhere Taonga for further information.

Attachment 8.7.2: Public Submissions

Submission text:

The New Zealand Transport Agency Waka Kotahi (NZTA) provides a lifeline utility, per clause 6, Part B, Schedule 1 of the Civil Defence Emergency Management Act 2002, as it is the entity that provides the State highway road network. The State highway road corridor is often used by other lifeline utility providers to locate their infrastructure, for example, power and telecommunications infrastructure and 3 Waters infrastructure.

Dangerous dams, earthquake-prone dams and flood-prone dams could present a risk to the safe and efficient functioning of the State highway road network, as well as any other lifeline utilities using the State highway road corridor to locate their infrastructure, where those dams are located within a proximity where their failure would adversely impact the State highway road corridor. For these reasons, it is considered vitally important that NZTA (and other lifeline utility providers) are directly notified about any dangerous, earthquake-prone and flood-prone dams. In being notified directly about these dams, in a timely manner, NZTA will be better placed to understand the risk presented to the State Highway network by various dams and prepare for dam failure scenarios and put in place procedures to keep workers (who, for instance, might be responding in the immediate aftermath of a flood or earthquake) and road users safe.

In section 4.1 of the proposed policy, it is noted that the Regional Council will notify the West Coast Civil Defence and Emergency Management Group ('West Coast Emergency Management', WCEM) of any dangerous, earthquake-prone and flood-prone dams it receives information about, and will request WCEM to notify potentially affected lifeline utility providers. NZTA supports this notification requirement and considers it'll help to ensure lifeline utility providers are kept appropriately informed of risk to their assets, in a timely manner, and enable NZTA to better protect employees and users of the state highway network from a dam failure.



WEST COAST REGIONAL COUNCIL

Consultation on Proposed Dam Safety Policy

Submission form – what do you think?

The West Coast Regional Council is currently seeking feedback on the Proposed policy on Dangerous Dams, Earthquake-prone Dams, and Flood-prone Dams in the West Coast Region.

Your details

First name: Fritz Surname: Fehling

Address: [REDACTED]

Phone: [REDACTED] Email: [REDACTED]

Are you ^{suggesting} submitting as an individual or on behalf of an organisation? (tick one)

☒ Individual ☐ Organisation [REDACTED]

Do you wish to speak in support of your submission at a hearing? (tick one)

☒ Yes ☐ No

Signature of submitter suggester

Date 29/7/25

All submissions are made available for public inspection.

Note that your submission, and any information you supply as part of your submission, is considered public information and will be made available in reports and documents relating to this process. It may also be published on our website.

Attachment 8.7.2: Public Submissions

All submissions must be received by the West Coast Regional Council no later than 5.00pm, Tuesday 12 August 2025.

The West Coast Regional Resource Management Committee would like to know

Please provide your comments and suggestions on the Proposed Policy on Dangerous Dams, Earthquake-prone Dams, and Flood-prone Dams 2024 here:

Around 1995, More than 30 years ago I provided a detailed drawing of future-proof safe dams, but the Council's fascist arrogance ignored it (an FPP-selection systemic failure). Since then ~~there~~ uninterrupted dams have multiplied and extremely increased in height, with extreme environmental damage and ugly sights. This simplistic power design will make every dam a dangerous dam, ^{all} as the riverbeds rise above adjacent land. It is not if, but when such dams will be breached and cause widespread death!

Post a submission:

Dams Policy Submissions
West Coast Regional Council
PO Box 66,
Greymouth 7840

Drop into our office:

388 Main South Road,
Paroa

between 8.00am and
4.30pm weekdays

Email:

dams@wrc.govt.nz

Complete submission online:

www.wcrc.govt.nz/community/consultation and complete the online form

Need help?

West Coast Regional Council – Freephone 0508 800 118

Fascist idiot Bruce Smith tried to insult me when I tried to inform him.
My 1995 2-page design and description should be recovered from the council's archive...

Attachment 8.7.3: Staff Analysis of Submission Points

Respondent	Submission summary	Staff recommendation	Comments
Fritz Fehling	Concerned about increase in number and height of dams with extreme environmental damage and ugly sights over the past 30 years. Around 1995 submitted a detailed drawing of future proof safe dams.	No change.	The matters raised by the submitter are to do with the design and consenting of dams. The policy is not intended nor able to guide the design and consenting of dams.
New Zealand Transport Agency Waka Kotahi (NZTA)	Dangerous dams, earthquake-prone dams and flood-prone dams could present a risk to the safe and efficient functioning of the State highway road network, as well as any other lifeline utilities using the State highway road corridor to locate their infrastructure, where those dams are located within a proximity where their failure would adversely impact the State highway road corridor. Submitter considers it vitally important that NZTA (and other lifeline utility providers) are directly notified about any dangerous, earthquake-prone and flood-prone dams. NZTA supports this notification requirement in 4.1 of the proposed policy	No change.	The notification requirement in 4.1 of the proposed policy addresses the submitter's concerns.