Data and Information Committee Agenda
9 June 2022

Meeting held at Harvest Hotel Conference Centre,
6 Barry Ave, Cromwell 9342
Members of the public may view the meeting live at: Otago Regional Council YouTube Channel

Members:

Cr Alexa Forbes, Co-Chair	Cr Kevin Malcolm
Cr Michael Laws, Co-Chair	Cr Andrew Noone
Cr Hilary Calvert	Cr Gretchen Robertson
Cr Michael Deaker	Cr Bryan Scott
Cr Carmen Hope	Cr Kate Wilson
Cr Gary Kelliher	

Senior Officer: Dr Pim Borren, Interim Chief Executive
Meeting Support: Liz Spector, Governance Support Officer

09 June 2022 01:00 PM

Agenda Topic — Page

1. APOLOGIES

No apologies were received prior to publication of the agenda.

2. PUBLIC FORUM

No requests to address the Committee under Public Forum were received prior to publication of the agenda.

3. CONFIRMATION OF AGENDA

Note: Any additions must be approved by resolution with an explanation as to why they cannot be delayed until a future meeting.

4. CONFLICT OF INTEREST

Members are reminded of the need to stand aside from decision-making when a conflict arises between their role as an elected representative and any private or other external interest they might have.

5. MATTERS FOR CONSIDERATION 3

5.1 HEAD OF LAKE WAKATIPU FLOODING AND LIQUEFACTION HAZARD INVESTIGATIONS 3

This report discusses findings of investigations into flood and liquefaction hazards at the Dart-Rees floodplain and Glenorchy township and provides updates on other programmes to develop a natural hazards strategy for the area.

5.1.1 Tonkin+ Taylor Ltd 2022 Glenorchy liquefaction vulnerability assessment 35

5.1.2 Wentz- Pacific Ltd 2022 Peer review of the T+ T Glenorchy liquefaction assessment 96

5.1.3 Land River Sea Ltd Flood Hazard Report 98

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6. CLOSURE

5.1. Head of Lake Wakatipu flooding and liquefaction hazard investigations

Prepared for:	Data and Information Committee
Report No.	HAZ2202
Activity:	Safety & Hazards - Natural Hazards
Author:	Tim van Woerden, Natural Hazards Analyst Jean-Luc Payan, Manager Natural Hazards
Endorsed by:	Gavin Palmer, General Manager Operations
Date:	9 June 2022

PURPOSE

[1] To inform the Committee of the findings of investigations of flooding and liquefaction hazards at the Dart-Rees floodplain and Glenorchy township and to provide an update on other activities in the ORC-led work programme to develop a natural hazards adaptation strategy for the area at the head of Lake Wakatipu.

EXECUTIVE SUMMARY

[2] Previous Otago Regional Council (ORC) reports[1] have identified the Dart-Rees floodplain and Glenorchy township as exposed to the potential impacts of natural hazard events such as flooding and liquefaction.

[3] A geotechnical investigation commissioned by ORC and completed by Tonkin + Taylor Ltd (T+T) has assessed the susceptibility of the Glenorchy township area to liquefaction and lateral spreading caused by a major earthquake, and the anticipated impacts of these hazards.

[4] A hydraulic modelling and flood hazard investigation commissioned by ORC and completed by Land River Sea Consulting Ltd (LRS) has assessed the flood hazard to the Dart-Rees floodplain and Glenorchy township from the Dart and Rees rivers, and high levels in Lake Wakatipu.

[5] This paper presents the key findings of the Tonkin + Taylor Ltd and Land River Sea Consulting Ltd technical reports, investigating liquefaction and flood hazards respectively.

[6] These new investigations contribute to a significant advance in natural hazards understanding for the Dart-Rees floodplain and Glenorchy, being the most detailed hydraulic modelling study at the Dart-Rees rivers, and the first liquefaction hazard assessment for Glenorchy based on comprehensive subsurface geotechnical data and analysis.

[1] e.g. ORC (2010). Natural hazards at Glenorchy; Tonkin + Taylor (2021). Head of Lake Wakatipu natural hazards assessment; and van Woerden and Payan (2021). Natural Hazards Adaptation in the Head of Lake Wakatipu. ORC Council report HAZ2105, 27 May 2021

[7] Natural hazard investigations have confirmed a major earthquake or flooding event would have severe impacts, and help understand in more detail the hazard characteristics, spatial extents and likelihoods.

[8] The purpose of the natural hazards investigations is to inform adaptation planning and decision-making in the Dart-Rees floodplain and Glenorchy township. The information will also assist emergency services response and the community readiness for natural hazards events.

[9] Natural hazards adaptation at the Dart-Rees floodplain and Glenorchy township will require a strategic, holistic approach, which incorporates consideration of all potential natural hazard types, future climate change, landscape changes, and multiple and cascading natural hazards.

RECOMMENDATION

That the Data and Information Committee:

1) ***Notes*** *this report.*
2) ***Notes*** *the report by Tonkin + Taylor Ltd;* Glenorchy liquefaction vulnerability assessment*, dated May 2022 and the report by Land River Sea Consulting Ltd;* Dart-Rees flood hazard modelling*, dated May 2022.*
3) ***Notes*** *the findings presented in these reports.*
4) ***Endorses*** *the use of the information presented in these reports to inform adaptation decision-making for Glenorchy.*
5) ***Notes*** *the Shepherd's Hut Creek debris flow event and the actions taken by ORC in response to that event.*
6) ***Notes*** *the establishment of the Queenstown-Lakes District Natural Hazards Steering Group which has further strengthened the working relationship between ORC and Queenstown-Lakes District Council staff on the management of natural hazards.*

BACKGROUND

[10] The area at the head of Lake Wakatipu (Whakatipu-Wai-Maori) is exposed to multiple natural hazard risks, including those due to flooding and seismic hazards.

[11] ORC, in collaboration with project partners, is leading a programme of work to develop a natural hazard adaptation strategy for the head of Lake Wakatipu area.

[12] The adaptation project approach is outlined in the Council paper *Adaptation in the head of Lake Wakatipu*,[2] considered by Council in May 2021. Council made the following resolutions:

   1) ***Acknowledges*** *the need for natural hazards adaptation planning in the head of the Lake Wakatipu project area.*
   2) ***Notes*** *the program of work completed to date.*
   3) ***Endorses*** *the use of the Adaptation Pathways approach.*
   4) ***Supports*** *the continued collaboration with project partners.*

[2] *Natural Hazards Adaptation in the Head of Lake Wakatipu*. ORC Report HAZ2105, Report to 27 May 2021 meeting of the Otago Regional Council.

[13] This paper is an update on new technical investigations completed up to June 2022. These are, an investigation of the liquefaction susceptibility in Glenorchy township, and a flood hazard investigation for the Dart-Rees floodplain including Glenorchy.

[14] This paper also includes brief updates on other project activities:

- The ORC environmental monitoring network in the head of Lake Wakatipu area, including the installation of a river flow monitor for the Rees River.
- A study in progress to assess potential floodplain hazard mitigation approaches for the Dart-Rees floodplain.
- A summary of a new investigation into alluvial fan hazards at the Buckler Burn.
- An overview of response to a debris flow event in April 2022 impacting on the Queenstown-Glenorchy road access (Shepherds Hut Creek).
- An update on natural hazards research projects in the head of Lake Wakatipu area that are supported by ORC.

[15] The occurrences of liquefaction and lateral spreading following the 2010-2011 Christchurch and 2016 Kaikoura earthquakes has created a greater awareness of, and focus on, the potential for liquefaction events in New Zealand. In response to recommendations[3] of the Royal Commission of Inquiry into Building Failure caused by the Canterbury Earthquakes, the Ministry of Business, Innovation and Employment (MBIE) and the Ministry for the Environment (MfE) released a guidance document in 2017 presenting a risk-based approach for the management of liquefaction-related risk in land use planning and development decision-making.[4]

[16] Recommendation 187 of the Royal Commission states that "*Regional councils and territorial authorities should ensure that they are adequately informed about the seismicity of their regions and districts. Since seismicity should be considered and understood at a regional level, regional councils should take a lead role in this respect and provide policy guidance as to where and how liquefaction risk ought to be avoided or mitigated*."

[17] In 2019 ORC commissioned GNS Science to complete an assessment of the liquefaction hazards in the Queenstown Lakes, Central Otago, Clutha and Waitaki districts[5] (the

[3] 186. Sections 6 and 7 of the Resource Management Act 1991 should be amended to ensure that regional and district plans (including the zoning of new areas for urban development) are prepared on a basis that acknowledges the potential effects of earthquakes and liquefaction, and to ensure that those risks are considered in the processing of resource and subdivision consents under the Act.
187. Regional councils and territorial authorities should ensure that they are adequately informed about the seismicity of their regions and districts. Since seismicity should be considered and understood at a regional level, regional councils should take a lead role in this respect, and provide policy guidance as to where and how liquefaction risk ought to be avoided or mitigated. In Auckland, the Auckland Council should perform these functions.
188. Applicants for resource and subdivision consents should be required to undertake such geotechnical investigations as may be appropriate to identify the potential for liquefaction risk, lateral spreading or other soil conditions that may contribute to building failure in a significant earthquake. Where appropriate, resource and subdivision consents should be subject to conditions requiring land improvement to mitigate these risks.

[4] MBIE & MfE. (2017). *Planning and Engineering Guidance for Potentially Liquefaction-prone Land*. New Zealand Ministry of Business, Innovation and Employment, Building System Performance Branch.

assessment of the liquefaction hazards for the Dunedin City district was completed by GNS Science in 2014).[6] The purpose of the assessment was to better understand the susceptibility of land to earthquake-induced liquefaction at a regional scale. The liquefaction susceptibility assessment highlights areas where liquefaction hazard may warrant further scrutiny (such as ground testing and detailed liquefaction assessments) for future planning and development activities. The GNS Science assessment was presented to the ORC Technical Committee in August 2019[7] and provided to the relevant district councils.

[18] Previous liquefaction studies (including the GNS 2019 study) in the Glenorchy area were largely based on geomorphic observations such as interpretation of landforms and sedimentary environments, and other characteristics such as the inferred depth to groundwater table. This level of detail is sufficient for identification and communication of a potential liquefaction hazard and are classified as Level A assessments (a basic desktop assessment) by the MBIE/MfE guidance for potentially liquefaction-prone land. The GNS Science assessment identified the Glenorchy area as an area where "liquefaction damage is possible".

[19] In early 2021, site-specific geotechnical investigations were undertaken for a proposed development near the Glenorchy waterfront.[8] These investigations identified the potential for significant liquefaction and lateral spreading to occur in that location, prompting the current study by ORC to understand the extent of which similar ground conditions or hazards impacts may occur elsewhere in the township area.

[20] Liquefaction and lateral spreading occur when strong ground shaking during an earthquake disturbs unconsolidated, saturated sediments, causing these to behave as a fluid. Lateral spreading occurs near an unsupported 'free face' such as riverbank or lake margin, and causes lateral movement, ground deformation and fissures at the ground surface. Liquefaction and lateral spreading effects are illustrated in Figure 1.

[21] Major earthquakes causing liquefaction and lateral spreading are natural hazards capable of causing significant risks to safety and social wellbeing, and severe damage and disruption to buildings, infrastructure, and businesses. These hazard consequences are illustrated by events of the 2010-2011 Canterbury Earthquake sequence, where widespread and damaging liquefaction occurred within Christchurch city, and which was likely the most extensive urban liquefaction event ever recorded.[9]

[5] Barrell D (2019). *Assessment of liquefaction hazards in the Queenstown Lakes, Central Otago, Clutha and Waitaki Districts of the Otago region*. GNS Science report 2018/67, prepared for Otago Regional Council.
[6] Barrell D et al (2014). *Assessment of liquefaction hazards in the Dunedin City District*. GNS Science report 2014/68, prepared for Otago Regional Council.
[7] *General Manager Operations Report to Technical Committee*, Report EHS1857, Report to 1 August 2019 meeting of the Technical Committee.
[8] ENGEO Ltd (2021). Detailed Design Support – The Grand Mt Earnslaw Hotel, 1 Benmore Place, Glenorchy. Report prepared for Blackthorn Ltd.
[9] Cubrinovski M (2013). *Liquefaction-induced damage in the 2010-2011 Christchurch (New Zealand) earthquakes*. International Conference on Case Histories in Geotechnical Engineering. 1.

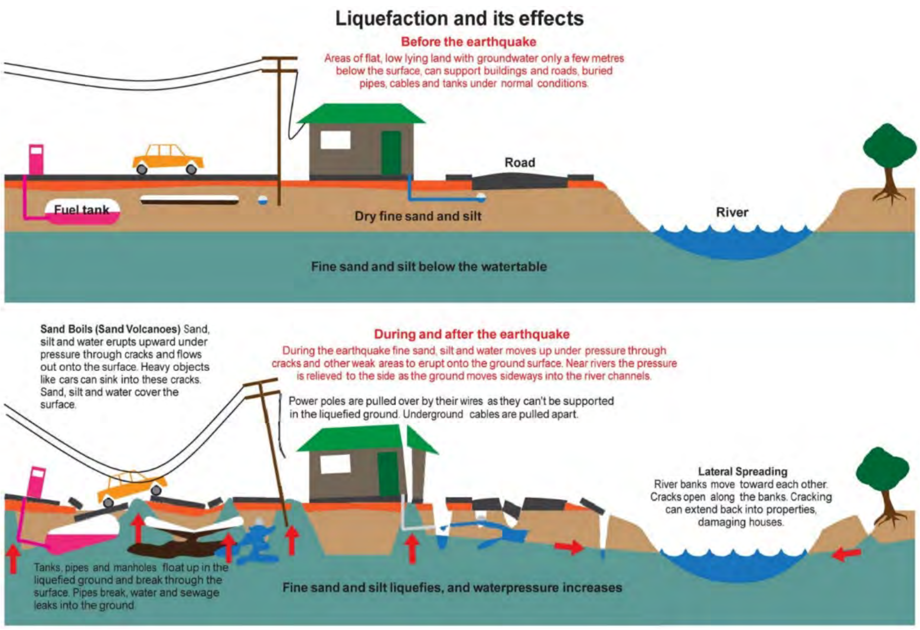

Figure 1: A diagrammatic illustration of liquefaction and lateral spreading and their effects (IPENZ, 2012).

[22] The flooding hazard at Glenorchy township is known from observations of several flooding events in recent decades. Flooding most recently impacted on the residential area of the township in February 2020 (Figure 2b). Previous recent floods include that November 1999 (Figure 2a).

[23] Flood hazard modelling has been previously completed for Glenorchy township by URS New Zealand Ltd (2007).[10] The resolution of the URS flood modelling was limited by a number of factors, for example, LiDAR topography was not yet available so topographic control was based only on sparse cross-section surveys, and the hydraulic modelling approach used allowed only a relatively simple analysis.

[24] Flooding of the lower Dart River floodplain is a relatively frequent occurrence, causing disruption to road access to Kinloch and the Greenstone area (Figure 3). A long-term westwards migration of the Dart River's active riverbed is also causing increasing erosion pressure on sections of this road.

[10] URS (2007). *Glenorchy floodplain flood hazard study*. Prepared for Otago Regional Council.

[25] Observations of past flooding extents, together with the flooded areas modelled by URS (2007), are the basis for the 'flood-prone area' layer displayed in ORC's natural hazards database[11] for the Dart-Rees floodplain and the Glenorchy township area.

[26] The investigations of liquefaction susceptibility and flood hazard reported in this paper are designed to provide greater understanding of these hazards, including hazard characteristics, spatial extents, and likelihoods. This level of details is a pre-requisite to inform the development of the natural adaptation strategy for the head of Lake Wakatipu.

Figure 2: Flooding in Glenorchy township in November 1999 (a, left) and February 2020 (b, right). (photo of 2020 event provided by Luke Hunter).

Figure 3: Flooding of the Dart floodplain in March 2019. The image is looking northwards (upvalley), with Glacier Burn flowing into the Dart River at centre. The approximate location of Kinloch Road is annotated as a dashed line.

[11] http://hazards.orc.govt.nz

LIQUEFACTION HAZARD INVESTIGATION
REPORT CONTENT AND STRUCTURE

[27] The report is titled *Glenorchy Liquefaction Vulnerability Assessment and* is attached as Appendix 1. The main report sections are listed below.

- Sections 1-5 provide a summary of report scope and description of the study area, and wider context including characteristics of liquefaction hazards, the MBIE/MfE guidance, and regional-scale seismicity.
- Sections 6-9 describe the relevant physical characteristics of the study area, including geology and geomorphology, topography, and groundwater, and give an overview of the geotechnical field investigations completed for this study.
- Sections 10-13 provide details of the geotechnical analysis completed for assessment of liquefaction and lateral spreading susceptibility.
- Section 14 outlines the report's conclusions regarding liquefaction and lateral spreading hazards in Glenorchy.
- Appendix A of the Tonkin + Taylor report is a map showing liquefaction and lateral spreading vulnerability categorization developed according to the criteria in the MfE/MBIE Guidance.
- Appendix B pf the Tonkin + T aylor report shows examples of liquefaction and lateral spreading observed following the 2010-2011 Darfield-Christchurch earthquakes and 2016 Kaikoura earthquakes.

METHODOLOGY

[28] Liquefaction hazard investigations were completed in accordance with MBIE/MfE[12] guidance for the management of liquefaction-related risk in land use planning and development decision-making.

[29] The MBIE/MfE guidance categorises liquefaction vulnerability studies based on their level of detail. In this categorisation, this Glenorchy township investigation is a Level C study, a 'detailed area-wide assessment'.

[30] The extent of investigations was limited to the Glenorchy township area (Figure 4). The study extent was bounded to the north, west and south by the Glenorchy Lagoon and Rees floodplain, Lake Wakatipu, and the Buckler Burn, respectively. The eastern extent of the study area was the base of Bible Terrace and the bedrock hillslopes.

[31] Field investigations completed were four boreholes to maximum depths of 20 metres, and cone penetrometer tests (CPT) at 19 locations (Figure 4). All borehole and CPT data from this investigation is publicly available on the New Zealand Geotechnical Database (NZGD).[13] A small number of additional borehole and CPT data were publicly available via the NZGD and were also used in analysis.

[32] Borehole geology, CPT results, groundwater data and LiDAR[14]-derived topography data were used in development of geological and groundwater models.

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[12] MBIE & MfE. (2017). *Planning and Engineering Guidance for Potentially Liquefaction-prone Land*. New Zealand Ministry of Business, Innovation and Employment, Building System Performance Branch.
[13] https://www.nzgd.org.nz/
[14] Light Detection And Ranging: LiDAR data is essentially a mass of spot height information captured over a wide area using an aircraft mounted sensor

[33] Seismic scenarios used in assessments were based on NZGS/MBIE Guidelines for earthquake geotechnical engineering practice,[15] for event likelihoods ranging from 25-year to 2500-year return periods. An update to these NZGS/MBIE guidelines was released in late November 2021, and analysis takes into account these updated PGA (peak ground acceleration) values.

[34] The New Zealand Seismic Hazard Model (NSHM) is currently being revised, with an update due to be released in August 2022. The revised NSHM ground motion values may differ, and may be of greater magnitude, than those used in seismic scenarios for this investigation.

[35] An Alpine Fault seismic scenario was also assessed. The Alpine Fault has an estimated recurrence interval of 250-340 years. However, due to the elapsed time since the last Alpine Fault rupture, the fault is estimated to have a conditional probability equivalent to a 30-year ARI event, or a 75% likelihood of rupture within the next 50 years. This is considered high.

[36] Liquefaction triggering and land damage modelling were completed for a lower bound, upper bound, and Alpine Fault Rupture Scenarios at 16^{th}, 50^{th}, and 84^{th} shaking percentiles, with PGA and M_w (moment magnitude) values for each scenario based on NZGS/MBIE guidance (2021).

[37] Probabilistic liquefaction land damage modelling was completed to estimate liquefaction severity numbers (LSNs),[16] giving a simulated, possible realization of liquefaction land damage across the study area.[17]

[38] Lateral spreading was estimated using empirical relationships based on the thickness of liquefiable material and free face height for arrange of seismic scenarios. A key factor in lateral spreading assessments is the height of the 'free face', which was estimated based on assessment of LiDAR topography, and lake bathymetry data provided by NIWA.

[39] Peer review of the technical report was carried out by Wentz-Pacific Limited, and peer review comments have been addressed and incorporated into the final Tonkin + Taylor report. Peer reviewer comments are attached as Appendix 2.

[15] NZGS & MBIE. (2021). *Earthquake geotechnical engineering practice, Module 1: Overview of the Guidelines*. Wellington: New Zealand Geotechnical Society and Ministry of Business, Innovation and Employment.

[16] The liquefaction severity number is a parameter summarising vulnerability of land to liquefaction-induced damage, developed by comparison of measured liquefaction damage attributes with ground parameters from geotechnical investigation.

[17] Note that this liquefaction damage modelling is for the effects of liquefaction only and does not include impacts of lateral spreading.

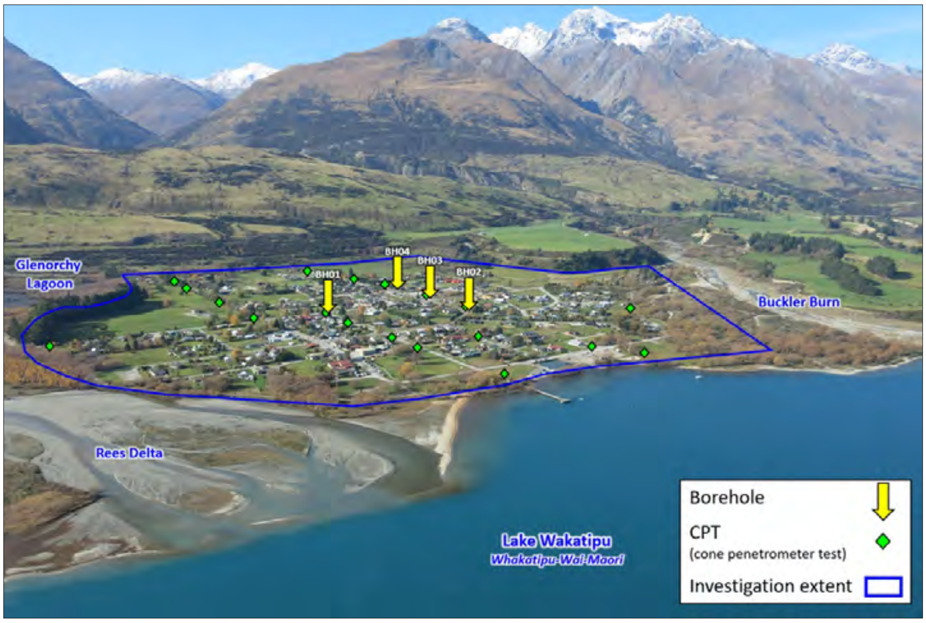

Figure 4: Overview of Glenorchy township showing geotechnical investigations completed for the liquefaction susceptibility study. This image also illustrates several of the factors influencing liquefaction susceptibility; the relatively recent sediment deposits formed by the Rees River and Buckler Burn, and low-relief terrain relative to the surface water bodies at the Glenorchy Lagoon, Lake Wakatipu, and the Buckler Burn stream.

KEY FINDINGS

[40] Geological investigations show the township area is underlain by a thick sequence of deltaic and alluvial sediments. The lower sedimentary units are interpreted as sub-lacustrine deltaic and fan delta sediments deposited when the post-glacial Lake Wakatipu was at a higher level (coloured yellow and orange in Figure 5).

[41] In the north-eastern part of the study area, the sedimentary sequence is interpreted to contain silts formed in a lower-energy backwater environment, such as an infilled lake arm or river oxbow channel (coloured pink in Figure 5).

[42] The deltaic and low-energy sediments are typically overlain by a surficial, 3-7m thickness, layer of coarser gravels interpreted as fluvial/alluvial fan sediments deposited during flood events from the Buckler Burn (coloured blue in Figure 5).

[43] All sediments underlying the surficial Buckler Burn gravels are highly susceptible to liquefaction, from their beginning at 3-7m below the ground but extending down to 20m depth and beyond.

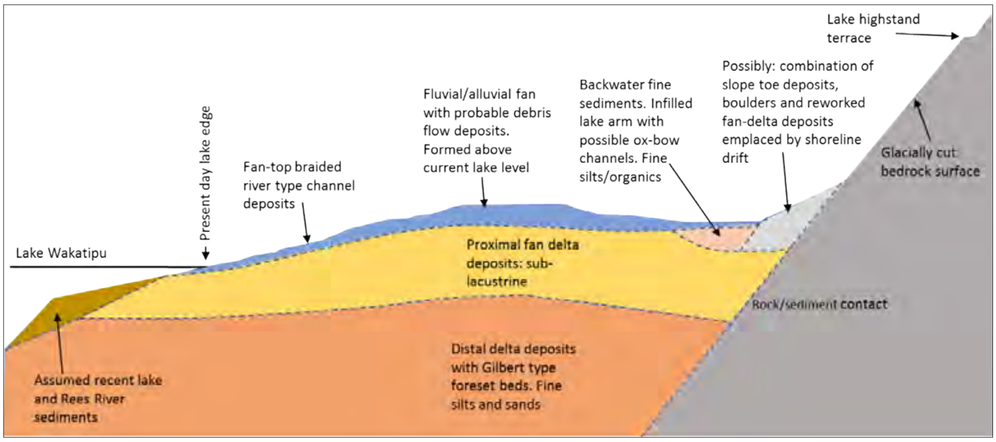

Figure 5: A conceptual geological cross section showing the main geological units interpreted in the Glenorchy township area. Note this is an informal section only for illustrative purposes and is not to scale.

[44] Assessments of liquefaction triggering show between 15 to 20m of the soil profile is predicted to liquefy at higher levels of earthquake shaking. Liquefaction triggering is initiated at 25 to 50-year return period levels of earthquake shaking and is fully developed at the 50 to 100-year return period levels of earthquake shaking. Liquefaction triggering is also likely for an Alpine Fault scenario.

[45] Liquefaction land damage modelling show that severe liquefaction land damage can occur at earthquake shaking levels as low as 25-year return periods. Between 25 and 100-year return period levels of shaking the liquefaction land damage becomes far more significant and widespread across all the lower lying areas of Glenorchy in the north and west.

[46] For the upper bound scenarios, and for 50th (median) and 84th percentile Alpine Fault rupture scenarios, there are widespread areas of the study area where the median Liquefaction Susceptibility Number (LSN) is 25 or greater, indicating ‘high to severe’ liquefaction damages are likely. For example, the 50th percentile Alpine Fault scenario shown as Figure 6.

[47] The T+T report shows examples from the 2011 Christchurch earthquake of the type of liquefaction land damage expected where the LSN is 25 or greater. These examples are Figures B10, B11 and B12 of Appendix B, with one of these shown as Figure 7.

[48] The maps of liquefaction land damages[18] are developed through an inherently probabilistic process and so these maps should not be used as a basis for site-specific assessment for any particular site. Instead, they show broad trends in liquefaction vulnerability across the Glenorchy study area.

[18] Tables 12.1 and 12.2 in the T+T report.

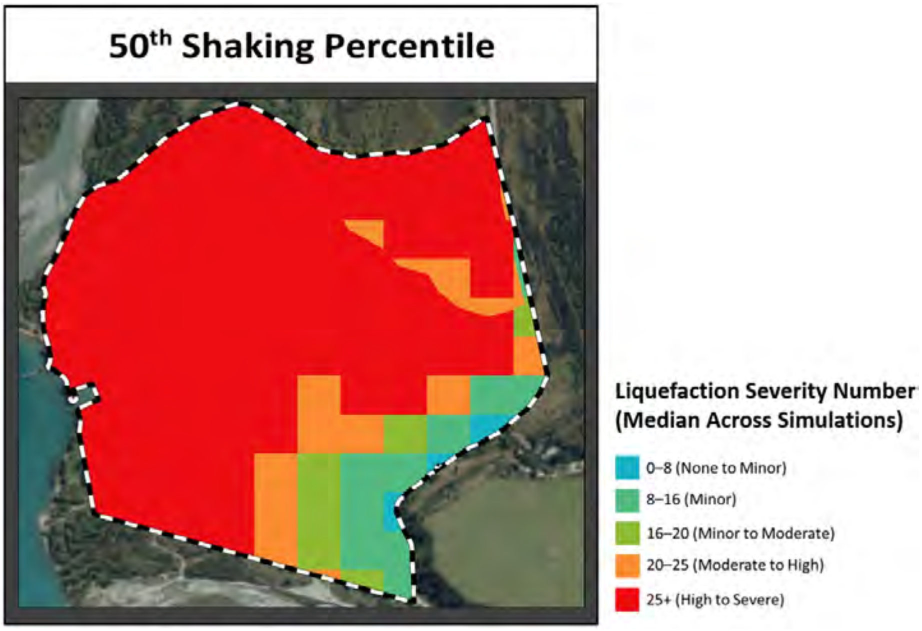

Figure 6: Median Liquefaction Susceptibility Number (LSN) from a large number of simulations, for the Alpine Fault rupture scenario, at 50th percentile shaking levels.

Figure 7: Example of liquefaction following the 2011 Christchurch earthquake, showing the type of liquefaction land damage expected where the LSN is 25 or greater.

[49] Lateral spreading assessments show the amount of lateral spreading is highest near the lake edge and decreases with an increasing distance from the lake. The magnitude of lateral spreading increases with earthquake shaking at larger return periods.

[50] At 500-year return period levels of earthquake shaking, the lateral spreading estimates range from 0.5m (lower bound) to 4m (upper bound) at the lake edge (Figure 8). For the

Alpine Fault Scenario, lateral spreading estimates range from 0 metres (16th percentile) to 3 metres (84th percentile) at the lake edge.

[51] The predicted lateral spreading near the lake in Glenorchy for the 500-year return period levels of shaking is comparable or worse to that observed in the worst parts of the residential red zone in Christchurch, which was typically in the order of 1m to 3m.

[52] The T+T report shows examples from the 2010 Darfield and 2011 Christchurch earthquakes of the type of lateral spreading damage expected where lateral spread is in the order of 1m to 3m. These are Figures B4 to B9 of Appendix B, with two of these examples shown as Figure 9.

[53] Lateral stretch is the differential spreading amount caused by lateral spreading. Assessments of lateral stretch show that for the 500-year and Alpine Fault scenarios a significant western portion of Glenorchy would experience severe or major levels of lateral stretch, defined as differential stretch of >500mm (severe), or >200mm (major), across a 25-metre length scale (Figure 11). Residential buildings cannot be expected to safely withstand these levels of lateral stretch without specific engineering design.

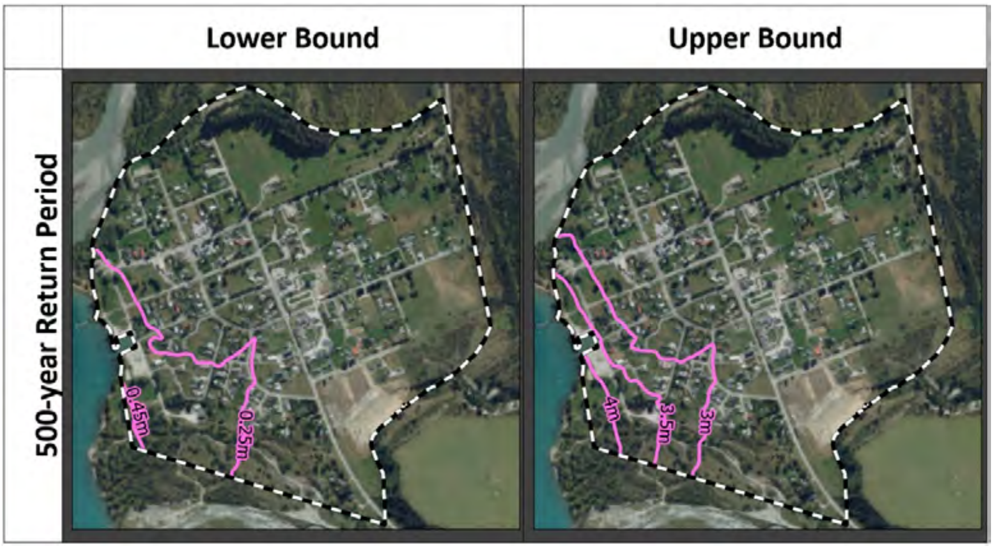

Figure 8: Lateral spreading for 500-year return period levels of earthquake shaking, showing the lower bound (left) and upper bound (right) cases. The ground would be expected to move towards the lake by the annotated distance (pink lines).

Figure 9: Example of lateral spreading damages following the 2010 Darfield and 2011 Christchurch earthquake, showing the type of damage to buildings or roads expected where lateral spreading is in the range of 1-3 metres.

[54] Liquefaction and lateral spreading effects can cause significant vertical subsidence due to volumetric consolidation, liquefaction ejecta, and lateral stretch. In the area of severe stretch, the vertical drop could be in the order of 0.5 to 1m, in addition to that caused by consolidation and ejecta effects. These levels of vertical settlement are likely to cause extensive damage to existing structures in the spreading zone.

[55] Figure 10 shows the liquefaction and lateral spreading vulnerability categorization developed for the Glenorchy township study area according to the criteria in the MfE/MBIE Guidance. This was developed based on the modelled liquefaction effects of vertical subsidence as well as lateral spread and stretch across the multiple earthquake scenarios assessed, especially the 100-year and 500-year scenarios.

[56] The boundaries between the hazard categories shown in Figure 11 are indicative of the spatial distribution of the liquefaction and lateral spreading vulnerability but are uncertain and not intended as a precise boundary between hazard categories. In reality, areas of damage might well occur on either side of the boundaries illustrated.

[57] The occurrence of liquefaction and lateral spreading in Glenorchy would also have secondary consequences through cascading impacts on other natural hazard risks. For example, widespread ground subsidence would increase the areas exposed to flooding hazards. Severe liquefaction would also be expected to cause damage to floodbank structures, reducing the levels of flood protection to those areas currently receiving flood protection by the Glenorchy floodbank.

[58] The T+T report shows an example from the 2016 Kaikoura earthquake where lateral spreading damage caused approximately 1 metre of vertical drop to land adjacent to a river channel, causing flooding and increased flood exposure. This example is Figure B3 of Appendix B.

[59] Strong ground shaking from an Alpine Fault rupture or other major earthquake may generate a tsunami on Lake Wakatipu, triggered either by a large landslide into the lake or a large-scale collapse of the delta sediments. Assessment of the potential lake tsunami hazard is one focus of a current PhD research project supported by ORC.[19] Paragraphs 119-121 and Figure 22 in this paper provide an update on recent research activities in this project.

[19] The research project title is *Post-glacial geomorphic evolution of Lake Wakatipu basin and landslide-generated tsunami hazards*. The research is being undertaken by NIWA, Massey University, and the University of Otago.

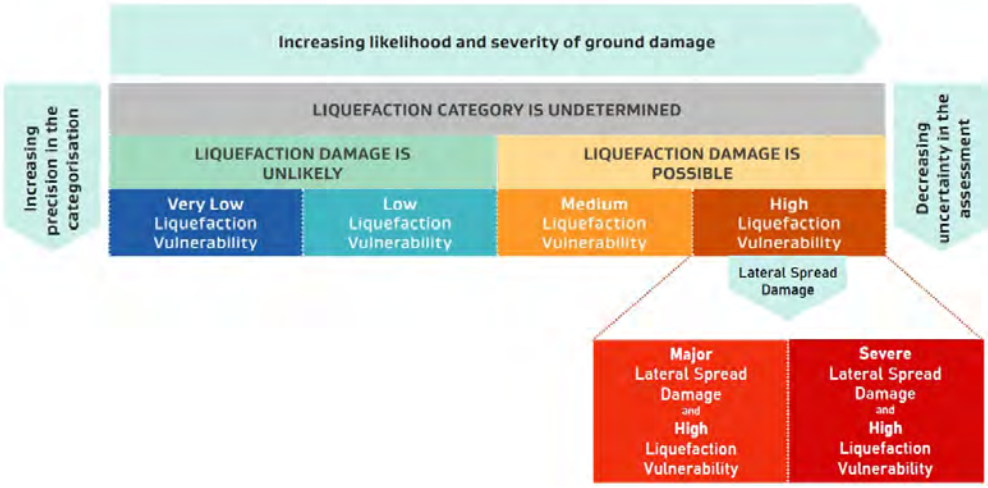

Figure 10: Liquefaction vulnerability categorization developed for the Glenorchy township study area. This follows the criteria in the MfE/MBIE Guidance (2017), with the addition of categories for those areas with high vulnerability to both liquefaction and lateral spreading damages.

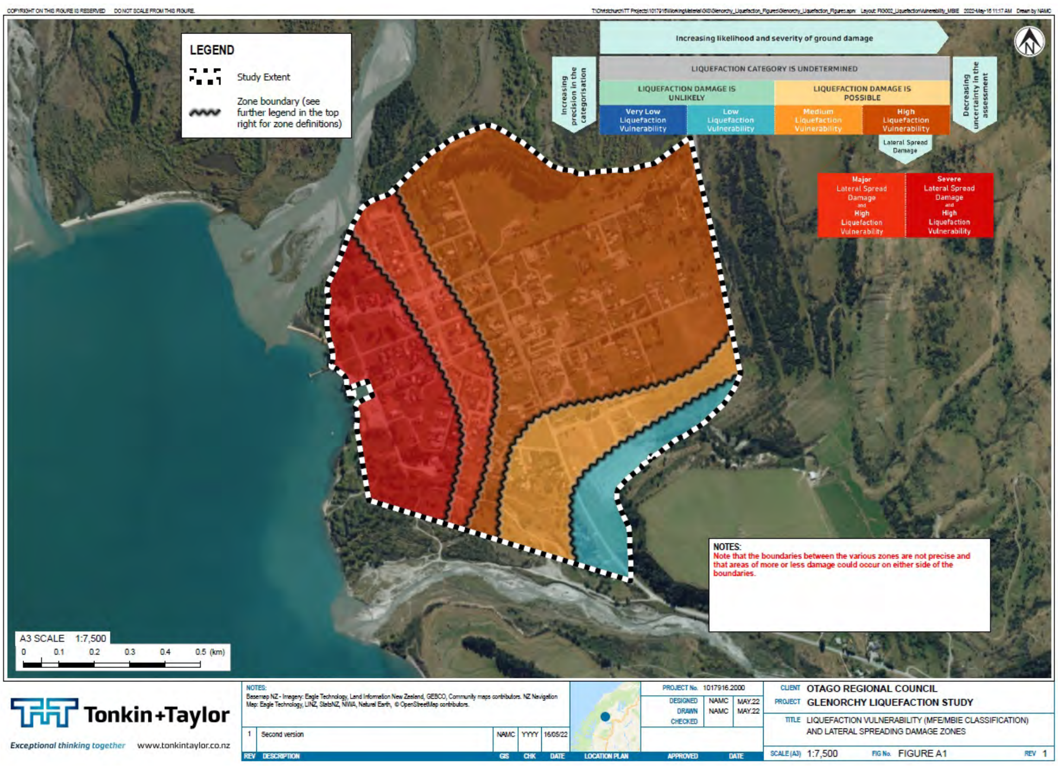

Figure 11: Liquefaction vulnerability categorization for Glenorchy township, based on the categorisation scheme shown in Figure 10.

FLOOD HAZARD ASSESSMENT

REPORT CONTENT AND STRUCTURE

[60] The report is titled *Dart-Rees flood hazard modelling* and is attached as Appendix 3. The main report sections are listed below.

- Section 1 introduces the study purpose and extent.
- Section 2 acknowledges uncertainties and limitations of the study.

- Sections 3 and 4 detail input data to the model such as topography, bathymetry and hydrology.
- Section 5 provides details of hydraulic model build and development.
- Section 6 describes model calibration and validation against the February 2020 flooding event.
- Section 7 summarises the model runs completed.
- Section 8 is an analysis of results and a commentary on findings.
- Appendices A-E provide supporting information to the study, such photographs from site visits, and detail of ORC's hydrology and climate change analysis.
- Appendices F-H contain maps of peak flood depths, peak flow velocities, and hazard classifications for all model runs.

METHODOLOGY

[61] Hydraulic modelling and flood hazard assessment was undertaken for the Dart-Rees floodplain and delta for the extent shown in Figure 12.

[62] Numerical hydraulic modelling for flood event scenarios was completed using MIKE21, an industry-standard 2D hydraulic modelling software.

[63] Model topography is based on a 2019 LiDAR dataset, with channel bathymetry interpolated based on surveyed cross-section data.

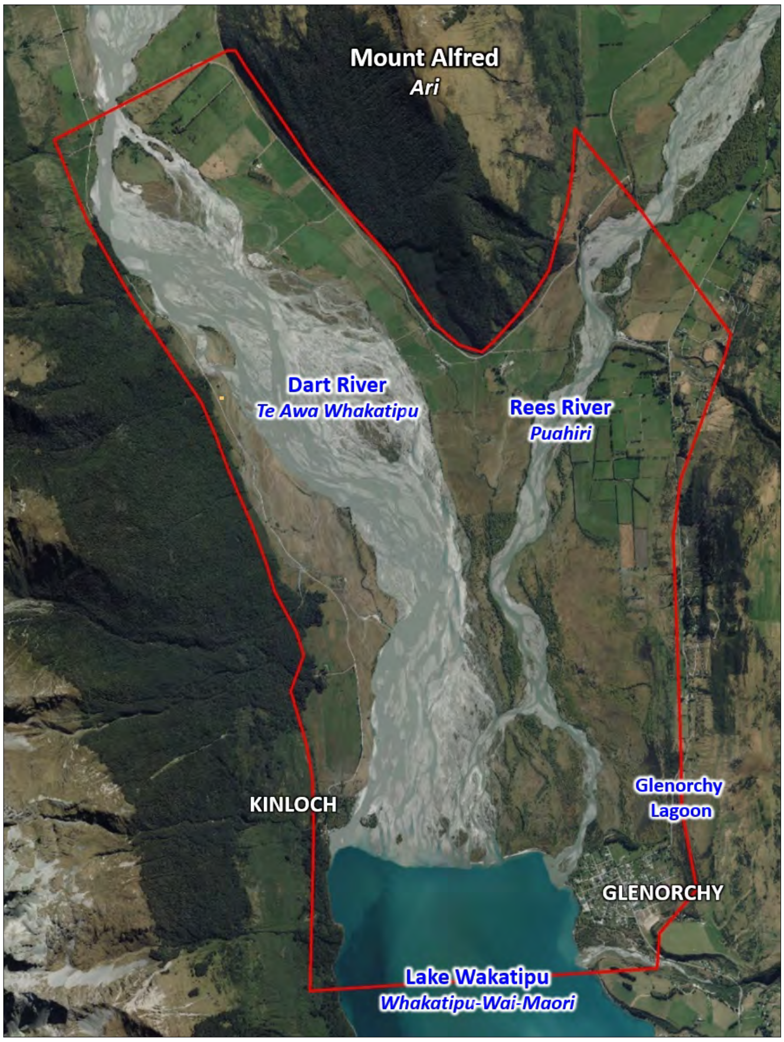

Figure 12: Overview of the lower Dart and Rees Rivers systems, showing the extent of hydraulic modelling and flood hazard assessment (red outline).

[64] Modelled flooding scenarios included combinations of large (up to 100-year ARI)[20] river flows and lake levels, and the effects of climate change on future river flows and flood events. Additional factors modelled include an avulsion of the lower Rees River channel, and a breach of the Rees-Glenorchy floodbank[21].

[65] Hydrology inputs such as design flow hydrographs and lake levels were based on analysis completed by ORC[22] and which is appended to the LRS report. For the Dart River and Lake Wakatipu analysis was based on the data record from ORC and NIWA monitoring stations, respectively. The Rees River has only a limited flow record, so flood flows were estimated by use of a rainfall-runoff model developed in HEC-HMS hydrological model.

[20] Annual Recurrence Interval. A 100-year ARI event has a 1% probability of occurrence in any specific year (Annual Exceedance Probability, AEP), and a 39% probability of occurrence within a 50-year time period.
[21] The floodbank is owned by QLDC.
[22] Mohssen M (2021). Analysis of flood hazards for Glenorchy. December 2021.

[66] Climate change effects on Dart and Rees River flows were estimated by ORC[23] for RCP6.0[24] and RCP8.5 scenarios.

[67] A breakout flood (avulsion) from the lower Rees River eastwards towards the Glenorchy lagoon area is considered an expected and inevitable future consequence of floodplain and braided river development.[25] [26] This scenario was modelled through simulation of an avulsion channel by modification of the riverbed and floodplain topography within the model. The modelled avulsion location was considered a probable site for a major avulsion based on modelled floodwater pathways, review of satellite imagery from past flood events, and anecdotal reports of floodwater spillover during the February 2020 flood event.

[68] Geotechnical assessments[27] of the Rees-Glenorchy floodbank structure have identified concerns regarding floodbank stability. Floodbank breach parameters were estimated based on additional geotechnical assessment completed to inform modelling of breach scenarios.[28]

[69] Model validation was undertaken through comparison of modelled floodwater extents with those observed in Glenorchy township during the February 2020 flood event.

[70] Flood hazard was classified as a function of floodwater depth and velocity, using the classification scheme of the Australian Rainfall and Runoff guidelines,[29] shown as Figure 13.

[71] Peer review was carried out by Tonkin + Taylor Limited, and peer review comments have been addressed and incorporated into the final Land River Sea Consulting Limited report. Peer reviewer comments are attached as Appendix 4.

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[23] Mohssen M (2021). Analysis of flood hazards for Glenorchy. December 2021.
[24] Future climate change projections are considered under a range of emission scenarios, called Representative Concentration Pathways (RCPs) by the Intergovernmental Panel on Climate Change (IPCC).
[25] Brasington J (2021). *Fluvial hazards at the top of the lake, living with rivers on the edge*. Public presentation in Glenorchy, 7th April 2021.
[26] This hazard threat has been identified in many previous reports, for example URS (2007) comment that "*there is a significant risk that the Rees River could change its course to flow directly into the lagoon area*."
[27] e.g. WSP (2020). *Glenorchy Rees floodbank: floodbank assessment*. Prepared for Otago Regional Council.
[28] Tonkin + Taylor (2021). *Rees-Glenorchy Floodbank structure failure modes assessment*. Prepared for Otago Regional Council.
[29] Ball et al (2019). *Australian Rainfall and Runoff - A Guide to Flood Estimation*.

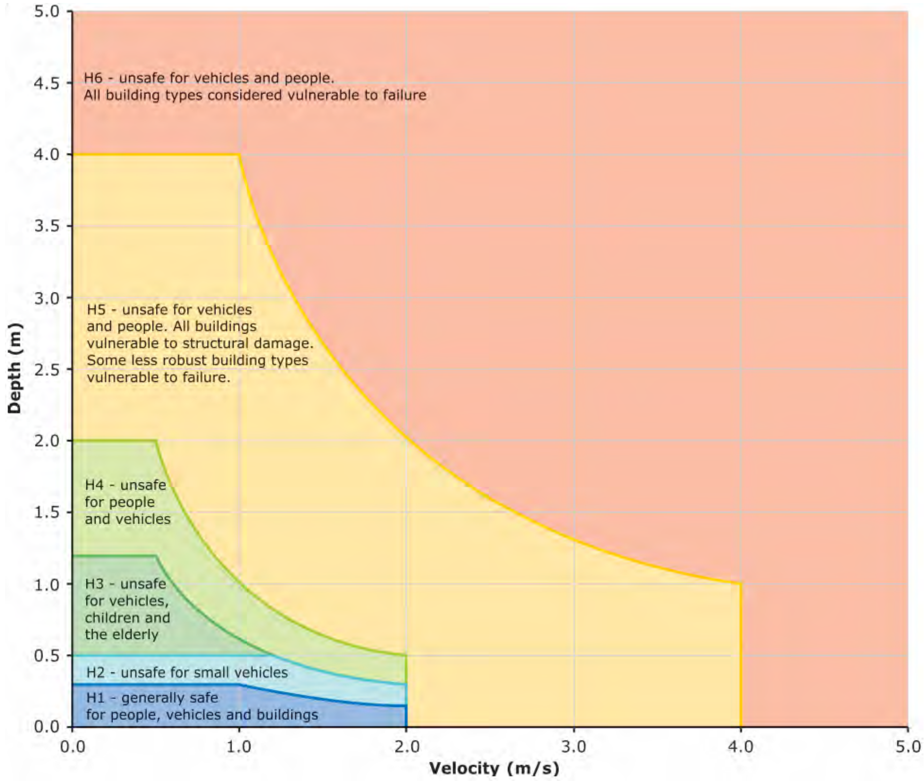

Figure 13: The flood hazard categorisation of the Australian Rainfall and Runoff Guidelines (Cox, 2016), based on a combination of floodwater depth and velocity.

KEY FINDINGS

[72] An overview of model results is shown in Figure 14. This shows modelled floodwater depths for a flooding scenario with 100-year ARI river flows, and a moderate lake level (10-year ARI).

[73] For Glenorchy township, model results showing flooding extents for a 100-year ARI flood event are shown in Figure 15.

[74] In this scenario, there is widespread overtopping by floodwaters over the Glenorchy floodbank, and floodwater inundation of a large northern portion of the township.

[75] In this scenario, the greatest floodwater depths within the township area are in the range 0.5-2 metres. The highest floodwater velocities are in the range 0.5-2 m/s, with a strong eastwards flow as floodwaters flow towards the lake.

[76] Effects of climate change on river flows, or an avulsion of the Rees River channel eastwards towards the Glenorchy lagoon, both exacerbate flooding however do not cause major increases in flooding severity due to the control of floodwater extents by the natural alluvial fan topography.

[77] Figure 16 shows model results for a flooding scenario including the effects of climate change on river flows, and an avulsion of the Rees River channel eastwards towards the Glenorchy Lagoon. Comparison with Figure 15 shows only minor increases in floodwater extents and depths due to these effects.

[78] Flood hazard classification (Figure 17) shows areas within the township where the hazard is categorised as H4 (‘*unsafe for vehicles and people*’) or H5 (‘*unsafe for vehicles and people, buildings vulnerable to structural damage, some less robust buildings vulnerable to failure*’).

[79] The Glenorchy floodbank is overtopped in all modelled flood scenarios, and it is estimated that this structure will not prevent flooding in the township for river flow events of a 20-year ARI or greater.

[80] A failure of the floodbank structure during modelled flood scenarios has no impact on overall flood extents, however the flood onset within the township is slightly sooner than would otherwise be the case.

[81] Flood hazard scenarios where Lake Wakatipu is at high levels (100-year ARI) show lake levels have an effect on flooding extents, particularly in locations nearer the lake, but also act to lower peak floodwater velocity near the lake (Figure 18).

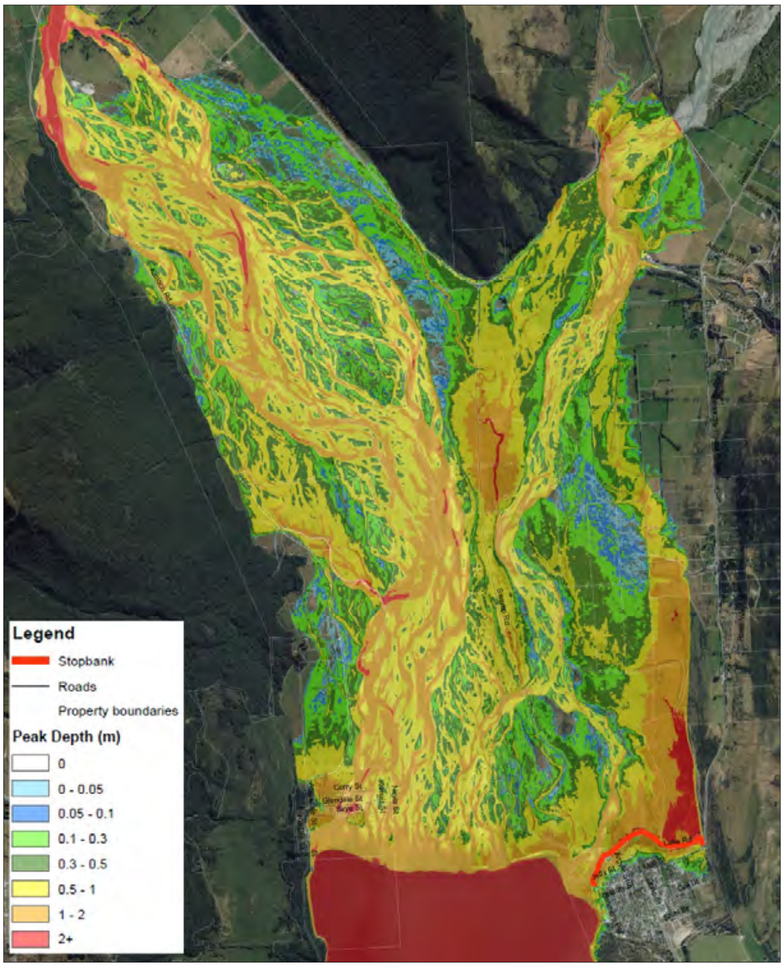

Figure 14: Model results for a Dart-Rees flooding scenario with 100-year ARI river flows, and Lake Wakatipu at 10-year ARI levels. Colouring shows peak floodwater depths according to the included legend. Figure 15 shows detail of the Glenorchy township area for this scenario.

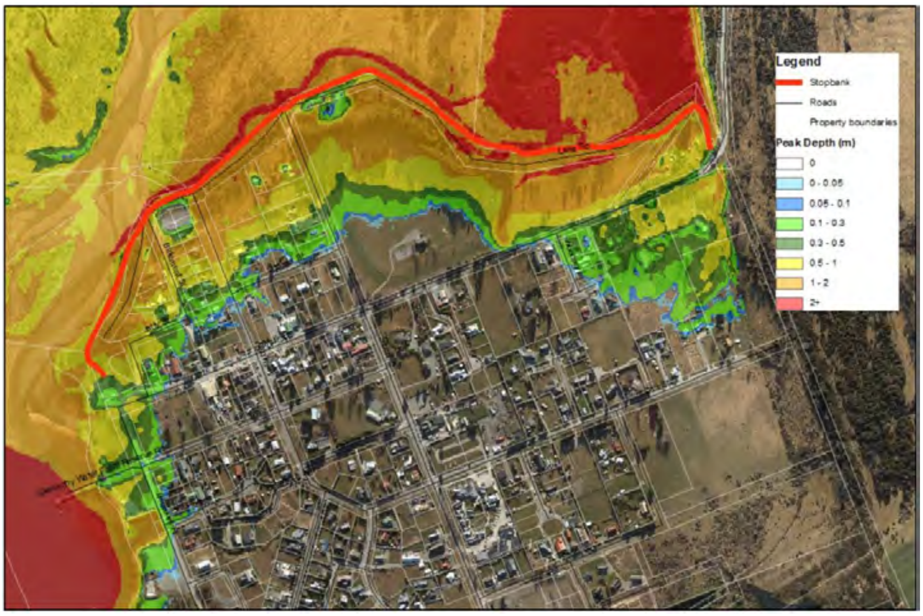

Figure 15: Model results for a Glenorchy flooding scenario with 100-year ARI river flows, and Lake Wakatipu at 10-year ARI levels. Colouring shows peak floodwater depths according to the included legend.

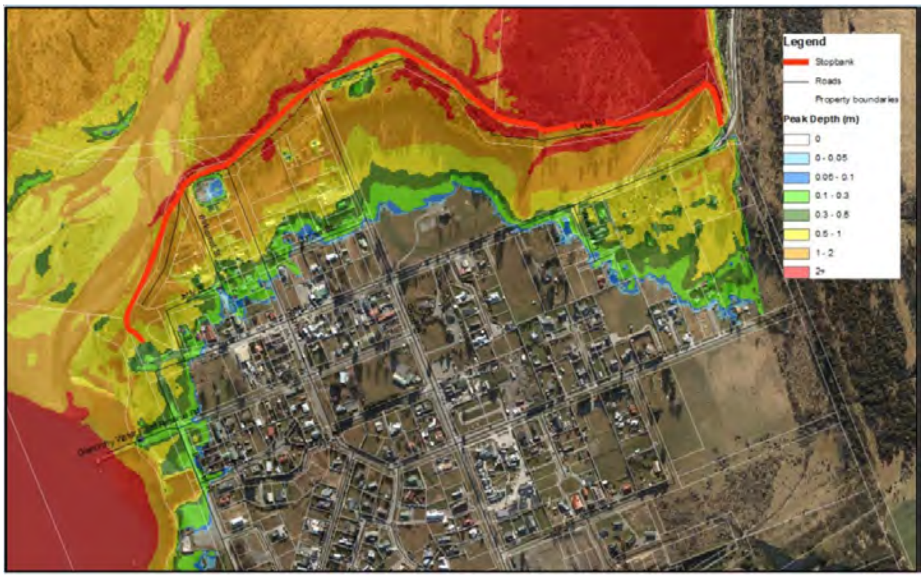

Figure 16: Model results for a Glenorchy flooding scenario with 100-year ARI river flows, and Lake Wakatipu at 10-year ARI levels. This scenario also includes the effects of climate change on river flows (RCP 8.5), and an avulsion of the Rees River channel eastwards towards the Glenorchy Lagoon. Colouring shows peak floodwater depths according to the included legend. The flood hazard categorisation for this scenario is shown as Figure 17.

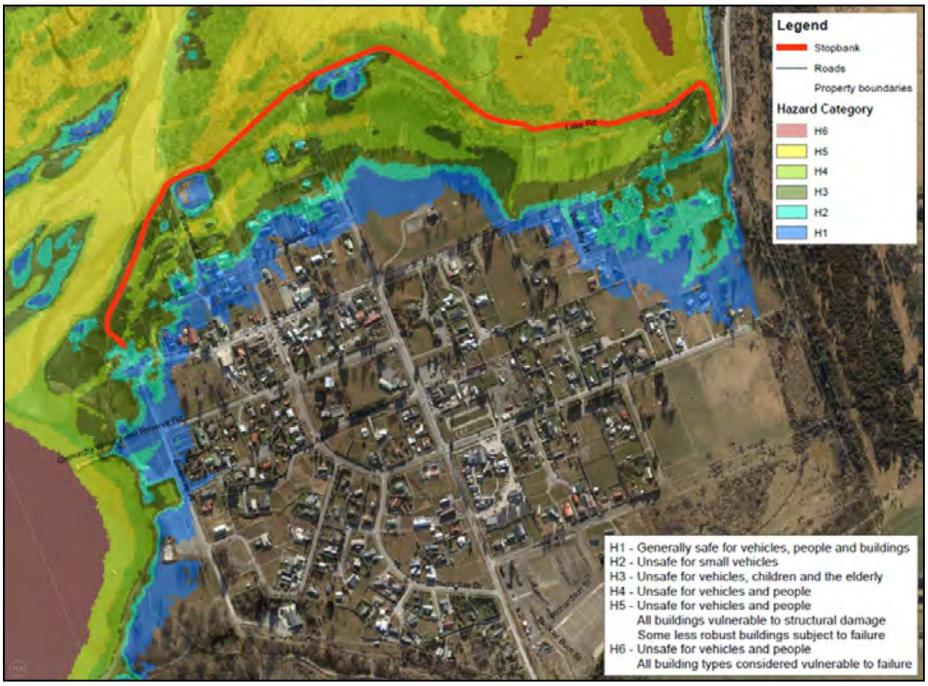

Figure 17: Flood hazard categorisation for a Glenorchy flooding scenario with 100-year ARI river flows, and Lake Wakatipu at 10-year ARI levels. This scenario also includes the effects of climate change on river flows (RCP 8.5), and an avulsion of the Rees River channel eastwards towards the Glenorchy Lagoon. Colouring shows hazard categorisation according to the included legend.

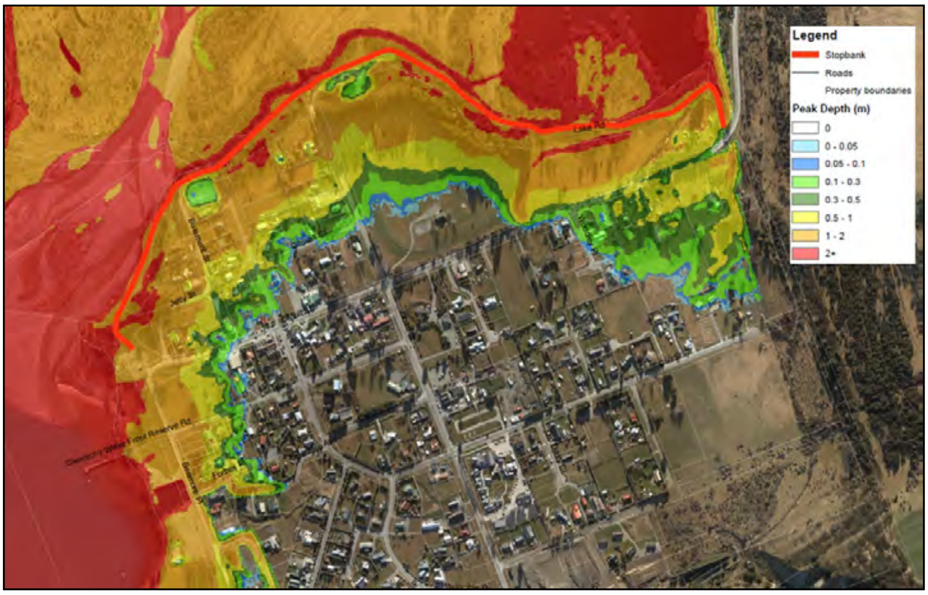

Figure 18: Model results for a Glenorchy flooding scenario with 100-year ARI river flows, and Lake Wakatipu at 100-year ARI levels. Colouring shows peak floodwater depths according to the included legend.

[82] Model results show large sections of the Kinloch Road, as well as parts of the Glenorchy-Routeburn road at the foot of Mount Alfred, would be inundated in a 100-year ARI flooding event (Figure 14).

[83] Along Kinloch Road, floodwater depths are up to within the 1-2 metre range (Figure 14), and velocities are up to the range 1-2 m/s.

[84] Model topography is based on that surveyed in 2019, but river bed levels will continue to rise through ongoing sediment deposition, raising flood stage relative to river banks and exacerbating flood hazards. This model will need to be revised with new topographic datasets in future to assess the influence of changing riverbed morphology and mean bed levels.

[85] As a fixed bed hydraulic model, the modelling does not account for any changes due to sediment movement or erosion during flood events.

[86] There is limited flow data at Rees River for hydrological analysis, so there is uncertainty in the flow estimates developed as model input. Flow data from the recently installed monitoring station near Invincible Creek (Figure 19) will help with improving future estimations of Rees River flows.

[87] There are a number of possible flood model refinements which could be made in the Glenorchy area, for example the addition of inflows from Bible Stream, and the inclusion of rainfall runoff from the hillslopes adjacent to the township. However, it would not be expected that these refinements would significantly alter the flood characteristics or hazard classification shown by the current modelling project.

UPDATE ON OTHER ACTIVITIES

Environmental Monitoring

[88] A Rees River flow recorder was installed by ORC in December 2021 near Invincible Creek. Following development of flow rating relationships, river flow data has been displayed online in near real-time from early-April 2022 at ORC's WaterInfo webpage.[30]

[89] This Rees River flow recorder will be a key site for use in continued assessments of flood hazard at the Rees floodplain and Glenorchy, allowing measurement of peak flows for future flooding events.

[90] In January 2021, ORC installed a water level recorder in Lake Wakatipu at the Glenorchy marina. Comparison of monitored water levels at Glenorchy with those measured at NIWA's monitoring station within Frankton Arm showed an apparent level offset of ~0.15m. ORC has re-surveyed benchmark points at both sites to determine the cause of this observed difference in water levels. Analysis of this data is currently underway.

[91] The Glenorchy Lagoon water level recorder has now been operating since October 2020. Alarms and actions linked to lagoon water levels have been put in place for the ORC flood response team in coordination with Emergency Management Otago.

[92] As a key monitoring site for flood hazard information at Glenorchy, ORC is investigating options to build resilience at this monitoring station to ensure effective operation during all flood events.

[30] www.orc.govt.nz/managing-our-environment/water/water-monitoring-and-alerts

[93] These three recently installed environmental monitoring stations were suggested by community members as actions to improve awareness of flood hazard following the February 2020 flooding event.

[94] Following these additions to ORC's previously established monitoring stations at the Hillocks (since 1996) and at Paradise (since 2003), the current environmental monitoring network provides greatly improved monitoring coverage and understanding of hydrological responses to major weather events. ORC's current environmental monitoring stations in the head of Lake Wakatipu area are shown in Figure 19.

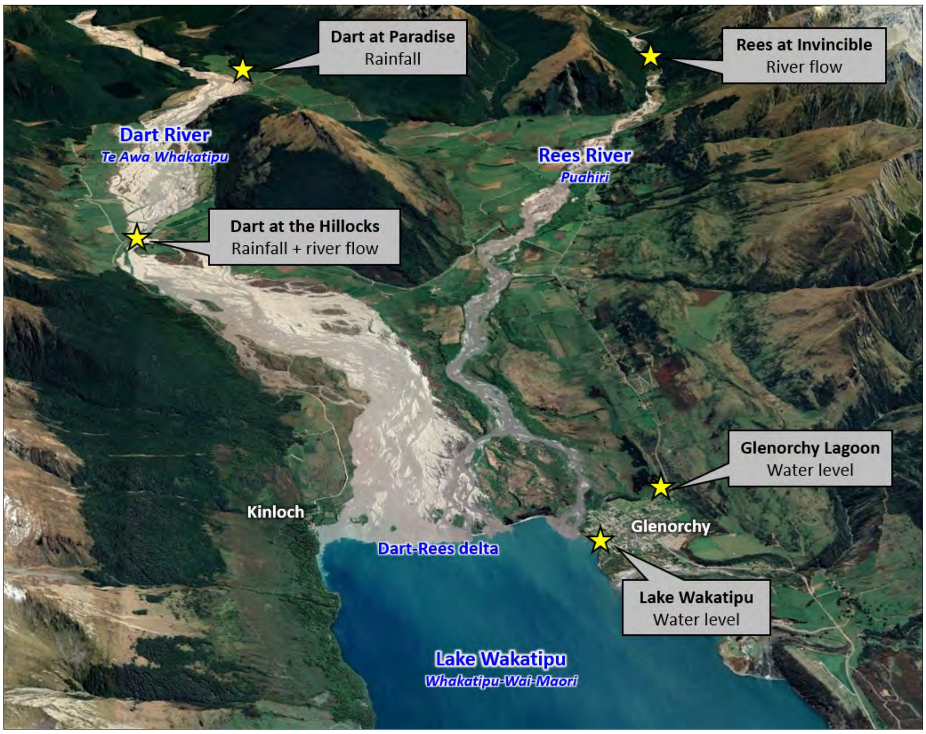

Figure 19: ORC environmental monitoring stations in the head of Lake Wakatipu area.

Buckler Burn alluvial fan hazards

[95] Glenorchy township is developed on an alluvial fan landform formed by sediments deposited by the Buckler Burn, so is exposed to the potential hazard of flooding or debris inundation from this catchment.

[96] The boreholes recently completed for the Glenorchy liquefaction study provide an opportunity to also view and assess sedimentary characteristics of the surficial deposits and interpret their depositional environment and processes (borehole locations are shown in Figure 4).

[97] A review of these borehole sediments has been undertaken by Professor Ian Fuller and Dr Sam McColl of Massey University, complemented by a site visit and assessment of LiDAR topography and aerial imagery.[31]

[31] Fuller I and McColl S (2021). *Key notes and observations from preliminary assessment of debris flood and flow hazard potential at Glenorchy, Otago*. Prepared for Otago Regional Council.

[98] The coarser gravel units seen in the upper parts of these boreholes have been deposited in a high-energy fluvial or lake-margin environment, with some evidence for deposition as debris-flood deposits.

[99] Assessments have confirmed flooding or debris-flooding is a potential hazard for Glenorchy township. There is geomorphic evidence for a former Buckler Burn flow channel northwards into the township area, indicating a potential breakout pathway which may be exploited by floodwaters in high-flow events.

[100] Flooding could be triggered by either a high-intensity rainfall event, or a catastrophic breach of a landslide dam formed in the Buckler Burn catchment. Aggradation of the Buckler Burn channel prior to, or during, a high flow event would exacerbate the flood hazard through reducing channel capacity.

[101] Additional assessments are planned to further investigate geomorphic changes at the Buckler Burn alluvial fan, and to improve understanding of the flood hazard. Findings will also be used to assess effectiveness of current river management approaches at the Buckler Burn, and to inform development of a river management plan.

[102] Debris flow hazards from the Buckler Burn have been assessed through numerical modelling by Geosolve Ltd.[32] Modelling was completed for a series of hypothetical large-magnitude debris flow scenarios originating in the Buckler Burn catchment.

[103] This modelling was not a comprehensive investigation of the Buckler Burn debris flow hazard for Glenorchy township, rather a test of sensitivity to factors such as failure locations, debris volumes and release mechanisms.

[104] Assessments show debris flow impacts to the Glenorchy township area to be possible but unlikely.[33] The occurrence of a major debris flow into the township requires both abundant debris (e.g. as would be caused by widespread coseismic landsliding) and a large stream flow (e.g. 100-year ARI flooding event or greater). The estimated joint probability of these events occurring is greater than a 100-year ARI event, and possibly closer to a 500-year ARI event.

Dart-Rees floodplain hazard mitigation approaches

[105] An investigation is in progress to evaluate the viability of river management or engineered approaches for mitigation of Dart-Rees floodplain hazards such as flooding and erosion. This study is being undertaken by Damwatch Engineering Ltd.

[106] The key questions this investigate will assess are:

- What river management approaches are viable and sustainable in the natural landscape around the Dart-Rees floodplain, and what are their potential outcomes?
- What does sustainable flood protection look like in the Glenorchy area, and what level of protection is realistically achievable?

[32] Faulkner P (2021). *Factual report – Debris flow modelling results. Buckler Burn, Glenorchy*. Report prepared by Geosolve Ltd for Otago Regional Council.

[33] Faulkner P and Rogers N (2021). *Joint witness statement on debris flow hazard*, prepared for Environment Court ENV-2021-CHC-70.

[107] These questions will help identify a short-list of approaches for more detailed consideration.

[108] The three main floodplain hazard concerns are being considered are:

1) Glenorchy township flooding from the Rees River (e.g., Figure 2b).
2) Dart floodplain flooding and erosion hazards, causing disruption to Kinloch access (e.g., Figure 3).
3) Rees floodplain flooding and riverbed aggradation in the area of the Rees bridge.

[109] This study is focused only on the evaluation of potential river management (e.g., channel modifications) or engineered (e.g., floodbanking or other structures) approaches, but is not considering other types of interventions such as building-scale mitigations (e.g., raising of floor levels), planning restrictions (e.g., zoning changes) or managed retreat. These latter approaches need to be considered in conjunction with approaches to managing the liquefaction and lateral spreading risks.

[110] The study will consider all river management or engineered adaptation approaches suggested by community members during previous engagement sessions.

[111] The first stage in this study was a collaborative workshop discussion held in February 2022. Workshop attendees were from ORC and QLDC, with specific expertise provided by Dr Grant Webby[34] (river engineering), Matthew Gardner[35] (flood hazard assessment), and Professor James Brasington[36] (river science and geomorphic change).

[112] Following completion of this investigation, a next step may be to utilise the recently completed hydraulic model to further assess details of some of these potential interventions identified. This will also inform the natural hazard adaptation strategy for the Head of Lake Wakatipu.

Shepherd's Hut Creek debris flow

[113] On the 21st April 2022, the Glenorchy-Queenstown Road was blocked by debris from Shepherds Hut Creek, requiring extensive work to re-open the road access (Figure 20).

[114] This debris flow was likely triggered by intense rainfall from thunderstorm activity. Debris flowed onto the Shepherds Creek alluvial fan which overwhelmed the road culvert and then caused debris to spill over and block the road. Within the creek channel, debris contained boulders up to ~2m in size (Figure 21).

[115] The event impacts were road closure and disruption to road traffic; however, this debris flow could potentially have had more significant consequences if it had struck any vehicles.

[116] WSP[37] and an ORC Engineering team member completed initial inspections of the site to review event impacts and assess any immediate hazards.

[34] Damwatch Engineering Ltd.
[35] Land River Sea Consulting Ltd.
[36] Waterways Centre for Freshwater Management, University of Canterbury.
[37] A preliminary assessment completed by WSP for Downer Ltd.

[117] ORC consultants will document the debris flow processes, characteristics and triggers, and the resulting hazard from debris flows at this location. Findings will be provided to Queenstown Lakes District Council.

[118] This event illustrates the vulnerability of Queenstown-Glenorchy road access to disruption by debris flows, landslides or rockfall.

Figure 20: Aerial view of debris flow impacts at the Queenstown-Glenorchy road, annotated to show the approximate extent of debris deposition (photo provided by Maddi Phillips, WSP Ltd).

Figure 21: A lower section of Shepherd's Hut Creek following the 21 April 2022 event, showing freshly deposited debris including large boulders (photo by Scott Liddell, ORC).

Research support

[119] A PhD research project by Steph Coursey (Massey University) is in progress, titled *Post-glacial geomorphic evolution of Lake Wakatipu basin and landslide-generated tsunami hazards*. ORC is providing support for operational field costs for this research project.

[120] The first field surveys for this project have been successfully carried out. Seismic reflection data and short cores of the lake floor were obtained in November 2021, followed by bathymetric mapping of the lake floor using a multibeam echosounder in January 2022 (Figure 22). The 2022 bathymetric data are now being compared with the bathymetric data collected by NIWA in 2019, and preliminary analysis has revealed some exciting changes on the lake floor.

[121] The project, which will continue over the next two years, is already yielding some promising results which will greatly improve the understanding of the lake-floor stability and associated tsunami hazards.

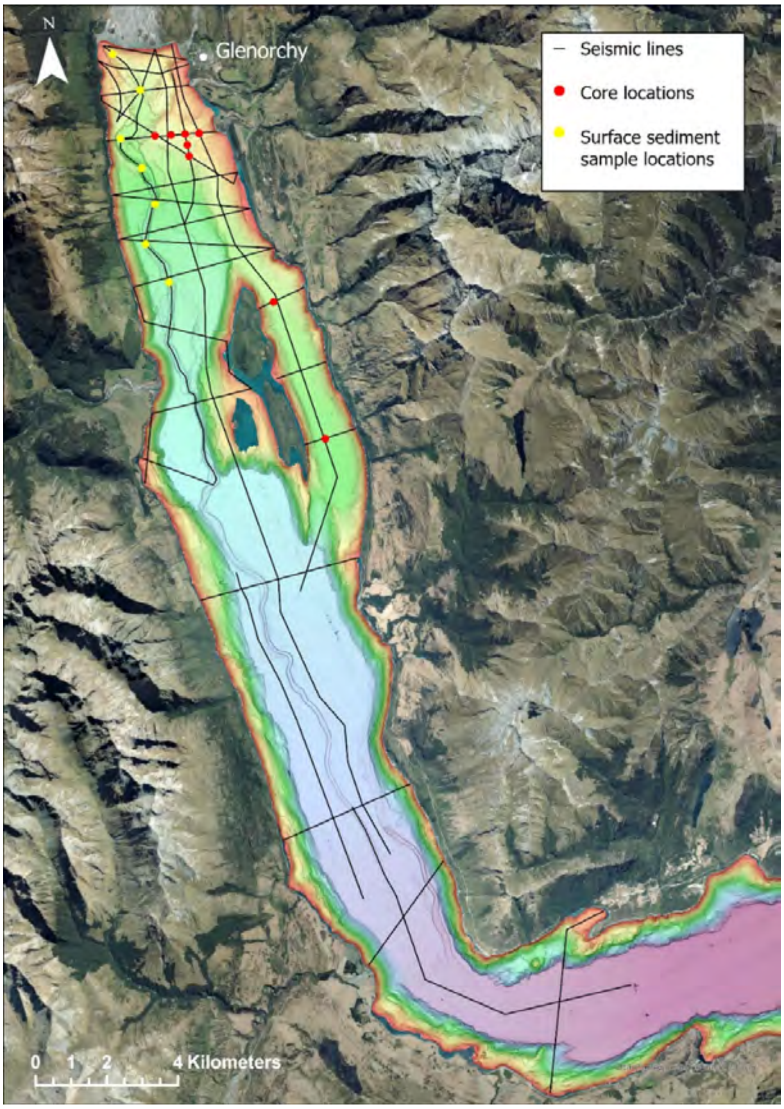

Figure 22: Lake-floor geomorphology of Lake Wakatipu, from 2019 NIWA bathymetry, and distribution of seismic, core, and surface sediment sample data obtained in 2021/2022 (Figure provided by Steph Coursey, Massey University).

[122] A Ministry of Business, Innovation & Employment (MBIE) Smart Ideas project that aims to examine the utility of novel airborne bathymetric LiDAR to support improved river management is underway. The project is led by Professor James Brasington (University of Canterbury) and is working with key stakeholders including the ORC to trial methods to understand the effects of environmental variables that effect LiDAR retrievals through the water (clarity, bed reflectance, water roughness) and optimize acquisition and processing strategies to maximize depth penetration. If successful, the airborne bathymetric LiDAR will be a cost-effective way to capture riverbed topography for long river sections.

[123] The ORC is providing support to help design a software tool that can be used by councils and other key stakeholders to help identify freshwater systems that are suitable for bathymetric LiDAR characterization.

[124] An early trial of the new sensor being tested was undertaken in the Rees River in August 2021 and revealed effective bed penetration throughout the river below Invincible Gorge, and capture of the delta foresets in Lake Wakatipu down to depths that exceeded 15m. The team will return to Otago for further surveys on the Rees and Dart Rivers later in the winter of 2022.

DISCUSSION

[125] The flooding and liquefaction hazard investigations presented in this paper are two important components of the knowledge base required for a thorough understanding of the multi-hazard risks in the head of Lake Wakatipu area and Glenorchy township.

[126] These new investigations contribute to a significant advance in natural hazards understanding, being the most detailed hydraulic modelling study at the Dart-Rees rivers, and the first liquefaction hazard assessment for Glenorchy based on comprehensive subsurface geotechnical data and analysis.

[127] Natural hazard investigations have confirmed a major earthquake or flooding event would have severe impacts, and help understand in more detail the hazard characteristics, spatial extents and likelihoods.

[128] The flooding and liquefaction hazard risks considered individually each pose a concerning hazard threat. However, there is also considerable overlap in the likely spatial extents of these hazard impacts, and potential for cascading hazard interactions between these hazards. The cumulative multi-hazard risks will therefore be higher than the individual hazard risk.

[129] The flooding risks are also not static through time but are modified in response to geomorphic and climatic factors. Aggradation of the Dart and Rees riverbeds is an important influence on changing flood hazard, as river channel capacity is gradually reduced as a consequence.

[130] Climate change is a key consideration in the assessment of future flood hazard, incorporated in hydraulic modelling through estimation and inclusion of climate change effects on river flows. Under the highest greenhouse gases emission scenario (RCP8.5) the magnitudes of 100-year ARI flood events in the Dart and Rees Rivers are projected to increase by ~20%.[38]

[131] Climate change effects on Lake Wakatipu flood levels have not yet been assessed. It is expected that projected increases in mean rainfall and river flows,[39] and the magnitude and frequency of flood events, will cause increases in mean lake levels, and therefore an increased likelihood of the lake reaching higher levels.

[132] The acceptability of these natural hazard risks to the head of Lake Wakatipu community will depend on the community's risk perception and risk tolerance. However, it is important to note that 'the community' as a whole may not have a single, collective view on whether these natural hazards risks are acceptable or tolerable. Risk perception is not static and will depend on individual factors including exposure to potential hazard

[38] Mohssen M (2021). Analysis of flood hazards for Glenorchy. December 2021.
[39] NIWA (2019). *Climate change projections for the Otago Region*. Prepared for Otago Regional Council.

events, vulnerability and ability to cope with disruption, and understanding of the hazards and their potential consequences.[40]

[133] Community and stakeholder input and collaboration is central to the Adaptation Pathways approach adopted by ORC and developed by the Ministry for the Environment (MfE),[41] shown as 10-step decision cycle in Figure 23. Any decision-making for management of these hazards should involve community input and collaboration. ORC will make all investigation findings available to the head of Lake Wakatipu community, including providing of opportunities for consultant experts to directly discuss findings with community members.

[134] The new hazards studies completed are within Step 4 (assessments of vulnerability and risk) of the Adaptation Pathways decision cycle. In-progress and future project work to identify and evaluate hazard mitigation approaches and 'pathways' of adaptation actions form Steps 5 and 6.

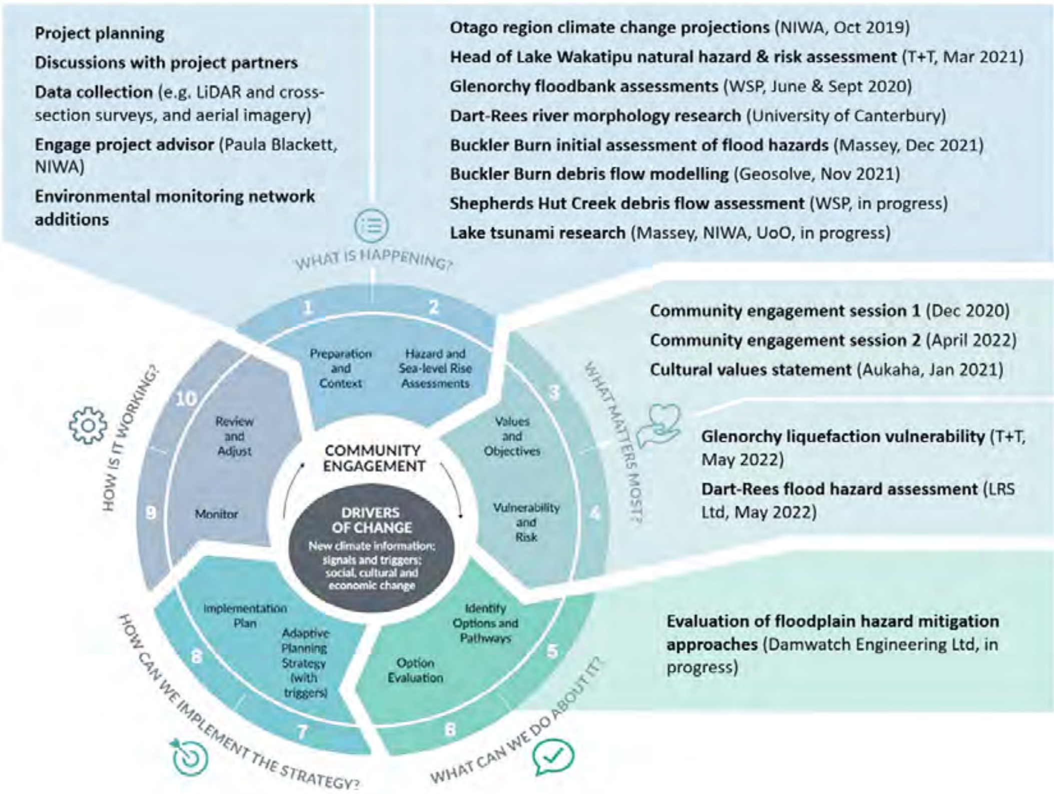

Figure 23: Overview of the 10-step decision cycle of the MfE Adaptation Pathways approach, showing the main activities which have been completed for this natural hazards adaptation project to date.

[135] ORC is considering the new natural hazards information. No assessment of potential approaches to the management of the liquefaction or flooding hazard risks have yet been made. These will be developed collaboratively in discussion with the community,

[40] Henrich et al, 2019. *Perceptions of risk characteristics of earthquakes compared to other hazards and their impact on risk tolerance*. Disasters 42 (1).
[41] Ministry for the Environment (2017), *Coastal Hazards and Climate Change: Guidance for local government*.

Queenstown Lakes District Council and other project partners. Decisions will be informed by finding of in-progress and future studies, for example the work in progress by Damwatch Engineering Ltd to assess possible approaches for mitigation of floodplain hazards.

[136] Continued ORC collaboration with QLDC will be essential to ongoing progress in development and implementation of an adaptation strategy. In March 2022, ORC and QLDC established a Natural Hazards Steering Group, to formalise the working relationship between the councils on this Head of Lake Wakatipu project, and other natural hazard projects such as the QLDC-led Brewery Creek/Reavers Lane debris flow hazards project. The steering group has the purpose of ensuring ORC and QLDC are taking a coordinated and collaborative approach to the management of natural hazards in the Queenstown Lakes District.

CONSIDERATIONS

Strategic Framework and Policy Considerations

[137] The information presented and the adaptation approach discussed in this paper reflects Council's Strategic Directions where our vision states: communities that are resilient in the face of natural hazards, climate change and other risks.

Financial Considerations

[138] The project is included in the ORC 2021-31 Long Term Plan with funding of $120,000 (excluding staff time) in the 2021/22 financial year and $70,000 (excluding staff time) for the two following years.

Significance and Engagement Considerations

[139] This paper does not trigger ORC's policy on Significance and Engagement.

Legislative and Risk Considerations

[140] The information in this paper helps ORC, and the head of Lake Wakatipu community and stakeholders, to understand and manage the risks associated with flooding and liquefaction hazards.

[141] The work described in this paper helps ORC fulfil its responsibilities under sections 30 and 35 of the RMA.

[142] The likely reforms of the Resource Management Act and strengthening of provisions to do with local authority leadership for climate change adaptation are noted.

Climate Change Considerations

[143] Climate change considerations are discussed above.

Communications Considerations

[144] ORC will make all investigation findings available to the head of Lake Wakatipu community. This will include providing opportunities for the consultant experts who undertook the investigations to directly discuss findings with community members.

[145] ORC has continued to provide a monthly update newsletter to the head of Lake Wakatipu community. This newsletter was established in August 2020 and gives

progress updates and an indication of upcoming project work. A link to sign up to this emailed newsletter and all previous newsletters are archived on the project webpage.[42]

[146] These reports and spatial hazards information will be made publicly available through ORC's Natural Hazards Database[43] and on the project webpage.

[147] This information will be provided to Queenstown Lakes District Council for incorporation into building control, utility infrastructure and land use planning decisions.

[148] A copy of our communications plan is attached as Appendix 5.

NEXT STEPS

[149] ORC will discuss, in partnership with the head of Lake Wakatipu communities, and other partners such as QLDC, the implications of these new natural hazards assessments, and decide on the next steps required.

[150] Next steps may include review of possible mitigation or management approaches for liquefaction and lateral spreading hazards. This would complement a study already in progress which is assessing possible approaches for mitigation of floodplain hazards.

[151] This new information will also be used to inform community response plans and emergency responses.

ATTACHMENTS

1. Tonkin+Taylor Ltd 2022 Glenorchy liquefaction vulnerability assessment [**5.1.1** - 61 pages]
2. Wentz-Pacific Ltd 2022 Peer review of the T+T Glenorchy liquefaction assessment [**5.1.2** - 2 pages]
3. Land River Sea Consulting Ltd Flood Hazard Report [**5.1.3** - 130 pages]
4. T+T Peer Review of LRS Ltd Flood Hazard Report [**5.1.4** - 4 pages]
5. Summary Comms Plan [**5.1.5** - 2 pages]

[42] https://www.orc.govt.nz/managing-our-environment/natural-hazards/head-of-lake-wakatipu
[43] http://hazards.orc.govt.nz

REPORT

Tonkin+Taylor

Glenorchy Liquefaction Vulnerability Assessment

Prepared for
Otago Regional Council
Prepared by
Tonkin & Taylor Ltd
Date
May 2022
Job Number
1017916

Exceptional thinking together
www.tonkintaylor.co.nz

Document Control

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26/05/2022	1	Report for Issue to ORC	NAMC	SVB	SVB

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Appendix A : Map of liquefaction and lateral spreading damage potential zones
Appendix B : Maps and photos showing examples of the liquefaction and lateral spreading that was observed following the 2010-2011 Christchurch earthquakes and 2016 Kaikoura earthquakes

LIQUEFACTION ASSESSMENT SUMMARY	
This liquefaction assessment has been undertaken in general accordance with the guidance document 'Assessment of Liquefaction-induced Ground Damage to Inform Planning Processes' published by the Ministry of Business, Innovation and Employment and the Ministry for the Environment in 2017 (MBIE & MfE, 2017). https://www.building.govt.nz/building-code-compliance/b-stability/b1-structure/planning-engineering-liquefaction-land/	
Client	Otago Regional Council (ORC)
Assessment undertaken by	Tonkin & Taylor Ltd, PO Box 13-055, Christchurch 8141
Extent of the study area	The Glenorchy Township, as shown in Figure 2.1 in Section 2.
Intended RMA planning and consenting purposes	To provide ORC with a liquefaction vulnerability assessment to help inform spatial planning and assessment of land use, subdivision and building consents in Glenorchy.
Other intended purposes	To provide ORC with an understanding of expected land performance for a range of potential future earthquake scenarios.
Level of detail	Level C (detailed area-wide assessment).
Notes regarding base information	The assessment leverages previous work conducted over the study area which includes: • Geotechnical investigation data available on the NZ Geotechnical Database (MBIE, 2022), • A LiDAR DEM provided by ORC, along with Bathymetry data from NIWA via ORC, and • Groundwater level monitoring undertaken by e3 Scientific (e3 Scientific Ltd., 2018)
Other notes	This assessment is intended to approximately describe the typical range of liquefaction vulnerability across Glenorchy. It is not intended to serve as a site-specific assessment, nor to precisely describe liquefaction vulnerability at an individual-property scale. This information is general in nature, and more detailed site-specific liquefaction assessment may be required for some purposes (e.g., for design of building foundations).

1 Scope of Work

Otago Regional Council (ORC) have engaged Tonkin + Taylor (T+T) to carry out an assessment of liquefaction hazard in Glenorchy township. ORC's objectives are to quantify the liquefaction and lateral spreading hazard for a range of seismic scenarios to assist ORC in making risk management and adaptation decisions.

The assessment undertaken in this study has been in accordance with the Ministry of Business, Innovation and Employment (MBIE) & Ministry for the Environment (MfE) guidance document: *Planning and engineering guidance for potentially liquefaction prone land*, (MBIE & MfE, 2017), henceforth referred to as "the MBIE/MfE Guidance". Following this document, the present study entails a risk-based assessment of liquefaction vulnerability across the township.

The spatial extent of the study includes the township area bounded by the Glenorchy lagoon, the Lake Wakatipu foreshore, the Buckler Burn, and the base of Bible Terrace (shown in Figure 2.1, below).

This study is solely an assessment of the liquefaction hazard at Glenorchy. There are various other natural hazards and geotechnical constraints which would also need to be considered as part of any future land development or building activities. It is emphasized that discussion in this report, especially references to "vulnerability categories" relates only to liquefaction hazard and not any other natural hazards.

2 Site Description

Glenorchy township is located at the head of Lake Wakatipu, approximately 30 km northwest of Queenstown and 40 km southeast of Milford Sound. The site location is shown in Figure 2.1 below.

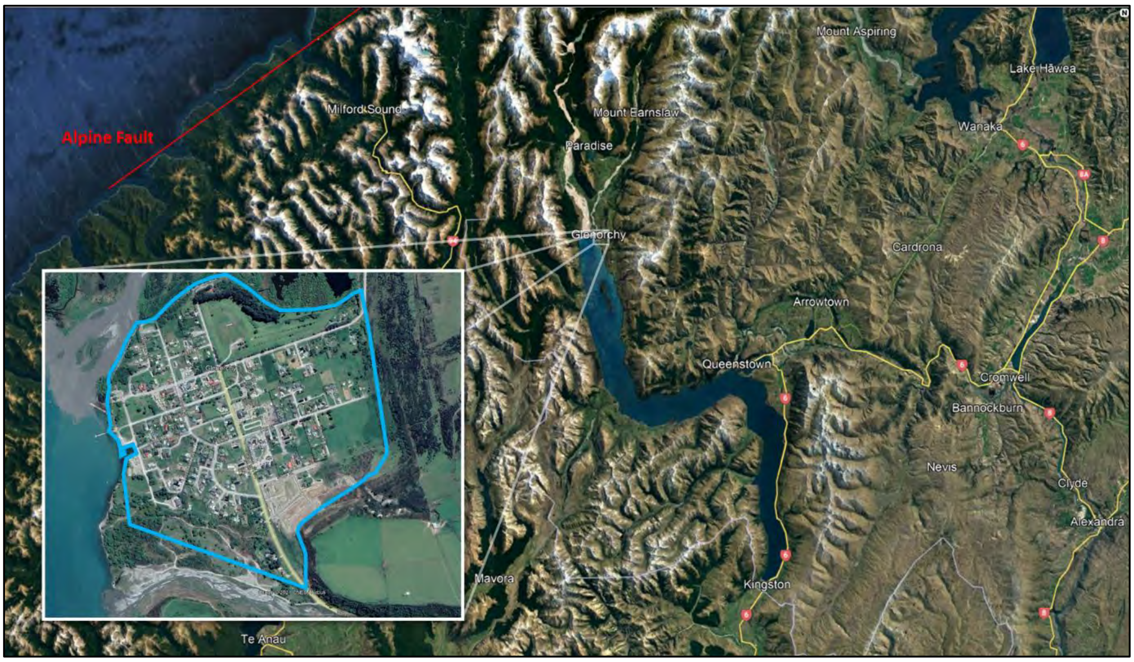


Figure 2.1: Glenorchy township location. The approximate location of the Alpine Fault is shown in red. The study area for this project is shown outlined in blue on the inset map.

3 Liquefaction Hazard in General

Liquefaction is a natural process where earthquake shaking increases the water pressure in the ground in some types of soil, resulting in temporary loss of soil strength.

The following three key elements are all required for liquefaction to occur:

- Sufficient ground shaking (a combination of the duration and intensity of shaking);
- A loose-to-medium-dense granular soil material (typically sands and silts, or in some cases gravel); and
- That these soils are saturated (i.e., below the groundwater table).

The severity of the liquefaction hazard therefore depends on the strength and duration of the earthquake shaking, the thickness and density of the granular soils and the depth of the groundwater table.

Figure 3.1 provides a schematic representation of the liquefaction process. For a more detailed explanation, refer to the MBIE/MfE Guidance (MBIE & MfE, 2017) from which these diagrams are reproduced.

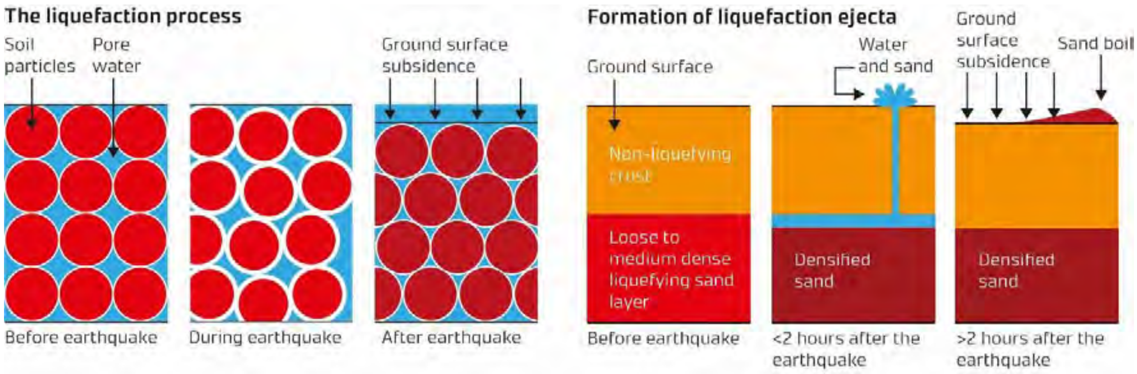


Figure 3.1: Schematic representation of the process of liquefaction and the manifestation of liquefaction ejecta. Reproduced from the MBIE/MfE Guidance (2017).

Liquefaction can give rise to significant land and building damage through multiple mechanisms, giving rise both to vertical settlement and sometimes also lateral/horizontal movement (*lateral spreading*), typically towards a lake, river, or other depressed water body, including large cracking in the ground. Some of these effects are illustrated in Figure 3.2. Appendix B provides a selection of maps and photos showing examples of the liquefaction and lateral spreading that was observed following the 2010-2011 Canterbury earthquakes and 2016 Kaikoura earthquakes.

Vertical settlement is often highly variable rather than uniform. Figure B1 in Appendix B provides a map showing the ground surface settlement that occurred due to liquefaction in the 2010 – 2011 Canterbury earthquakes. It is caused by several compounding factors, including:

- *Volumetric consolidation*: where the earthquake shaking causes the loose sand particles to pack more tightly together resulting in settlement of the ground surface (see Figure 3.1);
- *Liquefaction ejecta*: where large quantities of water and sediment come out of the ground and are deposited at the ground surface resulting in additional settlement. Refer to Figures B10, B11 and B12 in Appendix B for examples; and
- Vertical drops caused by lateral spreading. Refer to Figures B3, B5 and B9 in Appendix B for examples.

Lateral spreading is a type of liquefaction-induced ground failure that occurs in areas with gentle slopes or with a free face in close proximity such as a river bank, lake edge or other depressed water body. Figure B2 in Appendix B provides a map showing the lateral spreading that occurred due to liquefaction in the 2010 – 2011 Canterbury earthquakes. Lateral spreading can result in significant total and differential, horizontal and vertical ground movement causing ground tearing and cracking, with areas close to the free face having the highest risk of lateral spread induced damage. Lateral spreading is often the cause of the most severely affected ground in liquefaction damaged areas, and therefore often results in the most significant damage to buildings and other infrastructure (refer to Figures B3 to B9 in Appendix B for examples).

In Glenorchy, there is a free face of up to 25m on the lakebed, roughly 30m away from the shore. For comparison: following the Canterbury Earthquake Sequence, the areas that were most severely affected by lateral spreading in the residential red zone areas of Christchurch adjacent to the Avon River had free face heights of about 4m. This means that the lateral spreading in Glenorchy is likely to be considerably worse compared to the lateral spreading that occurred in Christchurch following the 2010 – 2011 Canterbury earthquakes. Sections 7 and 13 explain this in further detail.

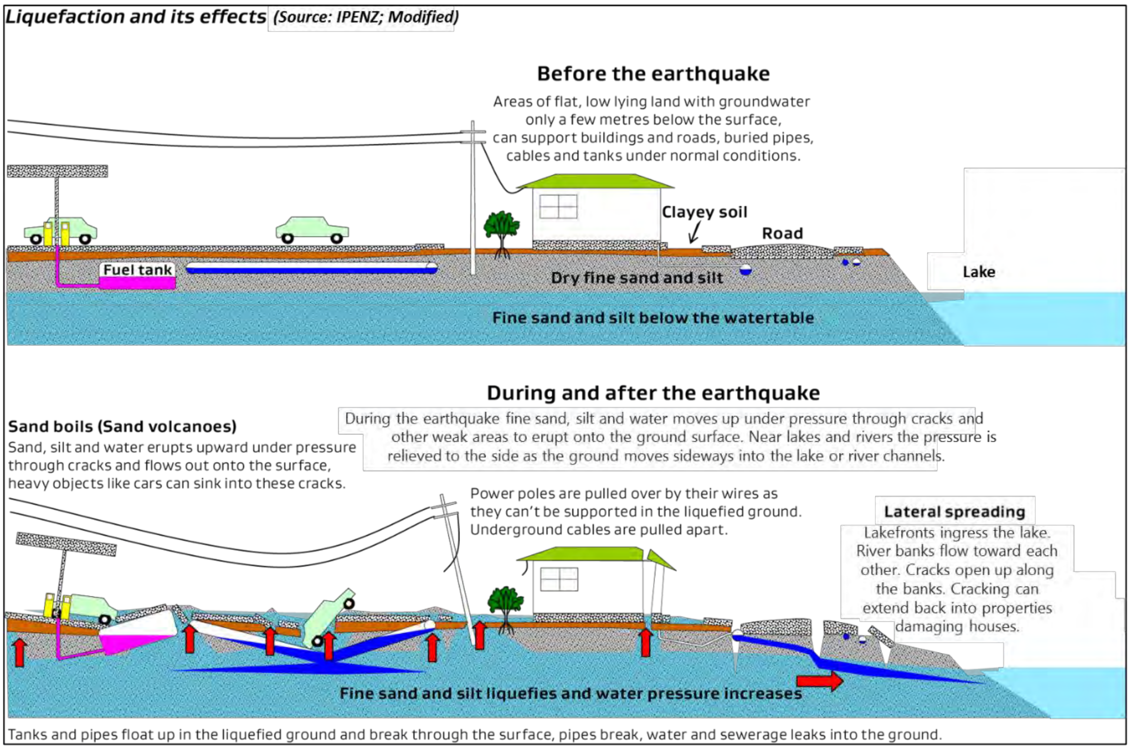
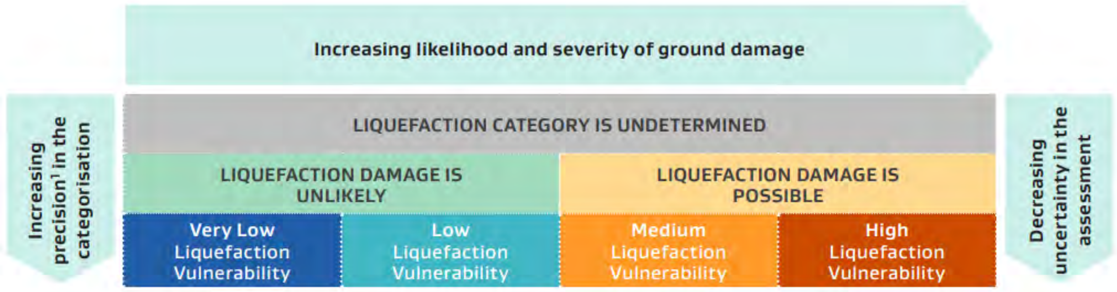


Figure 3.2: Visual schematic of the consequences of liquefaction. Reproduced from the MBIE/MfE Guidance (2017) with modification for the context of a lake.

4 The MBIE/MfE Guidance

The MBIE/MfE Guidance (MBIE & MfE, 2017) presents a risk-based approach for the management of liquefaction-related risk in land use planning and development decision-making. The guidance was developed in response to the Canterbury Earthquake Sequence 2010–2011 following recommendations made by the Royal Commission of Inquiry into Building Failure caused by the Canterbury Earthquakes.

For the purposes of categorizing the liquefaction vulnerability of land, the MBIE/MfE Guidance specifies a performance-based framework to inform planning and consenting processes. That framework is based on the severity of liquefaction-induced ground damage that is expected to occur at various intensities of earthquake shaking. Figure 4.1 shows the recommended liquefaction vulnerability categories for use in that performance-based framework.



Note:

1 In this context the 'precision' of the categorisation means how explicitly the level of liquefaction vulnerability is described. The precision is different to the accuracy (ie trueness) of the categorisation.

Figure 4.1: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform planning and consenting processes. Reproduced from the MBIE/MfE Guidance (2017).

As shown in Figure 4.1, the liquefaction vulnerability categories established in the MBIE/MfE have varying levels of precision in the categorisation based on the degree of uncertainty in the assessment. Highly precise categorizations are not justified if there are high levels of uncertainty in the assessment. The uncertainty depends on a number of factors including an understanding of the seismicity, geological factors, subsurface variability, groundwater, the availability of subsurface geotechnical test data, among other things.

Less precise categorizations may not be sufficient for some applications, so the MBIE/MfE Guidance provides recommendations for the minimum level of detail required in the liquefaction assessment for a variety of specific applications. Figure 4.2 shows the categories used to define the levels of detail for liquefaction vulnerability studies.

The present study has been carried out at a Level C level of detail – a detailed area-wide assessment.

LEVEL OF DETAIL
Level A – Basic Desktop Assessment
Level B – Calibrated Desktop Assessment
Level C – Detailed Area-Wide Assessment
Level D – Site-Specific Assessment

Figure 4.2: Categories of level of detail used to define the levels of detail for liquefaction vulnerability studies. Reproduced from the MBIE/MfE Guidance (2017).

5 Seismicity

For a Level C level of detail, the MBIE/MfE Guidance recommends considering multiple different earthquake scenarios when assessing liquefaction vulnerability. Larger earthquakes have the potential to cause more severe liquefaction damage than smaller ones, but smaller earthquakes can occur more frequently. Determining representative seismic scenarios for the study requires an understanding of the seismotectonic context around the Glenorchy township study area.

Glenorchy is positioned on the Pacific tectonic plate, east of the Australian-Pacific tectonic plate boundary (that is, the Alpine Fault). The relative displacement between the Australian and Pacific tectonic plates is largely taken up along a single dextral (right lateral) strike-slip movement along the Alpine Fault. The remainder of the plate motion is taken up by and expressed on numerous smaller active faults. Known active faults in the lower South Island included in the development of the 2012 New Zealand Seismic Hazard model's fault source model are illustrated in Figure 5.1, which has been reproduced from a report on that Model (Stirling, et al., 2012).

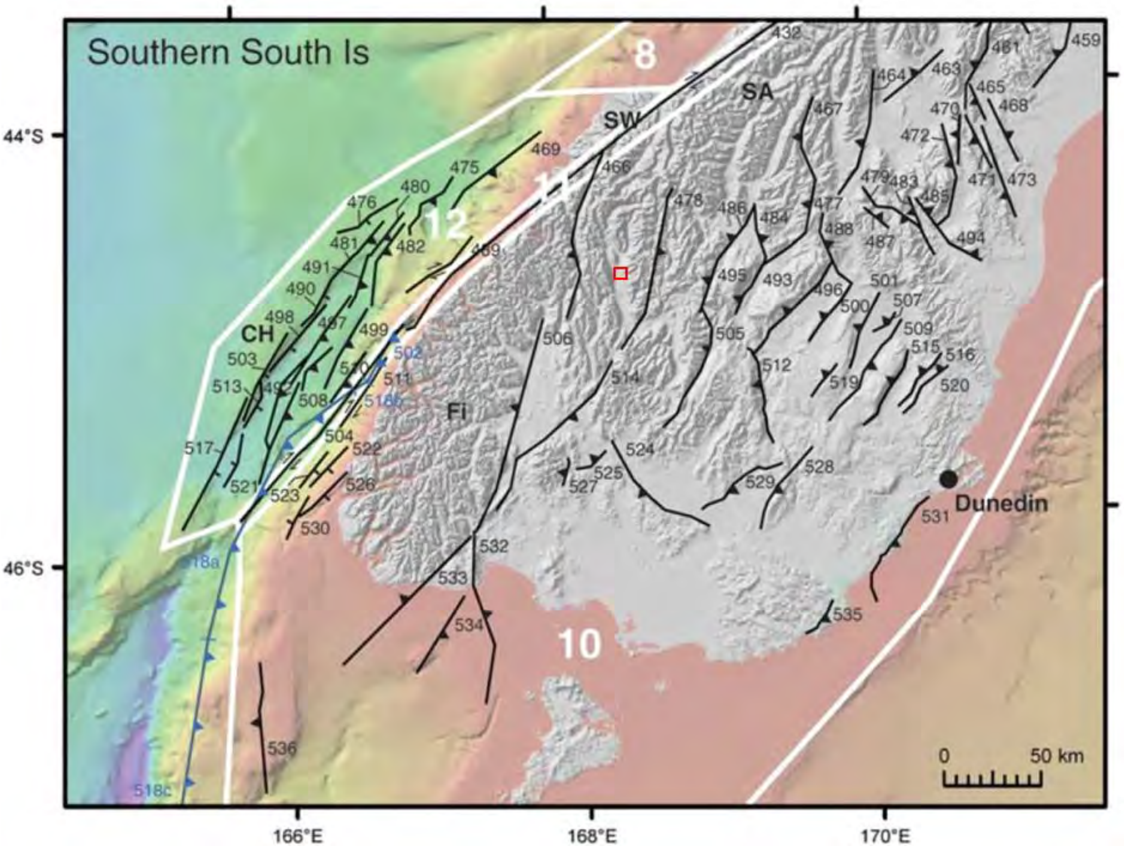


Figure 5.1: Known active faults in the Southern South Island, shown by the black lines with directional arrows (with annotated ID numbers ranging from 432 up to 536). Glenorchy is outlined with a red box. Reproduced from Figure 3(e) the National Seismic Hazard Model (NSHM) for New Zealand (Stirling, et al., 2012).

There are numerous earthquake faults in the region that can produce strong shaking which would affect the Glenorchy township. The main ones are the Alpine Fault (annotated as area 11 in Figure 5.1), the Hollyford Fault (the southern segment of the line annotated as 466), and the Greenstone Fault; all of which are located to the west of Glenorchy; also, the West Wakatipu fault located to the south; and the Moonlight Fault (annotated as 478) located to the east of Glenorchy. Of these faults, the Alpine Fault is the furthest away, but is also the most active (in the sense that it has the most frequent recurrence intervals). Glenorchy is located approximately 55 km from the nearest point on the Alpine Fault (shortest horizontal distance).

For this study, a range of different earthquake scenarios have been considered, ranging from a smaller 25-year event up to a larger 2500-year event, incorporating an allowance for uncertainty in the seismic hazard running lower bound and upper bound ground motions. In addition, an Alpine Fault Rupture Scenario has been considered (with a return period of approximately 30-years) for 16%, 50% and 84% ground motion levels.

As recommended in Module 1 of the Guidelines for earthquake geotechnical engineering practice in New Zealand (NZGS & MBIE, 2021a), the return periods for our scenarios have been determined using Table A1 from Appendix A of the 2021 guidelines to determine the earthquake magnitude (M_w) and the earthquake shaking intensity (which is measured as a Peak Ground Acceleration (PGA) and expressed as a proportion of the acceleration due to gravity, *g*). Note that Glenorchy is not listed in Table A1 from Appendix A of the 2021 guidelines, so interpolation was necessary to determine the M_W and PGA for the various return periods as discussed below.

The adopted peak ground acceleration and causal magnitude values are summarised in Table 5.1 below (with the exception of the Alpine Fault Rupture Scenario which is considered separately; see the discussion which follows).

Table 5.1: Seismic hazard PGA and Magnitude values adopted for this study. The Alpine Fault Rupture Scenario's return period is conditioned on the time that has elapsed since the most recent 1717 rupture.

Return Period	**25-yr**	**Alpine Fault Rupture Scenario (approx. 30-yr, conditional)**	**50-yr**	**100-yr**	**250-yr**	**500-yr**	**1000-yr**	**2500-yr**
Annual Exceedance Probability	**4%**	**3%**	**2%**	**1%**	**0.4%**	**0.2%**	**0.1%**	**0.04%**
PGA (*g*)	0.1 to 0.16	0.11 (16th percentile) 0.19 (50th percentile) 0.32 (84th percentile)	0.14 to 0.22	0.20 to 0.32	0.31 to 0.48	0.41 to 0.63	0.53 to 0.82	0.74 to 1.14
M_w	6.1 to 6.5	8.1	6.1 to 6.5	6.1 to 6.5	6.1 to 6.5	6.5 to 7.1	6.5 to 7.1	6.5 to 7.1
Seismic Source (km)[1]	62 to 17	55	60 to 17	57 to 17	54 to 17	50 to 17	46 to 17	41 to 17

Note 1. The site-to-source distance (e.g. distance from site to surface projection of fault plane) is used for the Gillins and Bartlett lateral spreading assessments and come from assessment of the distance to nearby faults

Glenorchy is located in between Queenstown (approximately 30km SE of Glenorchy) and Milford Sound (approximately 40km NW of Glenorchy). The PGA in Milford Sound is significantly greater than Queenstown (especially at longer return periods). Conversely M_W in Queenstown is greater than Milford Sound for the more frequent return periods. As a result, interpolation would result in considerable uncertainty and therefore for the upper bound values, the larger of the PGA and M_W values for Queenstown and Milford Sound have been combined, whereas for the lower bound values, the lower of two have been combined. The seismic hazard is typically the largest source of uncertainty and that the selected combinations were used to try and envelope the uncertainty.

The values in Table 5.1 (obtained from the Table A1 from Appendix A of the 2021 guidelines) are based on the 2002 National Seismic Hazard Model using the rupture reoccurrence intervals for each fault. However, neither the 2002 Model nor the updated NZGS/MBIE 2021 Module 1 Guidelines incorporate time dependency (i.e., elapsed time since the last earthquake). This means, based on the current understanding of the probability of an Alpine Fault rupture, the values in Table 5.1 are likely to be unconservative (excluding the ones for the Alpine Fault Rupture Scenario). The improved understanding of the Alpine Fault is currently not captured in the values presented in Table 5.1, which is significant since the Alpine Fault is likely to have a major contribution to the seismic hazard for Glenorchy.

To be more specific, the Alpine Fault has a relatively short rupture recurrence interval, estimated to be between 250 and 340 years. The Alpine Fault last ruptured in 1717 which means that 304 years have since elapsed. Because of this significant amount of time which has elapsed relative to the average (time-independent) recurrence interval, the time-dependent conditional probability of rupture is likely to be significantly shorter as shown by recent studies (Biasi, Langridge, Berryman, Clark, & Cochran, 2015); (Howarth, et al., 2021).

Moreover, recently published research (Howarth, et al., 2021) uses paleoseismic evidence to estimate a long-term time-independent recurrence interval of about 250 years, which is even lower than previous estimates of 300 to 340 years (N.B. Intervals between historical events have ranged from approximately 140 to approximately 510 years). Using this lower recurrence interval gives very high estimates of conditional rupture probability within the next 50 years; Howarth, et al. estimate this to be a 75% probability, with an 80% chance of it being an earthquake with a magnitude of 8 or above. A 75% probability of an Alpine Fault Rupture Scenario in the next 50 years is equivalent to an approximate conditional return period of 30 years.

Based on a deterministic calculation, the median PGA at Glenorchy for an Alpine Fault Rupture Scenario is 0.19*g* and the 16th and 84th percentile values are 0.11*g* and 0.32*g*. These estimates are based on a combination of Ground Motion Models (GMMs) with a 40% weighting assigned to the GMM developed by Bradley, et al. (Bradley, et al., 2017) and 20% weight assigned to each of three NGAWest2 GMMs (Abrahamson, Silva, & Kamai, 2013); (Boore, Stewart, Seyhan, & Atkinson, 2014); (Campbell & Bozorgnia, 2014).

These values have been tabulated in Table 5.1 under the Alpine Fault Rupture Scenario. It is noted that a 30-year return period event with a median PGA of 0.19g is a significantly higher than the published PGA values for the 25-year and 50-year return period events. This illustrates the unconservative nature of the values obtained from the 2021 NZGS & MBIE guidelines (which are based on the 2018 NZTA Bridge Manual values) which do not account for the time dependency of the Alpine Fault ruptures and are also based on older ground motion and source models (currently being updated by GNS). This update may well lead to the overall seismic hazard at Glenorchy for the range of return period levels of earthquake shaking being nearer the high side of the estimated range.

Howarth et al. estimate a 75% probability of occurrence of an Alpine Fault rupture within the next 50 years, which means that the next Alpine Fault rupture is almost certain to happen within current planning horizons and is highly likely to trigger liquefaction (discussed in Sections 11 and 12) resulting in significant lateral spreading and ground surface subsidence. An Alpine Fault rupture earthquake will have a larger magnitude and therefore a longer duration. While liquefaction triggering is less sensitive to magnitude than it is to shaking intensity, in contrast lateral spreading is *more* sensitive, and larger magnitudes are likely to cause greater lateral displacements than the PGA and magnitude combinations from the 2021 NZGS & MBIE guidelines. As such, an Alpine Fault rupture scenario has also been considered for assessing the likely range of lateral displacements across Glenorchy.

6 Geology and Geomorphology

In addition to seismicity, the geology at Glenorchy plays an important role in assessing its liquefaction vulnerability. What follows is a detailed summary of the geological and geomorphological history of the location.

Sedimentation into the Wakatipu basin is estimated to have begun around 17,000 years before the present day. At that time, the Wakatipu Lake was larger than at present, with a prominent high-stand lake level at approximately 360mRL elevation (NZVD), inferred from well-preserved lake-edge terraces. This is around 50m higher than today; the lowering elevation can be attributed to a number of factors, but recently this has primarily been due to incision at the outlet.

Lake Wakatipu's outlet has changed since its formation after the last glacial maxim, but the present-day outlet (the Kawarau River) is thought to have captured the drainage during the last 10,000 years. The Kawarau outlet was incised through sediments and rock, resulting in a semi-progressive lowering of the lake level as this incision took place. The lake level stabilised between periods of lowering, and this formed further, lower lake terraces that are preserved in places on the present-day landscape. At least ten lake terraces have been mapped around the Glenorchy area.

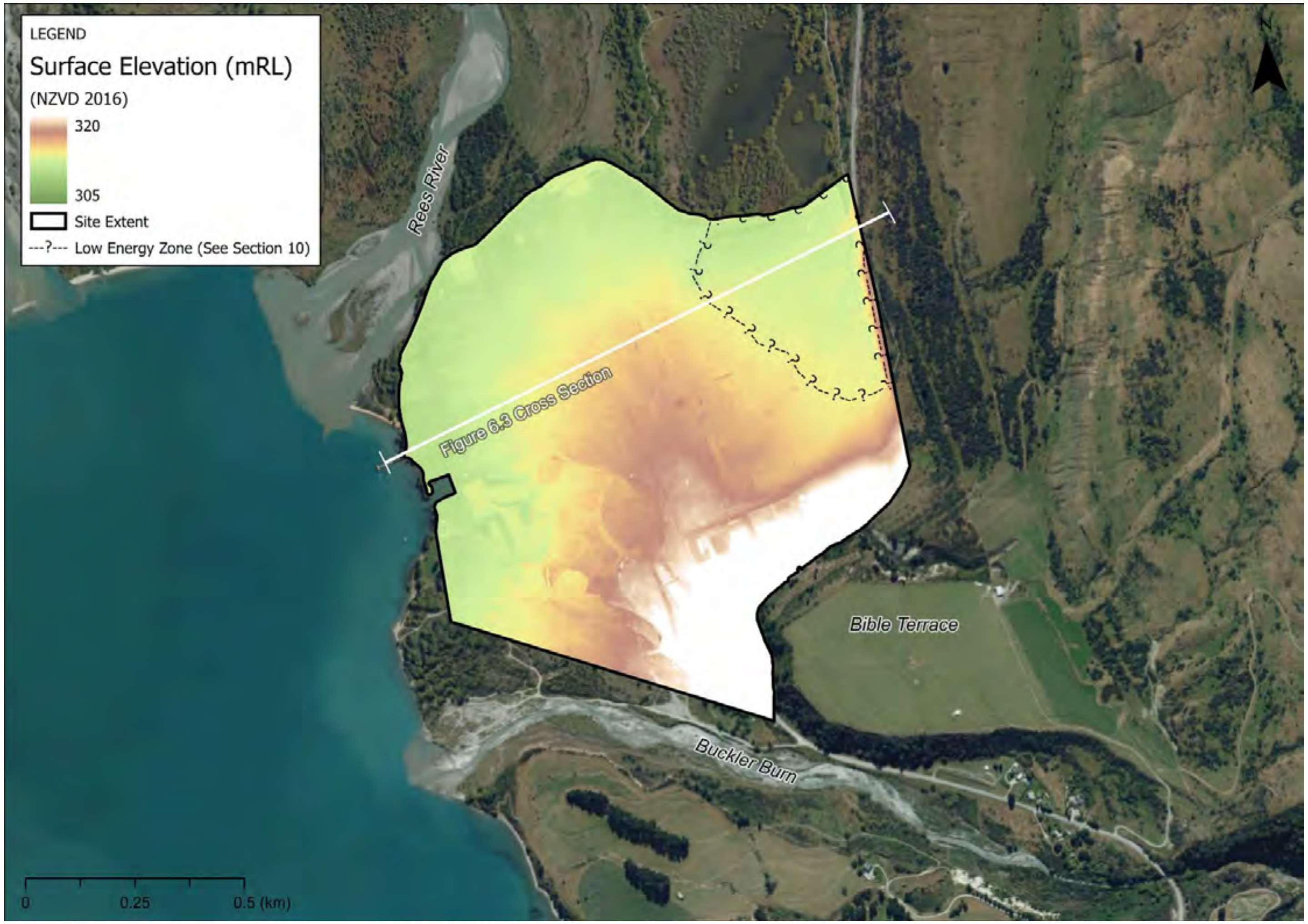


Figure 6.1: Surface elevation of Glenorchy, based on LiDAR survey. The location of the cross-section from Figure 6.3 is annotated. Elevations above 320mRL are truncated. The location of the low energy zone (discussed later in Section 10) is also annotated.

At a prominent lake high stand, the Buckler Burn formed what is now the Bible Terrace (annotated in Figure 6.1) and the terrace adjacent to Stone Creek. These terraces are part of the original Buckler Burn Fan/Delta complex which formed at the shoreline of the Lake when water levels were around 40m higher than today. The associated Alluvial Fan, Proximal delta topsets, and Gilbert Type delta foreset beds in distal deposits can all be observed in the river-cut exposures along the true left bank of the modern-day Buckler Burn (see Figure 6.2).

Figure 6.2: A photo of proximal delta topsets and Gilbert Type delta foreset beds in distal deposits in the river cut exposures along the true left bank of the modern-day Buckler Burn.

Along the western, lake-side edge of the township, it is likely that the building of the Bible Terrace Fan/Delta resulted in the accumulation of gently inclined fine silt sediment 'bottomset beds' on the lake floor sediments. These delta beds would conceivably dip north through west.

As the Lake Wakatipu water level lowered, the front of the Fan/Delta migrated around the edge of the existing fan, building out mainly westward. A comparatively deep lake basin, off the north edge of the Buckler Burn Fan/Delta (i.e., the north-east of the study area), seems to have had low sediment input during that time resulting in a lower energy deposition zone (shown in Figure 6.1). The top of the fan delta, which would now have been out of the water, became an alluvial fan with fluvial and alluvial modes of sediment deposition that created the present land surface there.

Once the lake had dropped to a level not much higher than the present day (estimated to be around 315–320mRL, NZVD) the Buckler Burn may have become entrenched as it eroded down through its fan delta, and flow was directed northward. This lake lowering is thought to have occurred in stages between about 5,000 and 500 years before the present day. During this time the Glenorchy township area appears to have been formed almost exclusively from sediment transported by the Buckler Burn, and so Glenorchy township is situated on the resulting lower fan delta complex.

During the building of this Glenorchy fan/delta, the Buckler Burn would have entered Lake Wakatipu several hundred metres from the current lake edge. The lake floor and bottomset sediments would probably have been overlain first by further bottomset type fine sediments at a low inclined angle northward, then by silt and fine sand dominated foreset beds which would have built out over the bottomsets as steeply inclined beds formed by finer sediments travelling down the delta front. The foreset beds would probably have been emplaced as a series of overlapping lobes and the dip of the beds would likely be west through north to east and quite variable.

As the delta front migrated outward, toward the present-day Rees valley, a sharp transition would have been formed as proximal delta deposits (silt, fine to coarse sand and gravel) were emplaced in shallowing water over the top of the finer sediments. This transition is illustrated in a conceptual geological cross-section shown in Figure 6.3, and can be seen as the transition between the orange and yellow layers. The shallowing water would likely have been due to a combination of lowering lake levels and the filling of the available space within the basin by Buckler Burn sediments at the then lake margin. The coarse proximal delta deposits (topsets) would probably be low angled semi-braided channel deposited sediments gently dipping to the north and east. Similar deposits can be seen forming at the Rees and Dart deltas in the present day.

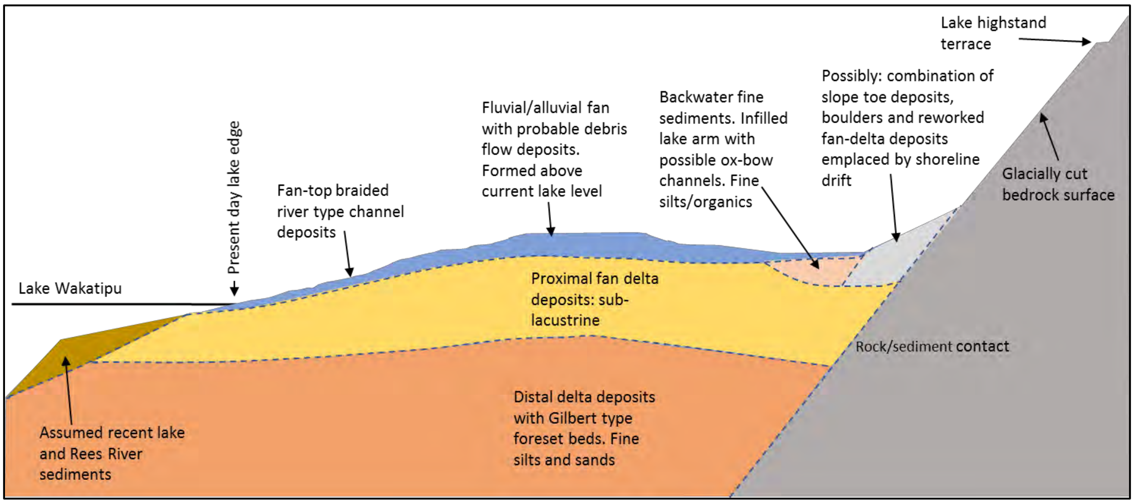


Figure 6.3: Informal, conceptual geological cross section (not to scale), at the location shown in Figure 6.1.

When the lake levels reached the present-day stand, fluvial and alluvial fan sediments (and probably debris flow deposits) from the Buckler Burn have overprinted on the Fan/Delta surface in fairly recent times forming a domed alluvial fan and many braided channels, especially on the western half of the Glenorchy township area. These coarse, generally gravel-dominated sediments vary in thickness between roughly 2m and 7m across the Glenorchy township, shown in the Figure 6.3 cross section in a blue colour. Deposition of these sediments seems to have ceased once the Buckler Burn became established in its present westward flowing channel.

Within the last 100–150 years it is likely that the Rees River delta has built out to connect with the Glenorchy fan/delta. The Rees River sediments are expected to onlap the Glenorchy delta front.

7 Topography

To undertake an assessment of liquefaction, and particularly lateral spreading, it is important to have a ground surface profile (including the surface of the lakebed underwater). For this study, a Digital Elevation Model (DEM) has been used. This DEM was derived from a LiDAR survey dating from 2019, provided by ORC, and illustrated in Figure 6.1. In addition, bathymetric data has been used (provided by NIWA via ORC) from a survey undertaken in Lake Wakatipu, likewise dating from 2019 (Survey RUK1901), using a Portable Hydrographic System.

Figure 7.1 shows a typical ground surface profile, together with a small map showing the line along which the profile is taken. There is a region near the edge of the lake where neither bathymetry nor LiDAR data is available (around point D); for this region an interpolation scheme was used based on the slope (in each direction). In some areas further hydrographic survey data provided via ORC was available which validates this interpolation approach.

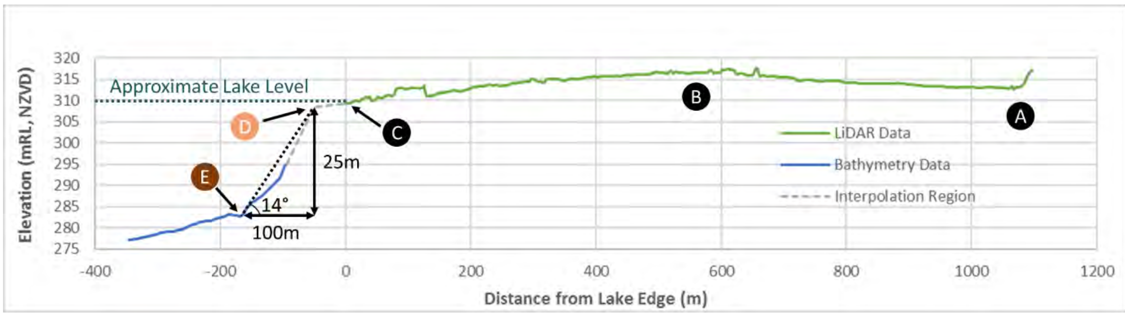


Figure 7.1: An example ground surface profile taken along the line shown in Figure 7.2. Note that the horizontal and vertical scales are not in a 1:1 ratio, so the vertical direction appears exaggerated. The significance of the points labelled A through E are explained in the text.

From point A (i.e., the foot of the ridge on the east side of Glenorchy), there is a gentle slope upwards for about 500m to point B, rising about 5m in elevation; at which point the highest elevation point is reached. Then, from point B there is a similarly gradual slope for about 600m down to point C, which corresponds to the edge of the lake, losing about 7m of elevation. The ground surface continues below the lake with a similar slope for about 50m to point D, at which point a significant drop-off begins: a vertical drop of about 25m over the span of 115m down to point E, at which point, the gradient of the slope eases off more.

For the purposes of a lateral spreading assessment, the drop-off starting at Point D is known as a *free face*. The edge of the free face (a.k.a. the crest) has been mapped along the lake edge (using the full Bathymetry and LiDAR data rather than a single cross section); shown in Figure 7.2. Likewise, the base of the free face (e.g., Point E in the cross section) has been mapped using a similar methodology.

Figure 7.2: The mapped free face crest location and base locations along the edge of Lake Wakatipu around Glenorchy, together with the line along which the surface in Figure 7.1 is taken. The crest and base intersect at points D and E from that figure, respectively.

Wherever significant liquefaction occurs, lateral spreading has the potential to occur on sloping land, and also flat land adjacent to free faces. At gently sloping sites, away from free faces, the lateral movement may be smaller, while sites adjacent to a free face, such as a riverbank or lake front, the movements can be larger and significantly more damaging. Damage is typically concentrated near to the free face and reduces with distance away from it.

The higher the free face, the larger the lateral spreading and the further back it extends. The free face height is up to 25m in this case, which is very significant. For comparison: following the Canterbury Earthquake Sequence, the areas that were most severely affected by lateral spreading in the residential red zone areas of Christchurch adjacent to the Avon River had free face heights of about 4m. Therefore, any lateral spreading in Glenorchy is likely to be more severe and extend much further back inland compared to the severity and extent of the lateral spreading observed in the residential red zone areas of Christchurch. Later, Section 13 explains this in further detail.

8 Geotechnical Investigations

Subsurface information from geotechnical testing is necessary to quantitatively assess liquefaction and its consequences. Accordingly, T+T engaged Geotechnics Ltd to carry out Cone Penetration Tests (CPT) and ProDrill Ltd to drill boreholes throughout Glenorchy township. These investigations were carried out during the week of 10–16 October 2021. T+T supervised the investigations, and an Engineering Geologist carried out a comprehensive walkover of the township and immediate surrounds to assess the geology and geomorphology of the area (see Section 6).

19 CPT were carried out, with a target depth of 20m. Of these, 11 CPT reached their target depth of 20 m and the remainder refused at shallower depths due to denser overlying gravels.

Four sonic boreholes were drilled. Two achieved a target depth of 20 m, and the other two were used to investigate and pre-drill the upper 7–8 m of medium dense gravelly sand, to enable CPT investigations at depth. SPTs were also performed for all four boreholes. While these boreholes and SPTs were not used directly for liquefaction vulnerability calculations, they provided important information to correctly interpret the CPTs and assist in the development of a geological model for the area (refer to Section 6).

The investigation locations are shown below in Figure 8.1, and the logs and data have been uploaded to the New Zealand Geotechnical Database (NZGD). Metadata, including the total test depth is shown in Table 8.1 for the CPT which were uploaded to the NZGD (one CPT was not uploaded due to data quality issues). The NZGD also contained six CPTs and one Borehole with SPT, all located at the historical site of the Mt. Earnslaw Hotel, and these are also shown in Figure 8.1. Note that in some cases multiple tests were carried out at the same location, so the multiplicity is not obvious on the map.

Table 3.3 of the MBIE/MfE Guidance (MBIE & MfE, 2017) guidelines specifies an indicative spatial density of 0.1 to 4 investigations per Ha for a Level C assessment. The spatial density of investigations undertaken for this study is about 0.2. While this is toward the lower end of the recommended density, because of the relatively uniform geology, there is not a very large spatial variability in the ground conditions, and it considered to be sufficient for a Level C assessment.

Figure 8.1: Geotechnical Investigation locations: data and logs available on the NZGD.

Table 8.1: Metadata for the geotechnical investigations available within the Glenorchy Study Region on the NZGD, including tests performed as a part of this study.

TTGD ID	Investigation Type	Test Depth	Reference ID	NZTM X	NZTM Y
BH_165999	Borehole	31.9	EGH-ENG21-BH01	1235186	5023260
BH_168505	Borehole	20.3	BH01	1235557	5023361
BH_168506	Borehole	20.3	BH02	1235507	5023126
BH_168507	Borehole	7.0	BH03	1235653	5023173
BH_168508	Borehole	7.6	BH04	1235751	5023214
CPT_166002	CPT	11.8	CPTu001	1235147	5023277
CPT_166004	CPT	20.0	CPTu001A	1235148	5023290
CPT_166006	CPT	1.4	CPTu002	1235233	5023259
CPT_166007	CPT	20.0	CPTu002A	1235232	5023262
CPT_166009	CPT	20.0	CPTu003	1235171	5023230
CPT_168486	CPT	3.0	CPT-P1b	1235339	5023174
CPT_168487	CPT	4. 6	CPT06a	1235271	5023258
CPT_168488	CPT	18.6	CPT-P2	1235479	5022865
CPT_168489	CPT	21.9	CPT08	1235117	5023199
CPT_168490	CPT	21.3	CPT02	1235897	5023615
CPT_168491	CPT	20.2	CPT01	1235983	5023652
CPT_168492	CPT	21.2	CPT03b	1235672	5023526
CPT_168493	CPT	22.0	CPT17	1235174	5022983
CPT_168494	CPT	20.2	CPT22b	1235658	5023178
CPT_168495	CPT	3.6	CPT20a	1235554	5023363
CPT_168496	CPT	20.0	CPT19a	1235513	5023473
CPT_168497	CPT	10.7	CPT10	1236104	5023373
CPT_168498	CPT	20.8	CPT13a	1235783	5023231
CPT_168499	CPT	21.1	CPT05a	1235348	5023286
CPT_168500	CPT	1.1	CPT15	1235503	5023129
CPT_168501	CPT	2.3	CPT16	1235233	5023033
CPT_168502	CPT	17.0	CPT04	1235467	5023331
CPT_168503	CPT	20.1	CPT12	1235905	5023267
CPT_168504	CPT	21.0	CPT18	1235403	5023720

9 Groundwater Model

A groundwater model was developed using data from monitoring for water quality purposes (e3 Scientific Ltd., 2018), together with the geotechnical investigations described in the previous section (Section 8).

Porewater pressure measurements for some CPTs were of a suitable quality to estimate a groundwater depth; this was converted to a groundwater elevation by subtracting from the LiDAR DEM surface. The monitoring well data reported by e3 Scientific (e3S) were already given in terms of elevation.

There were e3S monitoring well data available at the Glenorchy Jetty, the Lagoon, as well as nine other locations throughout the township. The mean well readings over a five-month period were used. The Jetty and Lagoon wells provide a boundary condition for the groundwater surface along the edge of the Lake and the Lagoon respectively (since the groundwater surface must be continuous with the water level). As such, the Lake was assumed to have elevation of 309.8mRL and the Lagoon; 311.0mRL (both NZVD).

While there was significant variability in the data, they supported a set of relatively gentle elevation contours increasing in the direction away from the lake. These contours are shown below in Figure 9.1.

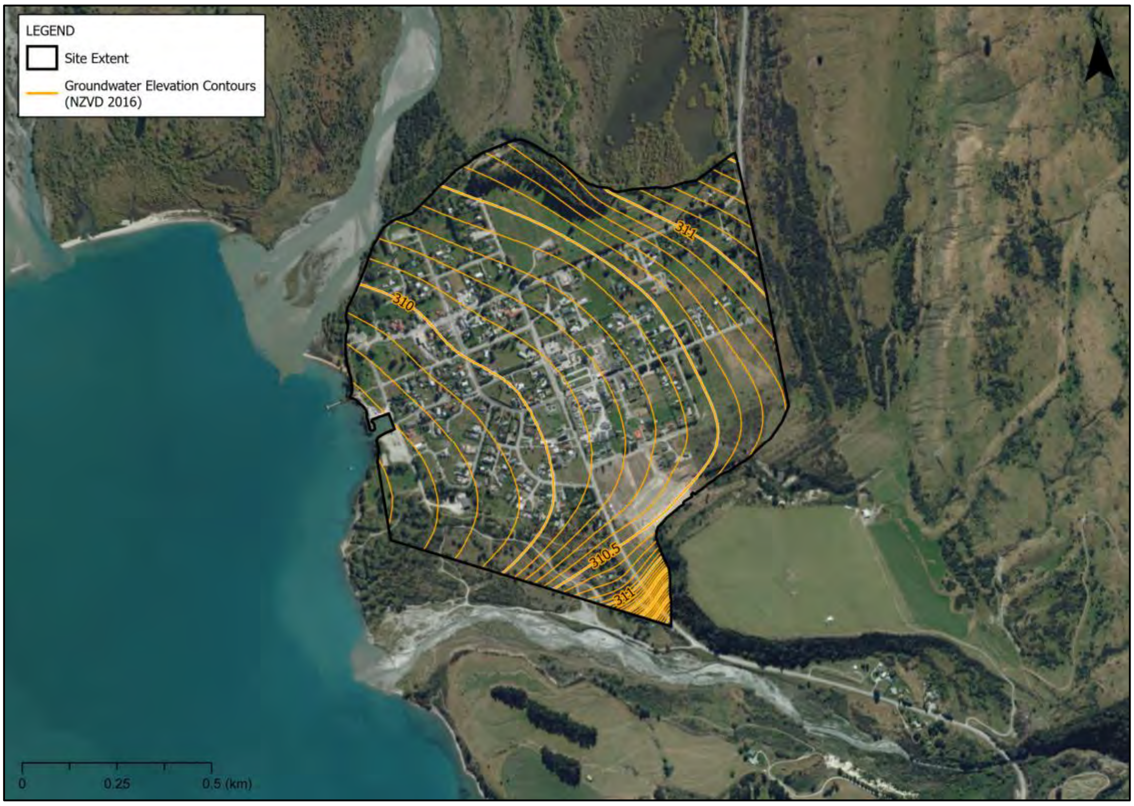


Figure 9.1: Contours for the groundwater surface model which has been developed for this study.

This Groundwater Elevation Model was then readily subtracted from the LiDAR DEM surface to give a Groundwater Depth Model, shown in Figure 9.2.

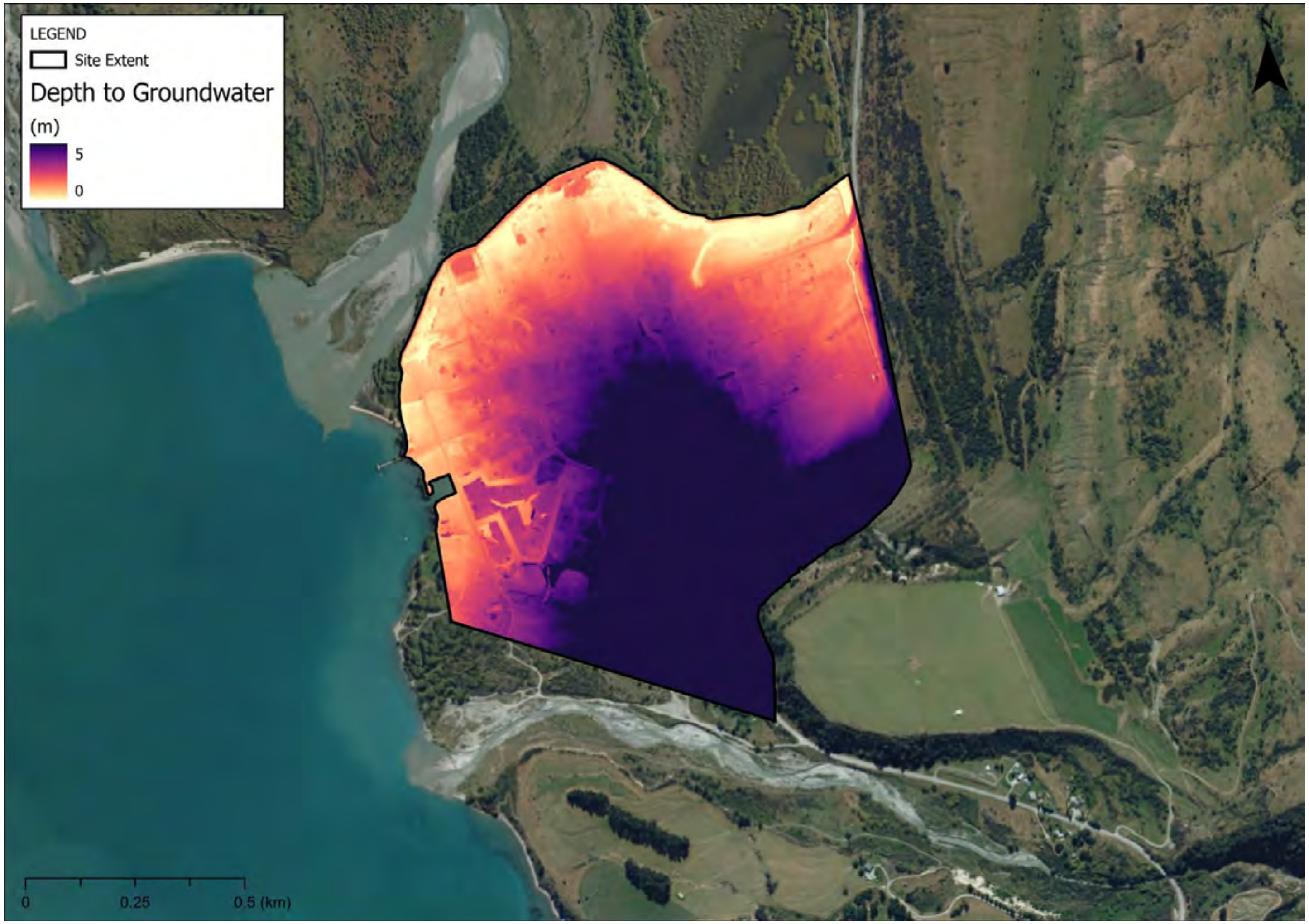


Figure 9.2: The modelled ground water depth for the study. Depths beyond 5m are truncated.

Due to the gentle slope in the groundwater surface, the groundwater depth is largely governed by the surface elevation (see Figure 6.1). The higher-elevation alluvial fan proceeding from Bible Terrace has deeper groundwaters, whereas near the lakefront, the lagoon, and in the north-east of the study area have significantly shallower groundwaters.

The e3S monitoring well data were collected during an exceptionally dry period, so the median groundwater could be higher. This would increase the liquefaction vulnerability, but not appreciably, as demonstrated later in Section 12 (in particular Table 12.3).

The groundwater model represents a possible, typical scenario for the purposes of a liquefaction vulnerability assessment. There is a certain level of seasonal variability which would be expected, and in time of flooding the lake and lagoon levels will be higher which will increase the groundwater levels. However, the probability of an earthquake occurring coinciding with elevated groundwater is very low, so for assessment of liquefaction and lateral spreading, the typical groundwater depths are more representative.

10 Ground Conditions

The geotechnical testing described in Section 8 were, in part used to develop the geological and geomorphological understanding presented in Section 6. Broadly speaking, there are two depositional environments in Glenorchy. Most of the study area has seen continuous deposition from the Buckler Burn and is has fairly consistent ground conditions apart from differences in soil unit layer thicknesses. The exception is the area off the north edge of the Buckler Burn Fan/Delta (i.e., the north-east of the study area), which seems to have generally seen lower levels of deposition, as evidenced in part by its depressed surface elevation; this region is annotated on the LiDAR DEM in Figure 6.1.

Following topographic contours and informed by the CPT data, which show the possible presence of organic silts in this low energy area, the north-east of the study area has been considered separately. The adopted boundary between the higher energy area and the lower energy area should be considered to have an uncertainty of approximately 100m either side of it, especially in the north near the Lagoon where CPTs are spaced further apart. This uncertainty could be reduced in the future through further subsurface geotechnical testing.

While the thicknesses and composition of layers varies throughout Glenorchy, a couple of general summaries of the subsurface conditions are provided for the high and low energy areas in Table 10.1 and Table 10.2 respectively. These correspond with the layers shown in the conceptual geological cross section in Figure 6.3.

In both the high and low energy zone, all strata below the Alluvial Fan Braided Channel Deposits consist of alluvial material, which is highly susceptible to liquefaction, beginning between about 3-7m below the ground but extending down to 20m and beyond. For comparison, these ground conditions are considerably worse than the ground conditions in the residential red zone areas of Christchurch where the thickness of highly susceptible material typically extended down to 10m below the ground surface.

Table 10.1: A general summary of subsurface conditions for the high energy area of Glenorchy (i.e., excluding the low energy zone shown in Figure 6.1).

Depth (m) (Approx.)						
From	**To**	**Unit**	**Generalized Description**	**Detailed Description**	**Typical CPT q_c and SPT *N* values**	**Figure 6.3 Cross Section Colouring**
0	**0.3**	Topsoil	Organic silt-sand	Organic silt-sand	N/A	N/A
0.3	**4 to 7**	Fluvial/Alluvial Fan and Fan-top Braided Channel Deposits	Gravels and Sands	Gravelly SAND to sandy GRAVEL. Medium dense to dense; well graded. Gravel is fine to course; subangular to subrounded, slightly weathered schist & quartz. Sand is fine to coarse. Silty CLAY (rare).	q_c typically 5–15MPa, occasionally higher: near 30MPa SPT *N* values of 13-20.	
4 to 7 (Only at Delta Edge)	**5 to 10 (Only at Delta Edge)**	Transitional Delta Edge Deposits	Interbedded Silts, Sands and Probable Gravels	Silty gravelly SAND; well graded to poorly graded; loose to medium dense. Silty CLAY; firm to stiff (occasional) Sandy GRAVEL; medium dense (occasional, below 12m).	q_c typically 1–10MPa	
5 to 10	**19 to >22**	Proximal Fan Delta Deposits	Sandy Gravel		q_c typically 5–15MPa SPT *N* values of 11-18	
19 to >22	**>30**	Distal Delta Deposits (Beds may be inclined)	Silts and Fine Sands		q_c typically 1–5MPa	

Table 10.2: A general summary of subsurface conditions for the low energy area of Glenorchy (shown in Figure 6.1).

Depth (m) (Approx.) From	To	Unit	Generalized Description	Typical CPT q_c	Figure 6.3 Cross Section Colouring
0	**0.3**	Topsoil	Organic silt-sand	N/A	N/A
0.3	**2.5 to 3.5**	Fan-top Braided Channel Deposits	Gravels and Sands	q_c typically 5–15MPa	
2.5 to 3.5	**3 to 10**	Backwater Fine Sediments	Silts, Fine Sands, Possible organic silt beds	q_c typically 1–5MPa	
3 to 10	**6 to 13**	Proximal Fan Delta Deposits, Transitional Distal Delta Deposits	Silts and Fine Sands (Beds may be inclined)	q_c typically 1–10MPa	
6 to 13	**10 to >20**	Distal Delta Deposits, Lake Deposits	Silt	q_c typically 1–5MPa	
10 to >20	**>30**	Possible Glacial Deposits or Bedrock	Rock	q_c > 50MPa	

11 Liquefaction Triggering

Liquefaction triggering at the site was assessed using the CPT data according to the methodology of Boulanger and Idriss (Boulanger & Idriss, 2014), as recommended by Module 3 of the NZGS/MBIE Earthquake geotechnical engineering practice guidelines (NZGS & MBIE, 2021b). Analysis was performed at using the 15th percentile cyclic resistance ratio equations and also the 50th percentile (median) equations.

Representative liquefaction triggering plots developed during the analysis are shown for three typical CPTs from the high energy zone (NZGD IDs 168502, 167503, and 16896) in Figure 11.1, Figure 11.2, and Figure 11.3; which correspond to a lower bound, upper bound, and Alpine Fault Rupture Scenario respectively. For the lower bound case, the lower bound PGA and M_W values from Table 5.1 were used, together with 50th percentile cyclic resistance ratio equations. For the upper bound case, the upper bound PGA and M_W values were used, and 15th percentile cyclic resistance ratio equations. Finally, for the Alpine Fault Rupture Scenario, the 50th percentile cyclic resistance ratio equations were used, but the three different PGA values in Table 5.1 were considered separately.

The silty gravelly SAND beginning at about 3 to 7m depth is mostly loose and the analysis shows it is highly susceptible to liquefaction. Of this material, the most susceptible zone is from about 5 to 12m depth. Below 12m the soil remains susceptible but there is a gradual increase in relative density with depth.

The upper crust from the surface down to 3 to 7m depth is considered unlikely to liquefy because it is significantly denser than the deeper soils and mostly above the ground water table.

The analyses show that triggering of liquefaction within the most susceptible zone (approx. 5 to 12m) is expected to occur when shaking intensity reaches a PGA of 0.13*g*. The remaining susceptible soils (approx. 12 to 20m and beyond) would likely liquefy with a PGA of 0.2*g* and above. The results indicate that soil liquefaction is significant and widespread across Glenorchy within these depth ranges and shaking intensity ranges.

Generally CPTs only reach 20m and the simplified liquefaction triggering assessment methodologies (Boulanger & Idriss, 2014) are only applicable for the top 20m; it is probable that liquefaction could trigger at depths below 20m, so for the upper bound case, the CPTs shown have been extrapolated. The extrapolation was performed using uniform values of q_c = 8.5MPa and I_c = 1.9, which correspond to the median values for available CPT data in the study region over the depth ranges of both 15-20m and 20m+.

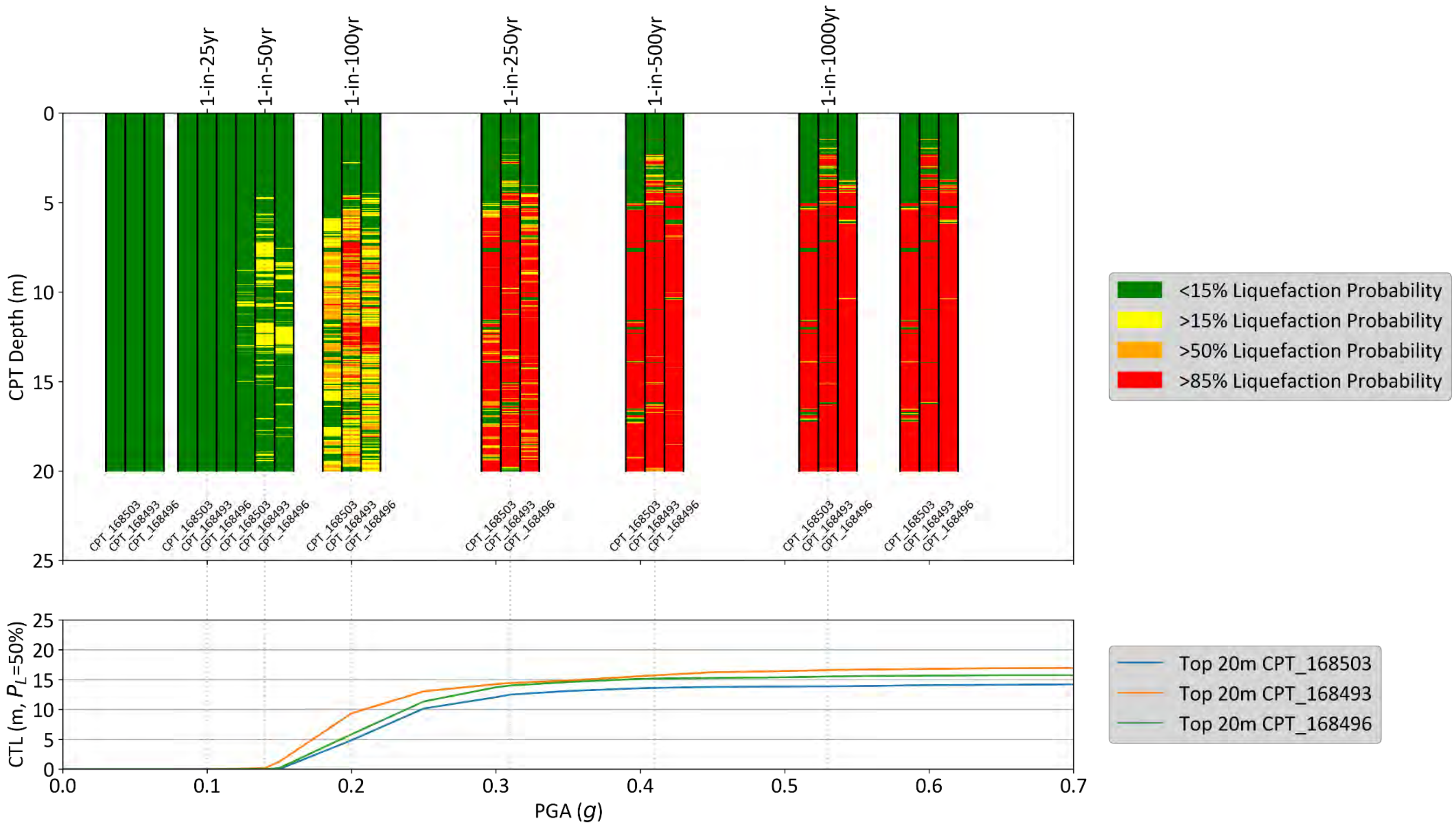


Figure 11.1: A plot of lower bound liquefaction triggering (and the resulting cumulative thickness) at increasing return period levels of earthquake shaking, for three representative CPTs from the high energy area.

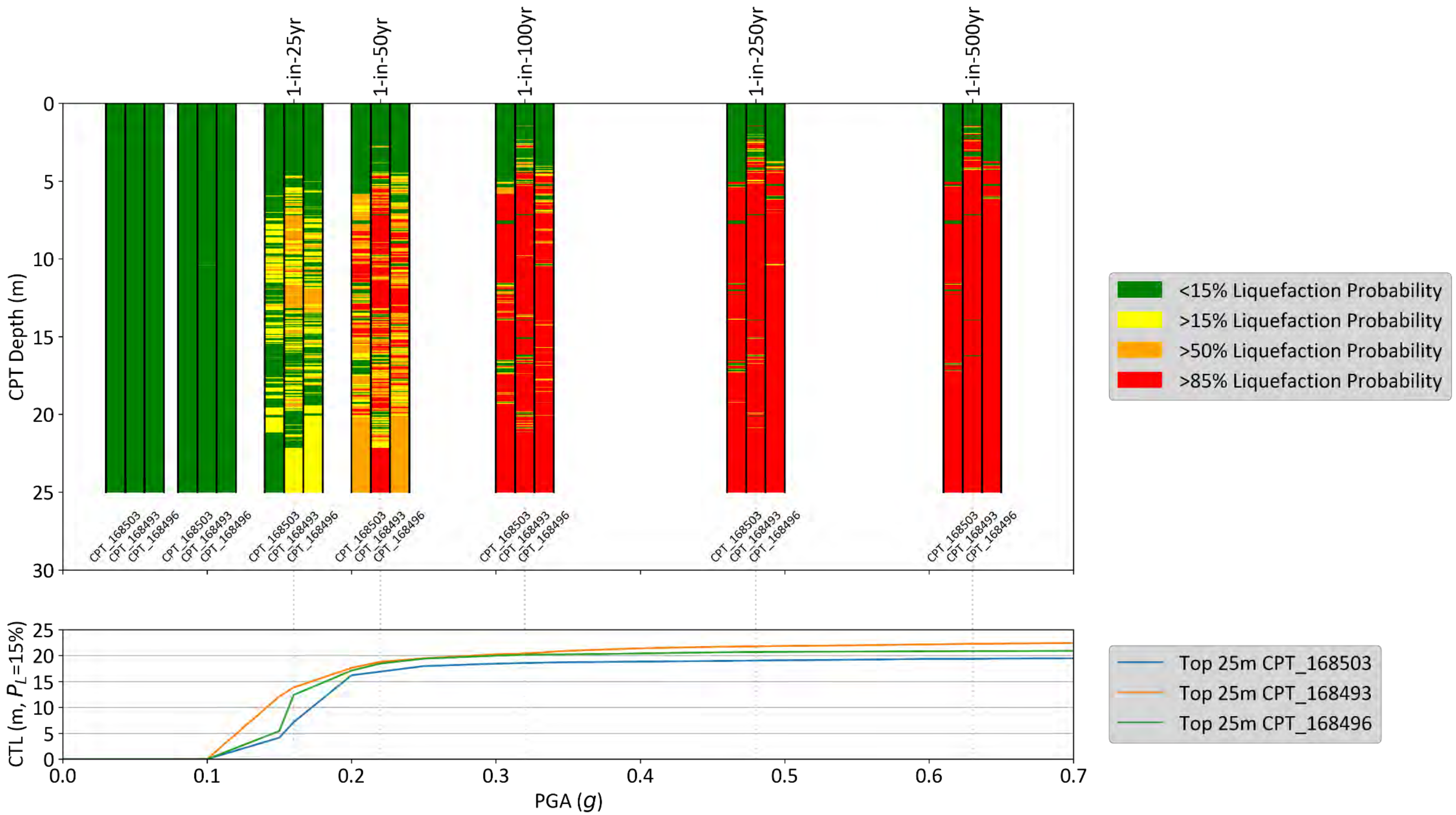


Figure 11.2: A plot of upper bound liquefaction triggering (and the resulting cumulative thickness) at increasing return period levels of earthquake shaking, for three representative CPTs from the high energy area.

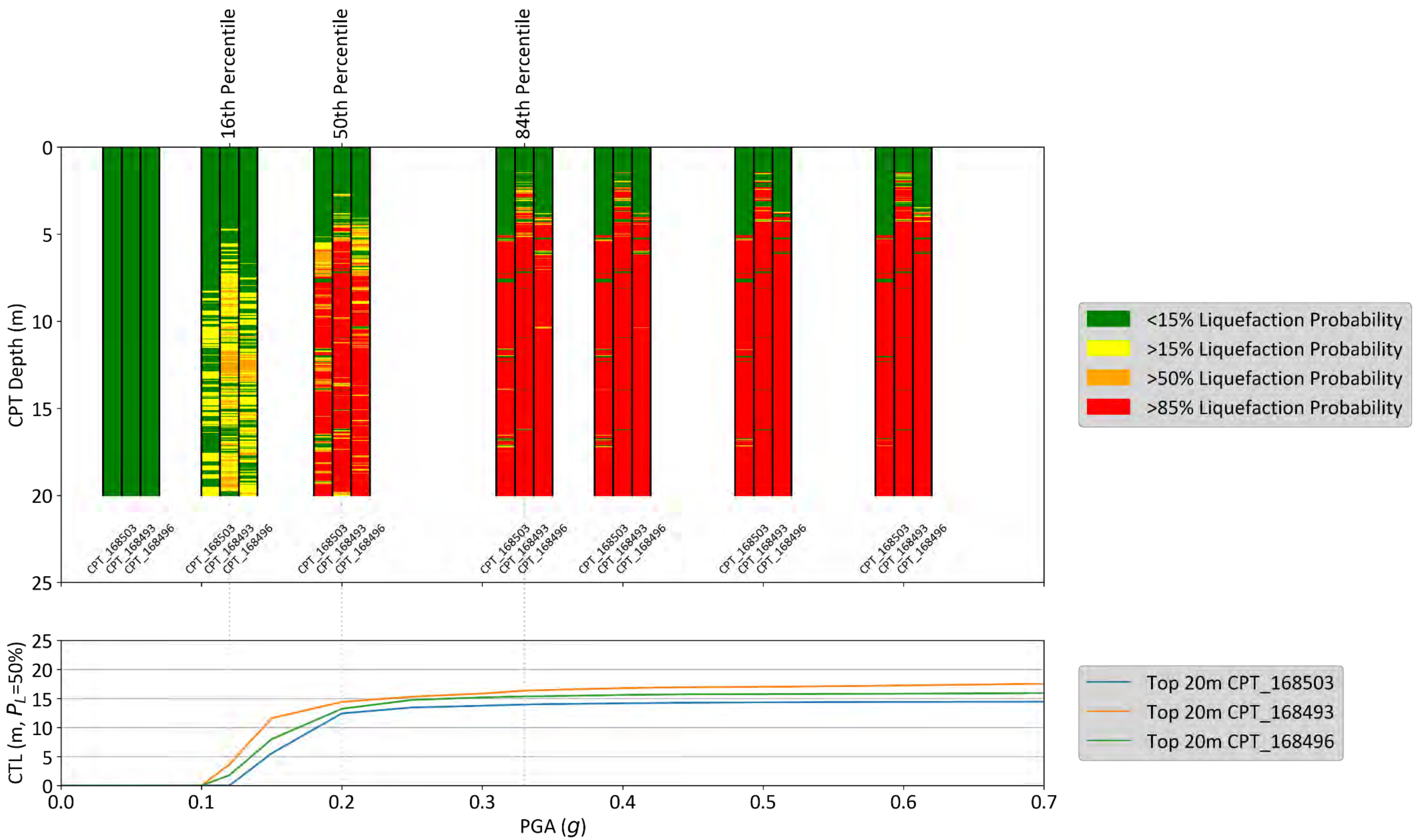


Figure 11.3: A plot of liquefaction triggering for an Alpine Fault Rupture Scenario (and the resulting cumulative thickness) for the 16th, 50th and 84th percentile shaking levels, for three representative CPTs from the high energy area.

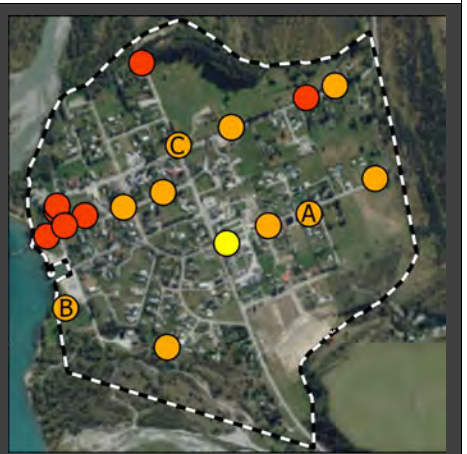
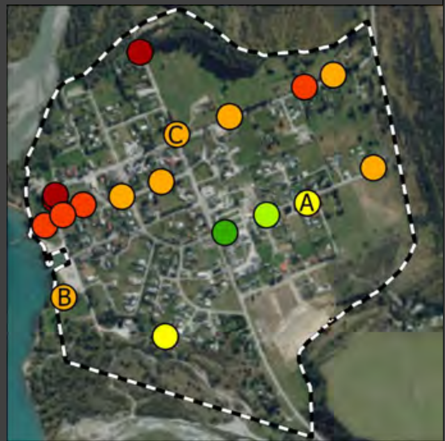
The results shown in Figures 11.1 to 11.3 show that for the higher levels of earthquake shaking between 15 to 20m of the soil profile is predicted to liquefy for the three selected CPT. The liquefaction triggering is initiated at 25 to 50-year return period levels of earthquake shaking and is fully developed at the 50 to 100-year return period levels of earthquake shaking. Higher levels of shaking at higher return periods do not significantly increase the thickness of the soil layers that are likely to liquefy. For the Alpine Fault Rupture Scenario, liquefaction triggering is predicted for the 16th, 50th and 84th percentile ground motions. This means that for an Alpine fault scenario, despite the uncertainties in the shaking intensities likely to occur at Glenorchy, liquefaction triggering is likely.

Tables 11.1 and 11.2 visually show the predicted thickness of the Cumulative Thickness of Liquefaction (CTL) for the deep CPTs for the lower bound, upper bound cases (Table 11.1), and Alpine Fault Rupture Scenario (Table 11.2) respectively. The three CPTs from Figure 11.1, Figure 11.2, and Figure 11.3 (NZGD IDs 168502, 167503, and 16896) are annotated as *A*, *B*, and *C* respectively in the figures in Table 11.1 and 11.2.

As mentioned in the previous section (Section 10); for comparison the thickness of liquefiable material is greater (approximately double) compared to the worst performing residential red zone land in Christchurch.

The low energy zone (see Figure 6.1) has a significantly higher presence of clayey silts in the 5 to 12m range, compared to the high energy zone. Whereas in the high energy zone this is the most susceptible range, in the low energy zone there is significantly more variability, mostly due to the variability in silt versus clay/organic content, rather than due to differences in density. CPT_168497 in the eastmost side of Glenorchy has a significant amount of sensitive, fine-grained material which is assessed as less susceptible compared to the other two CPTs in the area, which instead have more silty material throughout. Further CPTs in the area would help to reduce the uncertainty associated with this spatial variability.

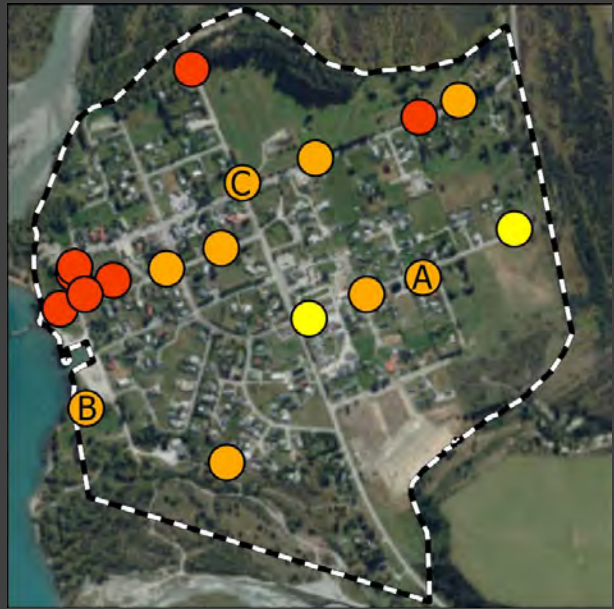
Table 11.1: The cumulative thickness of liquefaction at each CPT for various return periods, for both the lower bound case (top row) and the upper bound case (bottom row). NZGD CPTs 168502, 167503, and 16896 are labelled as A, B, and C respectively.

	25-year	50-year	100-year	250-year
Lower Bound				
Upper Bound				

Cumulative Thickness of Liquefaction

- Less than 2m
- 2–5m
- 5–10m
- 10–15m
- 15–20m
- 20–25m

Table 11.2: The cumulative thickness of liquefaction at each CPT for the Alpine Fault Rupture Scenario for the 16th, 50th and 84th percentile shaking estimates. NZGD CPTs 168502, 167503, and 16896 are labelled as A, B, and C respectively.

	16th Shaking Percentile	**Median Shaking**	**84th Shaking Percentile**
			

Cumulative Thickness of Liquefaction

- Less than 2m
- 2–5m
- 5–10m
- 10–15m
- 15–20m
- 20–25m

12 Liquefaction Land Damage Model

There are significant and widespread subsurface soil layers where liquefaction is likely to trigger. To understand what a realistic liquefaction scenario might look like with these ground conditions, a spatially probabilistic liquefaction land damage model (ignoring the effects of lateral spreading effects on the lake side of Glenorchy) has been developed. Note the lateral spreading effects are assessed separately (refer to Section 13). This was deemed necessary since within each geological layer there was no apparent spatial trend to the varying CPT tip resistance values used to infer the relative density of the material. In other words, the variability in relative density in each geological layer was found to be randomly distributed spatially within the Glenorchy area. Therefore, calculating liquefaction land damage indices at each CPT location and then interpolating the results could result in misleading outcomes necessitating the need to utilise a spatial probabilistic approach.

CPT and Borehole logs were used to establish the thicknesses of different geological layers as a continuous surface across Glenorchy. Then, the liquefaction triggering methodology (Section 11) was used to determine vertical settlement strain due to liquefaction-induced volumetric consolidation for each geological layer.

These volumetric strain values for each CPT were used to fit a probabilistic distribution for the volumetric strain for each geological layer separately. This was repeated for the range of return period earthquakes listed in Table 5.1. Then, the study area was divided into a grid of 100m-by-100m cells representing areas which have statistically independent volumetric strains. Volumetric strains were then sampled from the probabilistic distributions for each geological layer separately to calculate the corresponding liquefaction severity numbers (LSNs), giving a simulated, possible realization of liquefaction land damage across the study area.

LSN values of 0 to 8 correspond to none to minor liquefaction land damage, values of 8 to 16 correspond to minor liquefaction land damage, values of 16 to 20 correspond to minor to moderate liquefaction land damage, values of 20 to 25 correspond to moderate to high liquefaction land damage and values greater than 25 correspond to high to severe liquefaction land damage. Examples of the type of liquefaction land damage that can be expected when LSN values are greater than 25 are shown in Figures B10, B11 and B12 in Appendix B.

The median LSN over a large number of simulations is mapped in Table 12.1 for the lower bound and upper bound cases for a range of return periods. Similarly, the median LSN over a large number of simulations is mapped in Table 12.2 for Alpine Fault Rupture Scenario for the 16th, 50th and 84th percentile ground motions. Note that once the shaking is high enough, the additional liquefaction resulting at higher levels of shaking is negligible (as shown in Figure 11.1, Figure 11.2, and Figure 11.3) so the 250-year event case is considered to be representative of larger earthquakes for the lower bound case and the 50-year event case is fairly representative of larger earthquakes for the lower bound case. For the Alpine Fault Rupture Scenario, the results at the 50th and 84th percentile shaking levels are similar, whereas the at the 16th percentile shaking levels the liquefaction damage is considerably less severe.

These maps of liquefaction show that severe liquefaction land damage can occur at earthquake shaking levels as low as 25-year return periods. Between 25 and 100-year return period levels of shaking the liquefaction land damage becomes far more significant and widespread across all the lower lying areas of Glenorchy in the north and west (similar to what is shown in Figures B10, B11 and B12 in Appendix B). It is very important to understand that these maps show an estimate of the median performance over many possible scenarios; however in reality there would likely be areas where the liquefaction is more severe than the median, as well as areas where it is less severe. This is an inherently probabilistic process and these maps are intended to show broad trends across Glenorchy. The maps should not be used as a basis for site-specific assessment for any particular site.

Table 12.1: The median LSN from a large number of simulations for various return periods, for both the lower bound case (top row) and the upper bound case (bottom row).

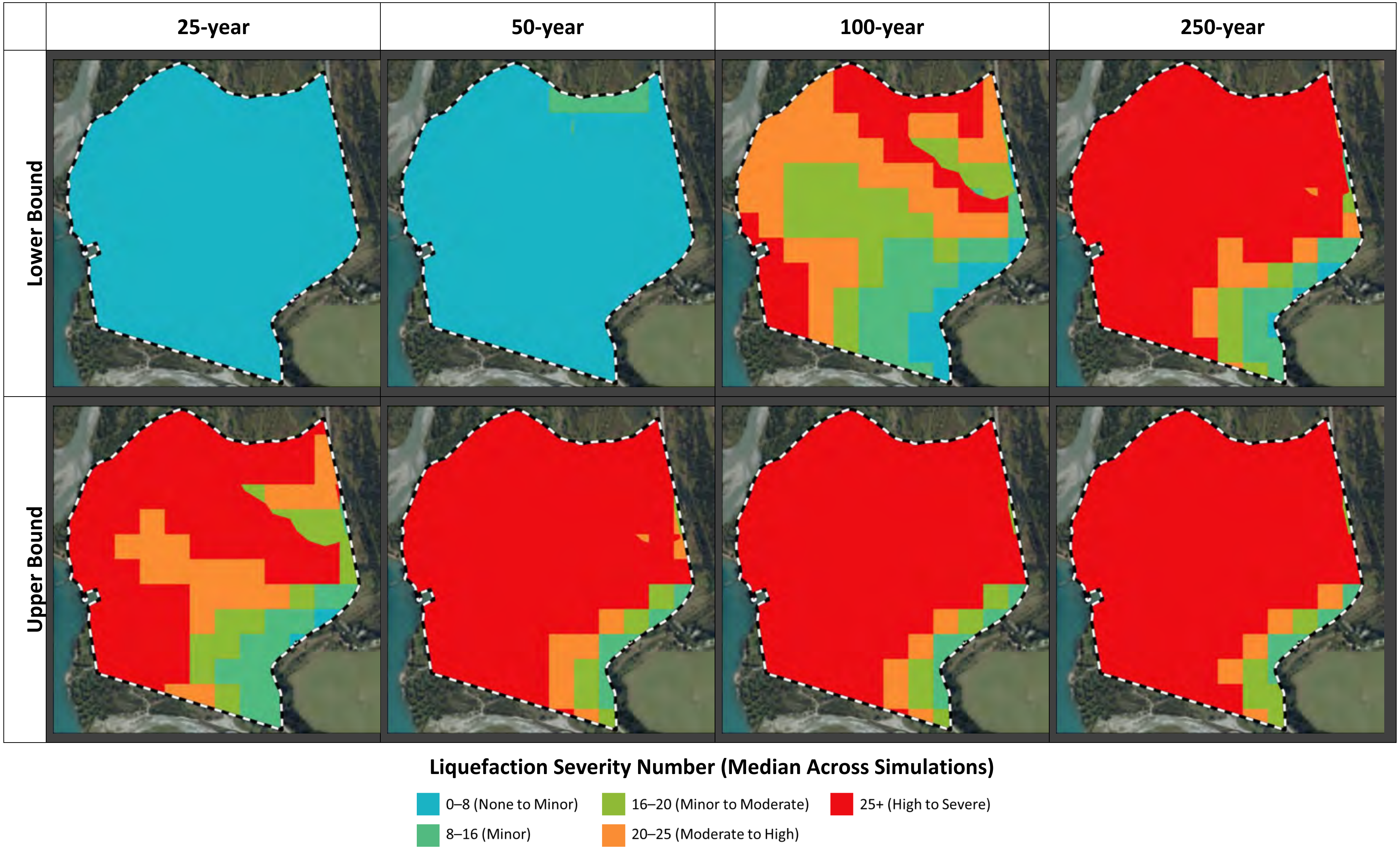
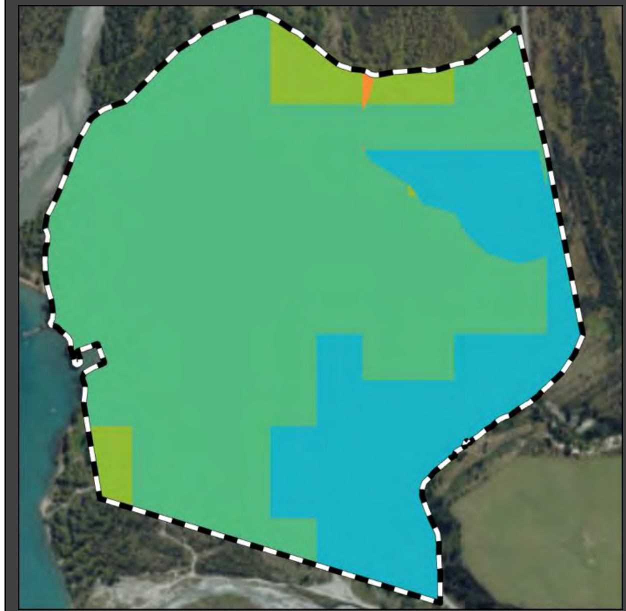


Table 12.2: The median LSN from a large number of simulations for various return periods, for the Alpine Fault Rupture Scenario.

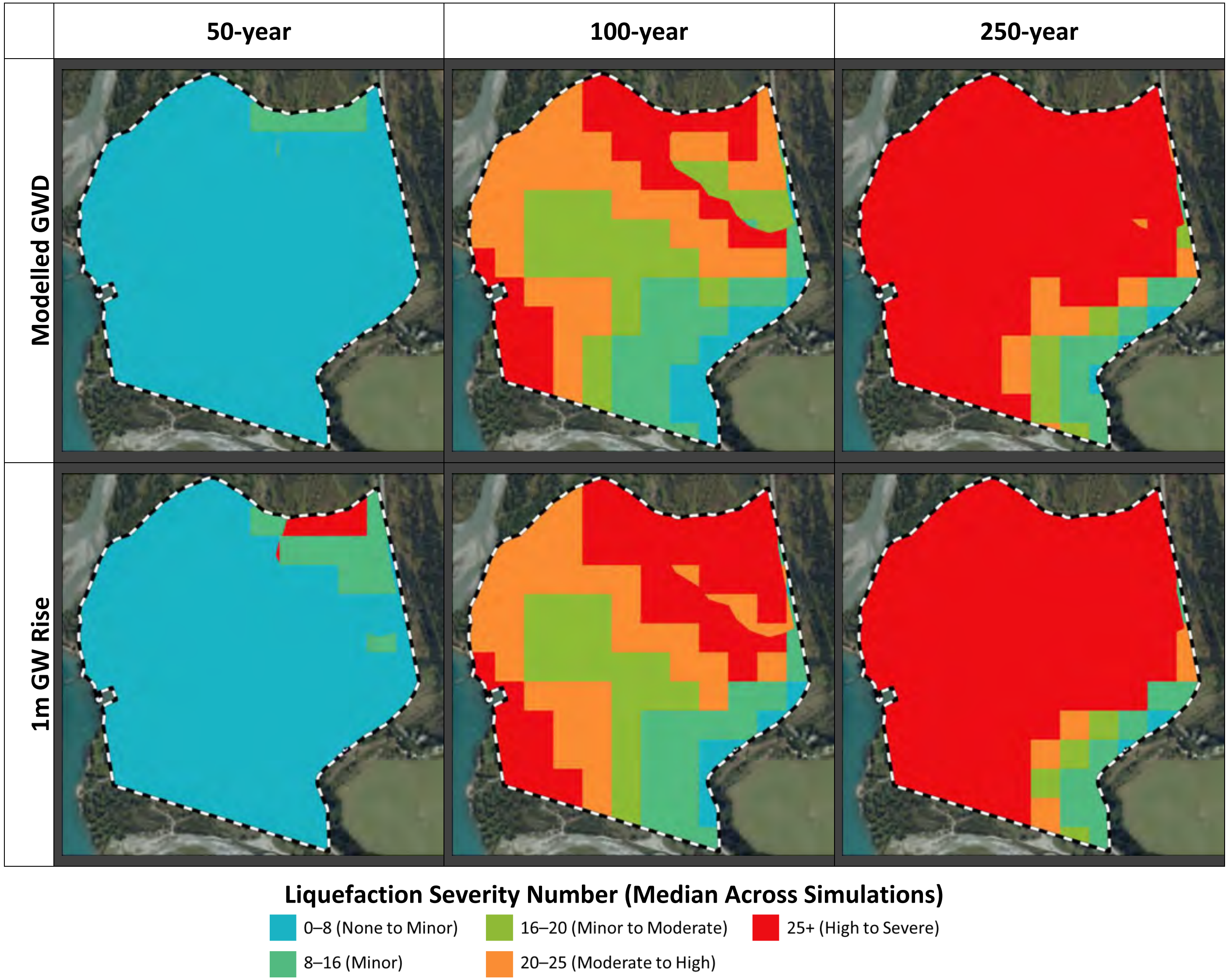
	16th Shaking Percentile	50th Shaking Percentile	84th Shaking Percentile
			

Liquefaction Severity Number (Median Across Simulations)

- 0–8 (None to Minor)
- 8–16 (Minor)
- 16–20 (Minor to Moderate)
- 20–25 (Moderate to High)
- 25+ (High to Severe)

As noted in Section 9, the data used to develop the groundwater model was collected over an exceptionally dry period, so the median groundwater could potentially be higher. Table 12.3 shows the results of a sensitivity analyses of a 1m groundwater rise on the liquefaction vulnerability model for the lower bound case. It demonstrates that the increase in liquefaction vulnerability is not appreciable for most of the Glenorchy study area, indicating that the liquefaction vulnerability model is not particularly sensitive to uncertainty in the groundwater levels. The exception is in the northeast where there is an increase in liquefaction vulnerability with higher ground water levels at the more frequent return periods.

Table 12.3: A comparison of the median LSN (for a large number of simulations) showing the effect of a 1m groundwater rise for the lower bound case, for various return periods.



13 Lateral Spreading Assessment

13.1 1D Lateral Spreading Assessment

Methods for estimating lateral spreading displacements at the site exist but these are known to have limited accuracy (typically the accuracy of predictions has been shown to be within a range of half to double when compared to the observed lateral spreading). Three methods have been used to assess the lateral spreading for both the lower and upper bound cases to understand the expected displacements that can be expected at the various return periods. The three methods that have been used are:

- The semiempirical approach proposed by Zhang et al. (Zhang, Robertson, & Brachman, 2004);
- The empirical equation proposed by Gillins & Bartlett (Gillins & Bartlett, 2014) has been adopted, which is a modification of an earlier equation proposed by Youd et al. (Youd, Hansen, & Bartlett, 2002); and
- The flexible sliding block method (Newmark block type assessment) proposed by Bray and Macedo (Bray & Macedo, 2019).

The Bray & Macedo method has a lot of steps and is time consuming to apply. At each offset distance from the lake new stability modelling is required to assess the lateral spreading at that point. Therefore, the Bray & Macedo method has only been applied for a limited extent as an independent check of the lateral spreading predicted by the other two methods with are much simpler and less time consuming to apply.

The lateral spreading assessments were undertaken for the typical cross section shown in Figure 7.1 and 7.2. The results are shown in Figure 13.1 for the upper and lower bound case, and in Figure 13.2 for the Alpine Fault Rupture Scenario. The analysis was performed at different offsets from the lake edge; in the case of the methodology proposed by Bray & Macedo (2019), the analysis has only been performed to approximately 140m from the lake edge.

The results for the Zhang et al. (2004) method are shown on the left-hand column, the results from the Gillins & Bartlett (2014) method are shown in the middle column and the results from the Bray and Macedo (2019) method are shown on the right hand column. For Figure 13.1 the top row is for the 25-year return period levels of earthquake shaking, and the bottom row is for the 500-year return period levels of earthquake shaking. The results for the lower bound case for each method for each return period are denoted by the lower bound dashed line in each graph and the results for the upper bound case for each method for each return period are denoted by the upper bound dashed line in each graph. The shading in-between the lower and upper bound lines represent the likely range of displacement predicted by each method. It is noted that the lower bound lateral spreading estimates are zero for return period levels of earthquake shaking of 25 years for the Zhang et al. method, 50 years for the Bray and Macedo method and 250 years for the Gillins and Bartlett method. The credibility of these lower bound estimates, in particular for the Gillins at Bartlett method, are discussed below.

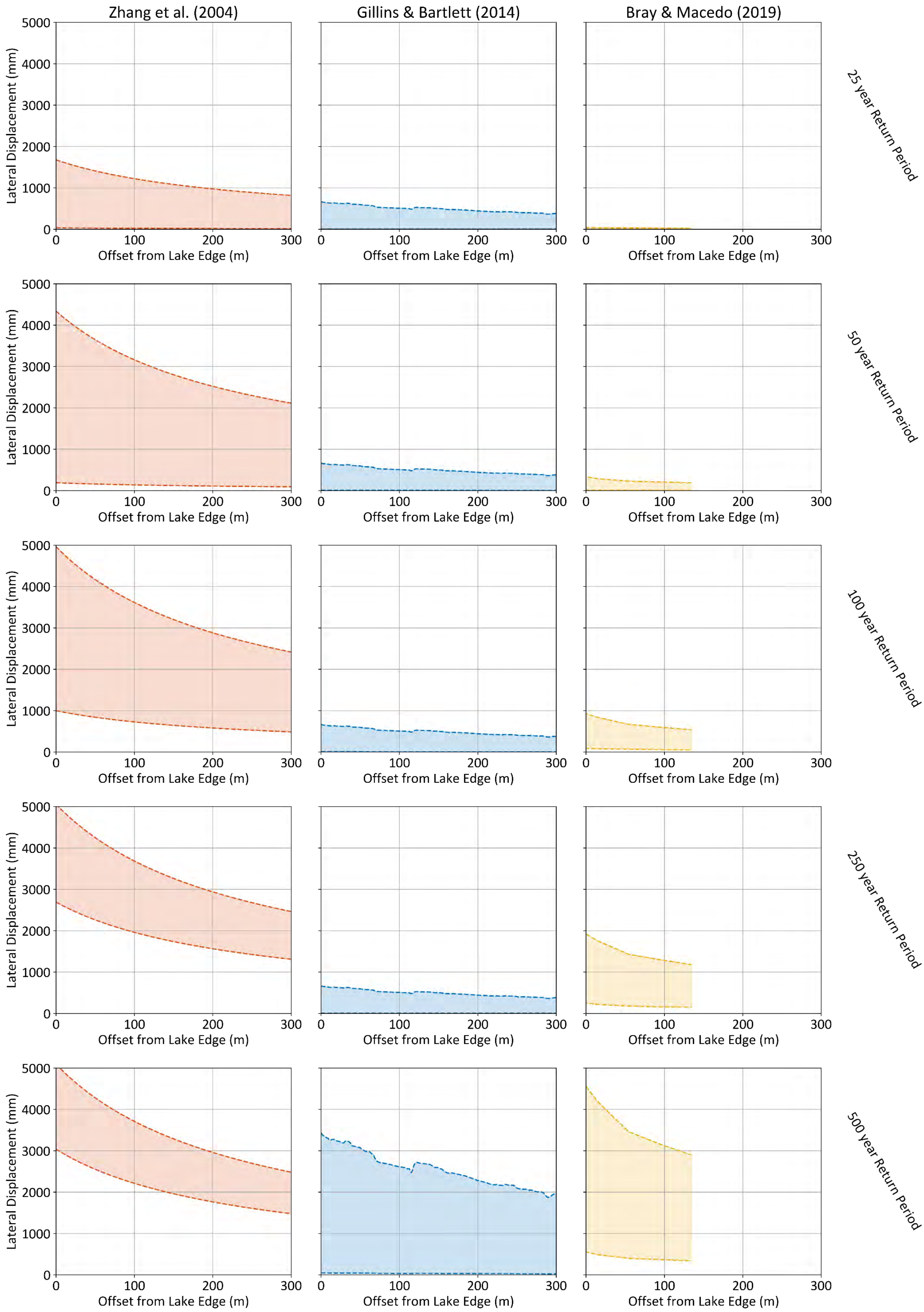


Figure 13.1: Lateral Spreading versus the distance from the Lake Edge for a representative cross section, comparing three different assessment methodologies (across columns) and different return-periods (across rows). On each graph, the upper dashed line represents the upper bound case, and the lower dashed line represents the lower bound case.

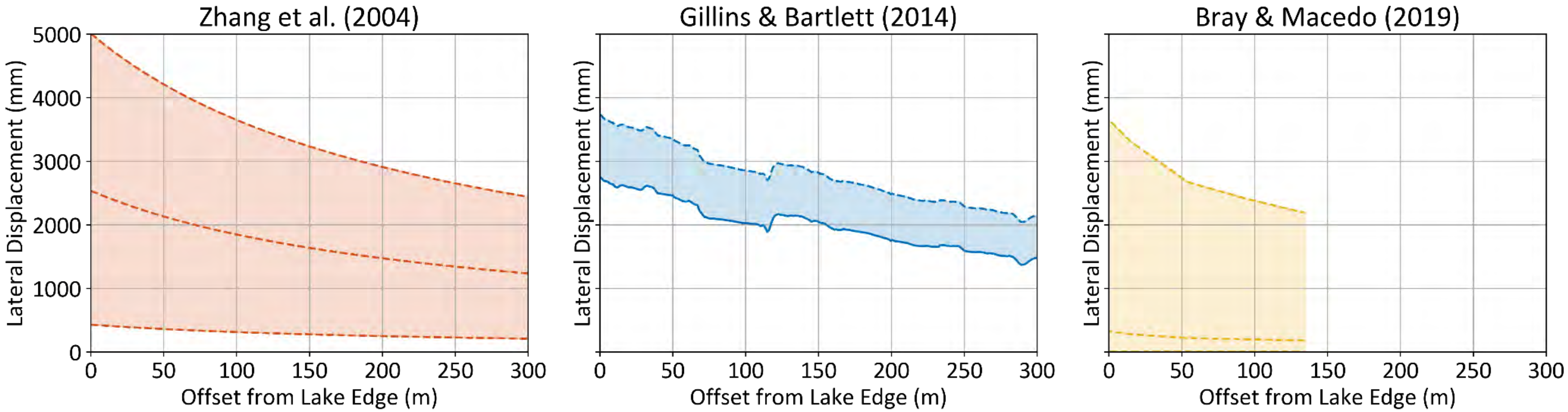


Figure 13.2: Lateral Spreading versus the distance from the Lake Edge for a representative cross section for the Alpine Fault Rupture Scenario, comparing three different assessment methodologies (across columns). For the method given by Zhang et al. there are three dashed lines corresponding to the 16th, 50th, and 84th percentiles of shaking. For that given by Gillins & Bartlett (2014), the 16th and 50th lines coincide as a solid line, whereas the 84th line is dashed. Finally, for the method given by Bray & Macedo (2019), the 16th line is approximately zero, while the 50th and 84th lines are shown as dashed.

The results for the typical cross section show:

- The lateral spreading is highest near the lake edge and decreases with increasing distance from the lake edge – as would be expected;
- The lateral spreading increases with larger return period earthquake shaking. At the 25-year return period levels of earthquake shaking the lateral spreading is likely to be less than 1m at the lake edge whereas at 500-year return period levels of earthquake shaking the lateral spreading could be up to 4 to 5m (typically twice as large as the lateral spreading that was observed in the residential red zone of Christchurch following the 2010 to 2011 Canterbury earthquakes – refer to Figures B1, B4, B5, B6, B7, B8 and B9 in Appendix B);
- The lateral spreading from an Alpine Fault Rupture Scenario is likely to be similar to the lateral spreading from 500-year return period levels of earthquake shaking (i.e. 3 to 5m at the lake edge);
- The different methods estimate different ranges of lateral spreading, particularly at the more frequent return periods. The estimates from the different methods become more consistent at the larger return periods and also for the Alpine Fault Scenario;
- The range of lateral spreading estimates obtained using the Gillins & Bartlett (2014) method are mostly within the same range given by the Bray and Macedo (2019) method up to 250-year return period levels of earthquake shaking; and
- The results using the Zhang et al. (2004) method generally indicate higher lateral spreading estimates and conversely the results using the Gillins & Bartlett (2014) method generally indicate lower lateral spreading estimates.

While each of the methods shows similar trends, the different methods result in a different range of lateral spreading predictions. They are all valid models and they each have technical strengths and weaknesses. They have been derived or validated against international case histories of lateral spreading from historical earthquakes. Therefore, to obtain an upper bound lateral spreading estimate, each method has given an equal weighting (i.e., a 33% weighting to each method).

It is noted that the upper bound weighted average lateral spreading estimate for the 500-year levels of shaking is approximately 1.2 times the upper bound Gillins & Bartlett (2014) method results.

For the Gillins & Bartlett (2014) method the lower bound estimates for the larger return periods indicate no lateral spreading. This is unrealistic but can be explained by the higher seismic source distances in Table 5.1 for the lower bound case. The Gillins & Bartlett (2014) method does not use shaking intensity as input variable, but instead uses the earthquake magnitude and seismic source distance[1]. However, at the larger return periods, even for the lower bound case shaking levels, liquefaction triggering *is* predicted using the methodology in Section 11. Therefore, the lower bound estimates for the Gillins & Bartlett (2014) method are not considered credible at the larger return periods. Hence, to develop a lower bound lateral spreading estimate, the Gillins & Bartlett (2014) method has been given a zero weighting, while the other two methods an equal weighting (i.e., a 50% weighting to each method).

It is noted that the lower bound weighted average lateral spreading estimate for the 500-year levels of shaking is approximately 0.5 times the upper bound Gillins & Bartlett (2014) method results.

For the Alpine Fault Scenario, the 16th percentile estimates from the Gillins & Bartlett (2014) method are higher than the lower bound estimates for a (time-independent) 500-year Return Period. This is because of the larger magnitude for that scenario.

[1] In other words, there is, embedded into the empirical equations, a simplified ground motion prediction allowance, which at larger seismic source distances results in negligible shaking intensity and hence negligible lateral spreading for the smaller earthquake magnitudes.

It is noted that the 84th percentile weighted average lateral spreading estimate for the Alpine Fault Scenario is approximately the 1.0 times the 84th percentile Gillins & Bartlett (2014) method results (i.e., they are approximately equal).

13.2 2D Lateral Spreading Assessment

The results from the 1D lateral spread assessment described in Section 13.1 have been used to develop and calibrate a 2D lateral spread assessment to enable the development of lateral spread contours for the 500-year levels of shaking as well as the Alpine Fault Scenario.

The Gillins & Bartlett (2014) method was used to develop lateral spread contours across the entire western side of Glenorchy in 2D at points in a 1m x 1m grid. The distance to the nearest point on the free face (mapped in Figure 7.2) was determined for each grid point, and the effective free face height was determined based on the maximum depth of predicted liquefaction (according to the assessment in Section 11), along with the cumulative thickness of liquefiable material. Lateral spread calculations were then performed at each grid point using these inputs, along with the seismicity information from Table 5.1.

To obtain an estimate for lateral spreading at a 500-year return period, the Gillins & Bartlett (2014) values have been scaled based on the analyses and results discussed in Section 13.1. In particular, to develop upper bound lateral spreading contours, the upper bound estimate from the Gillins & Bartlett (2014) method were scaled by a factor of 1.2. To develop lower bound lateral spreading contours, the upper bound estimate from the Gillins & Bartlett (2014) method were scaled by a factor of 0.5. The lower bound and upper bound estimates are shown in Table 13.1. The lateral spreading estimates range from 0.5m (lower bound) to 4m (upper bound) at the lake edge.

Similarly, for the Alpine Fault Rupture Scenario, the 84th percentile lateral spread values were determined as 100% (i.e., the same) as the Gillins & Bartlett (2014) values. For the 50th and 16th percentile, scaling factors of 50% and 0% have been applied respectively. The 16th, 50th and 84th percentile lateral spreading contours for the Alpine Fault Scenario are shown in Table 13.2. The lateral spreading estimates range from 0 metres (16th percentile) to 3 metres (84th percentile) at the lake edge.

For context, the lateral spreading that occurred in the worst performing land in Christchurch (which subsequently became the residential red zone) was typically in the order of 1 to 3m. Therefore, based on Table 13.1, the predicted lateral spreading near the lake in Glenorchy for the 500-year return period levels of shaking is comparable or worse to that observed in the worst parts of the residential red zone in Christchurch (refer to photos B4 to B9 in Appendix B).

The higher the free face, the larger the lateral spreading and the further back it extends and the more potential damage at any given distance (i.e., greater displacements). As already discussed in Section 7, the free face height is 25m in this case, which is significant. Following the Canterbury Earthquake Sequence, the areas that were most severely affected by lateral spreading in the residential red zone areas of Christchurch had free face heights of about 4m. Consequently, the lateral spreading damage is likely to be more severe compared to the residential red zone areas of Christchurch and also likely to extend further inland and hence be more extensive compared to the extent of the residential red zone areas of Christchurch.

Table 13.1: Lateral Spreading for the lower bound and upper bound cases. The ground would be expected to move towards the lake by the annotated distance.

	Lower Bound	**Upper Bound**
500-year Return Period		

Table 13.2: Lateral Spreading for the Alpine Fault Rupture Scenario at different percentiles of shaking. The ground would be expected to move towards the lake by the annotated distance.

	16th Percentile	50th Percentile	84th Percentile
Alpine Fault Rupture Scenario			

While lateral spreading movement can damage land (including causing significant vertical settlement), lateral stretch is what causes the most significant ground cracking and damage to infrastructure and buildings (refer to photos B4 to B9 in Appendix B). Lateral stretch is the differential spreading amount: i.e., if the front of a building moves 1m toward the lake and the back only moves 0.5m, the lateral stretch is 500mm over the length of the building. Based on the lateral spreading contours presented in Tables 13.1 and 13.2, the potential lateral stretch was estimated for a length scale of 25 metres (i.e., the length of a typical residential house) to identify the areas where the lateral spreading would have the most damaging effects. The various lateral spread damage zones are shown on Figure A1 in Appendix A.

Figure A1 in Appendix A shows that a significant western portion of Glenorchy would experience severe (>500mm) levels of lateral stretch, and an even larger portion would experience major (>200mm) lateral stretch for both the 500-year and Alpine Fault scenarios. These are the areas where the most severe lateral spreading damage are expected to occur. If the study were a greenfield that was being considered for development, then these major and severe lateral spread damage zones should be avoided based on the MBIE & MfE (2017) guidance.

However, the study area is an existing township and there is no guidance on what to do when major and severe lateral spreading damage zones are identified for existing developed areas. It is unlikely that the existing buildings will safely withstand the lateral spread damage. Without specific engineering design, residential buildings in these zones cannot be expected to safely withstand these levels of lateral stretch. For any new building work in these lateral spreading zones, Section 12.2.2 of the Canterbury Recovery Residential Guidance (MBIE, 2012) provides guidance for various levels of lateral stretch vulnerability. At major levels (between 200 and 500 mm), the most heavy duty robust foundation design option for residential buildings (i.e. the TC3 Type 2B system in the Canterbury Residential Guidance) could potentially be used subject to specific engineering assessment. This foundation system is approximately $50 to $100k over and above the cost of a residential house on conventional foundations. At severe levels (>500mm), more substantial engineering works are required, which are outside of the scope of the Canterbury Residential Guidance.

Severe liquefaction on flat ground away from lateral spreading areas can cause significant vertical subsidence through volumetric consolidation, as well as through loss of ejecta. Lateral spreading further compounds this vertical settlement effect. The vertical drop related to lateral spreading typically ranges from 3 to 15% of the horizontal predicted amount of lateral spread but can increase up to 50% when lateral spreading becomes larger. Refer to Figures B3, B5 and B9 in Appendix B for examples. Based on observations from the 2010–2011 Canterbury earthquakes and 2016 Kaikoura earthquake, when the lateral spreading becomes large, the crust has an increased tendency to break up into blocks and the performance becomes increasingly less predictable. Some blocks only drop vertically by a small amount whereas other blocks drop vertically by a larger amount. Sometimes larger vertical drops occur further away from the free face and the settlement of these blocks push and translate the blocks horizontally nearer the face. In the severe stretch zone (>500mm) the vertical drop due to lateral spreading for both the 500-year and Alpine Fault scenarios could be in the order of 0.5m to 1m in addition to the vertical settlement caused by liquefaction ejecta and volumetric consolidation. These levels of vertical settlement are likely to cause extensive damage to existing structures in the spreading zone.

Vertical subsidence poses a special concern in Glenorchy due to its effect on the flooding hazard. The large vertical subsidence for the properties nearer the lakefront could cause significant flood level issues following an earthquake event, since for the same flood level the inundation depth experienced by houses would be greater.

14 Final Map and Conclusion

Figure A1 in Appendix A shows the liquefaction vulnerability categorization developed according to the criteria in the MfE/MBIE Guidance and the framework shown in Figure 4.1. This has been developed based on the modelled liquefaction effects of vertical subsidence as well as lateral spread and stretch across multiple the earthquake scenarios, especially the 100-year and 500-year scenarios as well as the Alpine Fault Rupture scenario which is approximately equivalent to a 30-year return period event.

Liquefaction damage is considered possible across the entirety of Glenorchy, except along the slope up to Bible Terrace where the liquefaction vulnerability is deemed low. In the north and in west, liquefaction vulnerability is considered high, whereas towards the Bible Terrance this vulnerability is considered medium.

Overall, liquefaction poses a significant hazard to Glenorchy. The large cumulative thicknesses of liquefiable material (between 10 and 20m in most cases) together with a large 25m free face near the lake and relatively low-lying land together are likely to result in severe and widespread liquefaction damage in a medium to large earthquake. The hazard posed by the Alpine Fault is extremely high over the next 50 years and so the likelihood of a severe level of liquefaction damage, including severe damage from lateral spreading in the western side of Glenorchy occurring in the next 50 years is very high.

For comparison, in the worst affected areas of Christchurch where liquefaction and lateral spreading effects were observed, the cumulative thickness of liquefiable material was generally 10m or less; free face heights along the Avon River were 4m, and the groundwater is comparably shallow. In such areas, following the Canterbury earthquakes, the government deemed that land repair would be prolonged and uneconomic and so the land was ‘red zoned’. The severity of damage to land, infrastructure and houses meant that solutions designed to deal with that level of damage, and prepare for comparable damage in the future, were not feasible at the time.

The vertical subsidence effects from liquefaction and lateral spreading are a special concern in Glenorchy owing to the lake flooding hazard. All areas experiencing significant vertical subsidence (in extreme cases predicted to be around 1m) would have an increased vulnerability to flooding. In the future, climate change is predicted to increase the frequency of flooding events in Glenorchy. The already high flooding risk would be further increased by any reduction in elevation from vertical subsidence following an earthquake.

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16 Applicability

This report has been prepared for the exclusive use of our client Otago Regional Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

The susceptibility analyses carried out represent probabilistic analyses of empirical liquefaction databases under various earthquakes. Earthquakes are unique and impose different levels of shaking in different directions on different sites. The results of the liquefaction susceptibility analyses, and the estimates of consequences presented within this document are based on regional seismic demand and published analysis methods, but it is important to understand that the actual performance may vary from that calculated.

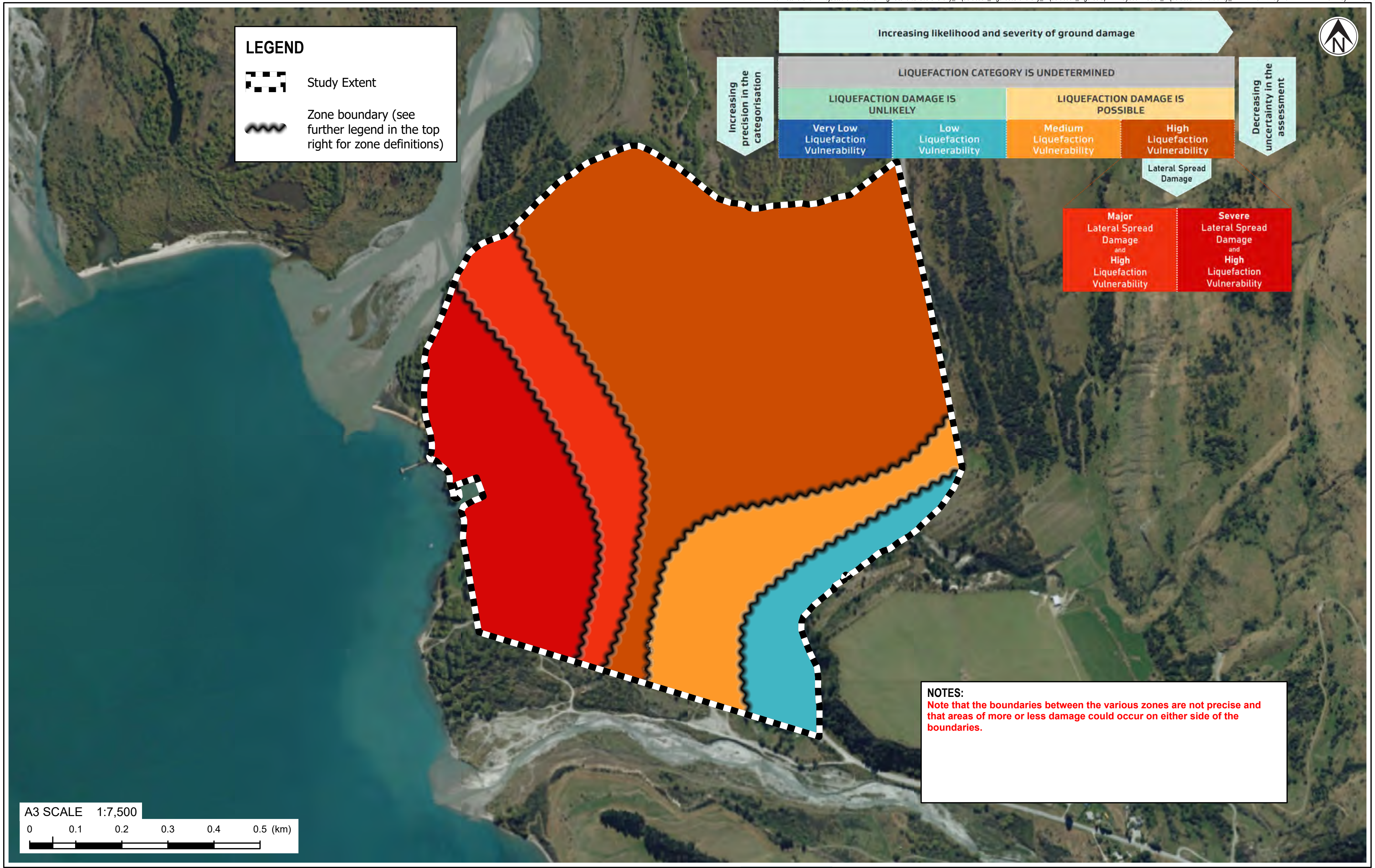
This assessment has been made at a broad scale across Glenorchy and is intended to describe the typical range of liquefaction vulnerability across neighbourhood-sized areas. It is not intended to precisely describe liquefaction vulnerability at individual property scale. This information is general in nature, and more detailed site-specific liquefaction assessment may be required for some purposes (e.g., for design of building foundations).

Tonkin & Taylor Ltd

Report prepared by:	Authorised for Tonkin & Taylor Ltd by:
....	....
Nathan McDougall	Sjoerd van Ballegooy
Engineer	Project Director & Technical Director

Appendix A: Map of liquefaction and lateral spreading damage potential zones

T:\Christchurch\TT Projects\1017916\WorkingMaterial\GIS\Glenorchy_Liquefaction_Figures\Glenorchy_Liquefaction_Figures.aprx Layout: FIG002_LiquefactionVulnerability_MBIE 2022-May-16 11:17 AM Drawn by NAMC



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NOTES:
Basemap NZ - Imagery: Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors. NZ Navigation Map: Eagle Technology, LINZ, StatsNZ, NIWA, Natural Earth, © OpenStreetMap contributors.

REV	DESCRIPTION	GIS	CHK	DATE
1	Second version	NAMC	YYYY	16/05/22

LOCATION PLAN

PROJECT No.	1017916.2000	
DESIGNED	NAMC	MAY.22
DRAWN	NAMC	MAY.22
CHECKED		
APPROVED		DATE

CLIENT OTAGO REGIONAL COUNCIL
PROJECT GLENORCHY LIQUEFACTION STUDY
TITLE LIQUEFACTION VULNERABILITY (MFE/MBIE CLASSIFICATION) AND LATERAL SPREADING DAMAGE ZONES
SCALE (A3) 1:7,500 FIG No. FIGURE A1 REV 1

Appendix B: Maps and photos showing examples of the liquefaction and lateral spreading that was observed following the 2010-2011 Christchurch earthquakes and 2016 Kaikoura earthquakes

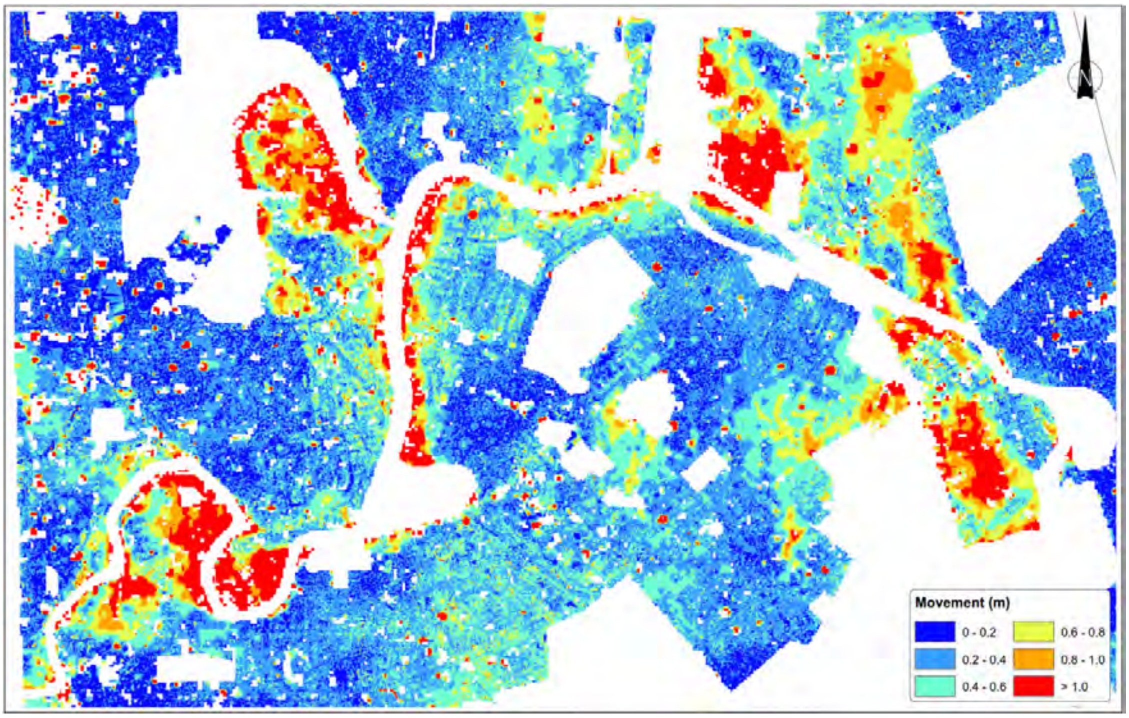

Figure B1 - Map showing the extent of lateral spreading in the eastern suburbs of Christchurch. The maximum lateral spread was approximately 3m.

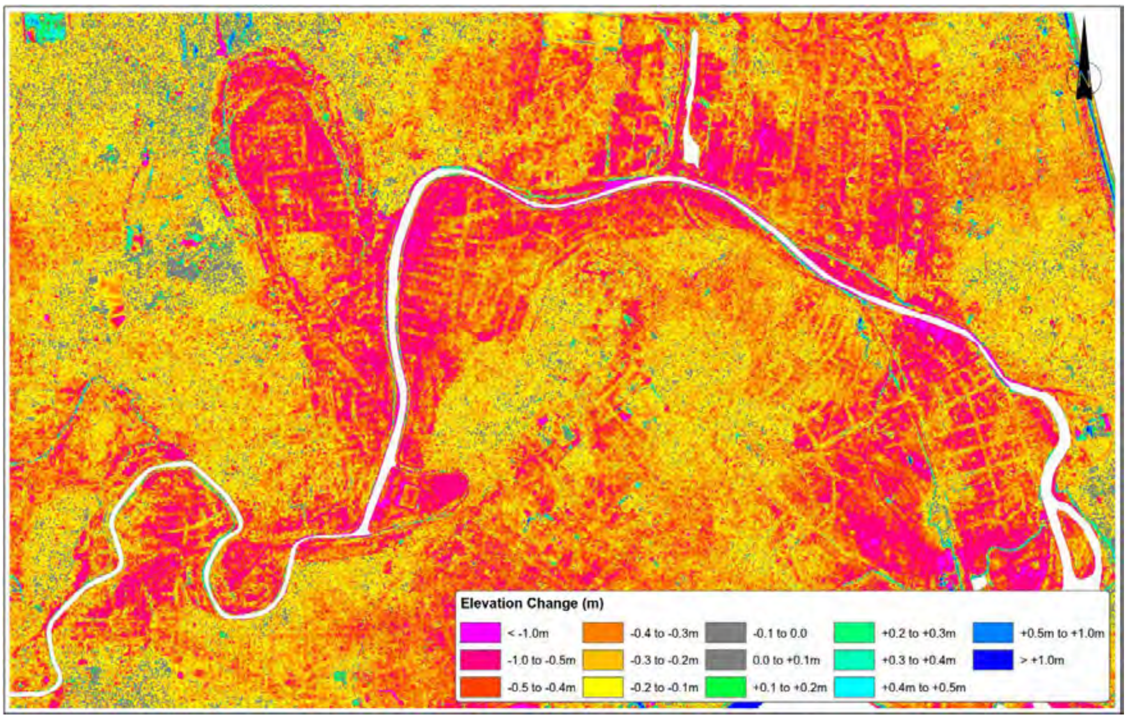

Figure B2 - Map showing the ground surface subsidence in the eastern suburbs of Christchurch due to liquefaction and lateral spreading. Visual comparison with Figure B1 shows that the areas where lateral spreading occurred have a significantly higher subsidence. This demonstrates that lateral spreading significantly increases subsidence.

Figure B3 – Photo showing the lateral spreading that occurred in Blenheim at a vineyard along the Wairau River following the 2016 Kaikoura earthquake. The lateral spreading horizontal movement was approximately 3m and the vertical drop was approximately 1m (approx. 33% of the horizontal movement).

Figure B4 - Photo showing lateral spreading effects at Courtenay Drive, Kaiapoi following the 2010 Darfield earthquake. The ground crack filled up with liquefied sand and resulted in a significant evacuation hazard following the event. The lateral spreading at this site was approximately 2m.

Figure B5 - Photo showing lateral spreading effects at Courtenay Drive, Kaiapoi following the 2010 Darfield earthquake. The lateral spreading caused approximately 1m of horizontal stretch and also a 300mm vertical offset. The total lateral spreading at this site was approximately 2m.

Figure B6 - Photo showing lateral spreading effects at Courtenay Drive, Kaiapoi following the 2010 Darfield earthquake. The total lateral spreading at this site was approximately 2m.

Figure B7 - Photo showing lateral spreading effects at Courtenay Drive, Kaiapoi following the 2010 Darfield earthquake. The total lateral spreading at this site was approximately 2m. If the lateral spreading at the site had been higher, this building would likely have collapsed.

Figure B8 - Photo showing lateral spreading at Charles Steet, Kaiapoi following the 2010 Darfield earthquake. The total lateral spreading at this site was approximately 1.5m. Vertical offsets in the order of 300mm can also be seen in the photo (approx. 20% of the horizontal movement).

Figure B9 - Photo showing lateral spreading at Fitzgerald Ave, Christchurch following the 2011 Christchurch earthquake. The total lateral spreading at this site was approximately 2m. Vertical offsets in the order of 500mm (approx. 50% of the horizontal movement).

Figure B10 - Photo showing liquefaction in Christchurch following the 2011 Christchurch earthquake. Approximately 400 to 500mm of liquefaction ejecta inundated the roads.

Figure B11 - Photo showing liquefaction in Christchurch following the 2011 Christchurch earthquake. Approximately 200mm to 300mm of liquefaction ejecta inundated the roads.

Figure B12 - Photo showing liquefaction in Christchurch following the 2011 Christchurch earthquake. There were significant roadway stability issues causing significant evacuation hazards.

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WENTZ - PACIFIC
GEOTECHNICAL ENGINEERS

26 May 2022

Otago Regional Council
via email: Tim.vanWoerden@orc.govt.nz

Attention: Tim van Woerden – Natural Hazards Analyst

Dear Tim

Glenorchy Liquefaction Vulnerability Assessment – Geotechnical Peer Review

A Liquefaction Vulnerability Assessment of the Glenorchy township was undertaken on behalf of the Otago Regional Council (ORC). The assessment was undertaken in general accordance with the Ministry of Business, Innovation and Employment National (2017)[1] guidelines to help inform planning and assessment of land use on potentially liquefiable land. The assessment was intended to achieve a "Level C" level of detail.

This final review includes the following:

- a summary of reviewer's relevant experience and expertise;
- a summary of reviewer's involvement in the assessment process;
- a summary of agreement with key assumptions, or otherwise, made as part of the assessment; and,
- confirmation that the results of the assessment are fit for purpose, or otherwise.

Summary of Reviewer's relevant experience and expertise

I am a Chartered geotechnical engineer with over 30 years of experience practising earthquake geotechnical engineering. For the past 10 years, much of my practise has been focussed on seismically-induced liquefaction and its effect on structures in New Zealand. I was a technical reviewer of MBIE's National liquefaction planning guidance document (referenced above) which was used to guide this assessment. I am a member of the New Zealand Geotechnical Society's Editorial Panel that developed the six guidance documents (modules) for performing geotechnical earthquake engineering in New Zealand and was the principal author of Module 2 – Site Investigation. I have participated in field research projects in New Zealand related to increasing understanding of the triggering of liquefaction in susceptible soils and improving the performance of liquefiable ground during an earthquake. I have undertaken peer reviews of liquefaction assessment and mitigation for several major NZ and international projects, as well as NZ district / regional council assessments similar to the Glenorchy study.

Summary of Reviewer's involvement in the assessment process

I participated in two meetings with project team to review the assessment methodology, level of mapping effort and detail, geomorphology, and preliminary findings. I completed a review of a draft

[1] Ministry of Business, Innovation & Employment (MBIE), 2017. Planning and engineering guidance for potentially liquefaction-prone land, issue date: September 2017.

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of the assessment report[2] in February 2022 and participated in a subsequent meeting with project team to discuss the key review comments. This initiated a more detailed assessment of: 1) the seismic hazard used for the vulnerability assessment; and, 2) what effects the potential uncertainty in the hazard might have on the liquefaction vulnerability.

I had further discussions with Tonkin & Taylor's project lead (Dr Sjoerd van Ballegooy) during preparation of the final report[3] which incorporates the findings and conclusions from the further detailed assessment.

Summary of agreement with methodology, key assumptions and uncertainties, or otherwise

I was involved in the discussion of the assessment methodologies to be used, and the key assumptions, uncertainties and limitations associated with the assessment through project review meetings and discussions with the consultant lead (Dr Sjoerd van Ballegooy). I believe that the assessment methodology, key assumptions, and level of detail achieved are appropriate given the available information.

Confirmation the results are fit for purpose, or otherwise

It is my opinion that the methodology used for the assessment is appropriate and that the work was performed to a satisfactory degree of rigor for a "level C" level of detail in accordance with the above-referenced MBIE guidance document. The approach taken is clear and specific in the treatment of the inherent and significant uncertainties associated with an area-wide assessment of liquefaction vulnerability.

I am satisfied that my review comments and recommendations have been adequately addressed, and it is my opinion that the assessment is fit for purpose and will be useful for district planning purposes and to help inform the subdivision consent process.

Limitations

This letter was prepared solely for the exclusive use of the Otago Regional Council (the Client) with respect to the particular brief given to Wentz Pacific Limited (WP). No other entity or person shall use or rely upon this letter without prior review and written agreement by us. WP's services consist of professional opinions and conclusions developed in accordance with generally accepted geotechnical engineering principles and practices, and relied exclusively upon the information provided to us as part of this project. There is no warranty, either expressed or implied.

Regards,

Wentz-Pacific, Ltd.

F. J. Wentz

Frederick J. Wentz, CPEng, IntPE, CMEngNZ
Principal Engineer

[2] Tonkin + Taylor. Glenorchy Liquefaction Vulnerability Assessment, V0.1 - Draft for Peer Review and Consultation, 28 January 2022.
[3] Tonkin + Taylor. Glenorchy Liquefaction Vulnerability Assessment, V1 – for essue to ORC, 26 May 2022.

Dart / Rees Rivers

Flood Hazard Modelling

01/06/2022

Client: Otago Regional Council

Report by: Matthew Gardner

Land River Sea Consulting Limited

www.landriversea.com

REES / DART RIVERS: FLOOD HAZARD MODELLING

REVISION HISTORY

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1. INTRODUCTION

1.1 SCOPE

Land River Sea Consulting has been contracted by the Otago Regional Council to develop a detailed flood model of the Rees and Dart Rivers for the reach downstream of the road bridges. The purpose of the model is to allow a better understanding of the potential flood hazard from both rivers to Glenorchy as well as the surrounding rural land for a range of return period events including the potential impacts of climate change and stopbank failure. The model is also intended to be used to understand better the flood hazard to the wider floodplain area including the access roads to, as well as the township of, Kinloch.

The area of interest for this project is presented in Figure 1-1 below.

Figure 1-1 – Area of Interest

Rees / Dart Rivers: Flood Hazard Modelling

The scope of the project involves

- Build a detailed MIKE21 model of the floodplain, based on the 2019 LiDAR data as well as available cross section survey data
- Create maps of flood depth / extent and hazard for a range of scenarios
- Simulate realistic avulsion scenarios in the Rees River and assess the impact on the town
- Simulate realistic breach scenarios of the Glenorchy Stopbank as well as complete bank down scenarios

1.2 PREVIOUS MODELLING

Previous modelling of the river has been conducted by URS NZ Ltd in 2007 (Whyte and Ohlbock 2007). Modelling was carried out using MIKE11 software and was a 1D model based on the limited cross section survey available.

Modelling included an assessment of the hydrology as well as an assessment of the level of service of the Glenorchy Stopbank.

1.3 SITE VISIT

A site visit was carried out by Matthew Gardner on the 12th and 14th of October. Matthew was accompanied by Tim van Woerden and Magdy Mohssen on the 12th of October.

The purpose of the site visit was to observe the terrain in person which is invaluable for gaining a full appreciation for the characteristics of the site. Key areas for the model were traversed over the two days with photography captured using both a drone and standard camera. A collection of images from the site visit is presented in Appendix A of this report.

Special attention was paid to the following areas:

- Town area and potential inundation areas
- Glenorchy stopbank
- Lagoon system and stream
- Rees and Dart river beds and berms
- Historic overtopping locations on the Rees River, in particular at Rees Valley Station at Scott's Lane
- Upstream boundary locations of the river
- Kinloch and the Kinloch access road.

2. LIMITATIONS OF STUDY

This study has been carried out using the information and data made available to the author at the time of this study. There are a number of uncertainties which should be acknowledged which include but are not limited to:

- LiDAR data – whilst there is good coverage, LiDAR data comes with a degree of vertical uncertainty typically considered to be in the range of +/-0.15m.
- The Rees River channel bathymetry has been interpolated based on surveyed cross sections using a relationship between depth / colour.
- The model is a fixed bed model and does not allow for bed mobilisation / gravel transport.
- Input hydrology data is based on hydrological modelling and there is no physical flow gauge in the Rees River.
- Model validation has only been focussed on the Glenorchy area with close attention not paid to the wider model area due to a lack of available data
- This study has only considered the impacts of flooding on its own and has not considered the potential impact of cascading natural hazard scenarios (i.e., earthquake induced liquefaction settlement in conjunction with flooding).

3. INPUT DATA

3.1 LIDAR / AERIAL IMAGERY

LiDAR

The LIDAR has been interrogated over the entire area and appears to be of high quality, however we have identified that the stated vertical datum is incorrect, and that the data appears to have been surveyed in NZVD2016 + 100m rather than Dunedin Vertical Datum 1958 + 100m as stated in the datasheet supplied with the LiDAR (see Appendix B for more details). A visualisation of a section of the LiDAR is presented in Figure 3-1.

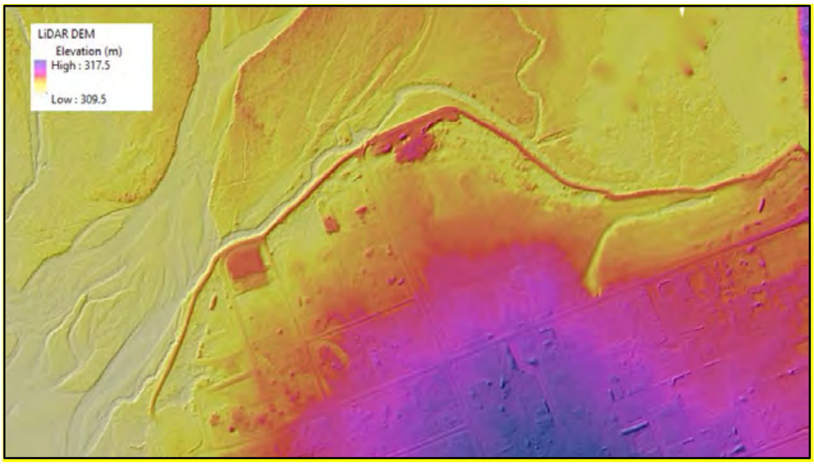

Figure 3-1 – Coloured hillshade visualisation of the LiDAR data in the area of the Rees River / Glenorchy

3.2 CROSS SECTION SURVEY

Limited cross section survey carried out in August 2019 was provided for both the Rees and Dart Rivers in the locations shown in Figure 3-2

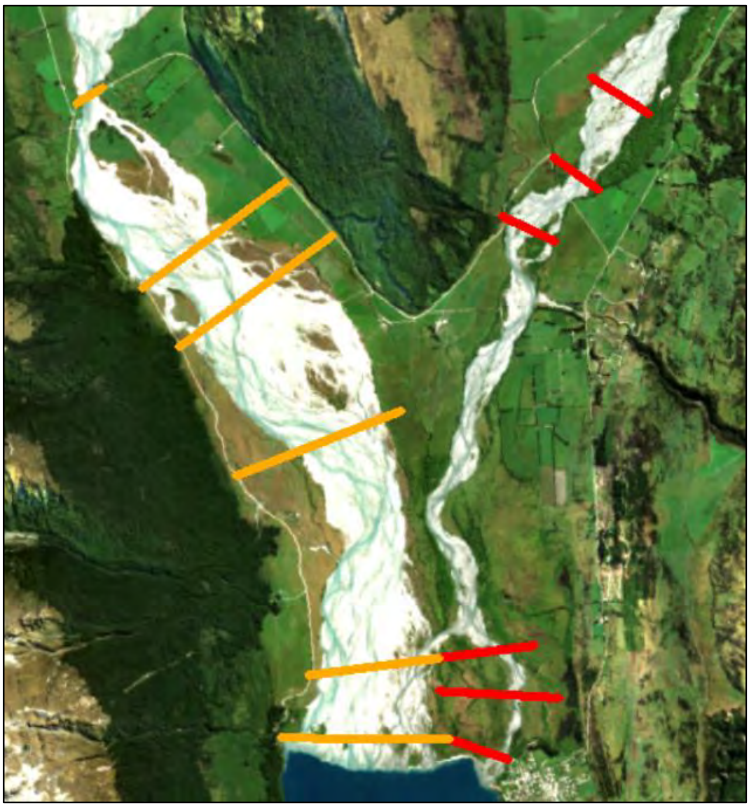

Figure 3-2 – Location of cross section surveys on the Rees and Dart Rivers (Orange lines – Dart River, Red lines – Rees River)

Comparison of the cross-section surveys with the LiDAR has highlighted the fact that datums for the cross-section surveys are not tied into any known vertical datum, with each cross section having a slightly different datum.

For this modelling, we have relied purely on the LiDAR data which has a significantly better spatial coverage and is in a fixed vertical datum, however we have used the cross-section data in order to develop a bathymetric DEM for the Rees River channel as detailed in section 5.1.1.

4. INPUT HYDROLOGY / LAKE LEVELS

Input hydrology has been developed by Dr Magdy Mohssen from Otago Regional Council and has been based on rainfall runoff modelling utilising HEC-RAS (Mohssen M 2021). Full details of the study are included in Appendix C with a summary of the adopted flows for this modelling study being presented in Table 4-1.

Table 4-1 – Adopted inflow boundary conditions

Event	Dart @ Bridge (m^3/s)	Rees @ Bridge (m^3/s)	Rees @ d/s bridge (m^3/s)
February 2020	1792	642	N/A
100-year ARI	2626	941	251
100-year ARI (RCP8.5)	3153	1138	307

In addition to the rainfall runoff modelling, ORC staff have also carried out a detailed lake level frequency analysis based on the available records (see Appendix C). The adopted lake levels based on this analysis is presented in Table 4-2.

Table 4-2 – Adopted Lake levels

Return Period	Lake Level – DUN58 (m)
2-year ARI	310.7
10-year ARI	311.5
100-year ARI	312.9

To put these levels into context, the highest lake level recorded was in November 1999 with a level of 312.78 m. The peak level recorded on the 4th of February 2021 was 311.35 m.

5. MIKE21 FM MODEL BUILD

5.1 MESH GENERATION / INTERPOLATION

The MIKE21 model has been set up using the Flexible Mesh module and used a variable mesh size allowing varying degrees of resolution over the floodplain. The model has been split into sub areas and assigned a maximum mesh element resolution ranging from 15 m^2 to 1000 m^2. Areas such as the river channel, berms as well as the urban area have been assigned the finest resolution, with areas such as the lake and farmland etc being assigned a coarser resolution. In essence, each mesh element is assigned an elevation, hence the finer the mesh, the greater definition of the underlying topography is able to be represented. There is a trade-off required however between model stability, model runtime and file size that needs to be made. The final model has been designed so that it can run in approximately 8 hours on a high spec computer with multiple GPUs. A summary of the final mesh resolution is presented in Figure 5-1. It should be highlighted that the mesh sizes stated below are the maximum element size within that area and that the majority of the mesh elements are significantly less than the maximum resolution.

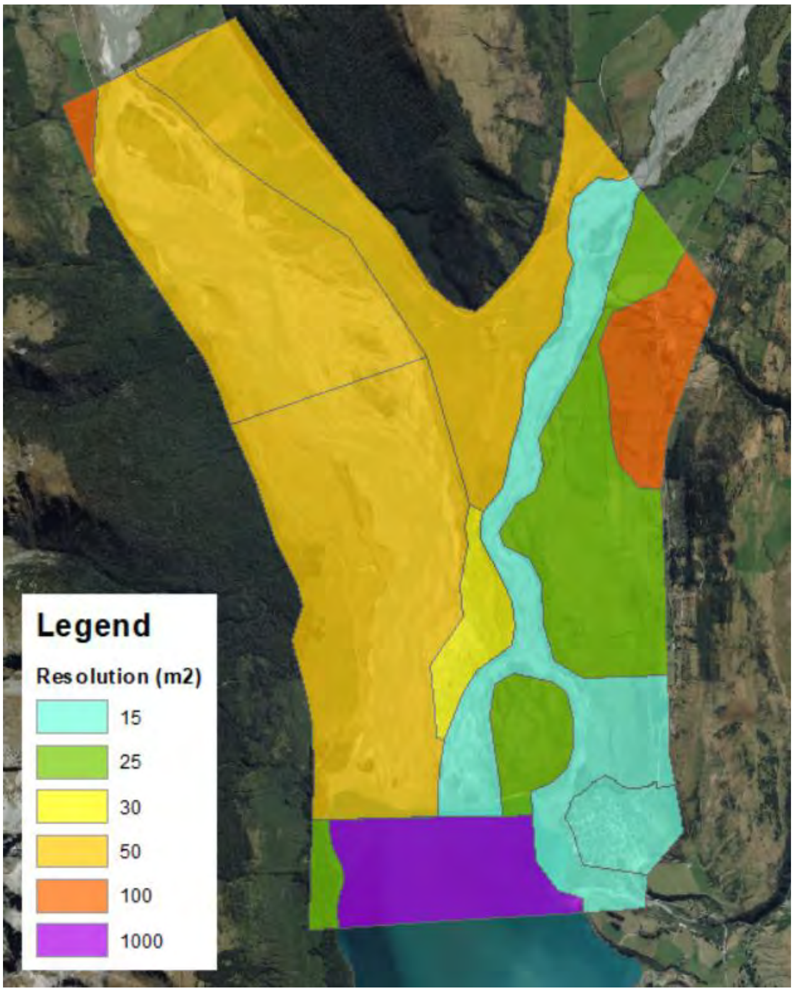

Figure 5-1 – Summary of assigned maximum mesh element resolution

The underlying topography has been based on the 2019 LiDAR (see section 3.1). Due to limitations with the software, it is not possible to interpolate the mesh elevations based on the raw LiDAR points for the entire model area. As a result of this, a compromise has been made with the urban area being interpolated based on the raw LiDAR points and the remaining areas being based on a 2m grid which was interpolated based on the raw LiDAR points.

The adopted vertical datum for the model is Dunedin Vertical Datum 1958 (DUN58) to be consistent with the recorded flood levels as well as the lake levels. (NB this differs from the raw LiDAR as noted in section 3.1.

5.1.1 BATHYMETRY INTERPOLATION

Whilst LiDAR is excellent at capturing accurate levels above water, it is limited in its ability to penetrate water and therefore the underwater terrain will not be well represented in a DEM generated purely from LiDAR. In order to overcome this, we have utilised a technique which we have been refining in recent years which we refer to as optical bathymetry. In essence the technique works by finding a relationship between the colour of the water and the depth. We have developed a software package which utilises the latest data science / machine learning techniques to help find a strong and reliable correlation between colour and depth.

In order to apply this technique, we require both aerial imagery and depth survey data which has been collected around the same time to ensure that the bed levels haven't changed significantly. We are fortunate to have concurrent cross section survey data as well as aerial imagery collected by LandPro in 2019 to allow this technique to be adopted.

Because the 2019 cross section survey has not been tied into an official vertical datum, we simply overlaid the survey data onto the LiDAR data and adjusted the data up and down until we got a good fit with the LiDAR data. We then estimated the water level at each cross-section location, based on the water's edge location in the aerial imagery and then calculated the water depth for each survey point. In total we had 6 cross section locations with a total of 88 water points.

We have split the data into training and validation datasets using 80% of the data for training and 20% for model validation and get the following validation statistics (Table 5-1)

Table 5-1 - Validation Metrics

	Root Mean Squared Error (m)	Mean Absolute Error (m)	Pearson Correlation Coefficient	Maximum Residual Error (m)	Explained variance Score
Training	0.041	0.033	0.98	0.105	0.937
Validation	0.074	0.062	0.746	0.158	0.556

A plot of a section of the validation data is presented below Figure 5-2 which shows a reasonable fit.

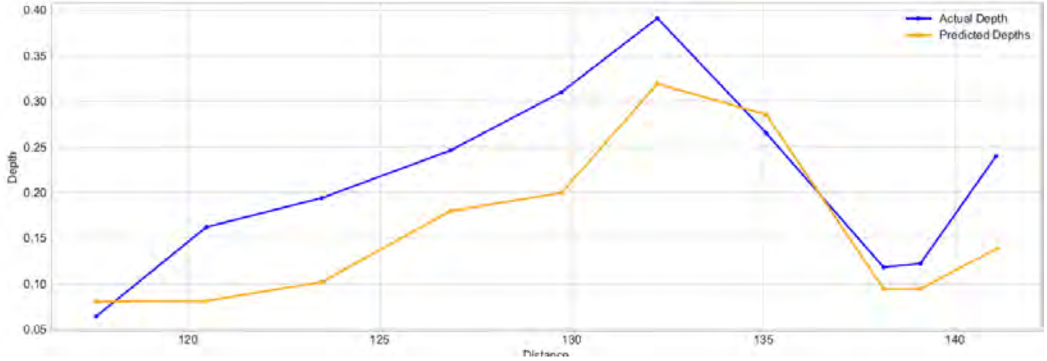

Figure 5-2 – Visualisation of interpolated 2D bathymetry

Whilst there is limited data available to enable the creation of a detailed bathymetry DEM, we consider that this technique will produce more terrain model than any other method available to us. A visualisation of the DEM of depth is presented on the following page (Figure 5-2,Figure 5-3).

It is apparent from the coloured visualisation that the DEM of depth shows a realistic and nature depth profile when compared with the aerial imagery.

In order to convert the DEM of depth into a DEM of bed elevation, a model of the water surface was generated by estimating the water level down the length of the channel from the LiDAR data. Once a satisfactory water surface was developed, the DEM of depth was subtracted from the water surface and therefore converting the data to bed elevation. Because the primary focus for this model build has been the Rees River, for now, no effort has been made to represent the bathymetry of the Dart River, however sensitivity tests on the Rees River have shown that the bathymetry makes little difference to the flood levels (~2cm). This is simply due to the significant size of the flow for the design events in relation to the channel capacity, i.e., most of the flood flows are conveyed outside the (braided) channels. More effort could be put into refining the DEM for the Dart River in the future if desired.

Figure 5-2 – Visualisation of DEM of Depth

Figure 5-3 – Aerial Image used for generating DEM of Depth

LANDRIVERSEA CONSULTING

Lake Bathymetry: Whilst not critical for the current scope, we have obtained an old contour map of depth from LINZ and interpolated a basic lake bathymetry. This could be important if we are to attempt to model wind setup etc in the future. An extract from the contour map is presented in Figure 5-4.

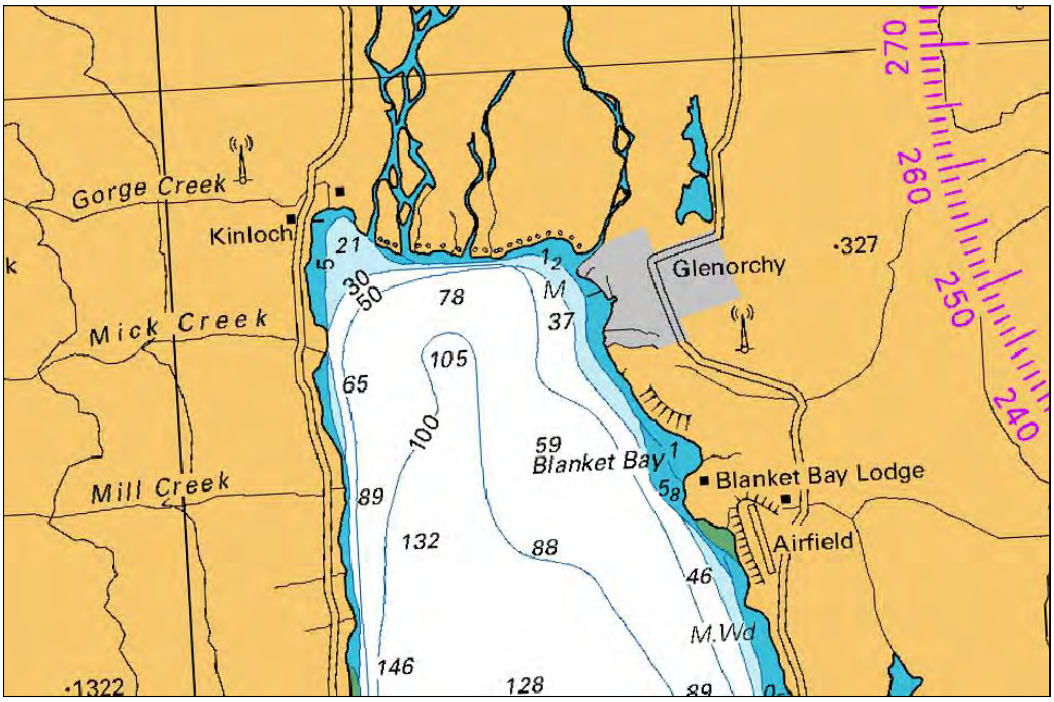

Figure 5-4 – Lake Wakatipu Bathymetric Contours obtained from LINZ

5.2 FLOODPLAIN RESISTANCE

Floodplain resistance has been represented in the model using a spatially varying Manning's 'n' coefficient.

To account for varying roughness values on the floodplain, a raster of roughness values with a grid size of 1m has been created where each cell has been assigned a Manning's 'n' value based on the land use visible in the latest aerial imagery.

This task has been carried out using a combination manual and automatic image classification techniques to ensure the most accurate classification of land uses. Buildings have been located based on a digitised building footprint shapefile supplied by Land Information New Zealand (LINZ).

Road centrelines were manually drawn due to discrepancies between the online datasets and the aerial imagery, and a buffer polygon was created around the road centreline since the available GIS datasets did not have sufficient accuracy. An example of the Manning's delineation is shown (Figure 5-5, Figure 5-6).

Figure 5-5 – Aerial imagery

Figure 5-6 – Land use classification corresponding to the aerial imagery in Figure 5-5

We have used the Strickler and Griffiths formulas as a check on Manning's for the main rivers using a d_{50} ranging from 0.15 to 0.23m based on PhD thesis(Williams 2014). These formulae give a range of 0.024 to 0.027 for Manning's 'n'. Because these formulae are designed for 1D models which account for a range of factors which are accounted for in the 2D equations, we have further lowered the Manning's 'n' to 0.019.

Whilst this value may seem low compared to a 1D model, 1D models are a simplistic representation of fluid behaviour and the Manning's 'n' factor in a 1D is actually a 'fudge' factor which accounts for a range of physical parameters which are not directly represented in the model, such as turbulence for example. It is therefore normal for a 2D model to have a significantly lower Manning's 'n' value than a 1D model. The Manning's value needs to be calibrated specific to a 2D model as the mesh size also has influence on some of these factors.

For this model the fine nature of the bed material was confirmed during a site visit, and based on my experience in modelling gravel bed rivers I consider that a Manning's 'n' value of 0.019 is suitable for this area. The sensitivity of the model to the selected Manning's 'n' value was tested as further detailed in section 5.4.

The adopted Manning's 'n' values for this model build are summarised in Table 5-2.

Table 5-2 – Adopted Manning's 'n' coefficients

Landuse	Manning's 'n'
Vegetation	0.07 – 0.12
Roads / Concrete	0.02
Grass / Pasture	0.033
Gravel River Bed (including wetted areas)	0.019
Buildings	2

5.3 ENFORCEMENT OF STOPBANK CREST

In order to ensure that the crest level of the Glenorchy stopbank (Figure 5-7) is represented in the model, the stopbank crest has been removed from the 2D terrain and has been represented using a 1D DIKE feature based on actual ground survey. This ensures the precise crest level is represented in the model, and also allows for stopbank heights to be modified dynamically allowing for the simulation of a range of breach mechanisms.

Figure 5-7 – Location of Glenorchy stopbank

5.4 SENSITIVITY TESTS

A range of sensitivity tests have been carried out during the model build process. In particular the following parameters have been decided on.

Viscosity – Both the 'Constant eddy formulation' as well as the 'Smagorinsky' definitions for viscosity have been tested within the model. The Smagorinsky definition was found to give the lowest water levels and was found to not be sensitive to the selected mesh element size. We have therefore selected a Smagorinsky coefficient of 0.2 as this allows a degree of flexibility to change the mesh size without needing to further adjust the viscosity parameter. This value is within the recommended range, we trialled a range of values from 0.2 to 0.35 and found the results were not sensitive to the value. Adopting a 'Constant Eddy Formulation' viscosity parameter resulted in higher water levels than could be expected and was therefore not adopted, it was also found to be sensitive to changes in the mesh size. The use of the Smagorinsky coefficient in this situation matches the official advice on the MIKEBYDHI online wiki[1].

Solution Technique – Both the lower order and higher order equations were tested for this model and gave very similar results. The lower order solution has the advantage that the run times are significantly improved and has therefore been selected for this study. Most importantly, the model has been validated based on the lower order equations and therefore the design runs are using the same parameters as used for the validation runs.

Initial Water Level in the Lagoons - the model has been tested to the sensitivity of the initial water level in the lagoons. Model results have shown that for large flood events which are likely to overtop the existing Glenorchy stopbank, the initial water level in the lagoons has minimal impact on the final flood extent with the volume of water coming in from the Rees River being several orders of magnitude greater than the available storage in the lagoons.

Manning's 'n' - The model has been tested with a range of potential Manning's 'n' values and suitable Manning's values have been selected within realistic physical parameters as a result as part of the validation process. A range of Manning's 'n' values were tested with the most sensitive being the gravel bed value. A range from 0.019 to 0.024 was tested for the gravel bed with 0.019 giving a good fit to the observed water levels as well as being within a sensible range based on the measured grain size.

Hydrology – During the validation stage of the model, sensitivity to inflows were assessed. Results showed that the flood extent / depths were most sensitive to the flow. In the initial stage of the model build process, draft inflows were provided from the rainfall runoff model for testing in the model. It was found however that the flood extent could not be reduced to meet the observed flood extent by any reasonable adjustment to any of the additional model parameters other than hydrology. Feedback was given to the ORC hydrology staff who then revisited their rainfall / runoff model for further refinement and when a second set of data was supplied with peak flows reduced, the flood extent matched much more closely with the observed extent.

[1] https://wiki.mikepoweredbydhi.com/mikeplus/dialog/2d_eddyviscositaet

6. MODEL VALIDATION

There have been a number of significant flood events in the Rees / Dart catchment over the years, however unfortunately there is a lack of data available which is suitable for detailed flood calibration. This is due to a lack of flow gauges in the catchment as well as reliable data of flood depth / extent recorded during flood events. Historic events are also difficult to calibrate due to the constantly changing nature of gravel bed rivers, making it difficult to replicate historic bed levels with a lack of detailed survey data available. Hence, we have relied on anecdotal and photographic evidence of the flooding which has being experienced within the catchment to assist with the model development. We have selected parameters within the conventional range which have produced modelling results consistent with the data available.

6.1 FLOOD EVENT OF 3/4 FEBRUARY 2020

The most recent flood event at the time of developing this model was recorded on the 3/4th of February 2020. Council records of the event record the following (van Woerden 2020).

"On the afternoon of the 4th of February, the Glenorchy floodbank appears to have been overtopped into the recreation grounds at a location near to eastern end of the floodbank.

The fire department confirmed that floodwaters commenced overtopping at about 1-2pm flowing over about a 20m length of floodbank, and over the next few hours increased to overtop along ~200 metres of floodbank length. The team continued to monitor the water levels through the night, and estimated that the overtopping flows started to recede at around 11.30 pm. There is no indication of any floodbank breaching or erosion, rather it appears the floodbank was simply overtopped by the floodwaters filling the wetland area.

At its eastern end the floodbank has a minimum crest level of ~312.5 m. Assuming an overtopping depth at the floodbank crest of 20-30cm, the water level within the lagoon is interpreted to have reached a peak elevation of about 312.7 to 312.8m. This is also consistent with observations of the water level at the Lagoon Creek footbridge, which has handrails surveyed at ~313.0 m.

Based on photographs of the floodwater extent, the water level appears to have reached a level of at least about 312.5 m in this recreation ground area. From this level of ~312.5 m, the floodwater had a gradient down to lake level at ~311-311.3 m, over a distance of about 1 km.

Floodwaters filled much of the Glenorchy recreation ground and golf course, before flowing along the northern/northwestern margin of the township to enter Lake Wakatipu near the lower end of Mull Street, with flooding of residential areas at the northern ends of Oban and Argyle Streets, and along much of Butement Street. Flooding caused inundation and damages at several houses, and precautionary evacuations of a number of others."

Figure 6-1 - ***Aerial image taken about 6.30pm 4th February, taken prior to the maximum floodwater extent (photo from Luke Hunter, Donerite Contracting)***

In addition to the ORC flood memo, material was located online which was useful for identifying the extent of flooding in various locations. Two videos of the flood event were located online at the Crux Community newsletter website. (Crux Community Newsletter).

SATELLITE IMAGERY

Freely available satellite imagery from the Sentinel-2B satellite was sourced online which has the advantage of capturing imagery using a range of sensors including a near infrared band, which is very useful for visualising water. Whilst the imagery was taken after the flood event, areas of significant overflow are clearly visible relatively dry areas showing as a red colour, whereas areas which have higher moisture content show as a blue/green colour. Areas of significant out of bank flow are roughly outlined in yellow below to assist with identification (Figure 6-2).

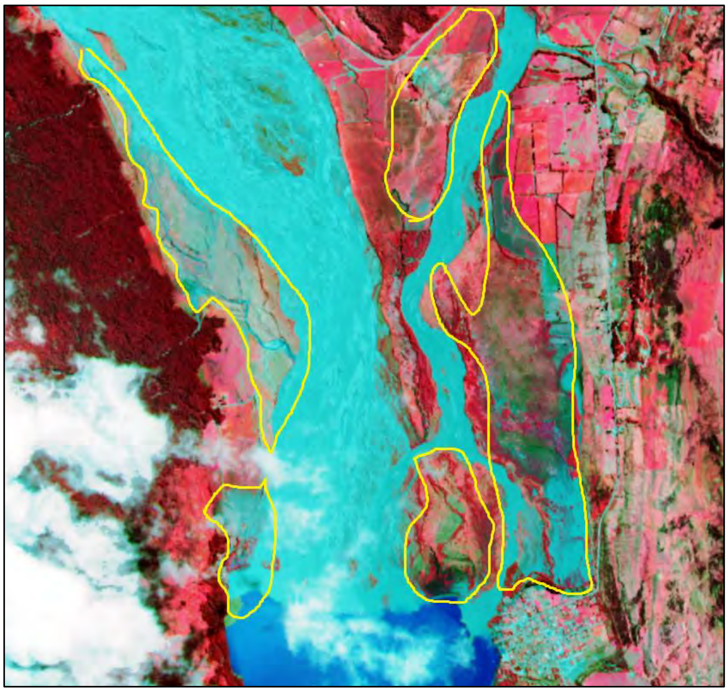

Figure 6-2 - Sentinel 2 Imagery taken on 4 Feb 2020 (UTC)

6.2 FLOOD HYDROLOGY 3/4 FEBRUARY EVENT

Flood hydrology has been developed by Magdy Mohssen of ORC using rainfall runoff modelling using HEC-RAS hydrologic model (Mohssen, 2021). It should be highlighted that due to the absence of flow gauge data for the Rees River, there is still significant uncertainty in the generated flow estimates and that model results should still be interpreted with a degree of caution, acknowledging the inherent uncertainty.

The modelling has estimated the peak flow to be 642 m^3/s in the Rees River and 1792 m^3/s in the Dart River.

Lake Levels have been taken from the ORC level gauge recorded at Willow Place. A plot showing the inflow hydrographs as well as the modelled lake level is presented below in Figure 6-3.

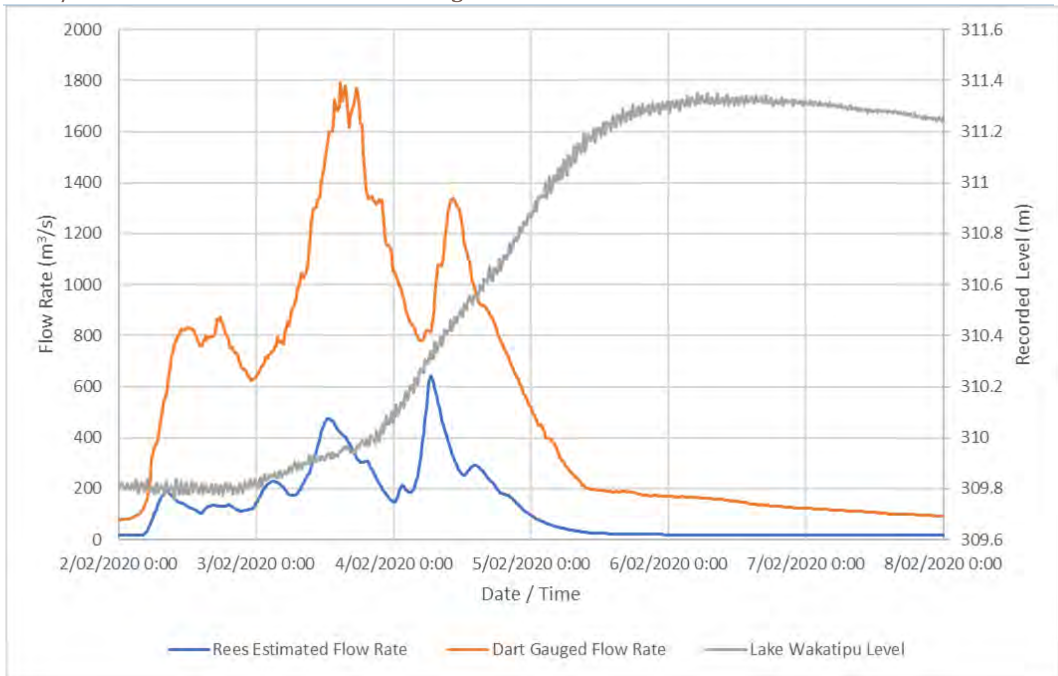

Figure 6-3 – Modelled hydrographs and lake levels for the 3/4 February 2020 validation event

6.3 HYDRAULIC MODELLING OF EVENT

The flood event has been simulated through the hydraulic model with parameters such as Manning's 'n', mesh size and viscosity being modified to test for sensitivity and to find the best fit to the observed results.

This main focus for this model build has been the township of Glenorchy, with accuracy of model validation focussed on this location. The model results have been output for the entire model domain, however, have received less attention as part of the model validation process so should not be relied upon for predictive flood hazard information without further investigation.

The model has been found to validate reasonably well to the February 2020 flood event with the Glenorchy township area. Flood levels are estimated to be within 0.1m of the modelled results (when compared to surveyed debris at the stopbank) and the estimating the terrain level at the edge of the flood extent. Tim van Woerden from ORC sought feedback on the model validation results from local community members. The general feedback was that the flood extent is close to what occurred during the flood event, however the model is likely slightly overestimating the flood extent in the vicinity of the golf course (the extent is generally within 30m of the observed flood extent). This may be due to a number of reasons including a) uncertainty in the input hydrology b) lack of fine detail in the model terrain such as fences etc which can divert water to some degree. A comparison of the model results with the estimated flood extent from the February 2020 event is shown in Figure 6-4.

Figure 6-4 – Comparison of modelled flood extent with estimated actual extent

Results show a close match between the red line and the modelled flood extent, and the differences are within the expected bounds of accuracy of the model considering the uncertainty in the flow inputs as well as the mobile nature of the gravel bed which can change the bed setup from day to day.

Rees / Dart Rivers: Flood Hazard Modelling

Close comparison of landmarks in online photography and video has also been used to confirm the extent of flooding. The following figures show the location of the floodwaters in relation to vegetation on waterfront properties in online video (https://crux.org.nz/community/glenorchy-homes-evacuated-qtown-lake-level-critical) compared to the modelled flood extent. It is understood that this video was taken close to the time of the peak.

Figure 6-5 – Screenshot from video of flood extent

Figure 6-6 – Modelled flood extent in same location

Comparison of water level at foot bridge

The peak water level at the footbridge crossing lagoon creek was estimated to be around 312.7 to 312.8m. The peak water level in the model at this location is 313.0m indicating the model is slightly over predicting the water levels. This finding is consistent with the comparison of the flood extent in Glenorchy (Figure 6-4), however considering the potential uncertainties in the input data, this is considered to be a reasonable fit.

Kinloch Access Road

Model results show significant disruption to the access to Kinloch. Whilst the exact depth and extent of flooding in this location has not been verified as part of the model build process, significant damage was experienced to large lengths of road, with access cut off for an extensive period. Model results for the Feb 2020 event at Kinloch Road are shown in Figure 6-7.

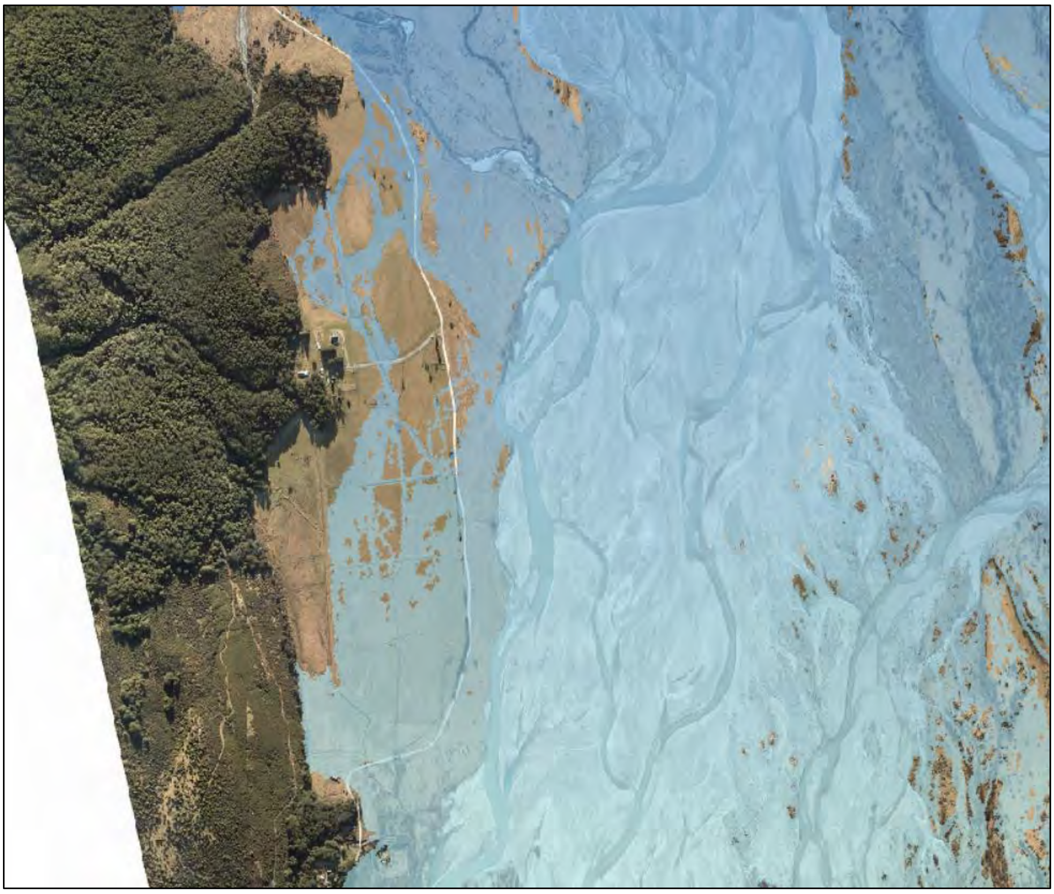

Figure 6-7 – Model flood extent at Kinloch Road

General commentary on model validation

Due to the dynamic nature of the gravel river bed, and the lack of specific gauging data for the Rees River there is considerable uncertainty in any model predictions. Taking this into account, the model is giving a reasonable representation of the overall flood extent in relation to the February 2020 flood event.

We consider that the model is fit for the purposes of assessing flood risk, however if future and more reliable calibration data becomes available then it would be worthwhile refining and upgrading the model to allow more confidence to be able to be taken in interpreting model results.

7. DESIGN RUNS

The validated model has been used to simulate a wide range of potential scenarios for an estimated 100-year ARI (1%AEP) event for both a historic climate as well as a future climate (RCP8.5) scenario as estimated by the rainfall runoff modelling.

The model has been used to assess the following;

7.1 CURRENT BED CONFIGURATION (2019)

The model has first been run to assess the likely flood hazard if a 100-year ARI event was to occur with the existing bed levels / configuration (based on the 2019 LiDAR survey). It should be noted that in reality no two events will ever be the same, and that the model does not allow for the mobilisation of the bed, which in reality occurs during a flood event.

7.2 LAKE LEVEL

The impact of the lake level on the flood extent has been investigated with both a 10 year and 100-year lake level coinciding with a 100-year river flood (historic climate) being simulated.

7.3 SIGNIFICANT AVULSION OF THE REES RIVER TOWARDS THE LAGOONS

Due to the aggrading and mobile nature of the bed of the river, experts consider that the possibility of a permanent avulsion of the Rees River channel is increasingly likely[2]. It is apparent from the LiDAR data that the Rees River is perched above the surrounding floodplain, and the land on the true left bank is particularly low and would be a path of least resistance for the river to distribute its vast volumes of sediment. Due to fixed bed nature of this model, an avulsion scenario cannot be modelled dynamically within the model, however the model terrain can be modified to represent the likely effects of an avulsion should it take place.

An avulsion scenario has been defined by using the actual model results to identify the most probable location for overflow based on the 2019 terrain levels. This location is consistent with the main overflow

[2] https://www.orc.govt.nz/media/9816/james-brasington-presentation_-fluvial-hazards-at-the-top-of-the-lake_20210407.pdf

path in the February 2020 event as evidenced by satellite imagery (see section 6.1) and discussion with local landowners. This avulsion channel has been simulated by further lowering the terrain by using a relationship between depth and velocity and assigning a maximum depth of 1m to the avulsion channel. This depth was decided upon based on the depth of the existing natural braids in the main river. This avulsion scenario has been designed in collaboration with Professor James Brasington and is considered to be a probable / credible location for a future avulsion. The modelled avulsion path is shown in yellow in Figure 7-1. To ensure sufficient flow goes down the avulsion path, a small weir was modelled across the river channel immediately downstream of the avulsion location. Whilst this is not a realistic physical process, this method was necessary to mimic the results of the likely physical behaviour of a gravel bed river system due to the significant mobilisation of the bed during a large flood event.

Figure 7-1 – Modelled avulsion path

7.4 GLENORCHY STOPBANK BREACH

Two stopbank breach scenarios have been simulated in the model based on the parameters provided in the Tonkin and Taylor memo[3] and an additional third breach scenario has been identified and tested for sensitivity. The breach scenarios have been run using both the mid-range and worst-case breach parameters provided in the report. The location of the breach scenarios is shown below. Breaches 1 and 3 had a maximum breach width of 90m and were timed to breach prior to overtopping. Breach two had a maximum width of 50m and was timed to breach after several hours of overtopping. Full details on the dam break mechanism can be found in the Tonkin and Taylor report attached in Appendix D.

Figure 7-2 – Modelled breach locations

An example of the modelled failure mechanism is presented in Figure 7-3.

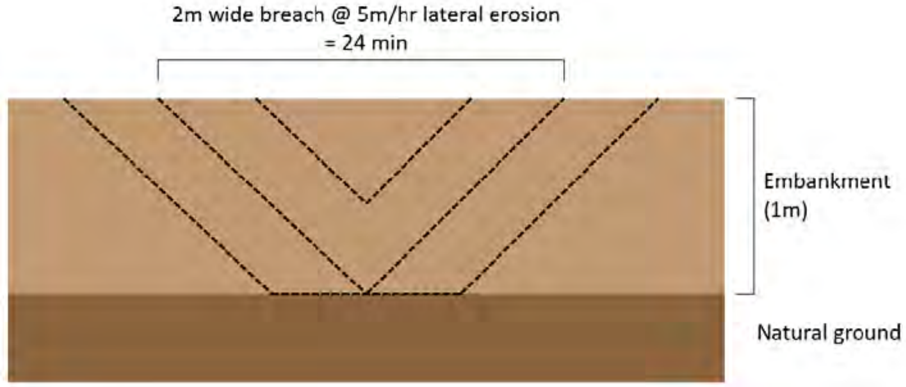

Figure 7-3 – Failure mechanism for overtopping failure (T&T, 2021)

[3] Tonkin and Taylor. 2021. Memo – Rees-Glenorchy Floodbank structure failure modes assessment (18 Nov 2021)

The following runs have been simulated:

Scenario	Average Return Interval (ARI) (year)	Climate Scenario	Terrain Scenario	Lake Level ARI (year)
01	100	Current Climate	Existing	10
02	100	Current Climate	Existing	100
03	100	Future Climate RCP 8.5 (2100)	Existing	10
04	100	Current Climate	Avulsion	10
05	100	Future Climate RCP 8.5 (2100)	Avulsion	10
06	100	Future Climate RCP 8.5 (2100)	Breach 1 / Avulsion	10
07	100	Future Climate RCP 8.5 (2100)	Breach 2 / Avulsion	10
08	100	Future Climate RCP 8.5 (2100)	Breach 3 / Avulsion	10

The results have been presented in the form of Peak Flood Depth Maps (Appendix E), Peak Speed Maps (Appendix F), and Hazard Maps (Appendix G) and have also been provided electronically in GeoTif format as well as shapefiles of flood extent.

There are a large number of potential hazard categorisations to use. For this report, hazard categories have been presented based on the general guidelines from the Australian Rainfall and Runoff and are based on a combination of depth and velocity (Ball J et al. 2019). The hazard categories are summarised in Table 7-1 and presented graphically in Figure 7-4.

Table 7-1 – Description of Hazard Categories

Hazard Vulnerability Classification	***Description***
H1	Generally safe for vehicles, people and buildings.
H2	Unsafe for small vehicles.
H3	Unsafe for vehicles, children and the elderly.
H4	Unsafe for vehicles and people.
H5	Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust buildings subject to failure.
H6	Unsafe for vehicles and people. All building types considered vulnerable to failure.

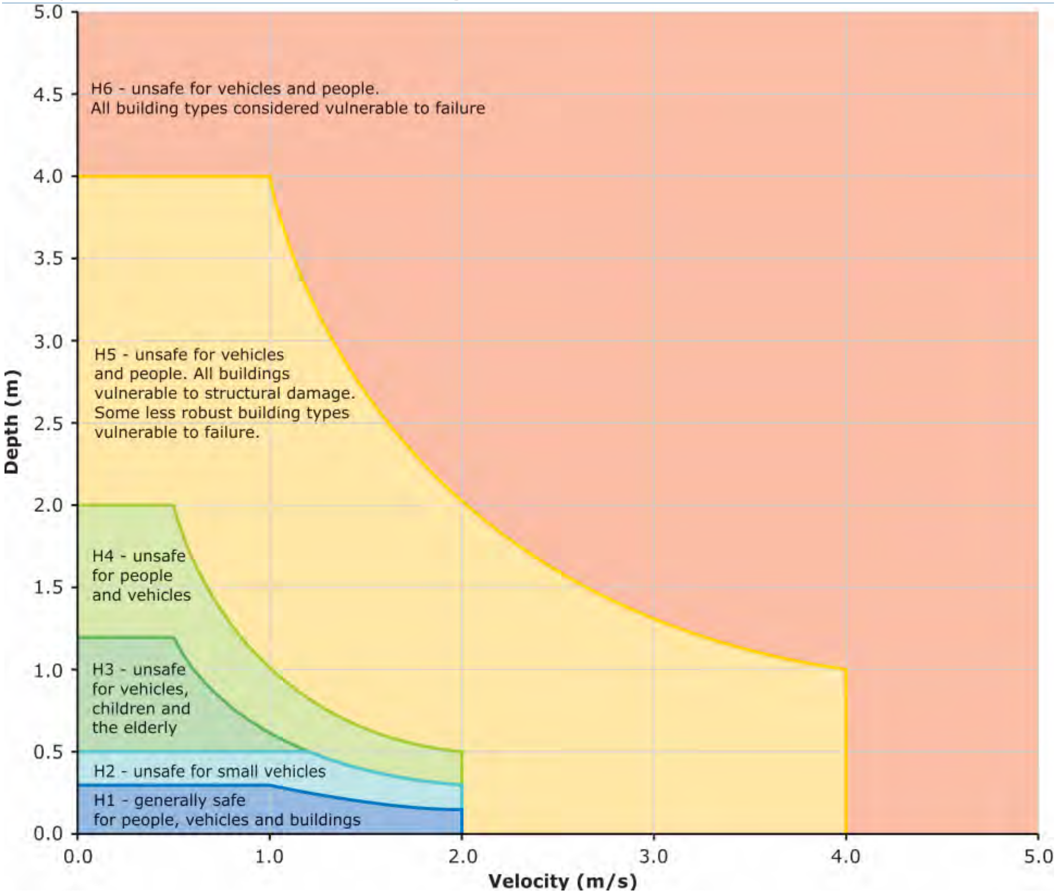

Figure 7-4 - Graphical representation of the Hazard Categories

More detailed information on the derivation of the Hazard Categories can be found in the Australian Rainfall and Runoff guidelines which can be accessed online at http://arr.ga.gov.au/arr-guideline (NB. hazard categories are discussed in Chapter 7 of Book 6 – Hydraulics).

There are a range of more specific hazard categorisations available which are more specific for evacuation planning etc, however the categories adopted for these maps are the most general and suitable for a wide range of purposes.

8. RESULTS ANALYSIS / COMMENTARY

8.1 GLENORCHY TOWNSHIP FLOOD RISK

Model results show a significant risk of flooding to the Glenorchy township particularly at the northern end of town closest to the Rees River.

The existing stopbank is significantly undersized for the current alignment of the river and will not prevent flooding in events upwards from a 20-year flood event. Figure 8-1 shows the modelled flood extent for a 100-year ARI event with a 10-year lake level.

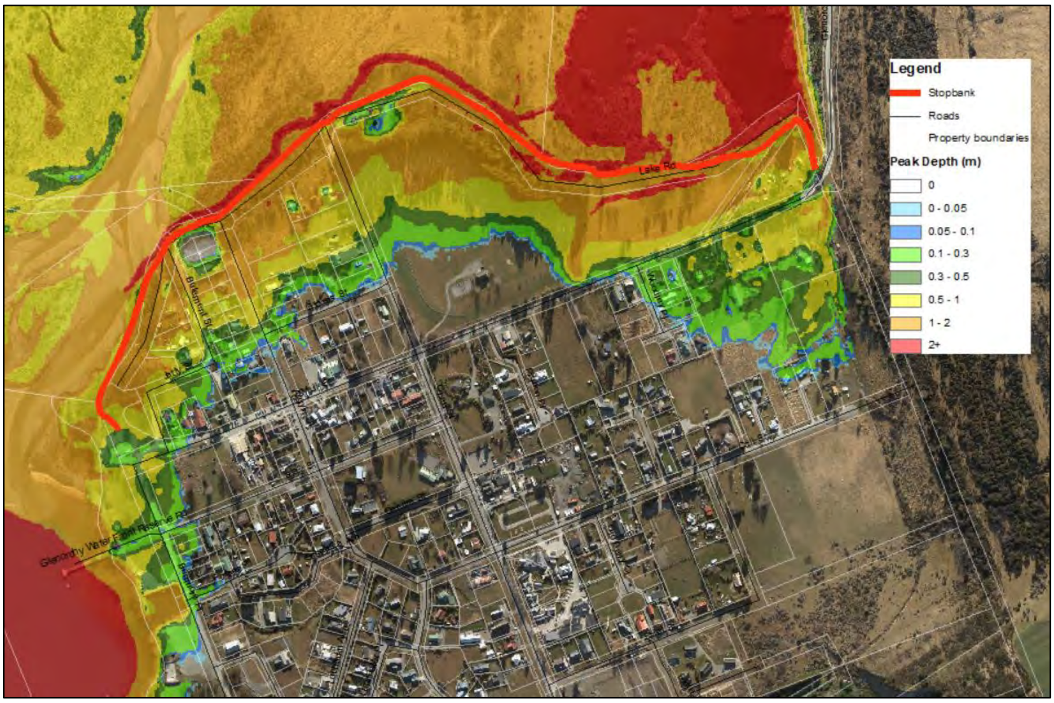

Figure 8-1 - Peak flood depth / extent for a 100-year ARI flood event combined with 10-year ARI Lake Level

The impact of increased flows due to climate change as well as an avulsion will send more water towards the lagoons and increase the depth and extent of flooding at the upstream end of the stopbank, however the flood extent closer to the lake remains largely unchanged as shown in Figure 8-2.

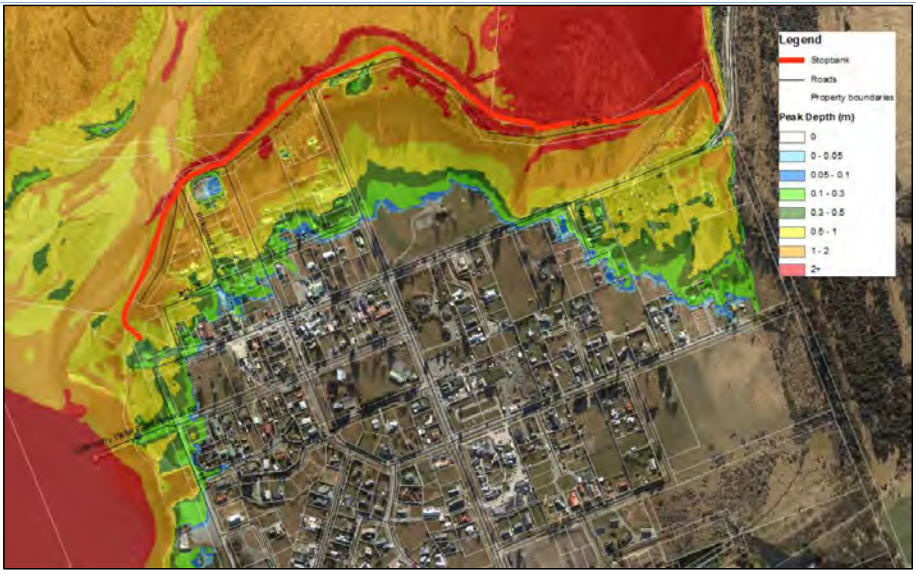

Figure 8-2 - Peak flood depth / extent for a 100-year ARI future climate (RCP8.5) flood event combined with 10-year ARI Lake Level combined with an avulsion in the Rees River

The reason for the minimal change in flood extent is largely due to the natural topography of the town, with the shape of the large fan funnelling the water around the toe of the fan into Lake Wakatipu. A coloured hillshade representation of the fan is presented in Figure 8-3.

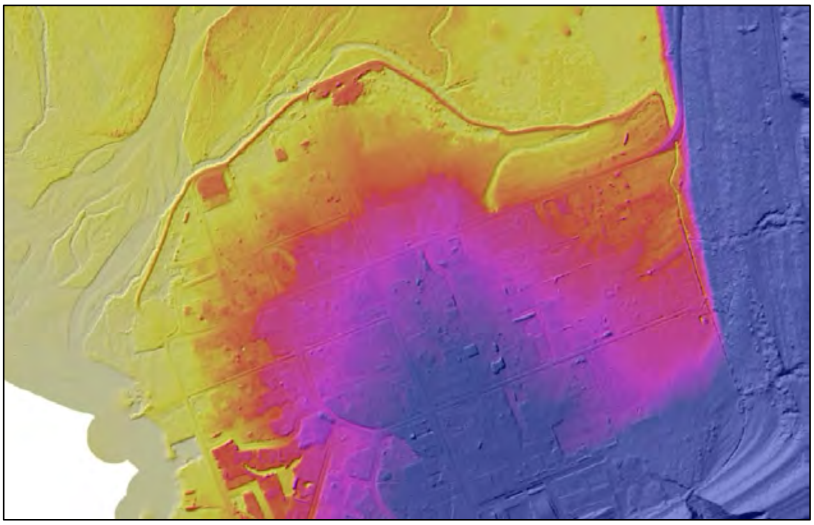

Figure 8-3 – Coloured hillshade representation of the topography in Glenorchy (Blue indicates high land, yellow indicates lower land)

8.2 KINLOCH FLOOD RISK

As previously noted, the model has not been calibrated in any detail for the area of Kinloch (however has been validated against flood photos and known damage areas) therefore there is a higher degree of uncertainty in the results.

Model results show that whilst existing buildings in the settlement of Kinloch will remain above the flood level, access will be completely cut off, with flood depths in excess of 0.5m over the access road for both the 100-year historic and future climate scenarios.

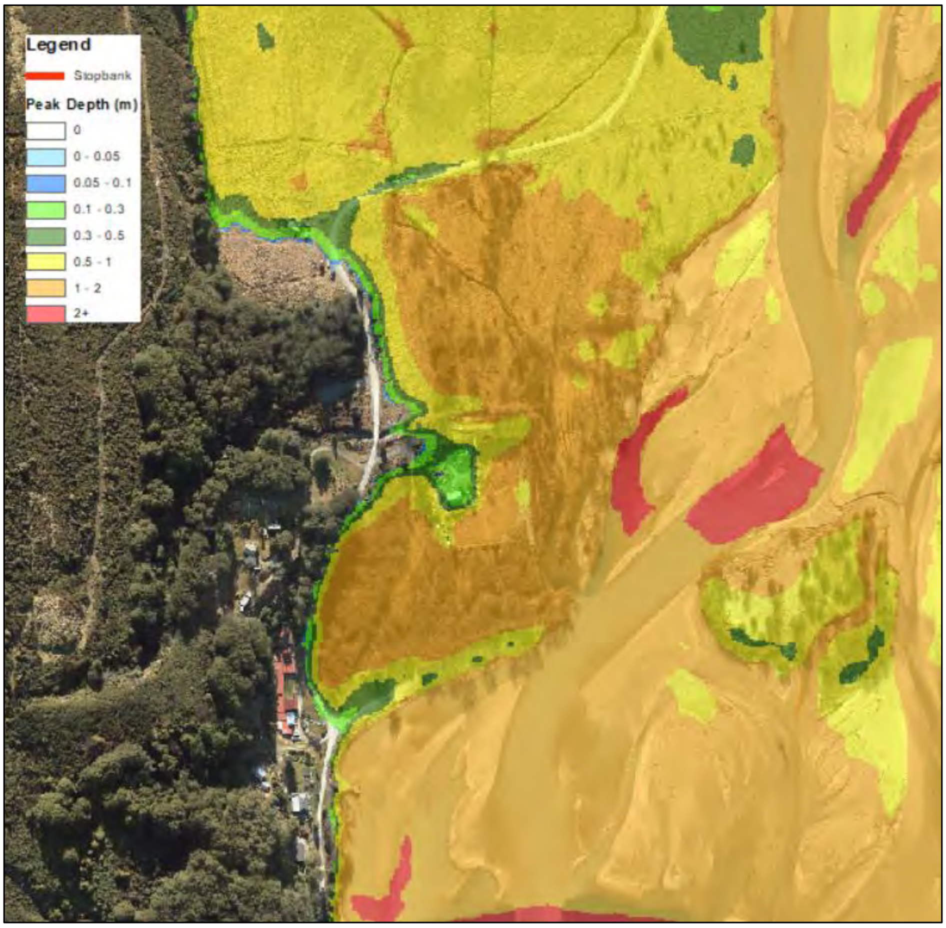

Figure 8-4 – Peak flood depth / extent for a 100-year ARI flood event combined with 10-year ARI Lake Level

Rees / Dart Rivers: Flood Hazard Modelling

Hazard categorisation place much of the road into the H2 (unsafe for small vehicles) and H3 (unsafe for vehicles, children and the elderly) categories for a 100-year event with 10-year lake levels, indicating that evacuation would be unsafe. It would also be quite likely that the local roads receive significant damage with flood velocities being sufficient to cause erosion and scour of the road surface / embankment.

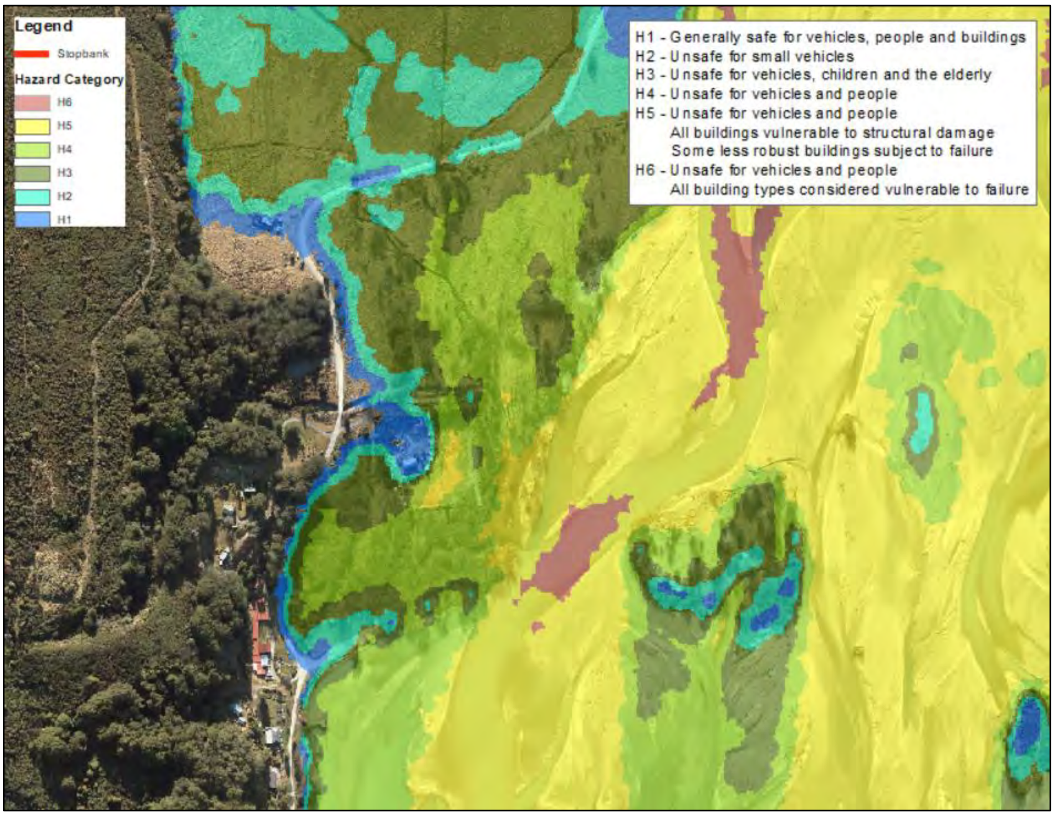

Figure 8-5 – Hazard map for a 100-year ARI flood event combined with 10-year ARI Lake Level in Kinloch

8.3 WIDER FLOODPLAIN ISSUES

Model results show that there will likely be significant issues with road access in the area with Glenorchy-Routebourn Road, Priory Road, Swamp Road and Kinloch Road all being cut off during a 100-year ARI event. Velocities are at levels indicating that there is significant risk for scour / erosion on the road surfaces.

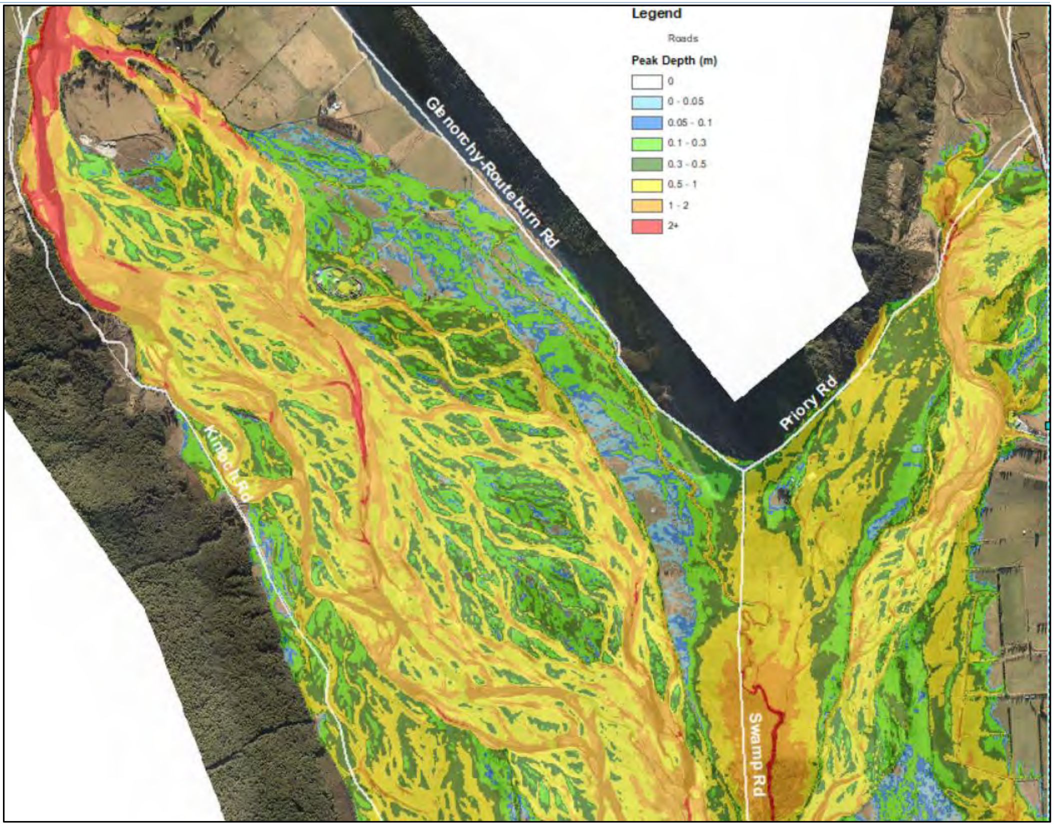

Figure 8-6 - Peak flood depth / extent for a 100-year ARI flood event highlighting road inundation

8.4 IMPACT OF STOPBANK BREACH

Model results show that the impact of stopbank failure for a 100-year ARI event has no impact on flood extent, however the flood onset is slightly sooner than would otherwise be the case. This is simply because a 100-year inundation event significantly overwhelms the existing bank.

The existing topography as highlighted in Figure 8-3, anyway confines the flood extent.

8.5 IMPACT OF LAKE LEVELS ON FLOOD EXTENT IN GLENORCHY

There are two general types of flood events in Glenorchy. The first is due to high lake levels on their own, and the second is due to river flooding. There is also a possibility for combined lake / river flooding.

Whilst the main cause of high lake levels is likely to be driven by persistent ongoing rainfall in the wider catchment area and will not always correlate to flood conditions in the Rees / Dart Rivers, there will always remain a possibility for flood conditions occurring in the Rees / Dart catchment after a period of extended wet weather.

HIGH LAKE LEVEL ONLY

Results show that a high lake level scenario result in significant flooding for the lower end of Glenorchy closest to the lake due to the relatively low land levels particularly in the vicinity of Benmore Place and the surrounding land. Land levels in this area range between 311 to 312 m (DUN-58) indicating that areas will be flooded in levels less than a 10-year return period lake level event.

COMBINED LAKE / RIVER FLOOD

Results show that the impact of a high lake level combined with a river flood has a relatively minor impact on flood extent (flood levels are increased by less than 0.1m), however the most significant impact is the high lake level actually dampens the flow to a degree and lowers the water velocities near the lake in comparison to an event with a low lake level.

Figure 8-7 compares the flood extents of a lake flood alone with that from a river flood combined with a high lake level. It can be concluded from this figure that the increased water from a river flood has minimal impact on the flood extent near the lake, with the lake level itself being the dominant factor influencing the flood extent.

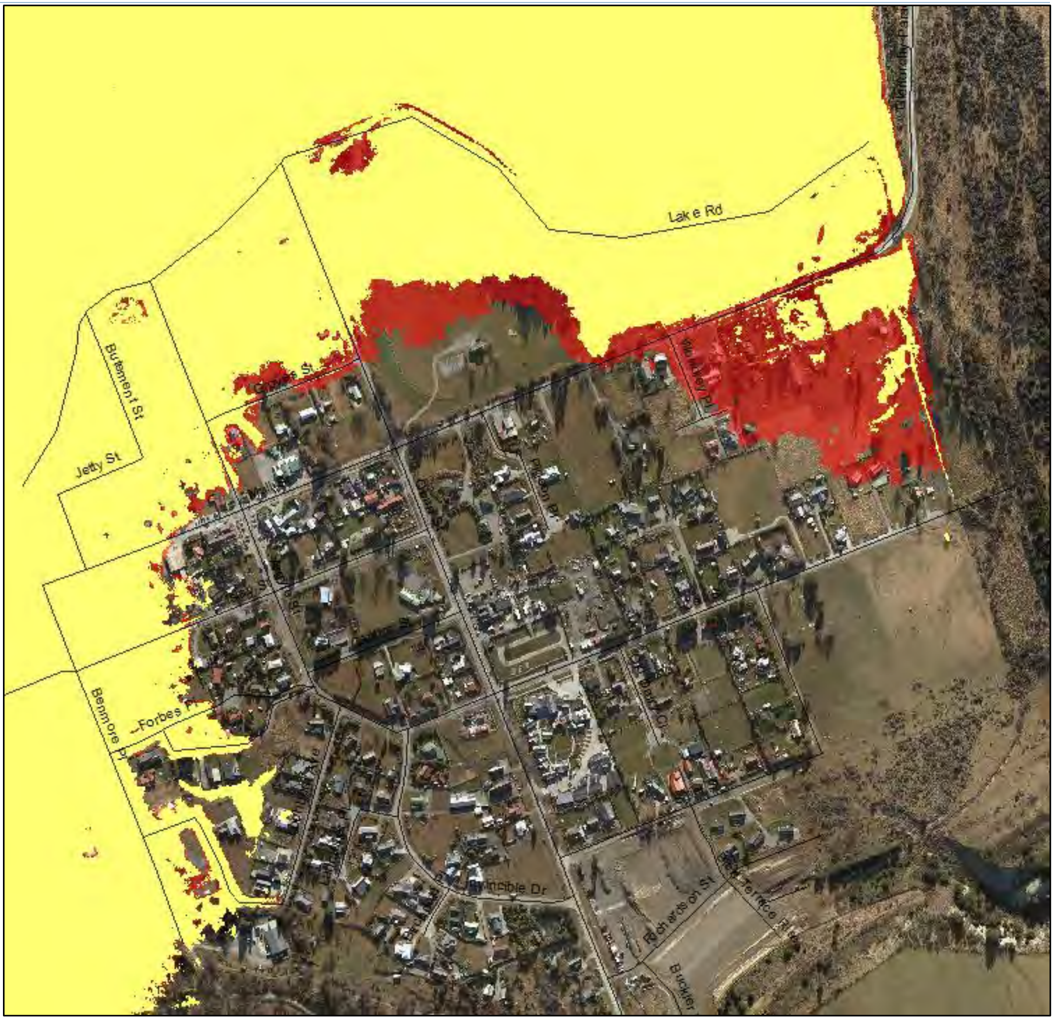

Figure 8-7 – Comparison of 100-year ARI lake level (yellow) with 100-year ARI river flood combined with a 100-year ARI lake level (red)

9. SUMMARY / CONCLUSIONS

9.1 MODEL BUILD

- A 2-dimensional hydrodynamic model of the Rees and Dart Rivers has been developed based on the 2019 LiDAR data.
- The model has been developed using the MIKE21 Flexible Mesh software made by DHI.
- Key hydrological inputs for the model have been provided by ORC
- There is insufficient data available to conduct a detailed model calibration process however anecdotal and photographic evidence has been used to validate the model outputs and it is considered fit for purpose.
- The model has validated well to the February 2020 flood event.

9.2 MODEL RESULTS / CONCLUSIONS

- Results show that the low-lying areas in Glenorchy are at particular risk of flooding from both the river as well as the lake. Properties closest to the stopbank as well as the lake are most at risk.
- The current Glenorchy stopbank is prone to overtop in small to medium sized flood events, however the extent of flooding is controlled by the existing topography
- Should a stopbank breach occur, the extent of flooding is unlikely to increase due to the current topography controlling the flood extent. The only impact is likely to be time of the onset of flooding
- The impact of increased flows due to climate change as well as an avulsion will send more water towards the lagoons and increase the depth and extent of flooding at the upstream end of the stopbank, however the flood extent closer to the lake remains largely unchanged.
- Model results show that whilst existing buildings in the settlement of Kinloch will remain above the flood level, access will be completely cut off due to inundation of the access roads. Velocities are sufficient to cause damage to the road surface.
- Model results show that there will likely be significant issues with road access in the wider catchment area, with Glenorchy-Routebourn Road, Priory Road, Swamp Road and Kinloch Road all being cut off during a 100-year ARI event.

10. REFERENCES

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APPENDIX A – COLLECTION OF SITE VISIT PHOTOS

View of Glenorchy Stopbank with Rees River on left

View of Glenorchy Stopbank with Lagoon Creek visible on the right through the willows

View of Lagoon Creek – Glenorchy stopbank is on the right behind the willows

View of culvert under Glenorchy-Paradise Road

Photo of Glenorchy Stopbank adjacent to the Golf Course (overflow location)

Example of house built on overflow path on stilts (section was significantly flooded in Feb 2021)

Photo of erosion on left bank of the Rees River (Rees Valley Station)

Photo of erosion on left bank of the Rees River (Rees Valley Station) – this photo also highlights the lack of available freeboard for the Rees River before it overflows onto the left bank

Photo of silt buildup due from Rees Rover overflows

Photo looking upstream of the Dart River from Kinloch Rd (photo highlights erosion as well as vicinity to road)

Photo of Rees River bridge, highlighting very limited capacity / freeboard available

Close up photo of Rees River bridge further highlighting the limited capacity

Example of a typical rock groyne constructed on the true right bank of the Dart River with significant scour on the downstream side of the groyne.

Drone photo of the Dart River bridge (upstream extent of the model)

Drone image looking downstream from the Dart River bridge showing the potential overflow paths on the true left bank with the Glenorchy-Routebourn Rd visible at the base of the hill.

Drone photo of the Rees River bridge (upstream extent of the model)

Drone image looking downstream from the Rees River bridge showing the potential overflow paths on the true left bank

Drone image of the significant delta at the mouth of the Dart River with the confluence of the upper branch of the Rees River visible at the right of the image

APPENDIX B – DATUM ISSUE FOR 2019 GLENORCHY LIDAR

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3 NOVEMBER 2021

To: Tim van Woerden
Otago Regional Council

DATUM ISSUE FOR 2019 GLENORCHY LiDAR

As part of our model build process for the Glenorchy model, we have carried out some basic checks on the 2019 LiDAR dataset which was supplied to us by ORC and was surveyed by LandPro.

The provided metadata states that the vertical datum is Otago Metric Datum (OMD), which is the Dunedin Vertical Datum (DVD1958) plus 100 metres (ORC, 2015).

In order to be sure that all of the data we use in the hydraulic model ties into each other, we carry out basic comparisons of any overlapping datasets that we have on file. The first comparison we carried out was between the lagoon stopbank survey of November 2020 which was provided in both DVD58 and NZVD2016.

In order to compare the two datasets we have extracted the maximum crest elevation along the stopbank from the LiDAR at 20m intervals and simply overlaid over a profile plot of the crest level survey (Figure 1). It can immediately be seen that the LiDAR survey aligns very well with the NZVD2016 dataset indicating that the LiDAR data is likely in NZVD2016+100 not OMD+100m as stated.

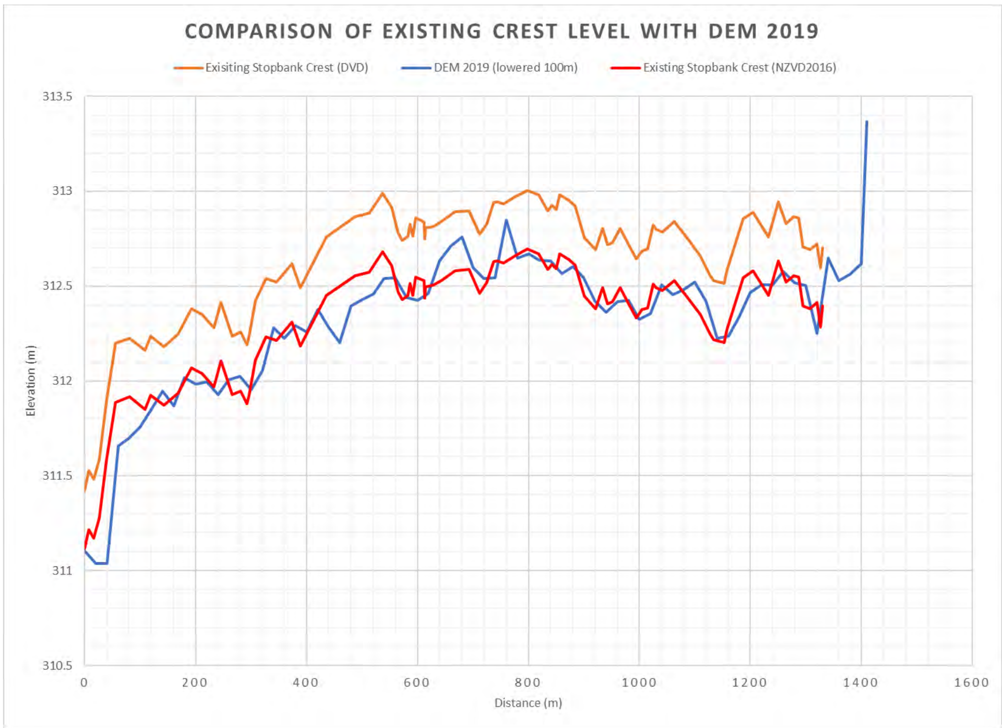


Figure 1 – Comparison surveyed crest level with 2019 LiDAR

LiDAR can be unreliable when capturing stopbank crest levels, particularly if there is a narrow top width and I have therefore carried out some additional checks with further independent data.

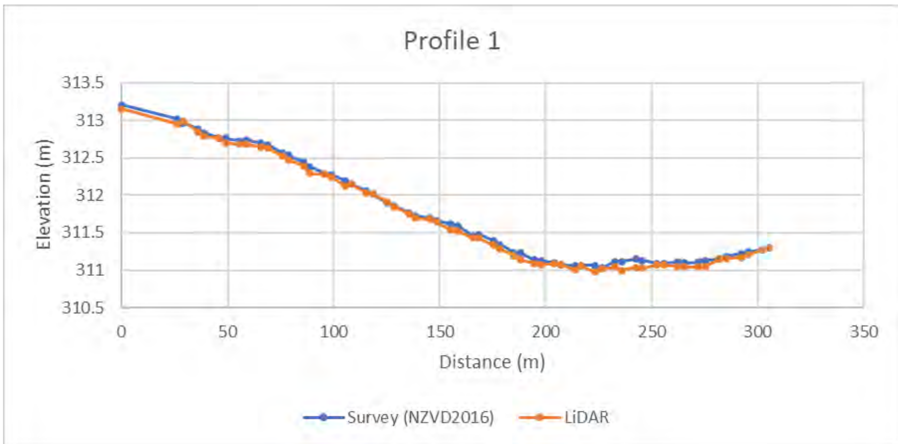
Professor James Brasington was set to be visiting Glenorchy on the 5th of October 2021, and I therefore requested that he collect some additional check data in reliable locations such as along road centrelines to allow us to confirm the datum shift.

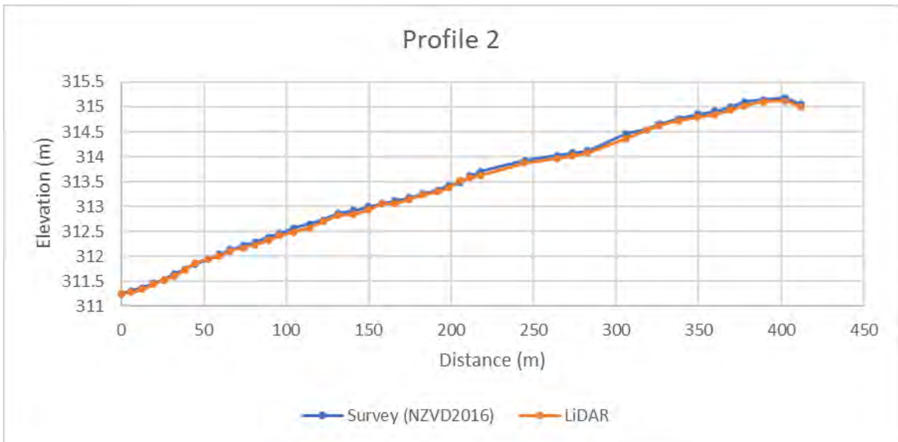
James collected a total of 354 points on hard road surfaces within Glenorchy township. Comparison of the survey data with the LiDAR data gives the following statistics:

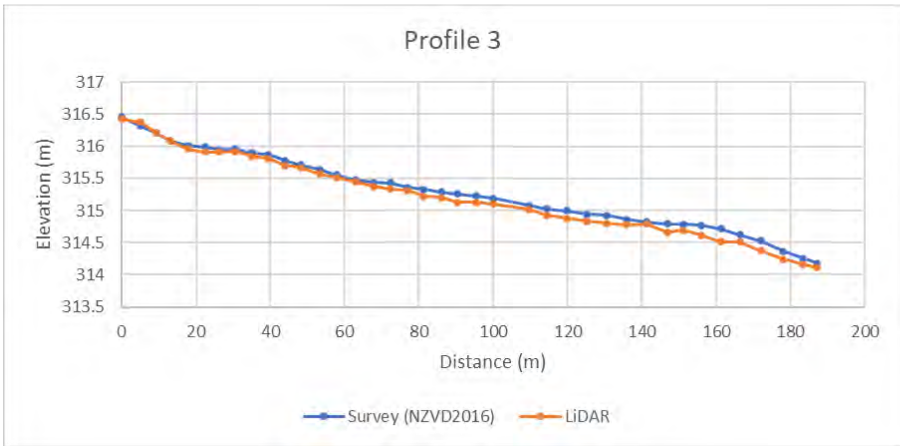
Average dz	-0.050
Minimum dz	-0.189
Maximum dz	+0.036
Average magnitude	0.052
Root mean square	0.064
Std deviation	0.039

Five long section profiles have been plotted in order to visualise the difference between the LiDAR DEM and the survey data as per the location shown in Figure 2.

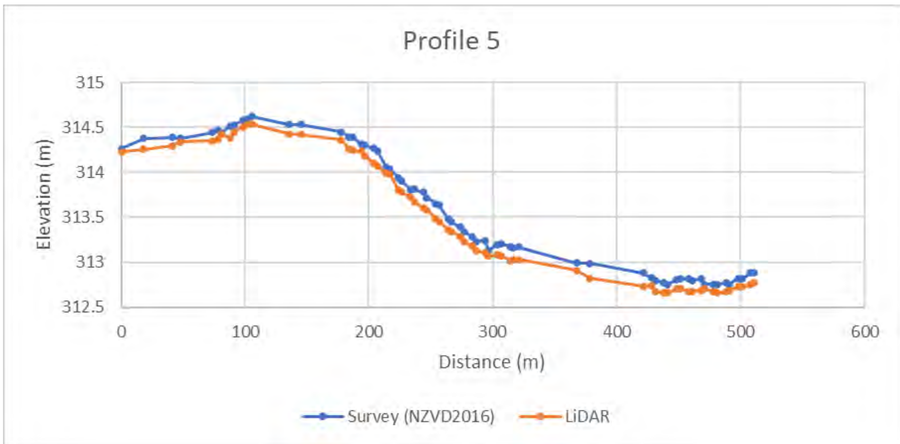
Figure 2 – Profile Locations






Profile 3
Elevation (m)
317
316.5
316
315.5
315
314.5
314
313.5
0
20
40
60
80
100
120
140
160
180
200
Distance (m)
Survey (NZVD2016)
LiDAR


Profile 4
Elevation (m)
314.5
314
313.5
313
312.5
0
50
100
150
200
250
300
Distance (m)
Survey (NZVD2016)
LiDAR


Profile 5
Elevation (m)
315
314.5
314
313.5
313
312.5
0
100
200
300
400
500
600
Distance (m)
Survey (NZVD2016)
LiDAR

Based on the checks carried out above, we therefore conclude that the LiDAR has been supplied in NZVD2016+100m rather than OMD+100 as stated in the metadata.

We have therefore converted the LiDAR to DVD1958 by subtracting 99.69m from the raw data which we have supplied electronically.

Don't hesitate to get in touch if you have any queries.

Kind regards,

M Gardner

Matthew Gardner

CMEngNZ, CPEng

Director, Land River Sea Consulting Ltd

APPENDIX C – HYDROLOGY MEMO

Analysis of Flood Hazards for Glenorchy

Magdy Mohssen

Otago Regional Council

December 2021

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Introduction

Available Data

Frequency Analysis of the Dart Peak Flows

Analysis of the correlation between the Dart and Rees catchments and flows

Rainfall-Runoff Analysis of the Dart and Rees catchments

Rainfall-Runoff Modelling of the Dart and Rees catchments

Estimated Rees flow hydrograph for the flood event of February 2020

Exceedance Probability flow hydrographs for the Dart and the Rees with climate change impact

1. Introduction

Glenorchy township lies about 46 km north west of Queenstown. Parts of the town have been flooded in the past, with recent flooding occurring during the February 2020 event. The main risk of flooding is from the Rees River, which drains its catchment to the northern end of Lake Wakatipu on the northern border of the township. The Dart River also drains its catchment to the northern end of Lake Wakatipu. A combination of high lake Wakatipu levels and significantly high flows in the Rees, which is usually associated with high flows in the Dart, poses a potential flooding hazard for Glenorchy township.

2. Available Data

Lake Wakatipu "reduced" levels are available for the NIWA's site at Willow Place (Queenstown) since 28 November 1962. Thus, there are 58 years of complete years of data to use for the MAS approach "1963 to 2020". There are also maximum annual series data based on daily levels taken at 8:00 am since 1924. This makes another maximum annual series of 97 years. While lake levels can change during the day especially during a high event, Lake Wakatipu levels take long time to recede, and this value of the level at 8:00 am could be a good representative of the highest level which occurred. In addition, there are historical records of two additional high level events in 1878 and 1919.

The Dart River has a level recorder at the Hillocks since 24 June 1996, while the Rees River has level records for only about 18 months during the period 18/09/2009 to 25/03/2011. The levels are transformed to flows through the rating curves which are established based on gauging done on both rivers during their recording period.

Table 1 Summary of Available Data for this Study.

Site	Measurement	Start Date	End Date	Easting	Northing	Altitude	
Lake Wakatipu[1] at Willow Place	Levels	28/11/1962	present	1263320	5005021		NIWA
Dart River at the Hillocks	Rainfall, levels and flows	12/06/1996	present	1230044	5031514	360	ORC
Rees River at Invincible[2]	Level and Flow	18/09/2009	25/03/2011				

3. Frequency Analysis

Frequency analysis of available Lake Wakatipu levels and the Dart River peak flows have been carried out to obtain Lake levels and Dart peak flows corresponding to selected exceedance probabilities “or average recurrence intervals in years”. Frequency analysis is quite useful to assess the risk associated with specified events of lake levels or river peak flows.

Two approaches are well known in the literature for carrying out frequency analysis. The first one is based on maximum annual series (MAS) where the observed peak level of every year is selected. The main advantage of this approach is that the series is usually guaranteed to be independent which is a requirement for using probability distributions in the modelling process. In addition, the annual exceedance probability and in turn the corresponding return period of each level is calculated directly from the fitted model. However, this approach has the main weak point that the peak lake levels of a year, but not the maximum for that year, can be much higher than maximum levels of other years, but still they are ignored and not considered in the modelling process. Moreover, MAS can be of a small size when the available record is not long enough, which in turn can be inflected on the reliability of the produced results.

The second approach is the Partial Duration Series (PDS) approach, in which all peak levels above a selected threshold are included in the frequency analysis. This approach has the clear advantage of including all peak events in the record, in addition to the potential of having so many events or a good size of the sample series to model. However, it has concerns regarding the choice of the threshold and the intensive work and investigation to insure the independence between the chosen events.

As mentioned above, one of the main disadvantages of the MAS approach for flood frequency analysis is that it can ignore peak level events which are not the highest for their year, but higher than the maximums of other years. The partial duration series which accounts for all peak flows above a threshold overcomes this issue

3.1 Frequency analysis of Lake Wakatipu levels

Average hourly lake levels at Willow Place during its available record starting from 28 November 1962, along with the daily levels starting rom 1924 and the available two historical levels of 1878 and 1919 have been used to produce the maximum annual series “MAS” of peak levels. However, for partial duration series, which accounts for all levels above a specified level, only the continuous record starting from November 1962 have been used, as this approach requires checking the independence of the selected events and the availability of a continuous record. Frequency analysis was carried out for both series, but only the MAS frequency analysis will be presented here as it has much longer years of record and additional two historical high events “total of 99 maximum annual values” and thus it is considered more reliable to simulate the population.

Figure 1 and Tables 2 to 4 show that the Generalised Pareto “GPareto” model fits well “and the best compared to other models” the MAS time series. Thus, the GPareto is selected to simulate the MAS of Lake Wakatipu levels, and Table 5 shows levels of Lake Wakatipu corresponding to different exceedance probabilities.

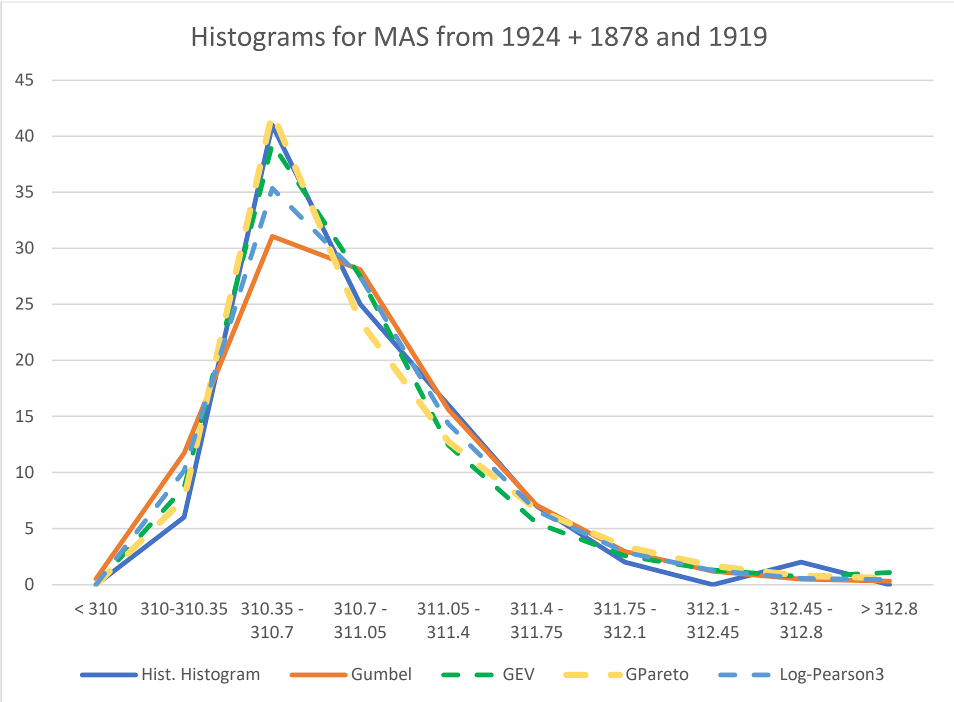

Figure 1 Histograms of Observed and MAS Modelled Peak L. Wakatipu Levels

Table 2 Kolmogorov Smirnov Goodness of Fit Test

Parameter	Gumbel	GEV	GPareto	Log-Pearson3
Tabulated statistic =	0.136685143	0.13668514	0.13668514	0.136685
Calculated Value =	6.93E-02	4.98E-02	8.78E-02	4.60E-02
Fitted Model is	Accepted	Accepted	Accepted	Accepted

Table 3 Chi2 Goodness of Fit test

Parameter	Gumbel	GEV	GPareto	Log-Pearson3
Tabulated statistic =	14.08	12.6	12.6	14.08
Calculated Value =	13.51918029	7.5198193	6.09131716	8.908751
Fitted Model is	Accepted	Accepted	Accepted	Accepted

Table 4 Filliben Correlation Coefficient Test

Filliben Correlation Coefficient	Gumbel	GEV	GPareto	Log-Pearson3
Filliben Correlation Coefficient	0.985828456	0.9953532	0.99081909	0.953914

Table 5 L. Wakatipu levels corresponding to different return periods and different model

Annual Return Periods (Years)	GEV	GPareto	Log-Pearson3
5	311.129	311.188	311.172
10	311.458	311.537	311.470
20	311.822	311.868	311.763
25	311.948	311.971	311.856
50	312.375	312.280	312.148
75	312.651	312.453	312.318
100	312.861	312.573	312.441
150	313.176	312.737	312.613
200	313.415	312.851	312.736

Based on the goodness of fit tests, The GEV and GPareto are the recommended models.

3.2 Frequency Analysis of the Dart River

Time series of peak Dart flows, either the maximum annual series "MAS" or the partial duration series "PDS", were based on 20 minutes average flows to smooth any ripples in the data due to fluctuations in the levels which are subsequently rated to flows. The highest "independent" 150 peak flow events with a threshold of 612 m^3/s were used for the partial duration series.

Figures 2 and 3 clearly show that frequency analysis for the Dart at the Hillocks based on partial duration series performs much better in simulating the observed histography of the peak flows. Other performed goodness of fit tests "Cumulative frequency of observed vs modelled, Kolmogorov Smirnov, Chi squared, and Filliben correlation" also favour the PDS approach for frequency analysis.

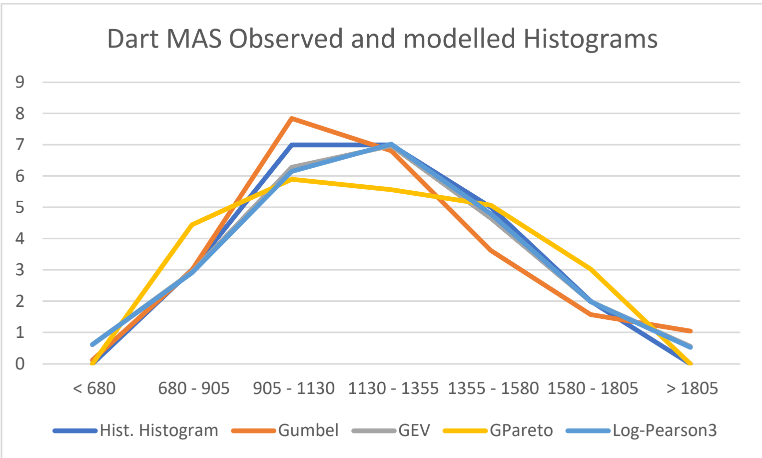

Figure 2 Dart MAS Observed and modelled Histograms

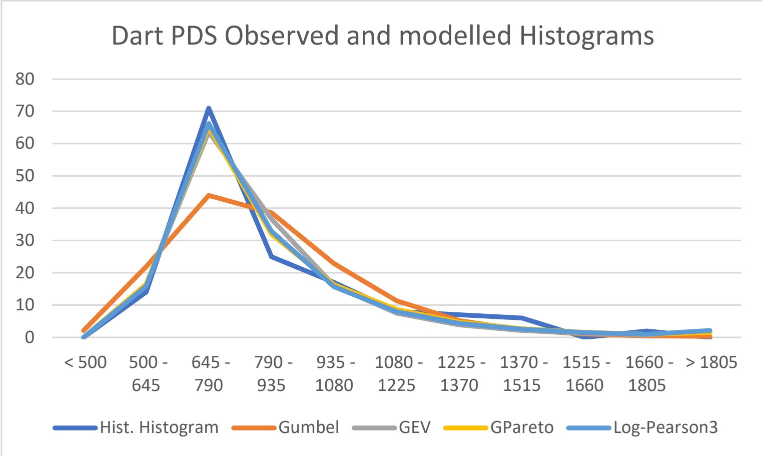

Figure 3 Dart PDS Observed and modelled Histograms

The Generalised Pareto "GPareto" and the Log-Pearson3 probability distribution models are the best to simulate the PDS of the Dart. Table 6 shows the design Dart "at the Hillocks" peak flows based on those two models. The design flows based on the GPareto model are adopted for producing design flow hydrographs for the Dart in this work.

Table 6 Design Peak Flows for the Dart at the Hillocks

Annual Return Periods (Years)	GPareto	Log-Pearson3
5	1390	1415
10	1623	1705
20	1853	2015
25	1928	2125
50	2168	2491
75	2314	2734
100	2420	2913
150	2575	3190
200	2688	3407
250	2777	3577
500	3067	4174

*Note that the GPareto design flows are the ones adopted in this work.

4. Analysis of the correlation between the Dart and Rees flows and Rainfalls

The Dart and the Rees catchments are neighbour to each other and both are expected to be exposed to similar patterns of rainfall events, as shown in Figures 4 and 5. Figure 6 shows the flows for both the Dart at the Hillocks and the Rees at Invincible for the period 18 September 2009 to 25 March 2011 for which flows are available for the Rees at Invincible. The figure shows the similar pattern of high and low flows for both rivers, and in turn their strong relationship. This is confirmed by calculating lagged correlations between the two sites, as shown in figure 7.

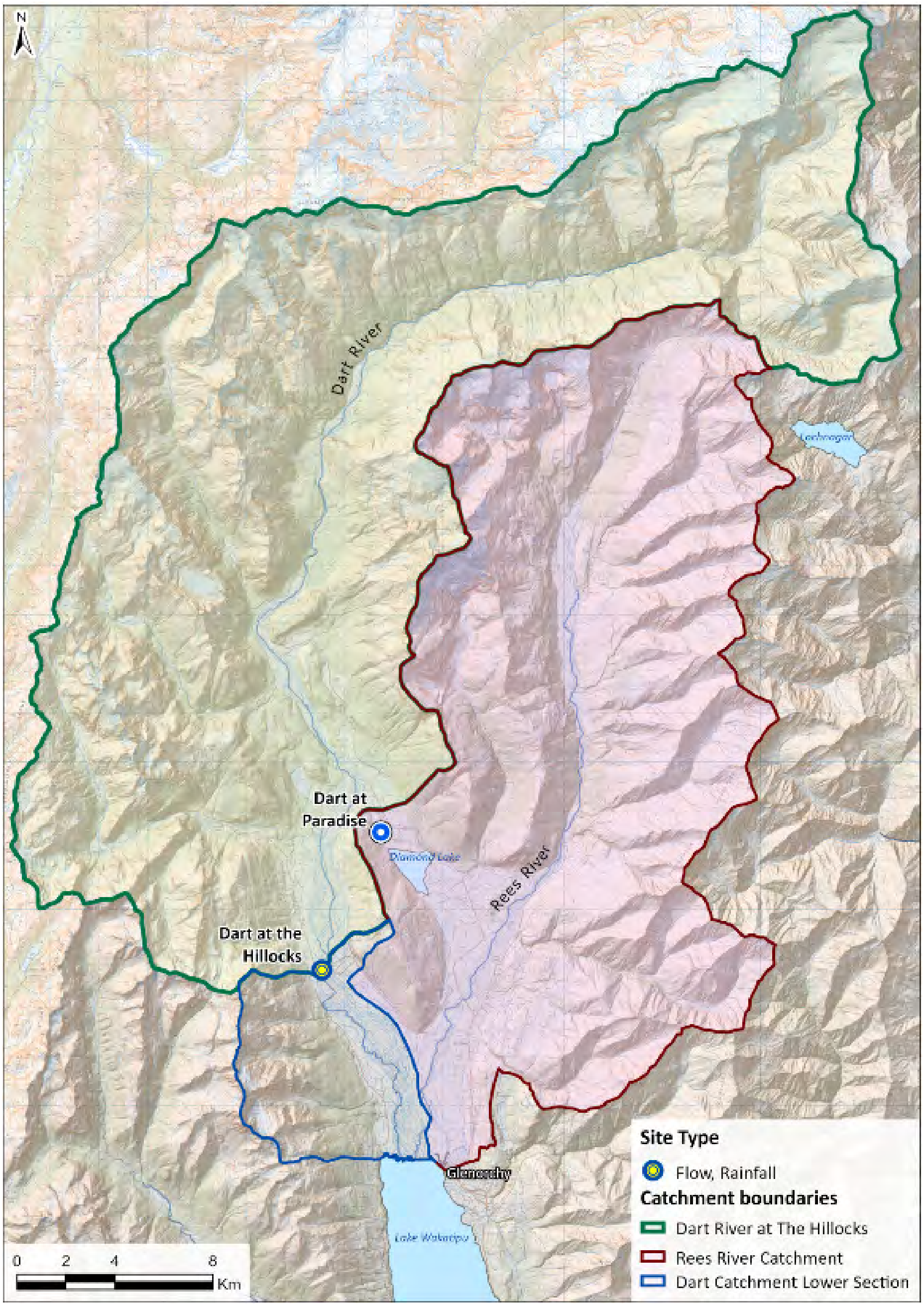

Figure 4 The Dart and Rees catchments

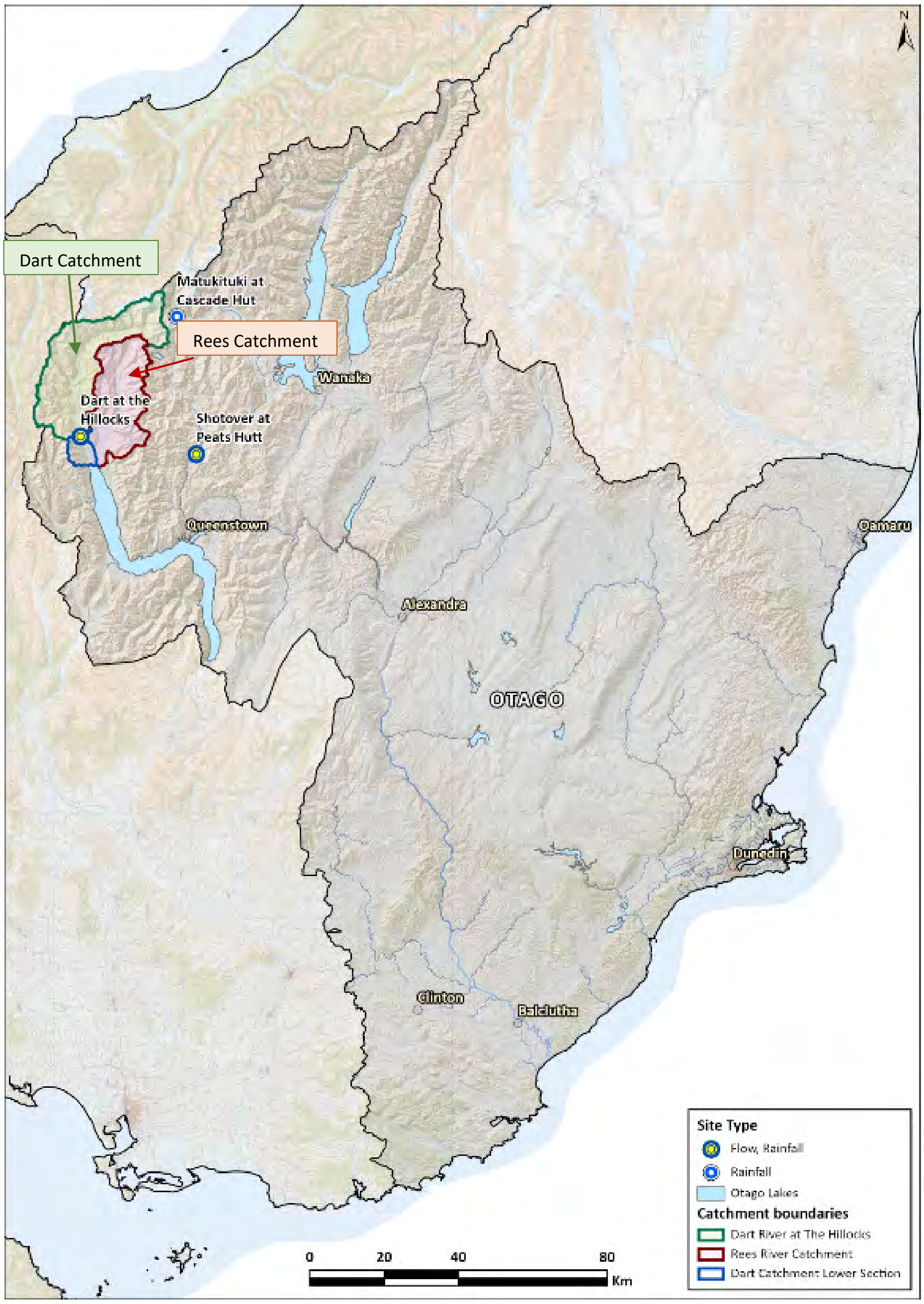

Figure 5 The Dart and Rees Catchments in Otago

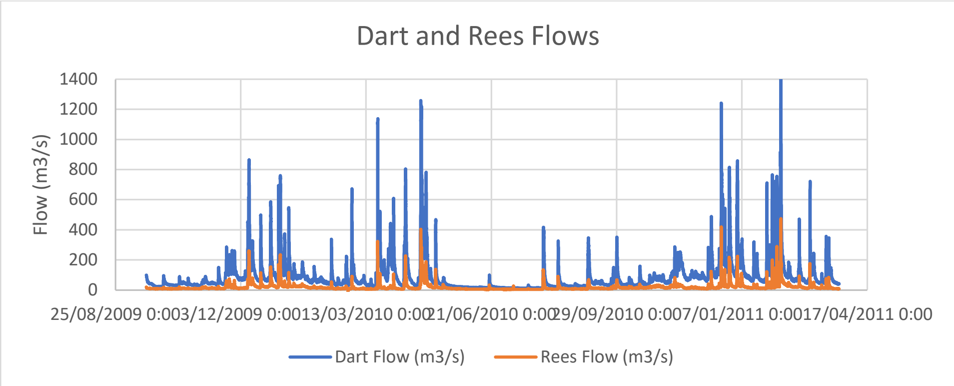

Figure 6 Dart and Rees flows during September 2009 to March 2011

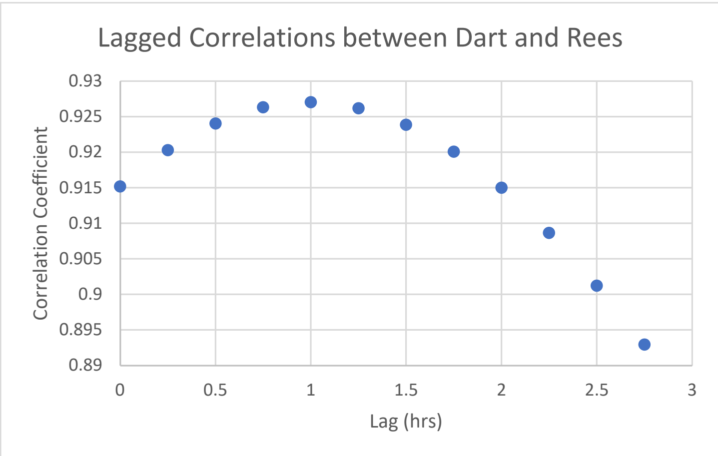

Figure 7 Lagged Correlations between the Dart and the Rees

Figure 7 suggests that the optimum lag time between the Rees and Dart flows is about 1.0 hour "Rees high flows occur first". Another analysis which focuses on high flow only, for which Dart River flows are > 500 m^3/s, confirmed this result.

Figure 8 shows the relationship between the Rees and Dart flows for high flows of the Dart which are > 850 m^3/s. The figure shows a high variability around the trend line which will make it unreliable to use it to estimate high flows of the Rees based on high flows in the Dart River. While it is expected that major rainfall storms will affect both catchments, still the spatial distribution of these events will never be exactly the same, and this will have impact on the amounts of rainfalls over the two catchments relative to each other. This, in turn, can result in high variability of the relationship between the flows of both catchments. A well-developed rainfall-runoff model which takes into account rainfalls observed at several sites in this region might be able to better simulate spatial variability of the rainfall over the two catchments, as will be developed in the following section "6" of this report. However, the figure confirms the strong relationship between the two catchments.

In addition to the flow relationship of the two catchments, analysis of rainfall over the two catchments of the Dart and the Rees has been carried out. Based on average annual rainfalls over the two catchments, the rainfall on the Rees catchment upstream of Invincible is about 60% of the rainfall over the Dart catchment. This justifies the lower ratio of the Rees to the Dart flows, compared to their catchments' areas. Moreover, ratios of rainfall depths over the whole Rees catchment and upstream of the Bridge to the Rees catchment upstream of Invincible have been also estimated, as shown in Table 7.

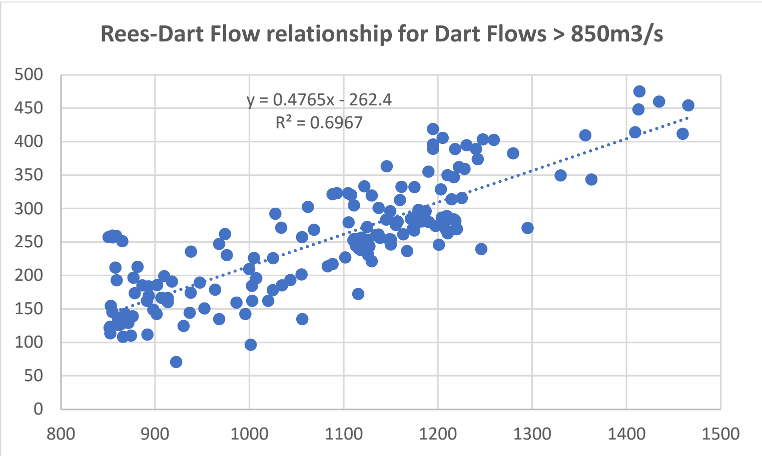

Figure 8 Rees-Dart Flow relationship for Dart Flows > 850m^3/s

Table 7 Rainfall Ratios of Rees' Catchments to Invincible Catchment

Catchment	Area (km^2)	Ratio of rain depth To Invincible Rain
Rees upstream the Bridge	296.9	0.96
Whole Rees	417.6	0.88

5. Rainfall-Runoff Analysis of the Dart and Rees catchments

A rainfall-runoff analysis has been carried for available high flow events for the Dart at the Hillocks and the Rees at Invincible to aid and support the modelling process in assessing rainfall losses and the runoff expected to occur from rainfall events. For the Dart, 126 high flow events where the Dart peak flow is > 500 m^3/s were identified and analysed (about 25 years of record), while only 37 high flow events for the Rees at Invincible, with peak flow > 50 m^3/s, were analysed as only about 1.5 years of record are available. For each event, total rainfall depths at the three rainfall sites: The Hillocks, Paradise and Cascade Hut was calculated, along with the corresponding runoff depth for the Dart at the Hillocks and the Rees at Invincible have calculated. A multiple regression analysis was carried out for all events to obtain the best relationship between observed rainfalls at the three rainfall sites and the corresponding runoff of the Dart and the Rees catchments.

Figures 9 and 10 show the results of the relationship between the runoff of the Dart and the Rees catchments and their corresponding estimated areal rain. Note that the areal rainfall is estimated by using the weights for the rainfall sites which are obtained from the multiple regression analysis of the rainfalls and runoffs of the high flow events. The figures indicate a “suitable” linear relation, with variability around the trend line, which is a typical pattern observed for other catchments.

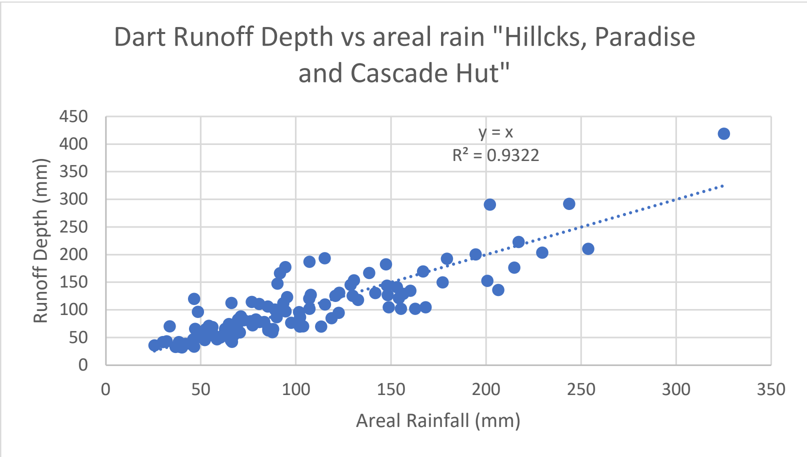

Figure 9 Dart Runoff Depth vs Areal rain from The Hillocks, Paradise and Cascade Hut

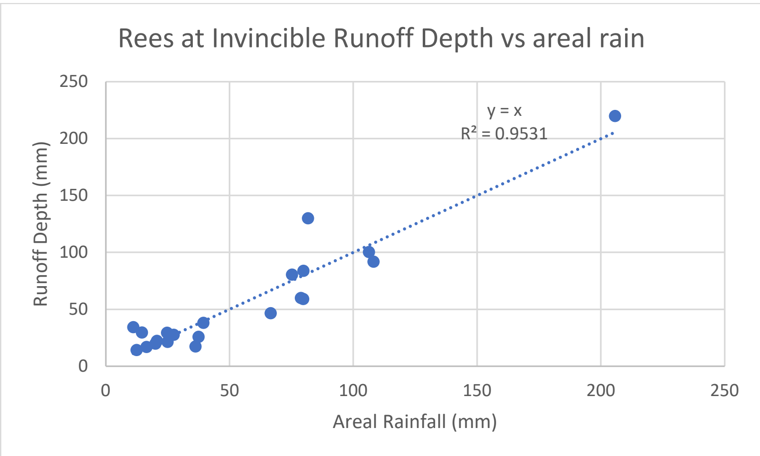

Figure 10 Rees at Invincible Runoff Depth vs Areal Rainfall

Table 8 shows the best fit weights for the rainfall at the three sites to produce the runoff depth based on the multiple regression analysis of total rainfall depths at the rainfall sites and the estimated runoff depths.

Table 8 Weights for rainfall Sites based on the Multiple Regression Analysis

Catchment	Dart at The Hillocks	Dart at Paradise	Matukituki at Cascade Hut	Intercept	R2	Wts sum
Dart upstream Hillocks	0.466	0.325	0.361	0.000	0.932	1.152
Rees upstream Invincible	0.108	0.043	0.393	-5.210	0.953	0.544

The table shows that the sum of the rainfall sites weights for the Dart catchment upstream of the Hillocks is > 1.00. The runoff coefficient (runoff/total rainfall) for any catchment should be < 1, due to rainfall losses such as intercept and infiltration. Weights' sum of all rainfall sites usually represents 100% of the rain, and these weights which are obtained from the rainfall-runoff analysis produce the effective rainfall (runoff volume divided by the catchment area), which should be < the total rain over the catchment. Thus, the sum of these weights should be < 1 as in the case of the Rees River. This indicates that the runoff of this catchment is higher than the rainfall which fell over the catchment, which of course can't be. This analysis is quite important to properly identify this relationship between rainfall and runoff.

6. Rainfall-Runoff Modelling of the Dart and Rees catchments

A HEC-HMS model has been developed for the two catchments of the Dart and the Rees. The model was established such that it accounts for the Dart upstream the Hillocks catchment and the whole Dart catchment. For the Rees River, three catchments have been considered in the model: Rees upstream of Invincible, Rees upstream of the Bridge and the whole Rees catchment. Table 9 shows the catchments included in the HEC-HMS model and their areas.

Table 9 HEC-HMS catchments

Catchment	Area (km^2)
Dart upstream The Hillocks	590.77
Whole Dart	642.67
Rees upstream Invincible	230.2
Rees upstream the Bridge	296.9
Whole Rees	417.6

The weights produced from the rainfall-runoff analysis, along with the relation to produce the runoff depth from the total rainfall depth, were utilised in an Excel template to produce areal rainfalls for each catchment which produces the total runoff for the event. Models parameters such as the concentration time and the storage coefficient were “initially” estimated by using available geographical and hydrological information, then were optimised through the calibration process which was carried out within HEC-HMS model.

Figure 11 and 12 show the calibration result, which utilised events 25 April 2010, 21 December 2010, and 7 February 2011. These are the highest events observed during the recorded flow period for the Rees River.

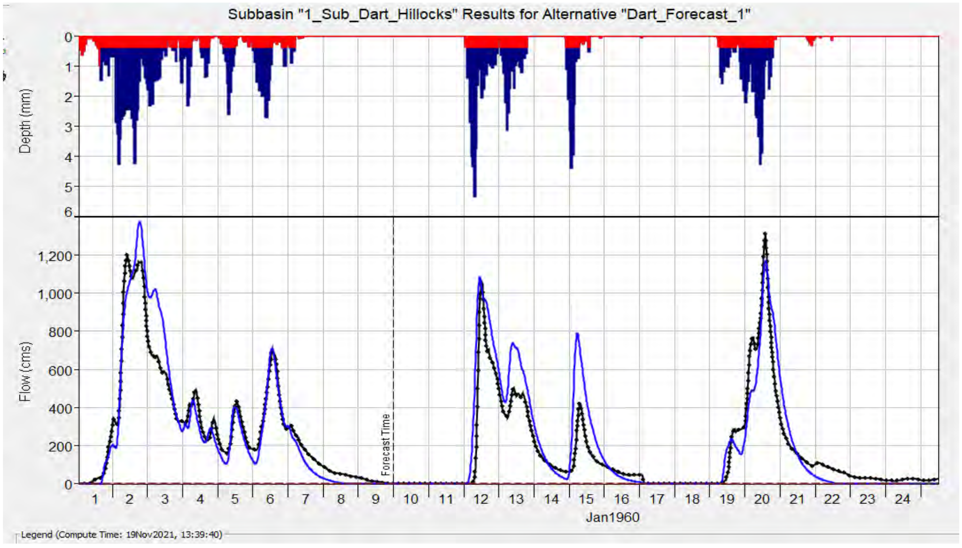

Figure 11 Dart at the Hillocks calibration to events 25 April 2010, 21 December 2010, 7 February 2011

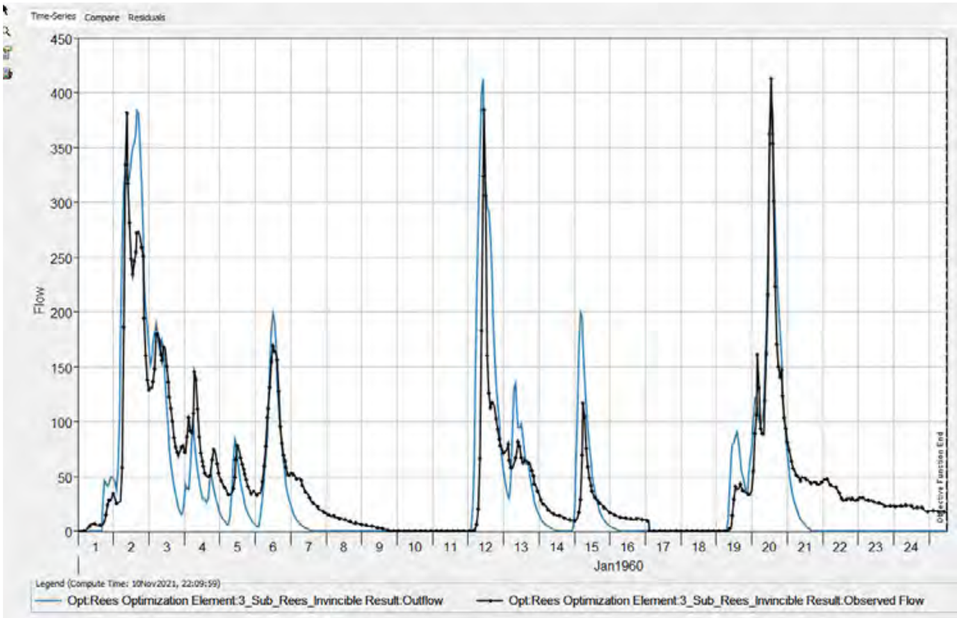

Figure 12 Rees at Invincible calibration to events 25 April 2010, 21 December 2010, 7 February 2011

Model's validation was carried out by simulating the event of March 2010, which was not included in the model's calibration. Figures 13 and 14 shows the results of this simulation to the observed flows of both the Dart at the Hillocks and Rees at Invincible.

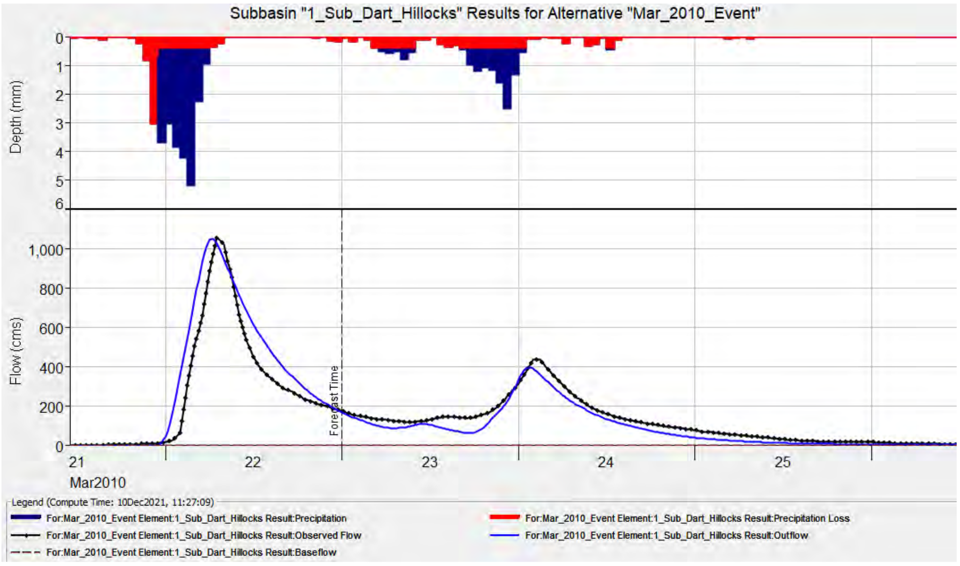

Figure 13 Simulation of the Dart flows for event March 2010

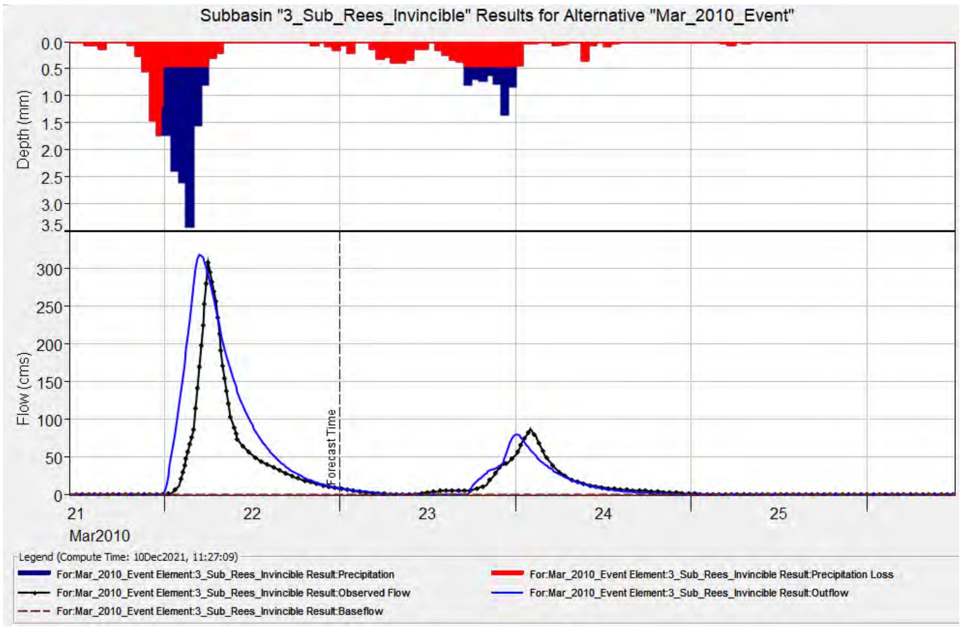

Figure 14 Simulation of the Rees Flows for event March 2010

The results of the model's calibration and validation suggest that model simulates the Dart and Rees catchment and can be used for simulation of their runoff flow hydrographs based on rainfall events.

7. Estimated Rees flow hydrograph for the flood event of February 2020

Based on the observed rainfalls at the Hillocks, Paradise and Cascade Hut for the event February 2020 which flooded parts of Glenorchy township, the developed HEC-HMS, has been used to simulate the flows for the Rees River during this event. The "modelled" flow hydrograph for the February 2020 even, as shown in figure 15, has been used to calibrate the hydraulic model which simulates the extent of Glenorchy flooding from the Rees River during high flows.

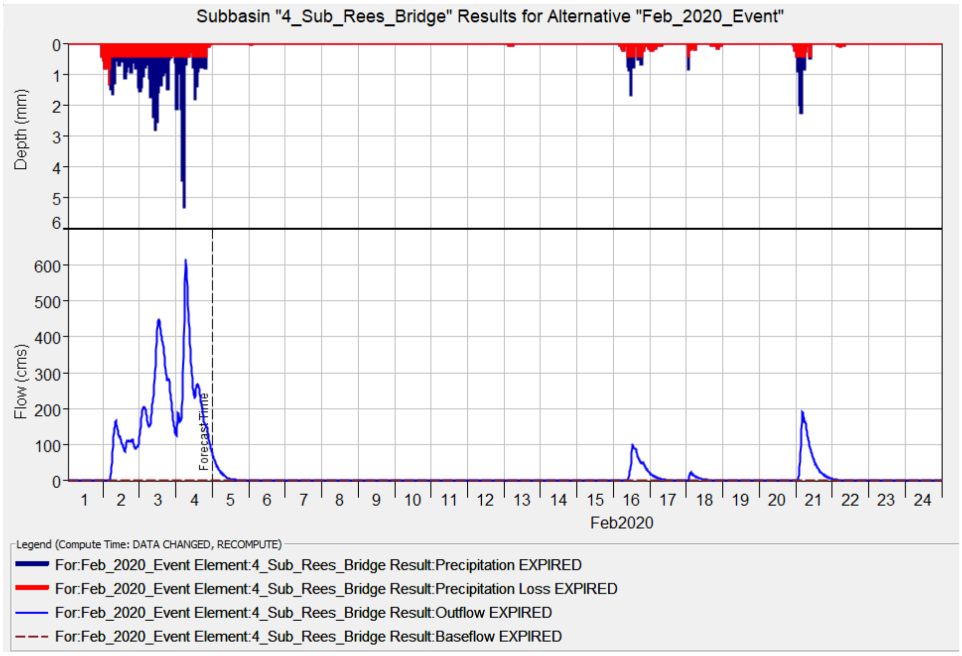

Figure 15 Rees at Bridge flow hydrograph for the Event February 2020

8. Exceedance Probability flow hydrographs for the Dart and the Rees with climate change impact

Frequency analysis of peak flows "either MAS or PDS" produces peak flows corresponding to exceedance probabilities of interest, as shown in Table 6 for the Dart River. These peak flows will be called herein design flow hydrographs. However, for the proper assessment of the flooding risk, the whole hydrograph is needed as the temporal distribution of the flow hydrograph, and not only the peak flow, can contribute to the extent of flooding of Glenorchy. Every rainfall event is different and can produce different flow hydrograph, even if the peak is similar to other events.

8.1 Design Flow Hydrographs based on historical record:

The following methodology have been applied to produce the design flow hydrographs:

For the Dart 100-year design flow hydrograph:

1- The Dart flow hydrograph for the Feb 2020 flood event will be used to produce flow relative hydrograph "to the peak" FRH

2- The Dart design peak flow will be multiplied by the FRH to produce the corresponding design flow hydrograph

For the Rees 100-year design flow hydrograph:

3- Rainfall relative hyetographs "RRH" are based on Feb 2020 rainfall hyetographs relative to total rain at Paradise. Thus, rainfall depth at any time for the 3-rainfall sites is divided by the total rainfall depth at Paradise for the Feb 2020 event to produce RRH

4- The total "estimated" runoff depth for the design 100-yr flow hydrograph for the Dart at the Hillocks is estimated from the produced 100-yr flow hydrograph, from which runoff depth will be calculated. This will be used to calculate the initial estimate for the total rainfall depth at Paradise to produce this runoff depth.

5- Change the total rainfall depth for Paradise to produce the rainfall hyetographs which will produce the design 100-yr peak flow for the Dart at the Hillocks. Get the corresponding flow hydrographs for the Rees. Based on the strong relationship between the Dart and the Rees high flows, it is expected that this corresponding Rees peak flow will have similar return period to the Dart flow.

Figure 16 shows the produced design hydrographs based on analysis of observed data.

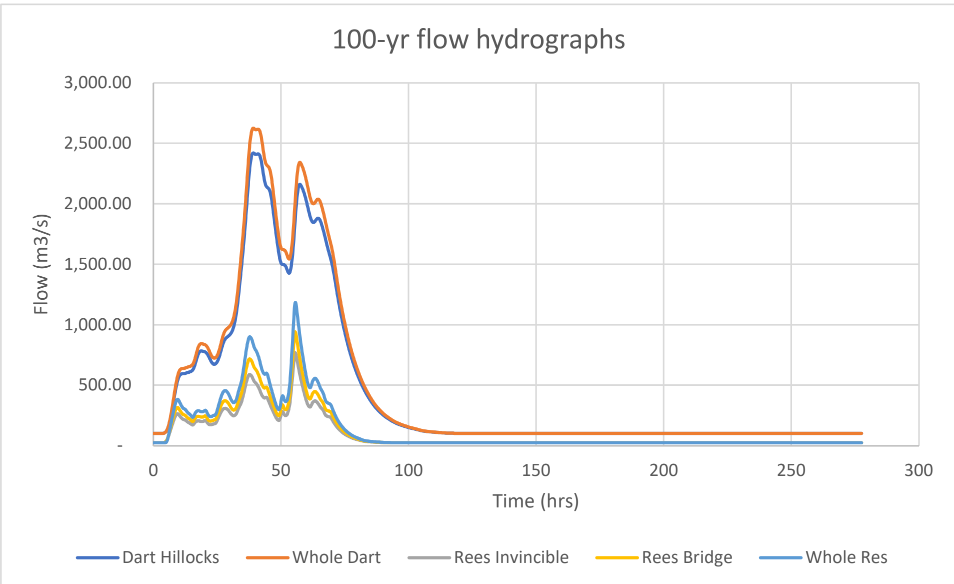

Figure 16 Design Flow Hydrographs for the Dart and the Rees

8.2 Design Flow Hydrographs with Climate Change Impact

It is well accepted in the literature that peak flows will change with climate change.

The High Intensity Rainfall Design System "HIRDS" developed by NIWA, is used to obtain the 100-yr rainfall depths, at Paradise rainfall site, corresponding to the historical data and climate change scenarios "CCS". These design rainfall depths will be applied to the relative rainfall hyetographs "RRH developed as mentioned in section 8.1" to produce rainfall hyetographs for the historical and climate change scenarios. These rainfall hyetographs will be applied to the developed HEC-HMS model to produce flow hydrographs for all scenarios. The following details the methodology to produce the 100-yr design flow hydrographs with climate change scenarios for the Dart and the Rees:

1- Obtain rainfall depths from HIRDS corresponding to historical and CCS for the required return period "Note: a duration of 72 hours is used as the duration of the Feb 2020 and Nov 1999 events are about 72 hrs"
2- Use the developed template in to produce areal rainfall hyetographs for HEC-HMS using these HIRDS rainfall depths for historical and CCS "each case at a time".
3- Use the HEC-HMS model to produce corresponding flow hydrographs to the historical and CCS HIRDS rain depths
4- Get the ratios of the peaks of CCS to the historical flows produced by HEC-HMS for each case of CCS
5- Apply these ratios to the already produced 100-yr peak flows for Dart and Hillocks to produce 100-yr peak flows for CCS
6- Apply these 100-yr CCS peaks to the relative hydrographs "relative to the peak flow" which are produced based on the "already" produced and submitted 100-yr design flow hydrographs for the Dart and Rees Rivers.

Figure 17 shows the estimated design flow hydrographs for the Dart and Res Rivers for climate change scenario RCP 8.5 2081-2100.

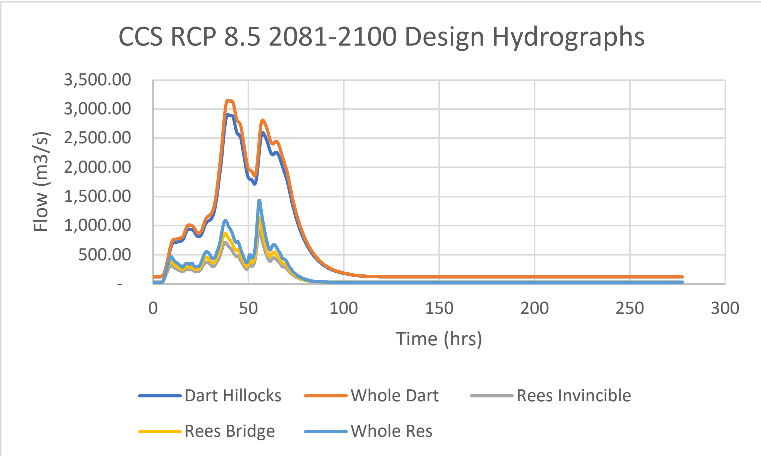

Figure 17 Design Flow Hydrographs for the Dart and Rees Rivers for CCS RCP 8.5 2018-2100

Table 10 presents a summary of the 100-year design peak flows for the Dart and the Rees rivers based on the available historical record of data and for two different climate change scenarios: RCP 6.0 2081-2100 and RCP 8.5 2081-2100.

Table 10 100-year Design Peak Flows for the Dart and the Rees

Scenario	Dart Hillocks	Whole Dart	Rees Invincible	Rees Bridge	Whole Rees
Freq Analysis of Available data	2,420.62	2,625.57	769.10	941.18	1,183.54
RCP 6.0 2081-2100	2,730.05	2,961.29	870.66	1,066.22	1,342.58
RCP 8.5 2081-2100	2,906.91	3,153.13	928.96	1,137.66	1,433.77

APPENDIX D – REES-GLENORCHY FLOODBANK STRUCTURE FAILURE MODES ASSESSMENT

Tonkin+Taylor

Memo

To:	**Tim Van Woerden**	**Job No:**	**1017916.1**
From:	**Tim Morris & Dan Ashfield**	**Date:**	**18 November 2021**
cc:	**Sjoerd Van Ballegooy**		
Subject:	**Rees-Glenorchy Floodbank structure failure modes assessment**		

1 Introduction

This memo overviews a qualitative rainy day/flood event failure mode assessment of the Rees-Glenorchy Floodbank. The Rees-Glenorchy Floodbank extends approximately 1,400 m from the Glenorchy-Paradise Road to the Glenorchy Scenic Walkway carpark adjacent to the Rees River mouth at Lake Wakitipu. Figure 1 provided by Otago Regional Council (ORC) illustrates the location and alignment of the Rees-Glenorchy Floodbank as well as the general arrangement of the site area including Glenorchy (bottom right), the Rees River, Glenorchy Lagoon (north of Glenorchy village and east of Lagoon Creek) and Lagoon Creek.

Figure 1 Site location plan (provided by ORC).

The assessment is informed by a walk over site appraisal of the Rees-Glenorchy Floodbank by Tonkin and Taylor Ltd (T+T) staff Tim Morris and Dan Ashfield on Tuesday 12 October 2021, carried out in part with ORC staff. Rees River, Lagoon Creek and Glenorchy Lagoon water levels were normal at the time of the visit.

The failure modes analysis is intended to inform hydraulic modelling undertaken by others. In particular, we understand that hydraulic model scenarios will be prepared whereby the floodbank is compromised by flooding/elevated water levels north of the Rees-Glenorchy Floodbank arising from various Rees River catchment flood events.

2 Observations

The following general observations were made at the time of the 12 October site visit:

i. Based on overall appearance, the Rees-Glenorchy Floodbank appears to be have been constructed and maintained with a low level of engineering input. Some observations that support this view include:
   - The fill appeared to have been constructed over a pre-existing fence.
   - Large trees and vegetation near the embankment.
   - Irregular appearance (e.g. quite different side slopes and crest widths).

ii. Whilst variable, side slopes were typical for a flood embankment of this nature.

iii. Crest widths were generally appropriate. Typical crest widths were mostly in the vicinity of 2 – 5 m wide. The narrower widths tended to be in the vicinity of the golf course, where the land side embankment slope was flatter than at other locations.

iv. Based on our walk over appraisal most of the embankment fill appeared to comprise non-cohesive material. Topsoil and grass had been placed over the crest in places and on the land side face of the floodbank in the vicinity of the golf course. The river side face was typically covered with vegetation that would aid erosion resistance although root systems of willow trees growing on the river side of the embankment may also lead to piping failures.

v. Works had been undertaken to widen the Lagoon Creek channel and improve flood capacity. The improvements have included removal of significant quantities of large willows on the true right bank of the Lagoon Creek (i.e. opposite to the Rees-Glenorchy Floodbank). Large piles of tree debris are located upstream of the confluence with the Rees. This work has been undertaken subsequent to the February 2020 flood, in August 2020.

vi. Between Butement Street and Argyle Street is a loop of public road called Lake Road. Fill appears to have been placed on the township side of the floodbank here presumably to create the road and nearby residential building platforms. The nature of the fill could not be determined.

vii. A 4wd crossing which runs over the floodbank is located off of the north end of Oban Street. The crossing is now closed to public traffic.

viii. Two stormwater culverts were located during the site visit, running from drainage channels on the township side of the floodbank through to the Rees/Lagoon Streem/Lagoon side. The culverts were formed using 450 mm diameter precast concrete pipe and were fitted with steel flood gates on the Rees side of the floodbank. The flood gate of the culvert near the 4wd crossing was partially jammed open.

ix. Deepened parts of the creek channel were observed near Lake Road and where Lagoon Stream currently meets a braid of the Rees. These scour deepened parts of the channel were located up against the toe of the floodbank.

3 Failure modes considered

Based on walk over appraisal and understanding of Rees-Glenorchy Floodbank performance during some recent floods as advised by ORC[1] (e.g. the February 2020 flood), we consider that overtopping and scour are more likely potential failure modes as described respectively at sections 3.1 and 3.2 following. These are "rainy day scenarios" i.e. coincident with extreme flood events. Indicative breach arrangements arising from these scenarios are outlined at 3.4. Some other possible failure modes are outlined at Section 3.5. Based on our present understanding we consider that these other potential failure modes are less likely than flood bank failure arising from the described overtopping and/or scour failure modes albeit it is noted that latent conditions may arise at a future time requiring review of this advice.

The potential failure modes considered in this memo are based on walk over visual inspection and discussion with ORC regarding recent flood events. They have been developed without the benefit of a flood hydraulic grade line/water level estimates, either developed by modelling and/or estimated from post flood survey. It is important that model development includes appropriate sensitivity analyses to understand the impact of the indicative breach formation parameters presented. It is essential that potential failure locations are reconciled with model results, and that we are contacted if there are significant discrepancies with model water level estimates and the potential failure scenarios outlined, e.g. as relates to estimated overtopping scenarios.

Other circumstances that may influence the likelihood and extent of potential failures manifesting include factors such as:

- Changes in Rees River morphology such as:
  - Long term aggradation of the Rees Riverbed.
  - Changes to Rees River braids such as alignment and channel size in the vicinity of the Rees-Glenorchy Floodbank.
- Changes to the channel capacity of Lagoon Creek. It was noted that at the time of the site appraisal that willows had been cleared to improve channel capacity.
- The amount of flow from the Rees River entering the Dart River upstream of the Glenorchy Lagoon area and thereby avoiding the Rees-Glenorchy Floodbank area (refer Figure 1).

3.1 Overtopping

Based on discussions with ORC[2] we understand during recent floods of significance (e.g. February 2020), that flood levels can rise in the Glenorchy Lagoon area to exceed the adjacent Rees-Glenorchy Floodbank crest level. When this has occurred, ORC have indicated that the Rees-Glenorchy Floodbank first overtops in the vicinity of where the golf course directly adjoins the Rees-Glenorchy Floodbank. We understand that during the February 2020 event the Rees-Glenorchy Floodbank first overtopped at isolated locations and as the upstream water level increased, shallow sheet flow subsequently occurred over most of the Rees-Glenorchy Floodbank adjacent to the golf course. The length of the golf course adjacent to the land side of the Rees-Glenorchy Floodbank is of approximately 230 m. Figure 2 following illustrates the location.

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[1] Pers. Comm. T Van Woerden/T Morris 12 October 2021.
[2] Pers. Comm. T Van Woerden/T Morris 12 October 2021.

Figure 2 Golf course adjacent to the Rees-Glenorchy Floodbank where sheet flow overtopping has been reported.

The Rees-Glenorchy Floodbank crest width at the area of interest in the vicinity of the golf course was typically over 2 m wide before transitioning to a flat land side slope. Land side slope angles were estimated to be in the order of 5° and 10° (noting the 5° estimate corresponds to a potential flow path oblique to the slope). The Rees-Glenorchy Floodbank is likely to behave as a broad crested weir during shallow overtopping flows. The crest and land side slopes were well grassed, indicating that the Rees-Glenorchy Floodbank can withstand shallow low velocity overtopping flows for an appreciable period if flow is not able to concentrate at irregularities (albeit the grass observed in the golf course environment was shorter than would provide optimum erosion protection). Based on ORC advice, we understand that no significant damage was reported during the recent floods when shallow overtopping depths were sustained for at least 10 hours and no significant debris accumulation was reported[3]. However, more adverse flood conditions may result in greater overtopping beyond what the existing flood bank can withstand.

In general, the most erosive flow occurs on the downstream slope, where the velocity is highest and where the slope makes it easier to dislodge particles and remove them. Where vegetation has been removed or is sparse and flow velocity and duration thresholds exceeded, the erosion will proceed to attack the soil directly until a "headcut" formed. Erosion generally continues in the form of "headcutting", by way of an upstream progression of a deepened eroded channel(s), that can eventually penetrate the floodbank. Lateral progression may then extend the breach as flow accelerates via the opening.

[3] ORC (Tim van Woerden); File Note Re: Review of the Feb 2020 Glenorchy flooding event; 20 February 2020.

Typically, on embankments that have been overtopped by floods in excess of erosion thresholds, severe erosion has often been observed to begin where sheet flow on the slope meets and/or is concentrated/disrupted by an obstacle/irregularity. For example trees and/or other irregularities in the vicinity of the Rees-Glenorchy Floodbank land side as shown at Figures 2 and 3.

Figure 3 Large willow trees at Rees-Glenorchy Floodbank downstream face.

Debris deposited by flood waters are also of concern. There was significant thick vegetation on the riverside of the Rees-Glenorchy Floodbank, between the floodbank and Glenorchy Lagoon. It is very likely that in an extreme flood event significant amounts of debris e.g. trees, logs and branches, will become stuck on the Rees-Glenorchy Floodbank crest because initial overtopping flows will be shallow. If this situation occurs, flows are likely to concentrate at the margins of debris piles, causing scour that may lead to head cutting.

The Lagoon Creek bridge downstream of the golf course did not have a lot of freeboard. Blockage of the Lagoon Creek channel with flood debris e.g. at the Lagoon Creek bridge downstream may influence a failure. Either by increasing upstream water levels adjacent to the golf course or locally at the bridge. The latter scenario may influence failure location.

More extreme floods than have occurred in recent times are likely to result in more adverse overtopping than has been observed, potentially leading to failure as described, albeit the depth may not increase to a large extent if modelling identifies that the lagoon provides significant attenuation i.e. it's surface area is significant relative to inflows. In this situation the duration of overtopping may be extended. Possible breach scenarios associated with this failure mechanism are described at Section 3.4.2.

The likelihood of failure occurring, as outlined above is highly dependent upon depth, duration and velocity of overtopping flows. Estimates of overtopping depth, duration and velocity during particular events of interest are not available. While we are of the opinion that overtopping is more likely than some other potential failure mechanism (it has occurred recently although not to the level that has instigated failure), we recommend that the various comments on potential overtopping failure scenarios are reviewed when model depth, velocity and overtopping duration data from key events are available.

3.2 Scour

Based on walkover visual assessment it is our opinion that the more likely location for scour damage is in the vicinity of the Rees River confluence with Lagoon Stream. There is a bend in the Rees River at this location, with the Rees River flow directed towards the Rees-Glenorchy Floodbank at an oblique angle as illustrated at Figures 4 and 5.

Figure 4 Rees-Glenorchy Floodbank adjacent to the Rees River confluence with Lagoon Stream. The Rees River is directed towards the Rees-Glenorchy Floodbank, increasing the likelihood of scour damage.

Figure 5 Rees River directed towards the Rees-Glenorchy Floodbank.

Figure 6 Butement Street on the land side of the Rees-Glenorchy Floodbank at the location assessed as vulnerable to damage instigated by scour.

Figure 7 Deeper Lagoon Creek water and bank prone to scour near confluence with Rees River.

A deepened section of Lagoon Creek in close proximity to the Rees River was also observed (Figure 7). The area of interest included an over steepened bank that was close to the riverside toe of the embankment and presents a location of enhanced scour risk to the Rees-Glenorchy Flood bank.

During flood conditions flow velocities will be substantial and given the orientation of the flow there is significant potential for high energy flows to scour the Rees-Glenorchy Floodbank. Scour may lead to slumping and potential Rees-Glenorchy Floodbank failure by way of collapse of the embankment river side, overtopping and flood waters entering the town near Butement Street. Lateral progression may then extend the breach. Possible breach scenarios associated with this failure mechanism are described at Section 3.4.1.

3.3 Works proposed by Queenstown District Council

We understand that Queenstown District Council (QLDC) is proposing engineering works comprising[4]:

- Armouring the river side of the Rees-Glenorchy Floodbank near the confluence of the Rees River and Lagoon Creek.
- Raising the Rees-Glenorchy Floodbank crest in the vicinity of the golf course (level and cross section information has not been provided).

The two locations where works are proposed coincide with our assessment of locations where failure is more likely to manifest than compared to other locations.

If the armouring works proposed by QLDC are well engineered from suitable materials, for the purpose of initial modelling, it is appropriate to consider a breach development scenario towards the optimistic end of the range outlined at Section 3.4.1. If properly implemented these works should be expected to reduce the risk of scour failure at this location.

If the crest raising works proposed by QLDC are well engineered from suitable materials, for the purpose of initial modelling, it is appropriate to consider a breach development scenario towards the optimistic end of the range outlined at Section 3.4.2 if modelling confirms overtopping at this location remains a risk. If properly implemented these works should be expected to reduce the risk of overtopping failure at this location.

It is appropriate to reassess the advice outlined in this memo when there is greater clarity on what QLDC are proposing e.g. levels, extent of work, standard of construction etc. This reassessment should consider if the QLDC works mean that other potential failure to those described in sections 3.1 and 3.2 are more likely.

3.4 Breach formation

Possible breach scenarios have been developed based on engineering judgement informed by the walk over site visit and criteria proposed by Zomorodi[5].

3.4.1 Scour

For a scour failure near the confluence of the Rees River and Lagoon Creek we consider the following breach parameters appropriate to inform initial modelling assuming an embankment up to approximately 2 m high formed from non-cohesive material:

[4] Pers. Comm., email from T van Woerden; Glenorchy floodbank; 7 October 2021.
[5] Zomorodi; Empirical equations for levee breach parameters based on reliable international data; September 2020.

- Breach width mid-range estimate of 40 m with optimistic and adverse estimates ranging from 10 – 90 m.
- Mid-range breach development time (lateral erosion rate) of 35 m/hr with optimistic and adverse estimates ranging from 20 – 100 m/hr.
- An initial, instantaneous slumping failure of a short section of embankment (for the full depth of the embankment), followed by lateral erosion.

3.4.2 Overtopping

For an indicative overtopping failure scenario where the golf course is adjacent to the Rees-Glenorchy Floodbank we consider the following breach parameters appropriate to inform initial modelling assuming an embankment up to approximately 1 m high:

- Breach width mid-range estimate of 20 m with optimistic and adverse estimates ranging from 5 – 50 m.
- Mid-range breach development time (lateral erosion rate) of 5 m/hr with optimistic and adverse estimates ranging from 3 – 75 m/hr.
- The vertical erosion rate is anticipated to be proportional to the lateral rate as illustrated in Figure 8, below.

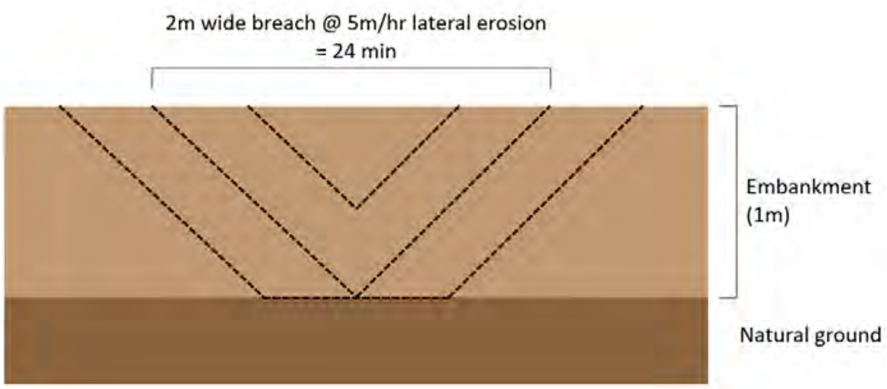

Figure 8 Illustrative diagram showing failure mode.

Behaviour will be influenced by factors such as the following:

- Depth, velocity and duration of overtopping. Model estimates of the extent of overtopping will guide selection of parameters to model i.e. some iteration of model runs is likely to reconcile results with the range of parameters presented.
- Condition of grass cover.
- Potential for debris accumulation.
- Extent to which scour may be governed by more cohesive golf course side material compared to inferred less cohesive river side material.

It is important that these uncertainties are acknowledged when preparing and interpreting model results.

3.5 Other failure modes

Non-rainy day failure scenarios are also a possibility. Some other potential failure modes are mentioned for completeness and are outlined below:

i. Piping/sunny day failure. Piping is the internal erosion of soil from seepage leading to voids and potentially collapse. Piping is more likely to occur following long periods of elevated floodbank river side water levels. Piping risk increases with water level/head. Piping could occur at locations associated with the following:

   - Foundation defects such as at old river channel/paleo channel location under the flood bank. One paleo channel was observed near the western location that the walkway diverges from the golf course.
   - At defects in the embankment fill. Defects leading to piping may arise from inappropriate fill grading and/or construction defects such as poor compaction of fill and/or lamination/horizontal discontinuities within the fill. The less engineered the structure, the greater the likelihood of either grading and/or construction defects. In their 2020 report, WSP mention a location where WSP assessed some potential for piping[6]. We acknowledge that the photograph referred to by WSP could indicate evidence of piping, albeit that at the time of the visit our observations were inconclusive (Figure 9). It is appropriate that locations where unusual observations are recorded are inspected on an ongoing basis as part of routine operation and maintenance procedures with appropriate action taken if adverse behaviour is confirmed.
   - From seepage and poor detailing at conduits/culverts under the embankment. Multiple culverts under the embankment were observed. Possible evidence associated with adverse seepage at one culvert was observed (Figure 10). It is appropriate that culvert crossings under the Rees-Glenorchy Floodbank are inspected on an ongoing basis as part of routine operation and maintenance procedures with appropriate action taken if adverse behaviour is confirmed.
   - Tree roots may cause piping. A number of large willow trees were observed adjacent to the embankment. In several instances it appeared that the fill had been placed around large trees (e.g. Figure 3). One way tree roots can lead to piping is the formation of preferential seepage paths as roots decay following tree removal.

Figure 9 Embankment at location inferred by WSP to be an area of interest for possible piping.

[6] WSP; Glenorchy Floodbank Rees River; 19 June 2020.

Figure 10 Embankment at location where culvert crosses under embankment. Potential area of interest for piping.

ii. A static slope failure is possible albeit unlikely.

iii. Deformation associated with shaking from a large earthquake, possibly including deformation from liquefaction of foundation materials and/or lateral spreading.

While possible, these failure modes are considered less likely that the scour and overtopping mechanism outlined at 3.1 and 3.2. Earthquake damage may also influence the likelihood of scour and/or overtopping failure if not promptly repaired post event, highlighting the importance of repairing any such damage promptly.

4 Conclusion

Based on our walk over visual inspection we conclude as follows:

i. The Rees-Glenorchy Floodbank does not appear to be a highly engineered structure.

ii. We consider that the Rees-Glenorchy Floodbank is vulnerable to damage, potentially leading to failure, from significant flood events in the Rees River catchment.

iii. The two most likely failure mechanisms include:
   - Scour of the Rees-Glenorchy Floodbank near the confluence of Lagoon Creek and the Rees River leading to collapse of the embankment and flood waters entering the town near Butement Street.
   - Overtopping of the Rees Glenorchy Floodbank. Based on our understanding of recent flood events we infer a more likely location is near the eastern end of the Rees Glenorchy Floodbank in the vicinity of where the golf course adjoins the floodbank.

iv. Indicative breach formation parameters are provided to inform modelling of a scour failure near the Lagoon Creek and Rees River confluence and an overtopping failure where the golf course adjoins the Rees-Glenorchy Floodbank.

v. It is important that model development includes appropriate sensitivity analyses to understand the impact of the indicative breach formation parameters presented. Also, that we are contacted in the event that the model is highly sensitive to the parameters described in this memo. It is more difficult to estimate breach parameters arising from an overtopping failure near the golf course and this is reflected in the range of estimates provided.

vi. Other failure modes may occur. For example:

- Piping associated with latent defects in embankment foundations such as a paleo channel location and/or floodbank fill with inappropriate grading.
- Blockage of the Lagoon Creek channel with flood debris e.g. at the Lagoon Creek bridge causing scour of the embankment.
- Sunny day failure.

Based on walk over assessment, we consider these scenarios to be less likely at this time.

Applicability

This report has been prepared for the exclusive use of our client Otago Regional Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

Tonkin & Taylor Ltd

Report prepared by:

....	....
Tim Morris	Dan Ashfield
Senior Civil Engineer	Engineering Geologist

Authorised for Tonkin & Taylor Ltd by:

....

Sjoerd Van Ballegooy

Project Director

18-Nov-21
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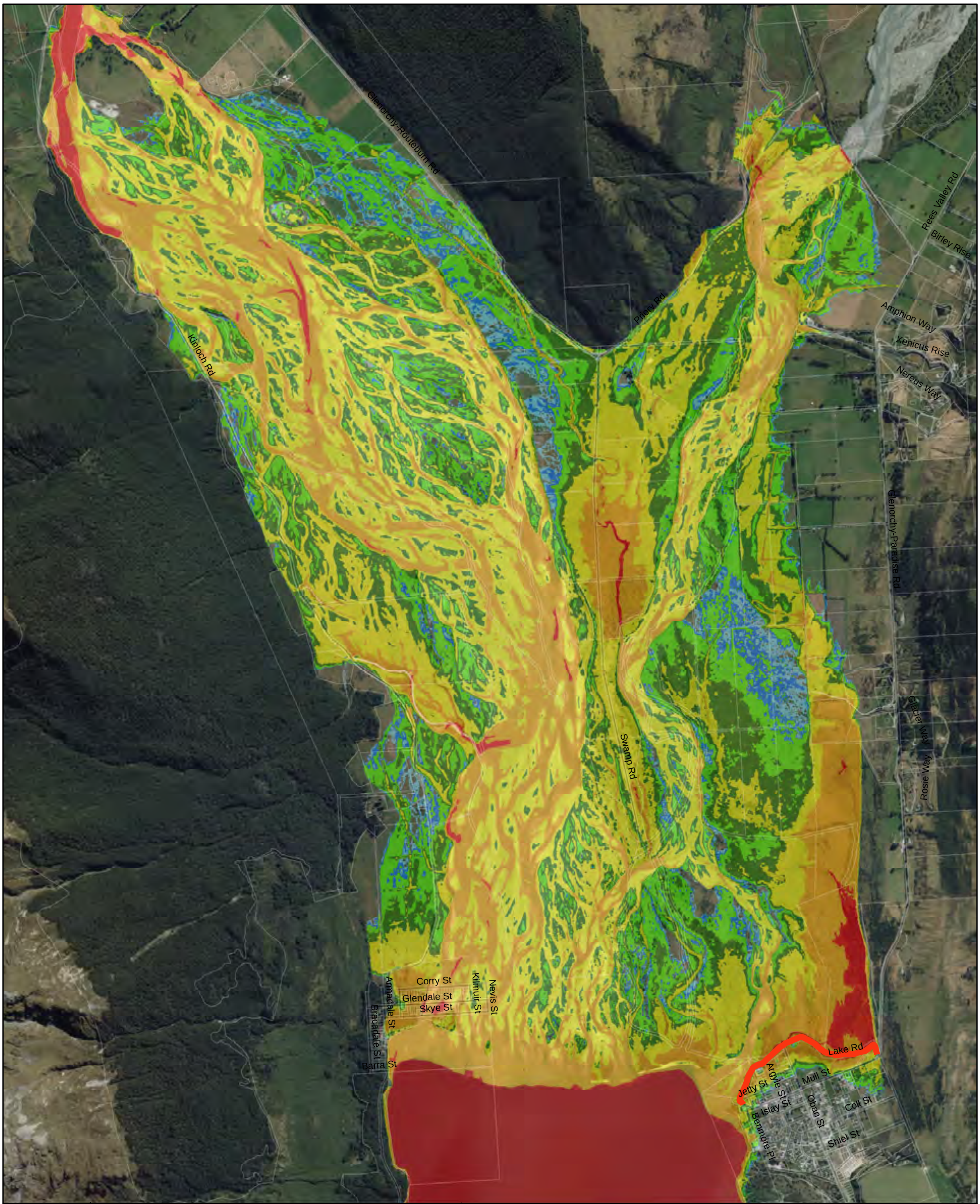
APPENDIX E – PEAK FLOOD DEPTH MAPS



Legend

Stopbank
Roads
Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

Otago Regional Council

0 305 610 1,220 Meters

A3 SCALE 1:25,000

MAP (1 of 1)

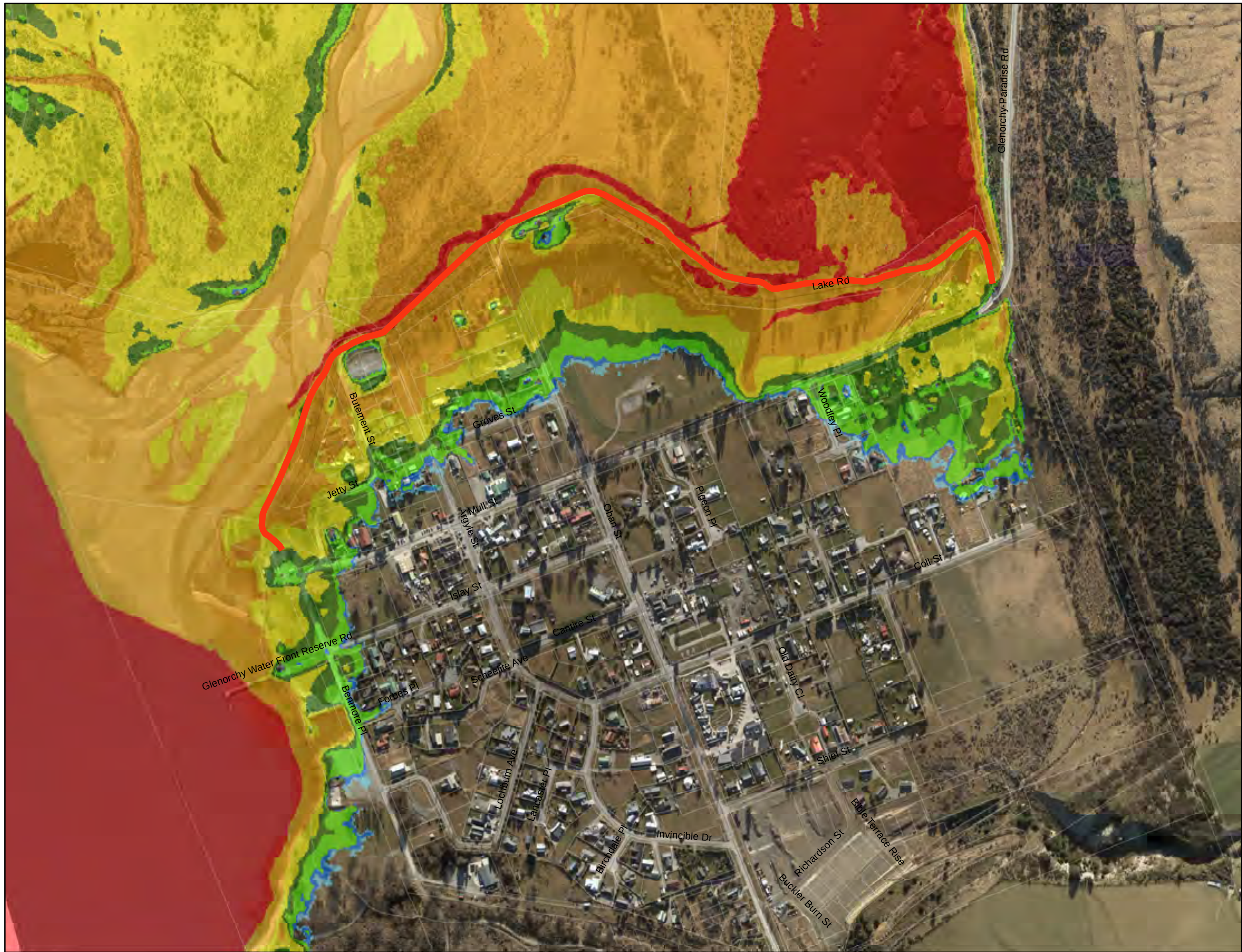
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK DEPTH OVERVIEW MAP
Scenario 1 – 100 year ARI flow (historic climate)
10 year ARI lake level

REVISION	01	Created By	PG	Reviewed By	MG	N
AUTHOR	Matthew Gardner		DATE	13/05/2022		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

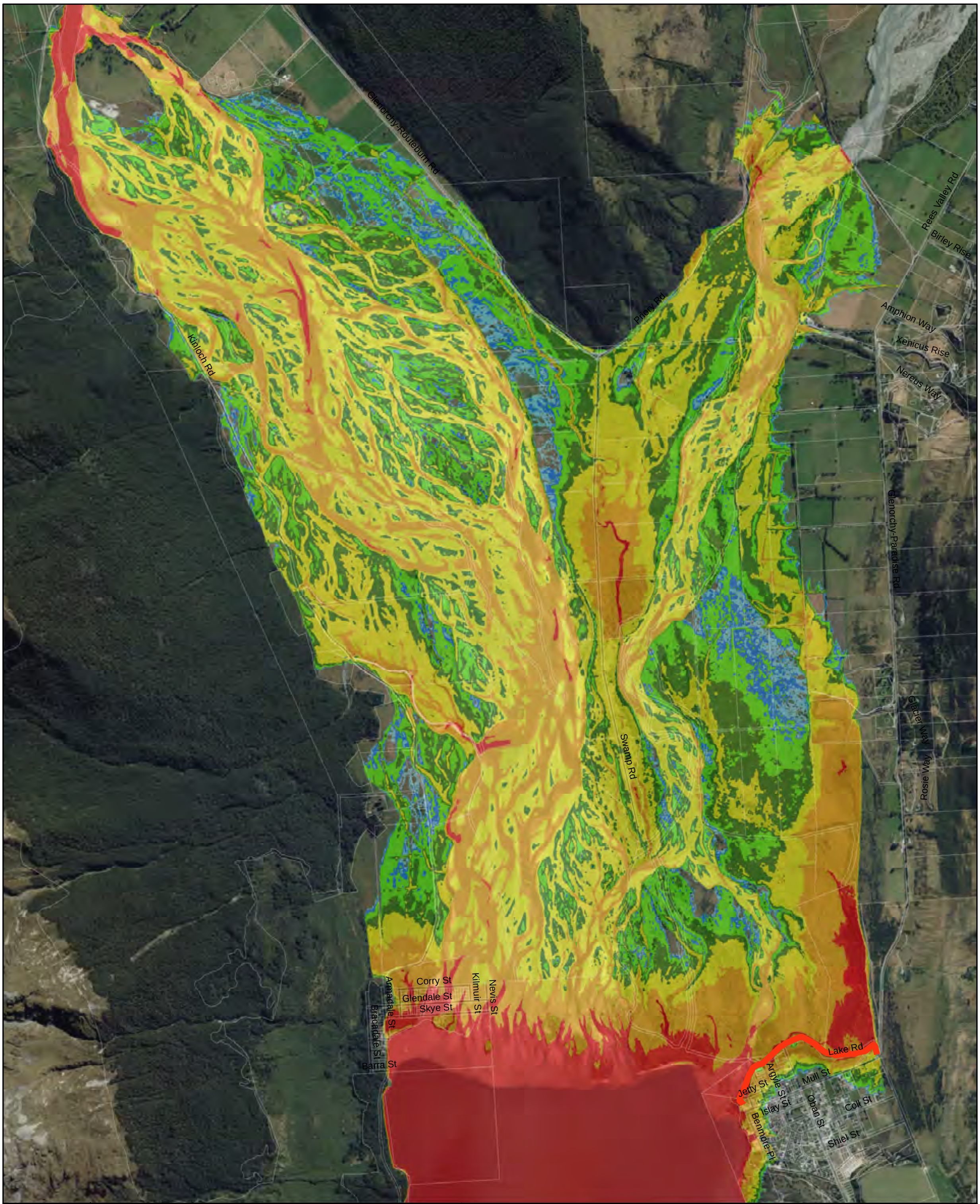
Otago Regional Council

0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**PEAK DEPTH MAP** **Scenario 1 – 100 year ARI flow (historic climate)** **10 year ARI lake level**	CREATED BY **BSB**	**13/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	N



Legend

- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

Otago Regional Council

0 305 610 1,220 Meters

A3 SCALE **1:25,000**

MAP (1 of 1)

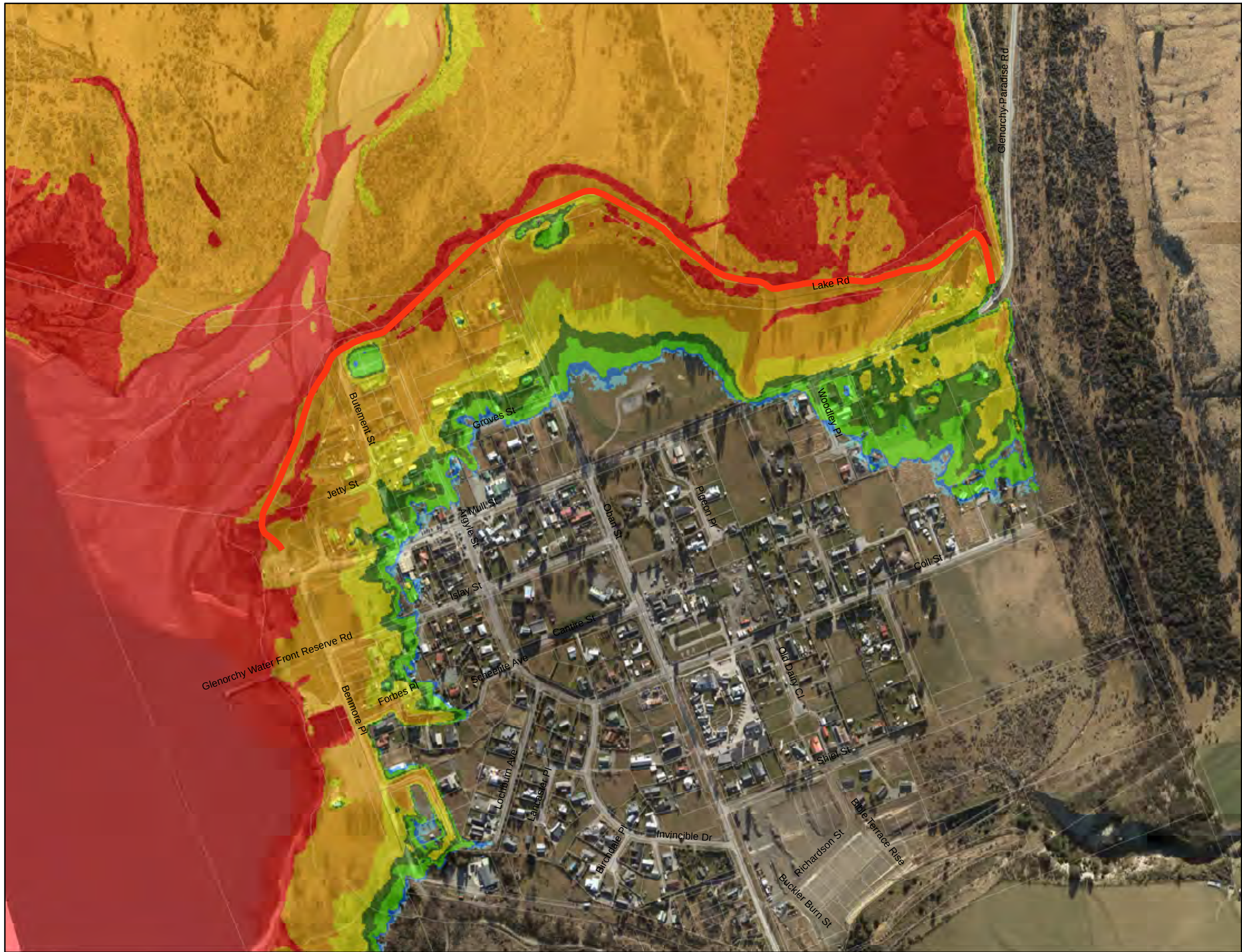
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK DEPTH OVERVIEW MAP
Scenario 2 - 100 year ARI flow (historic climate)
100 year ARI lake level

REVISION	01	Created By	PG	Reviewed By	MG	N
AUTHOR	Matthew Gardner		DATE	13/05/2022		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

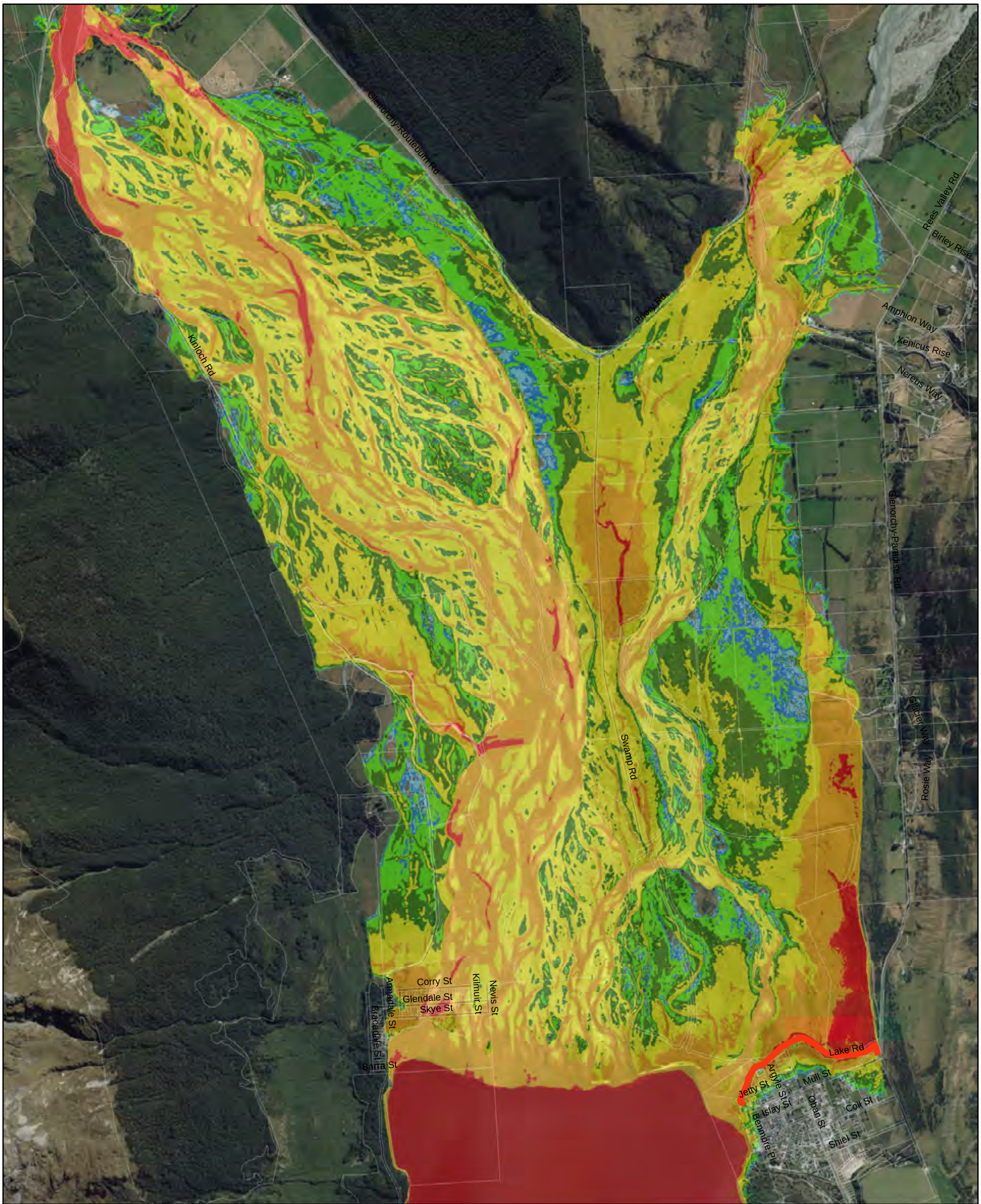
Otago Regional Council

0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **PEAK DEPTH MAP** **Scenario 2 - 100 year ARI flow (historic climate)** **100 year ARI lake level**	REVISION **01** CREATED BY **BSB** REVISED BY	DATE **13/05/2022** AUTHOR **Matthew Gardner**	A3 SCALE **1:5,000**	N



Legend

Stopbank

Roads

Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

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Otago Regional Council

0 305 610 1,220 Meters

A3 SCALE **1:25,000**

MAP (1 of 1)

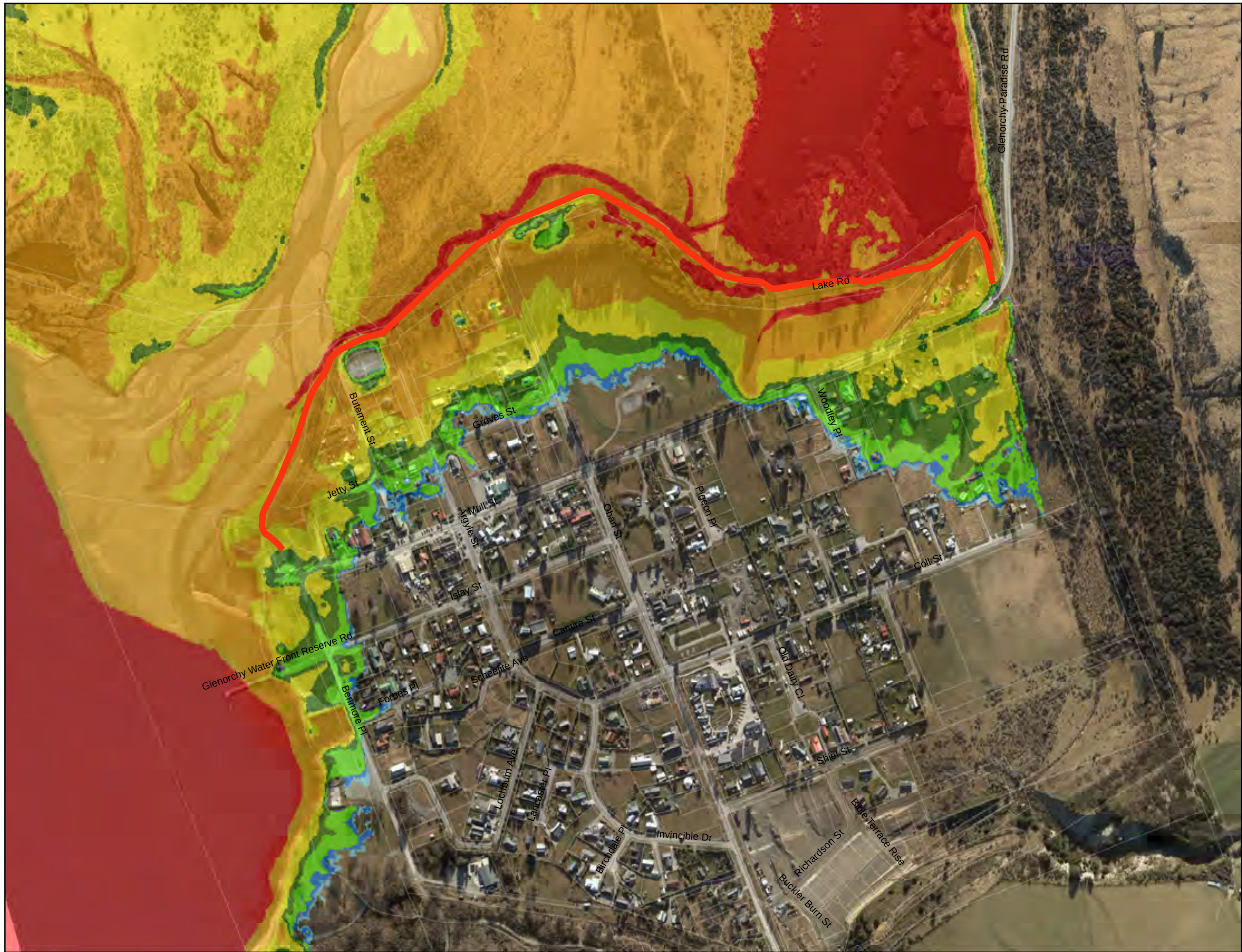
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK DEPTH OVERVIEW MAP
Scenario A3 – 100 year ARI flow
(Future Climate, RCP8.5) 10 year ARI lake level

REVISION	**01**	Created By	**PG**	Reviewed By	**MG**	N
AUTHOR	**Matthew Gardner**		DATE	**13/05/2022**		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

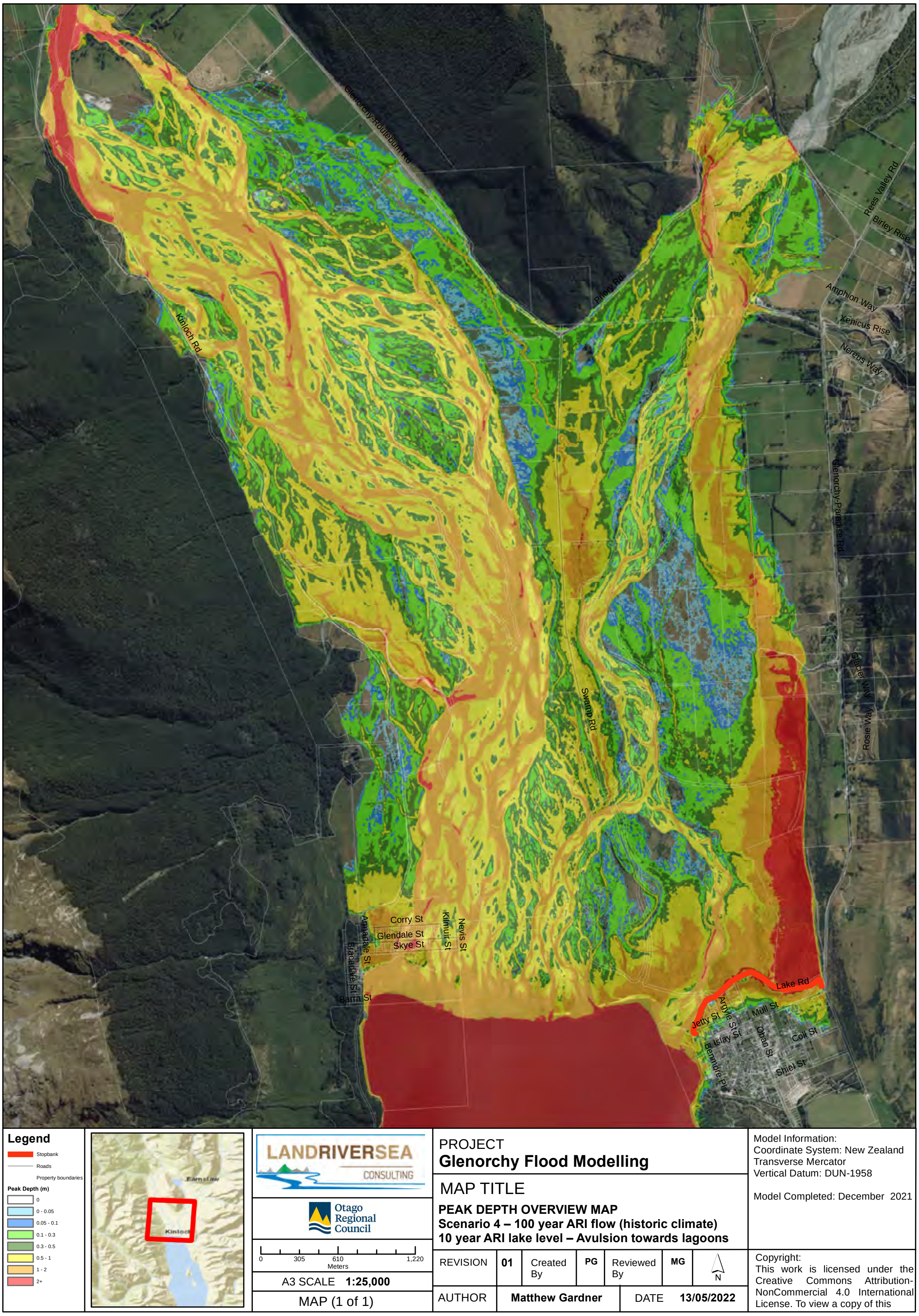
Otago Regional Council

0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**PEAK DEPTH MAP** **Scenario 3 – 100 year ARI flow (Future Climate, RCP8.5)** **10 year ARI lake level**	CREATED BY **BSB**	**13/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	N


Glenorchy-Routeburn Rd
Kinloch Rd
Priory Rd
Rees Valley Rd
Birley Rise
Amphion Way
Xenicus Rise
Nereus Way
Glenorchy-Paradise Rd
Oban Way
Rosie Way
Swamp Rd
Corry St
Glendale St
Skye St
Kilmuir St
Nevis St
Arrandale St
Bradshaw St
Barra St
Lake Rd
Jetty St
Argyle St
Mull St
Islay St
Oban St
Coll St
Benmore Pl
Shiel St
Legend
Stopbank
Roads
Property boundaries
Peak Depth (m)
0
0 - 0.05
0.05 - 0.1
0.1 - 0.3
0.3 - 0.5
0.5 - 1
1 - 2
2+
Earnslaw
Kinloch
LANDRIVERSEA CONSULTING
Otago Regional Council
0 305 610 1,220 Meters
A3 SCALE 1:25,000
MAP (1 of 1)
PROJECT
Glenorchy Flood Modelling
MAP TITLE
PEAK DEPTH OVERVIEW MAP
Scenario 4 – 100 year ARI flow (historic climate)
10 year ARI lake level – Avulsion towards lagoons
REVISION 01 Created By PG Reviewed By MG
N
AUTHOR Matthew Gardner DATE 13/05/2022
Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958
Model Completed: December 2021
Copyright:
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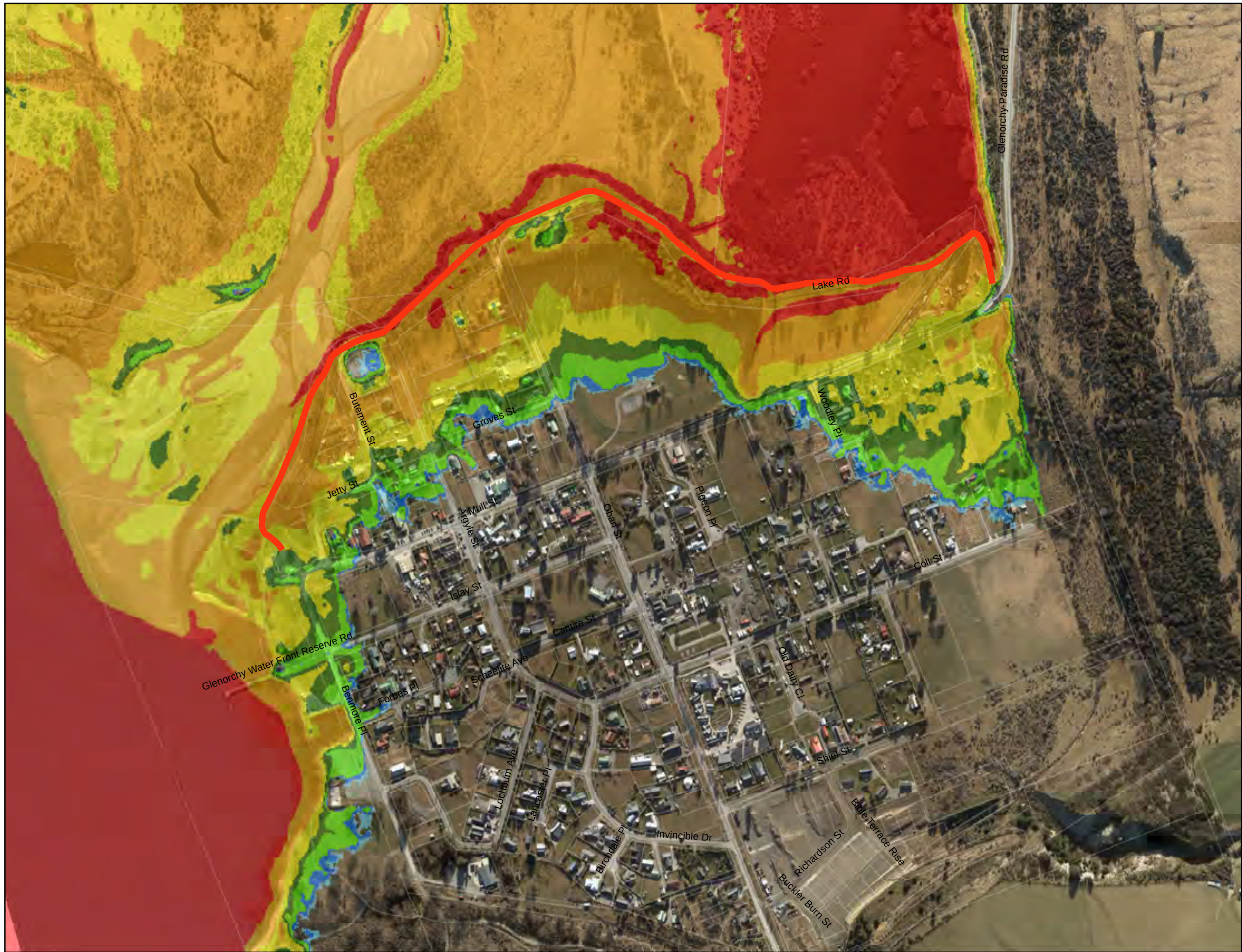

Legend

- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

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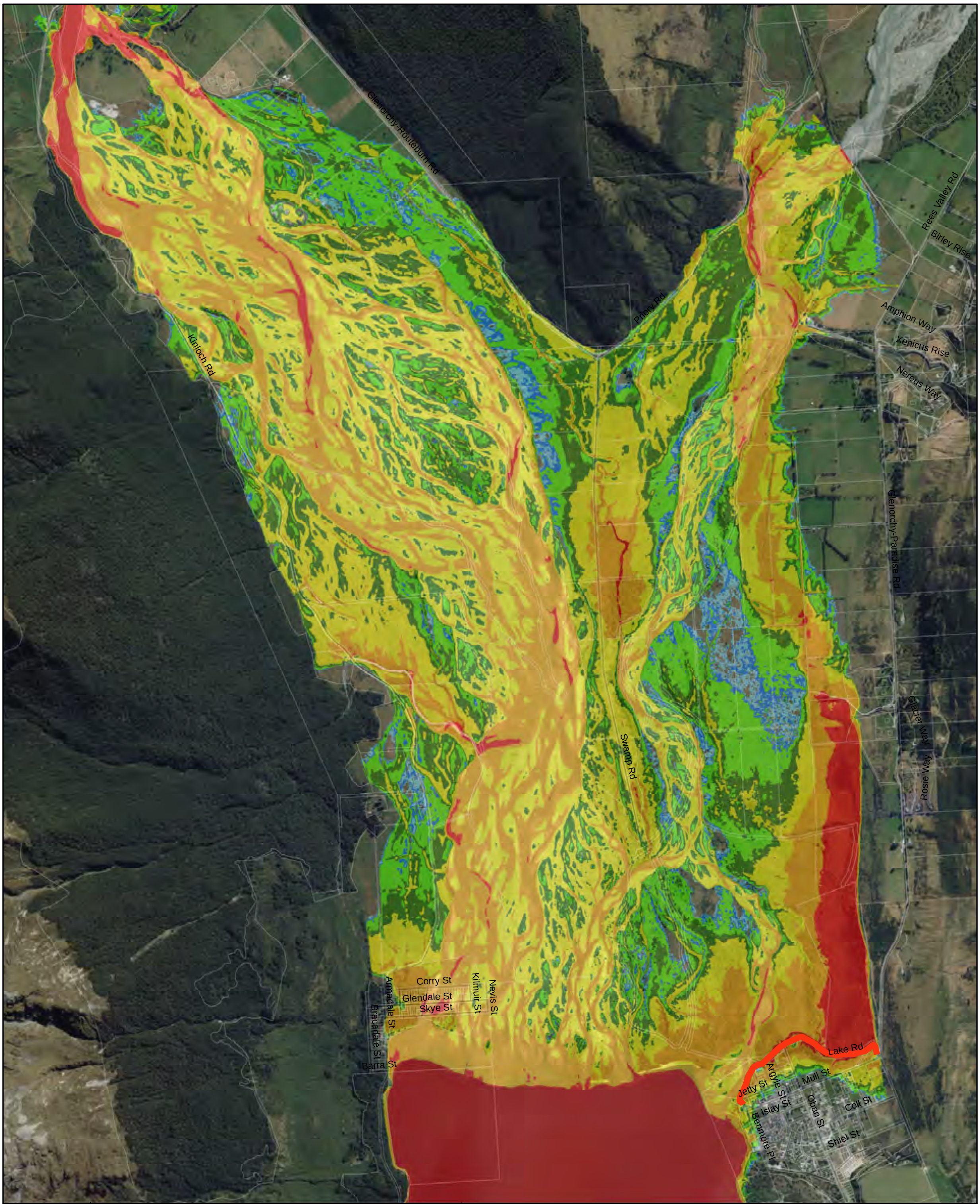
0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**PEAK DEPTH MAP** **Scenario 4 – 100 year ARI flow (historic climate) 10 year ARI lake level – Avulsion towards lagoons**	CREATED BY **BSB**	**13/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	N



Legend

- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

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0 305 610 1,220 Meters

A3 SCALE **1:25,000**

MAP (1 of 1)

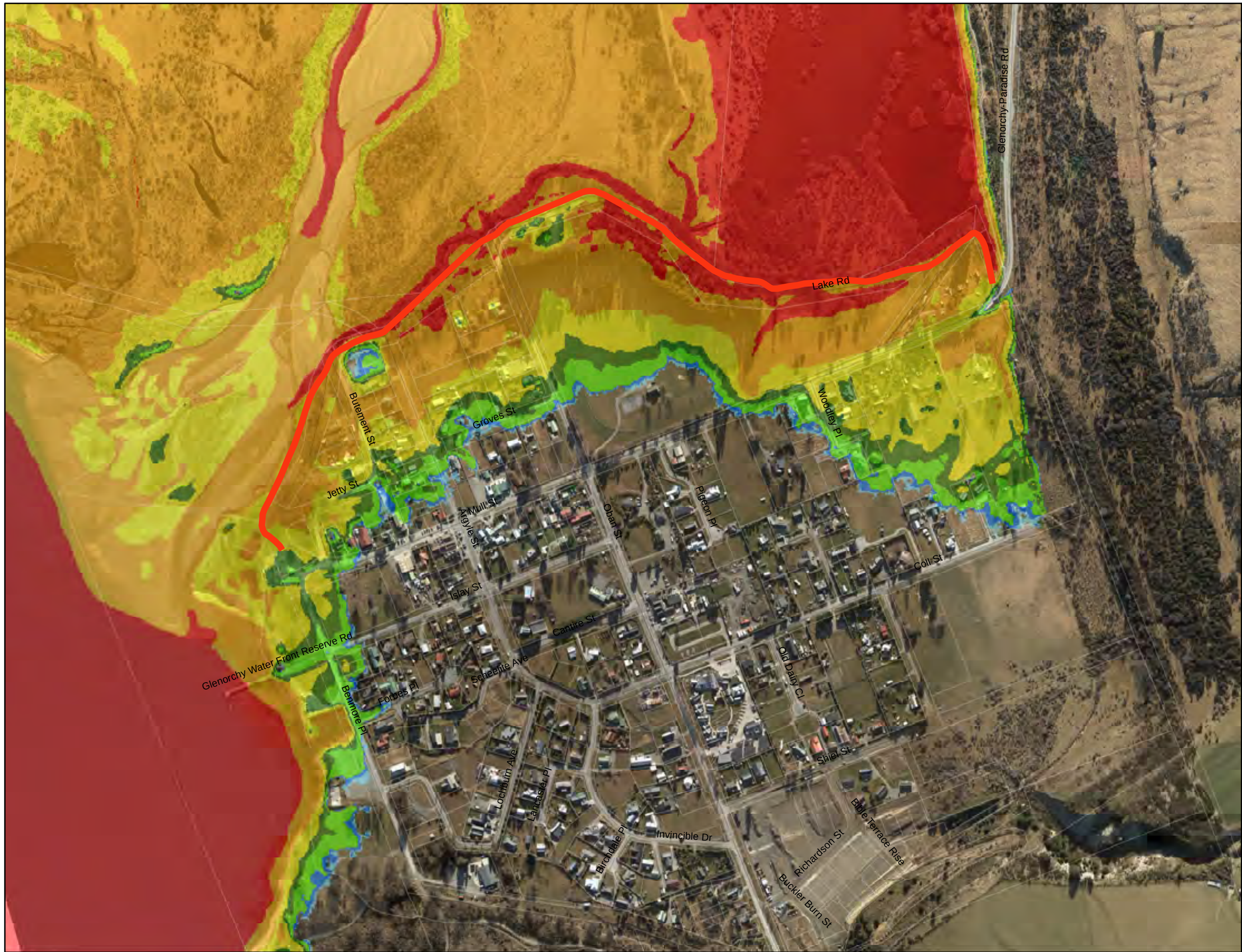
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK DEPTH OVERVIEW MAP
Scenario 5 – 100 year ARI flow
(Future Climate,RCP8.5) 10 year ARI lake level
Avulsion towards lagoons

REVISION	01	Created By	PG	Reviewed By	MG	N
AUTHOR	Matthew Gardner		DATE	13/05/2022		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

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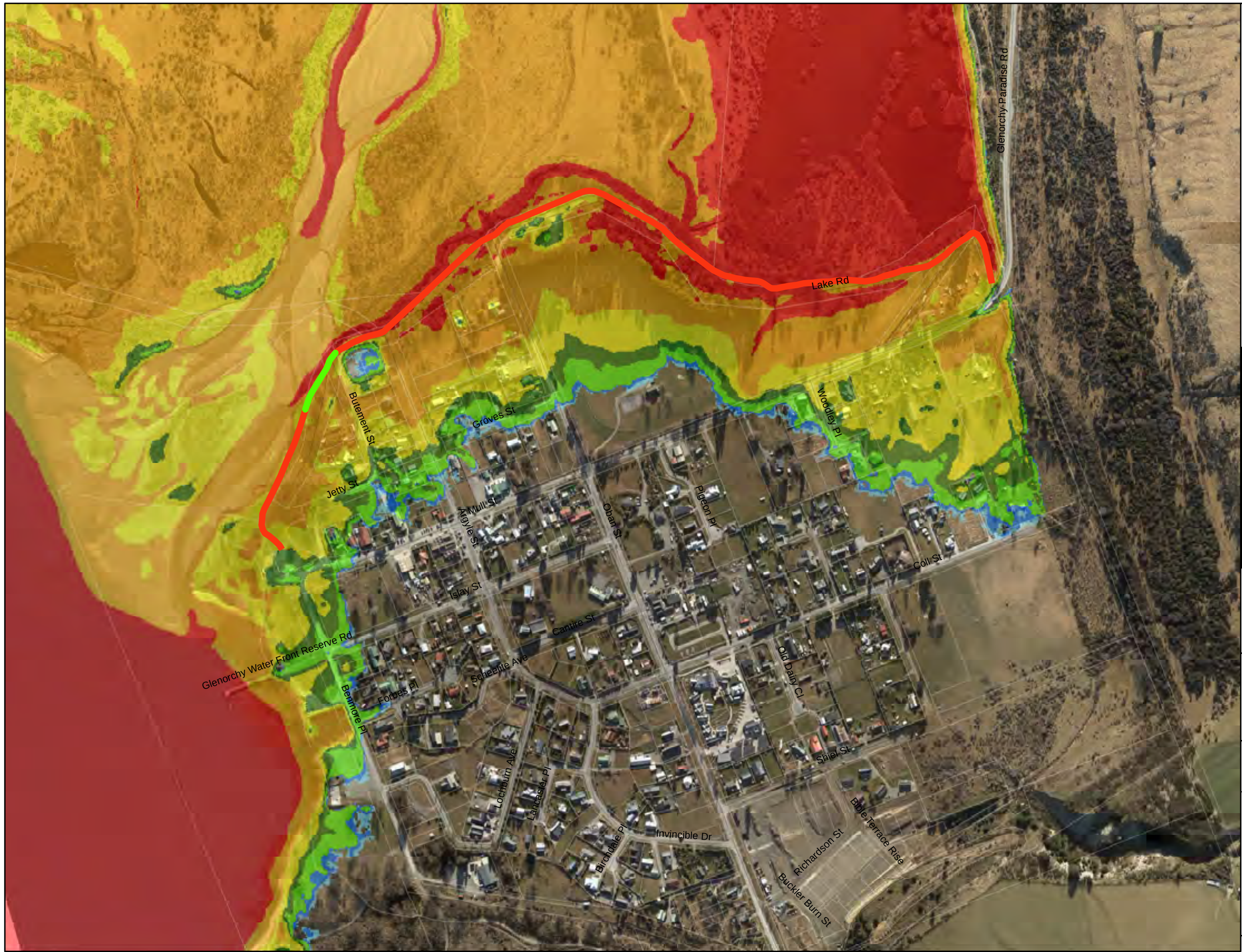
0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **PEAK DEPTH MAP** **Scenario 5 – 100 year ARI flow (Future Climate, RCP8.5)** **10 year ARI lake level – Avulsion towards lagoons**	REVISION **01** CREATED BY **BSB** REVISED BY	DATE **13/05/2022** AUTHOR **Matthew Gardner**	A3 SCALE **1:5,000**

N



Legend

- Breach 1
- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

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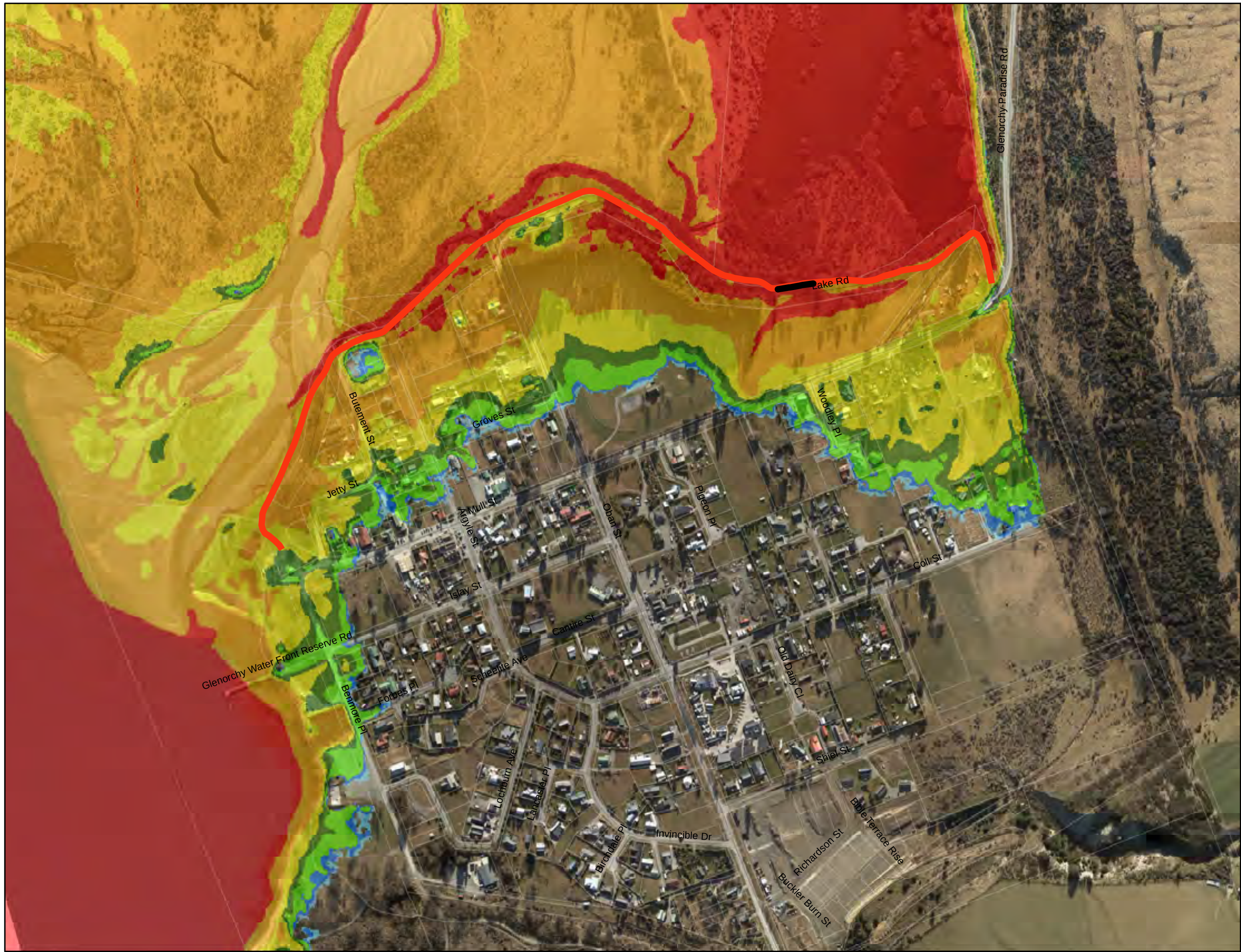
Otago Regional Council

0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE	
Glenorchy Flood Modelling	**PEAK DEPTH MAP** **Scenario 6 - 100 year ARI flow (Future Climate, RCP8.5)** **10 year ARI lake level - Breach 1 (90m Wide)** **Avulsion towards lagoons**	CREATED BY **BSB**	**12/05/2022**	**1:5,000**	N
		REVISED BY	AUTHOR **Matthew Gardner**		



Legend

- Breach 2
- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

Otago Regional Council

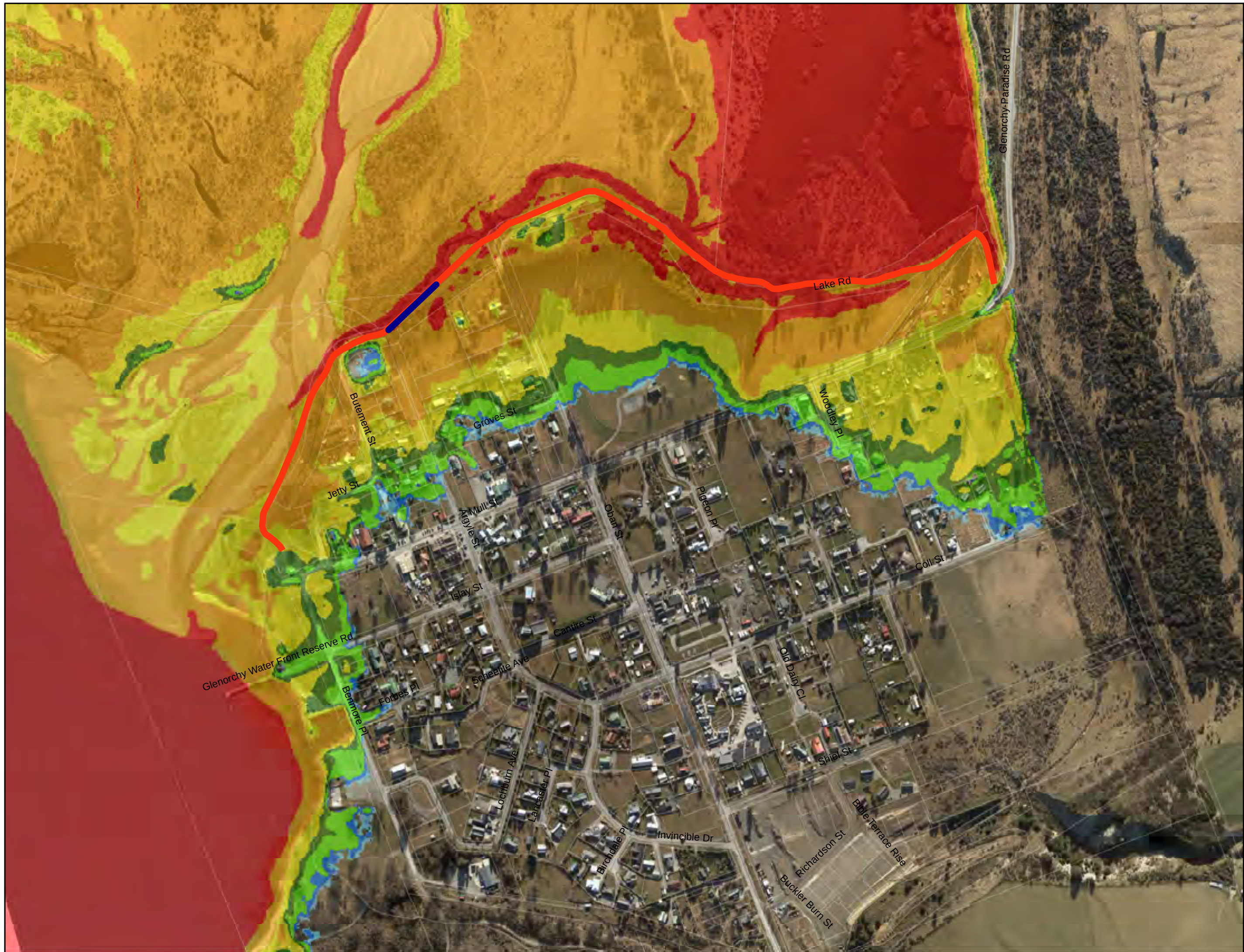
0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **PEAK DEPTH MAP** **Scenario 7 - 100 year ARI flow ((Future Climate, RCP8.5)** **10 year ARI lake level - Breach 2 (90m Wide)** **Avulsion towards lagoons**	REVISION **01** / CREATED BY **BSB** / REVISED BY	DATE **12/05/2022** / AUTHOR **Matthew Gardner**	A3 SCALE **1:5,000**

N



Legend

- Breach 3
- Stopbank
- Roads
- Property boundaries

Peak Depth (m)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

Otago Regional Council

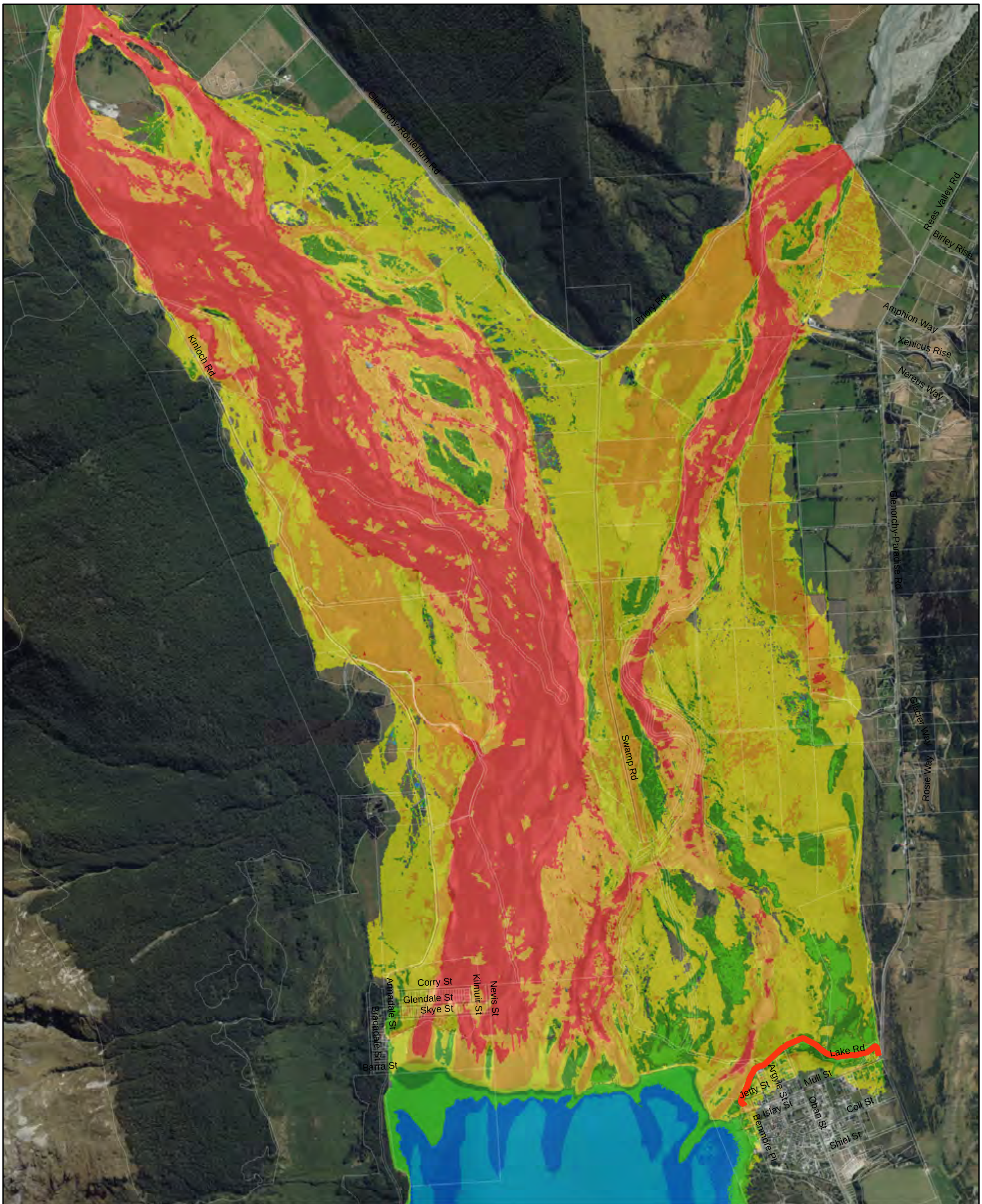
0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **PEAK DEPTH MAP Scenario 8 - 100 year ARI flow (Future Climate, RCP8.5) 10 year ARI lake level - Breach 3 (90m Wide) Avulsion towards lagoons**	REVISION **01**	DATE **12/05/2022**	A3 SCALE **1:5,000**	N
		CREATED BY **BSB**			
		REVISED BY	AUTHOR **Matthew Gardner**		

APPENDIX F – PEAK SPEED MAPS



Legend

Stopbank	
Roads	
Property boundaries	

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

Otago Regional Council

0 305 610 1,220
Meters

A3 SCALE **1:25,000**

MAP (1 of 1)

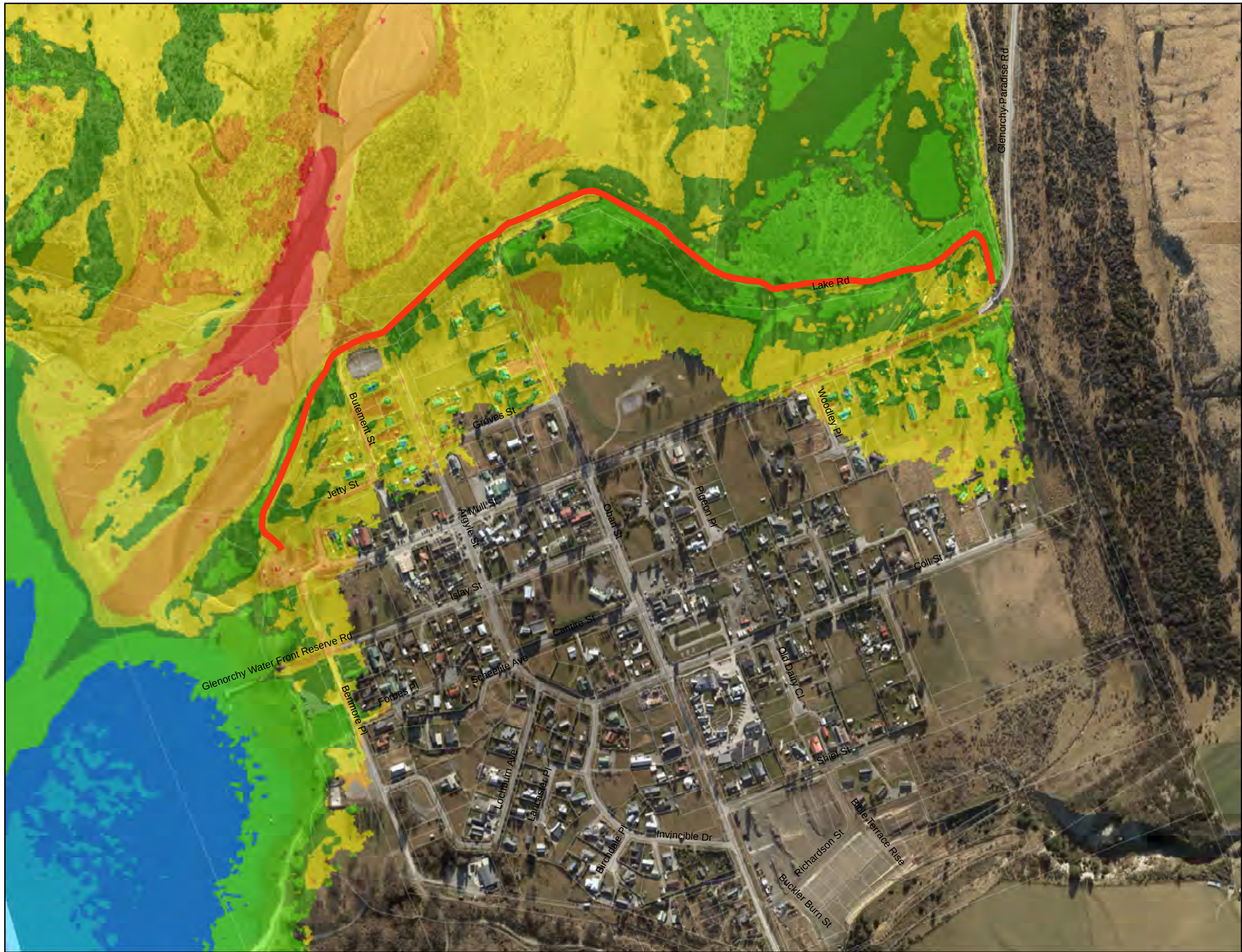
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK SPEED OVERVIEW MAP
Scenario 1 – 100 year ARI flow (historic climate)
10 year ARI lake level

REVISION	**01**	Created By	**PG**	Reviewed By	**MG**	N
AUTHOR	**Matthew Gardner**		DATE	**13/05/2022**		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

Otago Regional Council

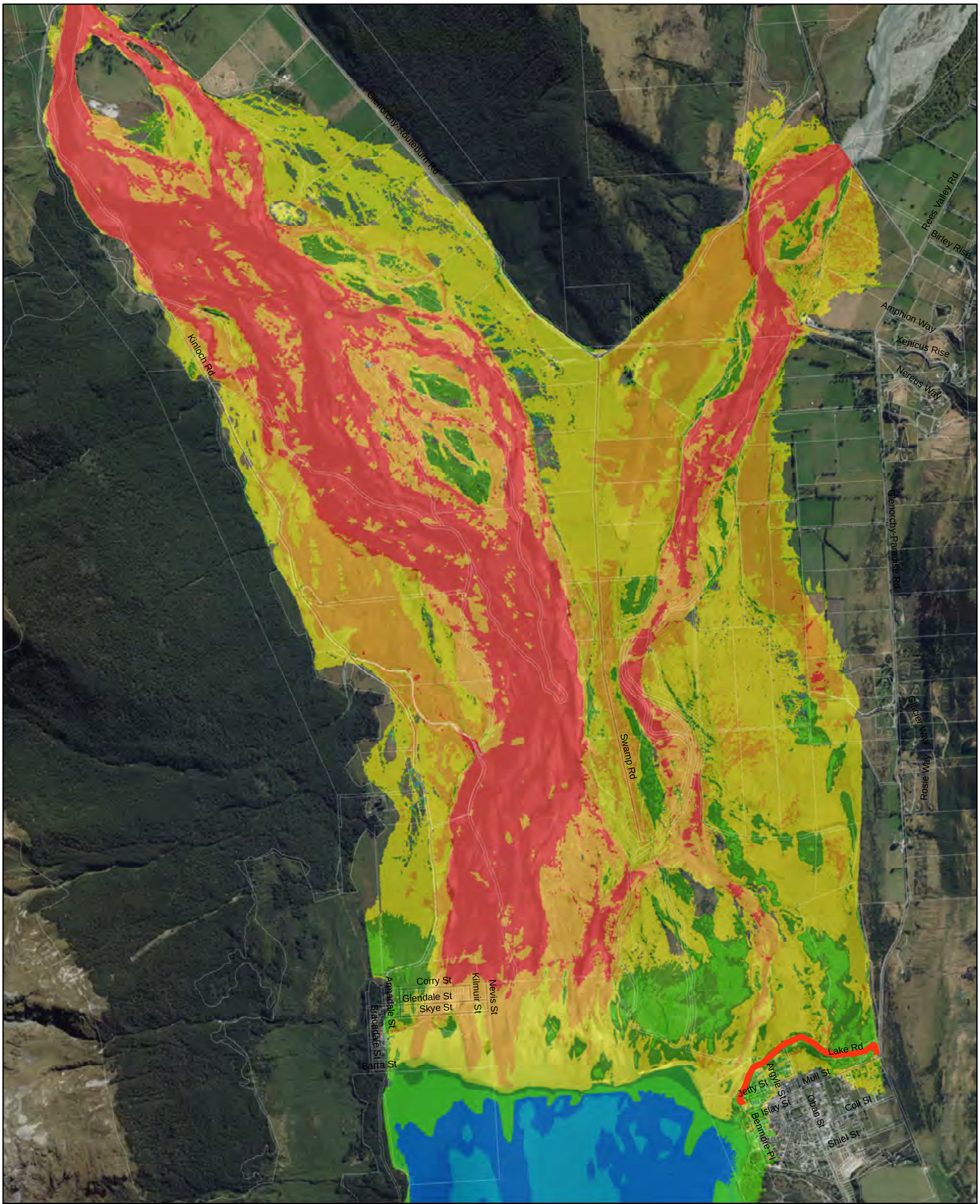
0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **PEAK SPEED MAP** **Scenario 1 – 100 year ARI flow (historic climate)** **10 year ARI lake level**	REVISION **01** CREATED BY **BSB** REVISED BY	DATE **13/05/2022** AUTHOR **Matthew Gardner**	A3 SCALE **1:5,000**

N



Legend

- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

Otago Regional Council

0 305 610 1,220 Meters

A3 SCALE **1:25,000**

MAP (1 of 1)

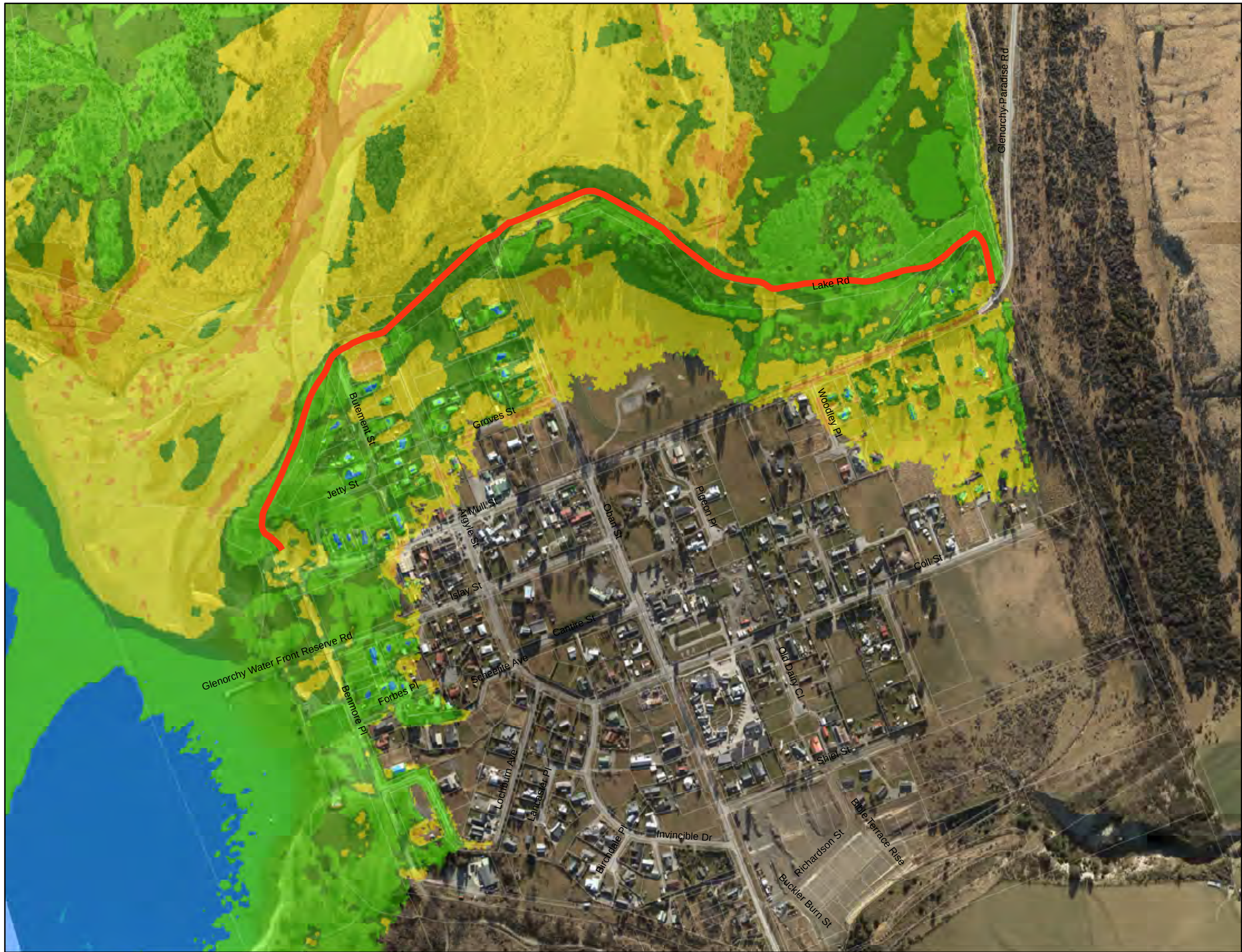
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK SPEED OVERVIEW MAP
Scenario 2 - 100 year ARI flow (historic climate)
100 year ARI lake level

REVISION	**01**	Created By	**PG**	Reviewed By	**MG**	N
AUTHOR	**Matthew Gardner**		DATE	**13/05/2022**		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

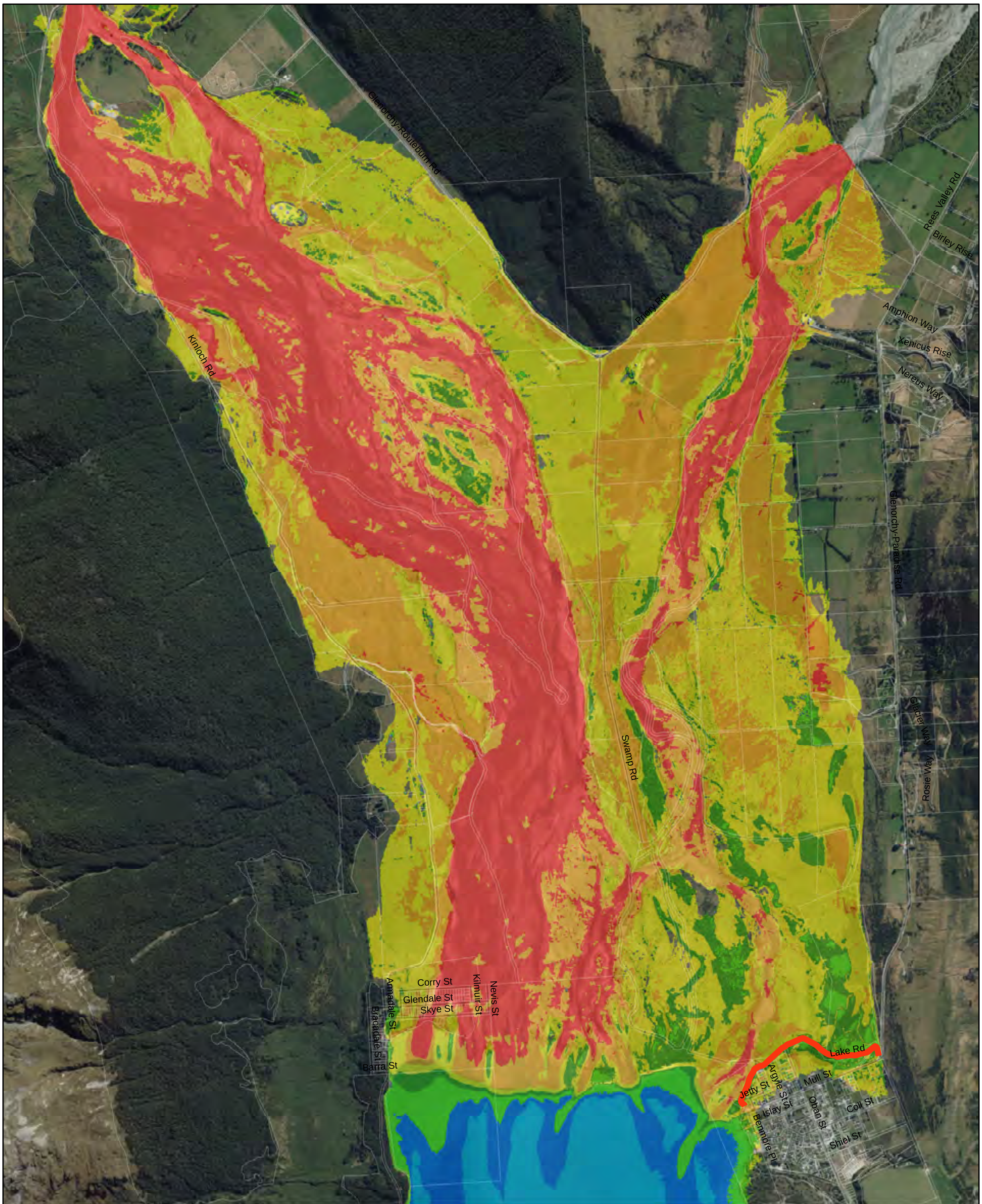
Otago Regional Council

0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**PEAK SPEED MAP** **Scenario 2 - 100 year ARI flow (historic climate)** **100 year ARI lake level**	CREATED BY **BSB**	**13/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	N



Legend

- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

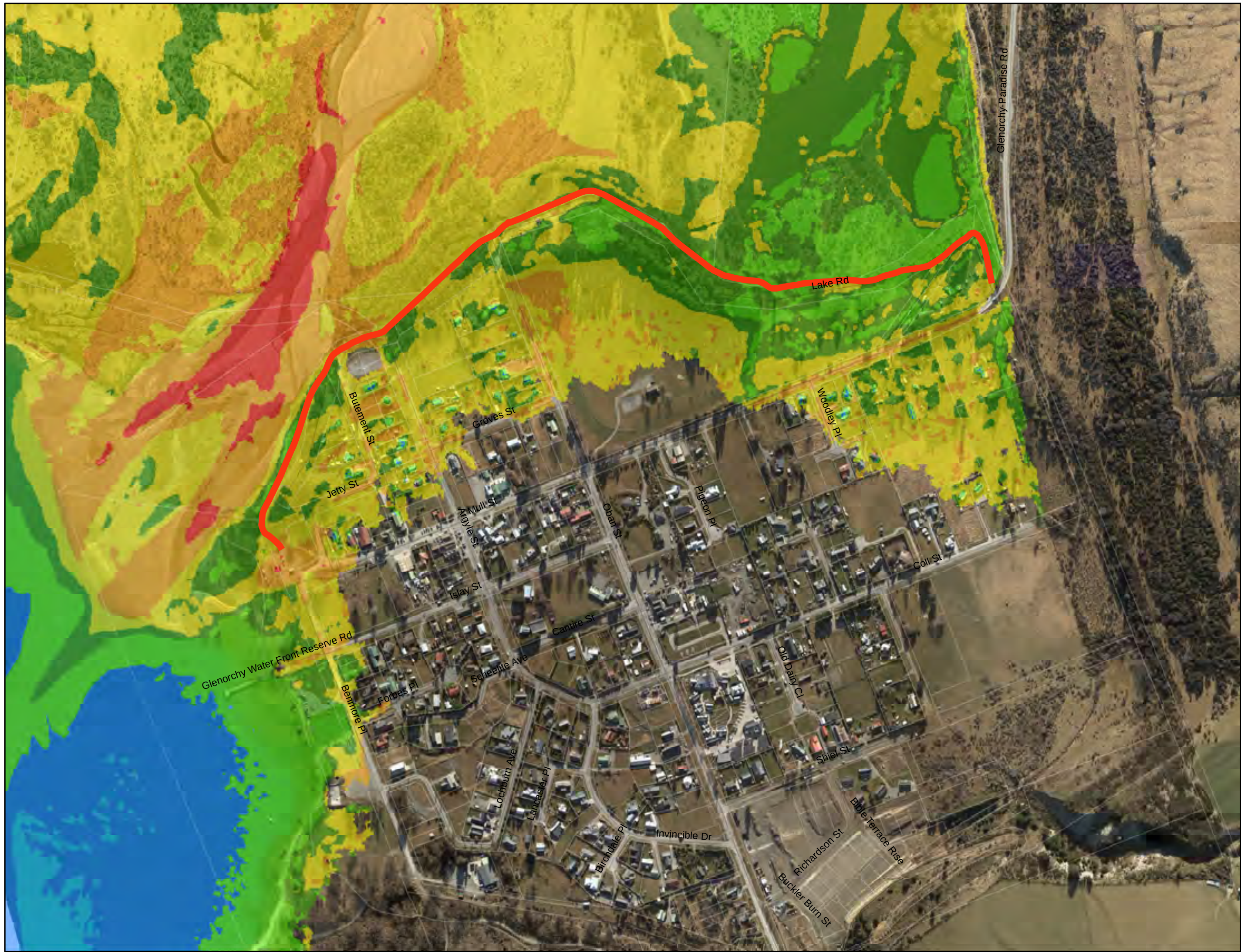
Otago Regional Council

0 305 610 1,220 Meters

PROJECT **Glenorchy Flood Modelling**							Model Information: Coordinate System: New Zealand Transverse Mercator Vertical Datum: DUN-1958 Model Completed: December 2021
MAP TITLE **PEAK SPEED OVERVIEW MAP Scenario 3 – 100 year ARI flow (Future Climate, RCP8.5) 10 year ARI lake level**							
REVISION	01	Created By	PG	Reviewed By	MG	N	Copyright: This work is licensed under the Creative Commons Attribution-NonCommercial 4.0 International License. To view a copy of this
AUTHOR	**Matthew Gardner**			DATE	**13/05/2022**		

A3 SCALE **1:25,000**

MAP (1 of 1)



Legend

- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

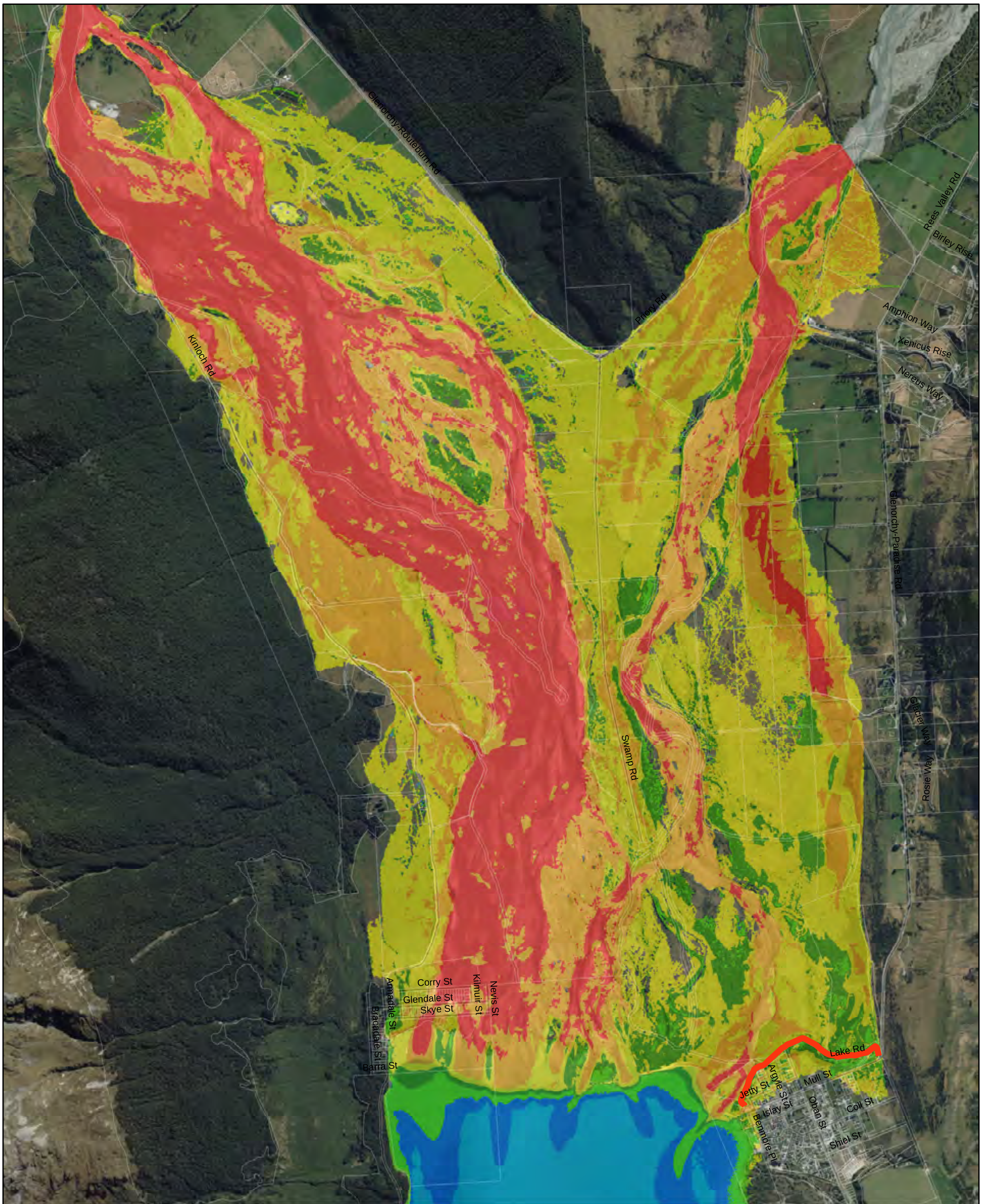
Otago Regional Council

0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE	
Glenorchy Flood Modelling	**PEAK SPEED MAP** **Scenario 3 – 100 year ARI flow (Future Climate, RCP8.5)** **10 year ARI lake level**	CREATED BY **BSB**	**13/05/2022**	**1:5,000**	N
		REVISED BY	AUTHOR **Matthew Gardner**		



Legend

- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

Otago Regional Council

0 305 610 1,220 Meters

A3 SCALE 1:25,000

MAP (1 of 1)

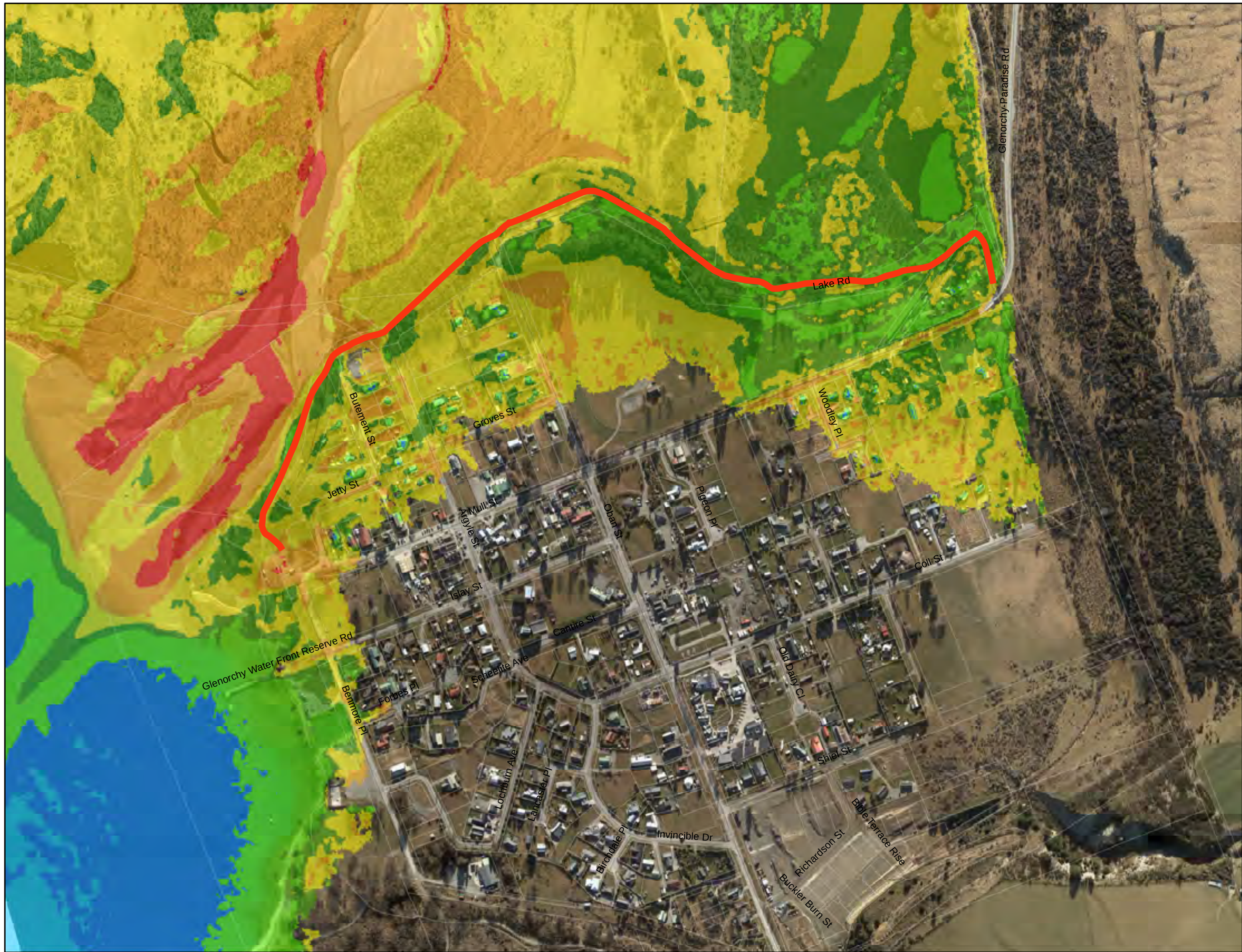
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK SPEED OVERVIEW MAP
Scenario 4 – 100 year ARI flow (historic climate)
10 year ARI lake level – Avulsion towards lagoons

REVISION	01	Created By	PG	Reviewed By	MG	N
AUTHOR	Matthew Gardner		DATE	13/05/2022		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

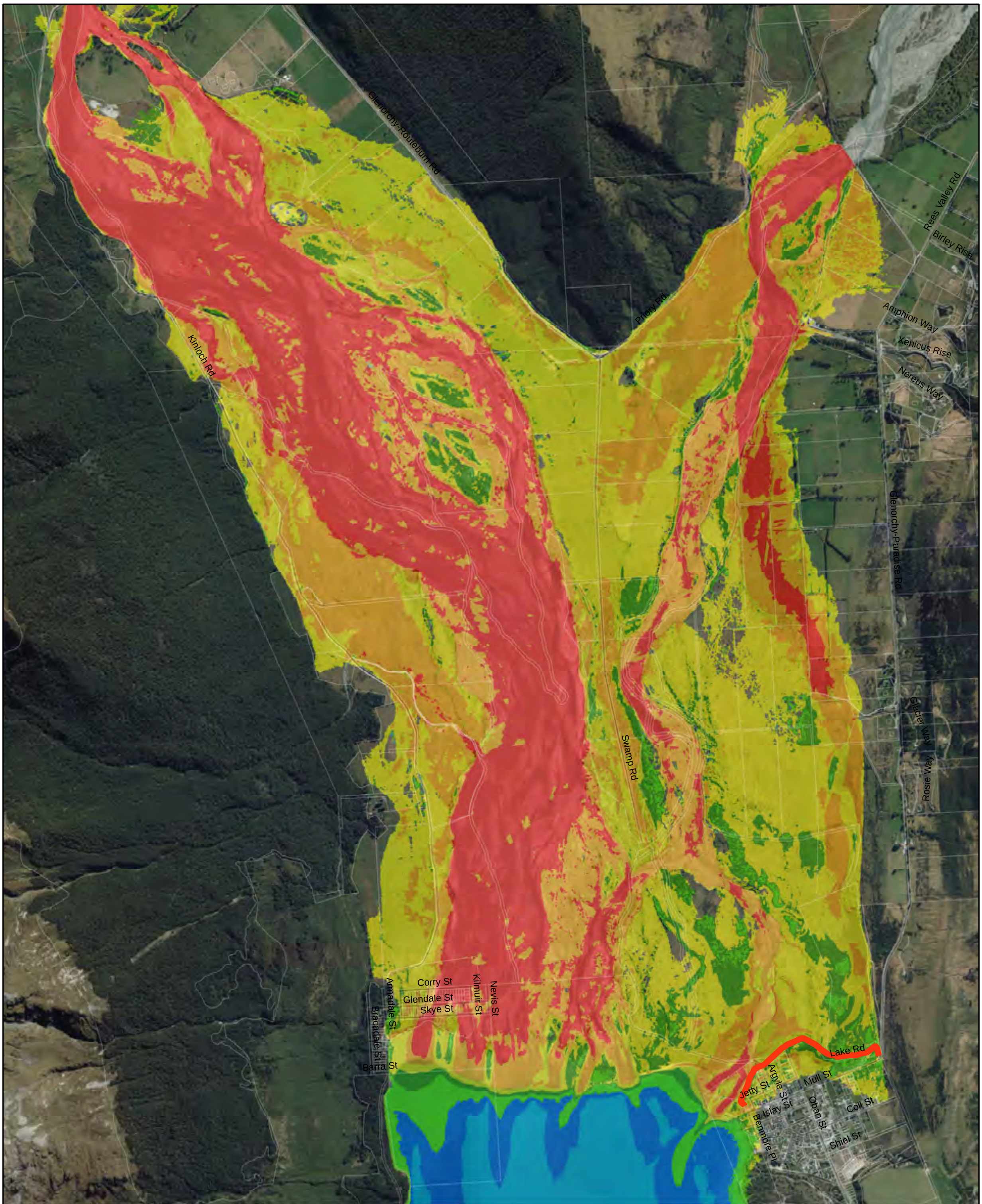
Otago Regional Council

0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**PEAK SPEED MAP** **Scenario 4 – 100 year ARI flow (historic climate) 10 year ARI lake level – Avulsion towards lagoons**	CREATED BY **BSB**	**13/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	N



Legend

- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

Otago Regional Council

0 305 610 1,220
Meters

A3 SCALE **1:25,000**

MAP (1 of 1)

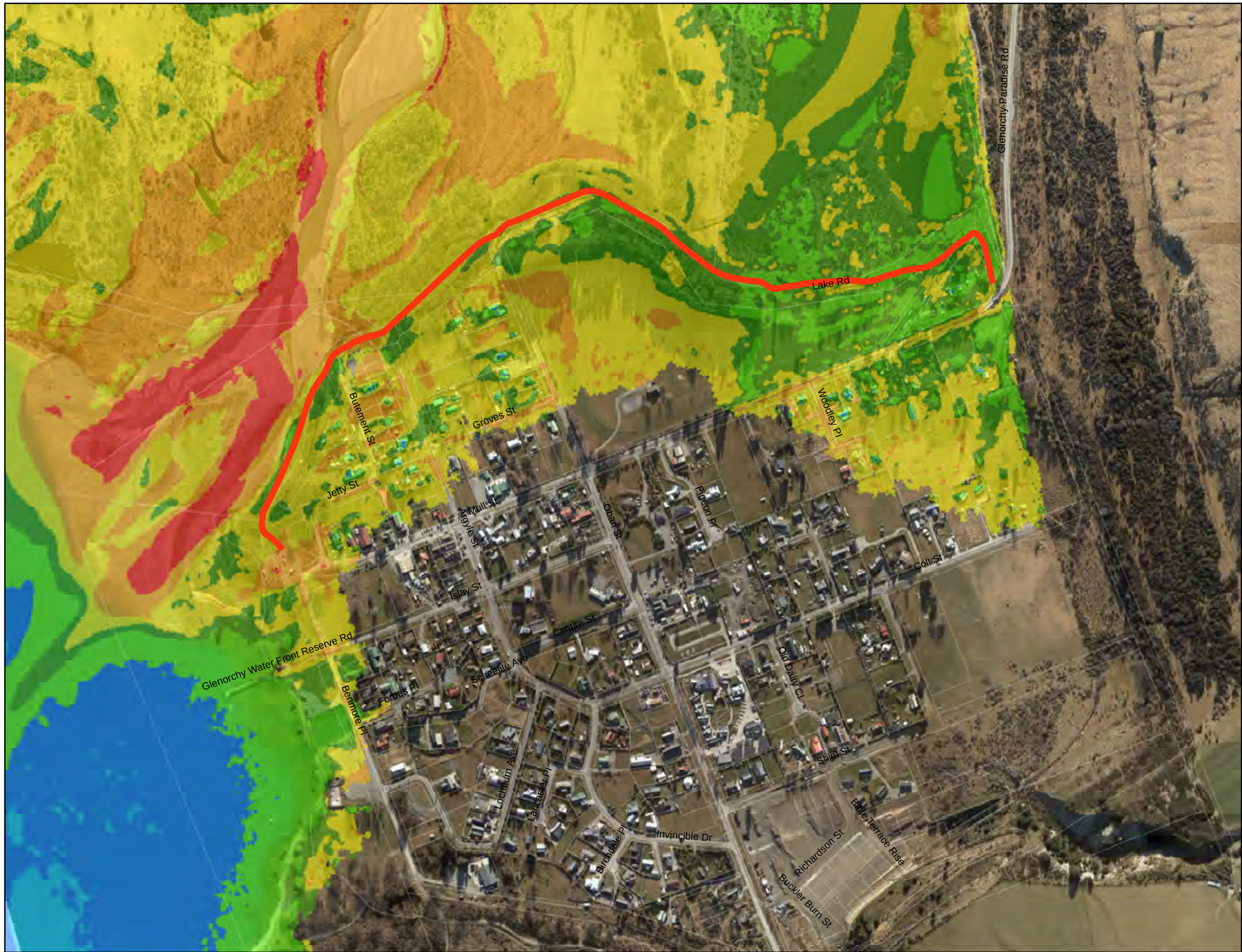
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK SPEED OVERVIEW MAP
Scenario 5 – 100 year ARI flow
(Future Climate,RCP8.5) 10 year ARI lake level
Avulsion towards lagoons

REVISION	01	Created By	PG	Reviewed By	MG	N
AUTHOR	Matthew Gardner		DATE	13/05/2022		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

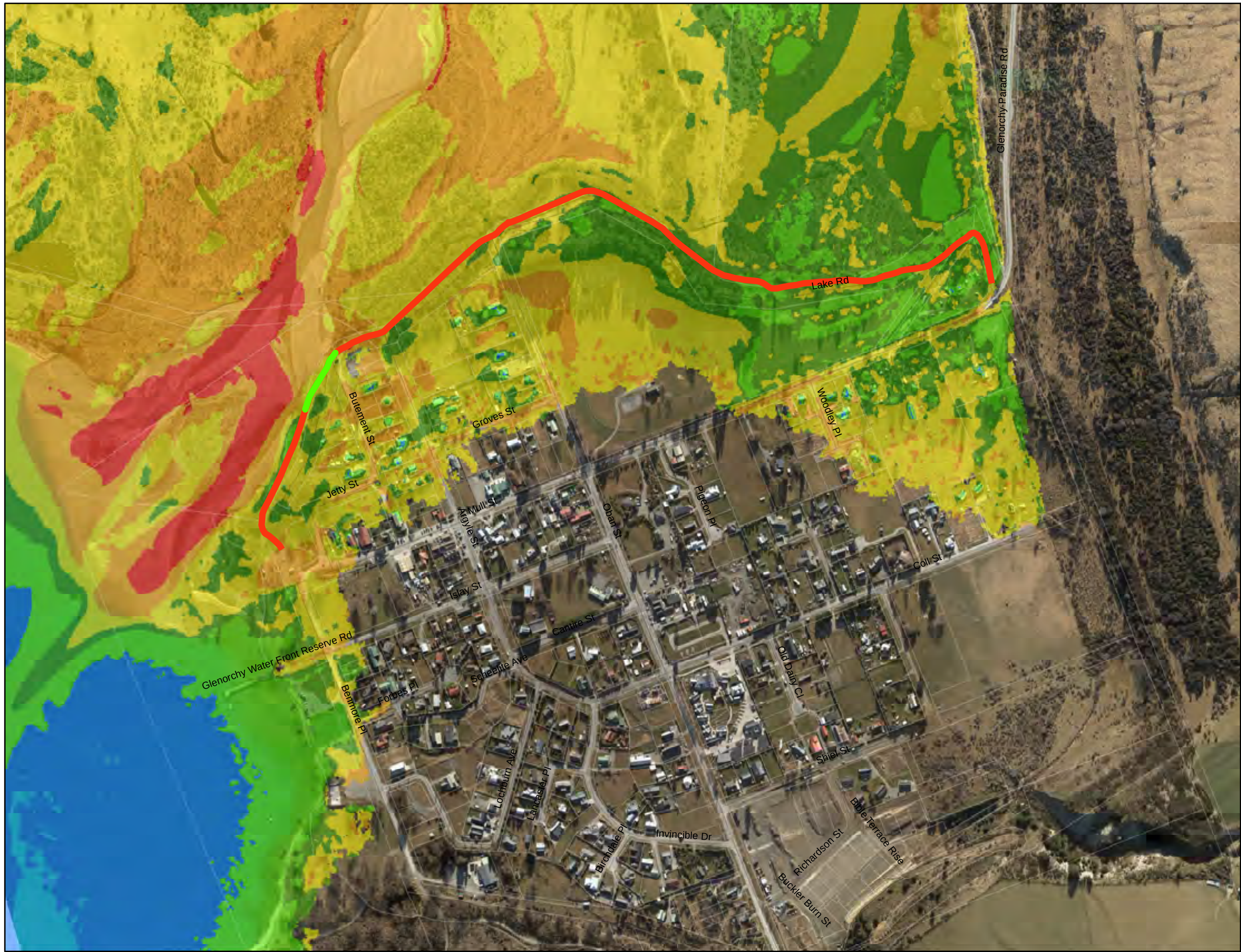
Otago Regional Council

0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**PEAK SPEED MAP** **Scenario 5 – 100 year ARI flow (Future Climate, RCP8.5) 10 year ARI lake level – Avulsion towards lagoons**	CREATED BY **BSB**	**13/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	N



Legend

- Breach 1
- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

LANDRIVERSEA CONSULTING

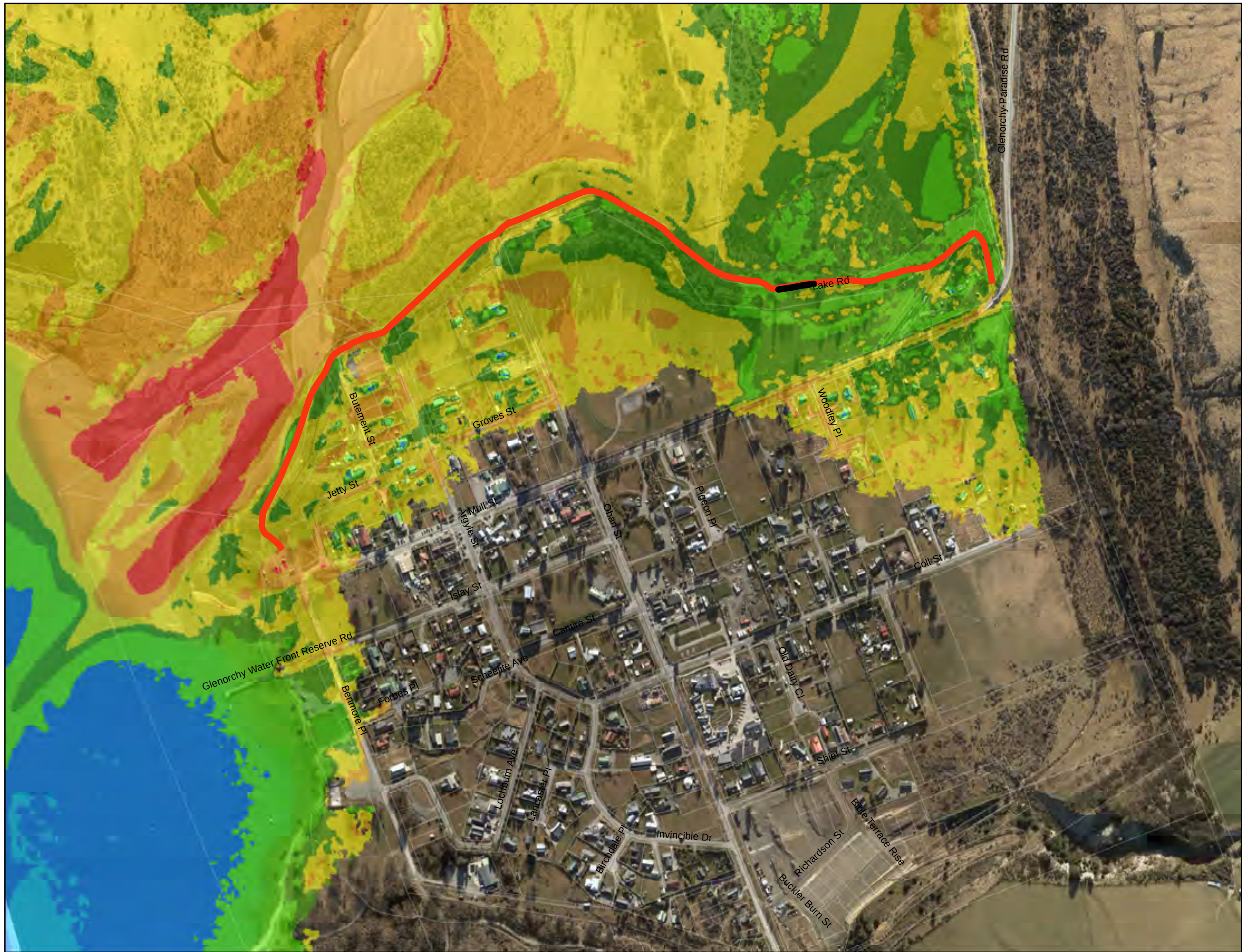
Otago Regional Council

0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**PEAK SPEED MAP** **Scenario 6 - 100 year ARI flow (Future Climate, RCP8.5)** **10 year ARI lake level - Breach 1 (90m Wide)** **Avulsion towards lagoons**	CREATED BY **BSB**	**12/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	N



Legend

- Breach 2
- Stopbank
- Roads
- Property boundaries

Peak water speed (m/s)

- 0
- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.3
- 0.3 - 0.5
- 0.5 - 1
- 1 - 2
- 2+

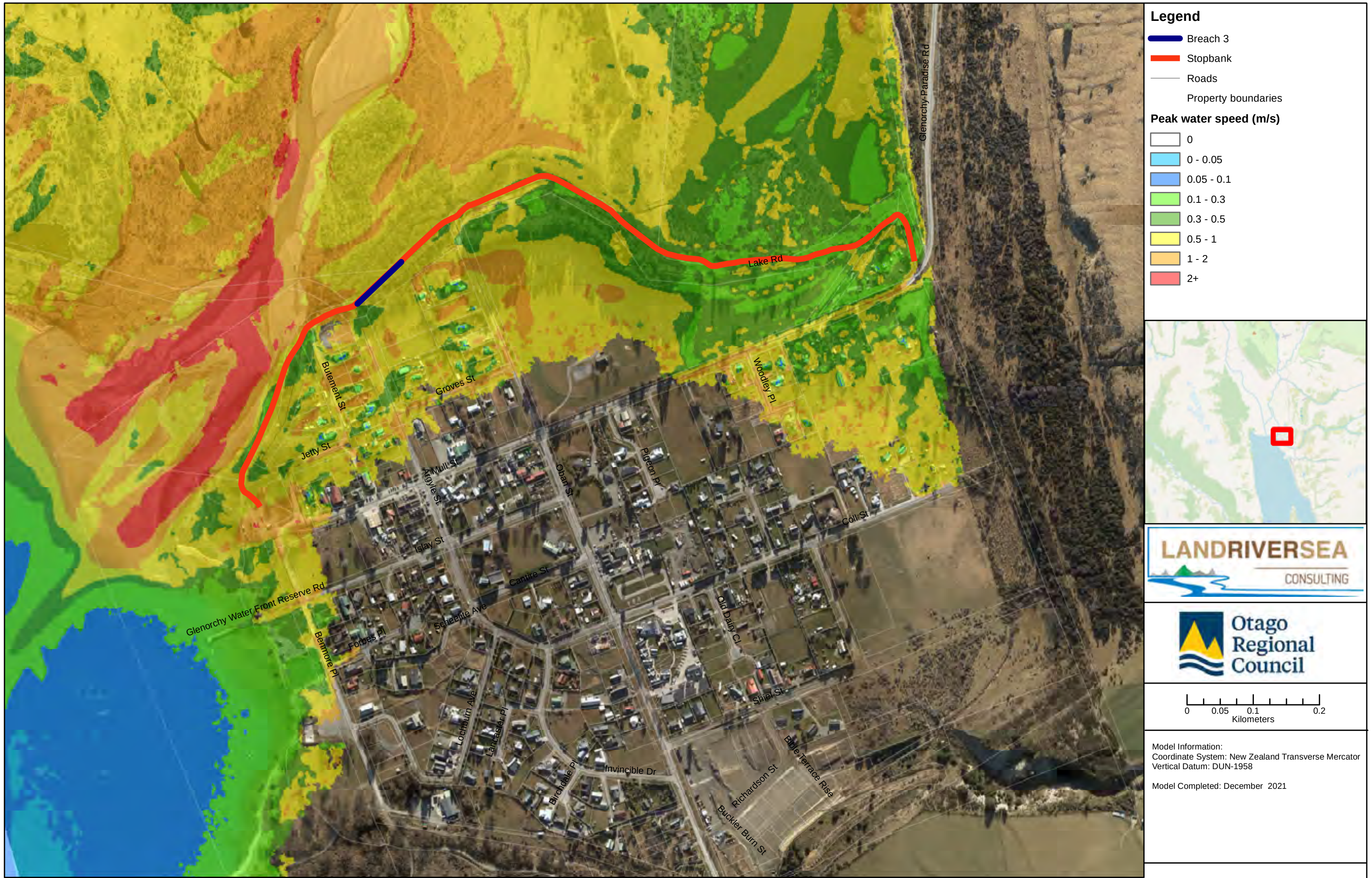
0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **PEAK SPEED MAP** **Scenario 7 - 100 year ARI flow ((Future Climate, RCP8.5)** **10 year ARI lake level - Breach 2 (90m Wide)** **Avulsion towards lagoons**	REVISION **01** CREATED BY **BSB** REVISED BY	DATE **12/05/2022** AUTHOR **Matthew Gardner**	A3 SCALE **1:5,000**

N

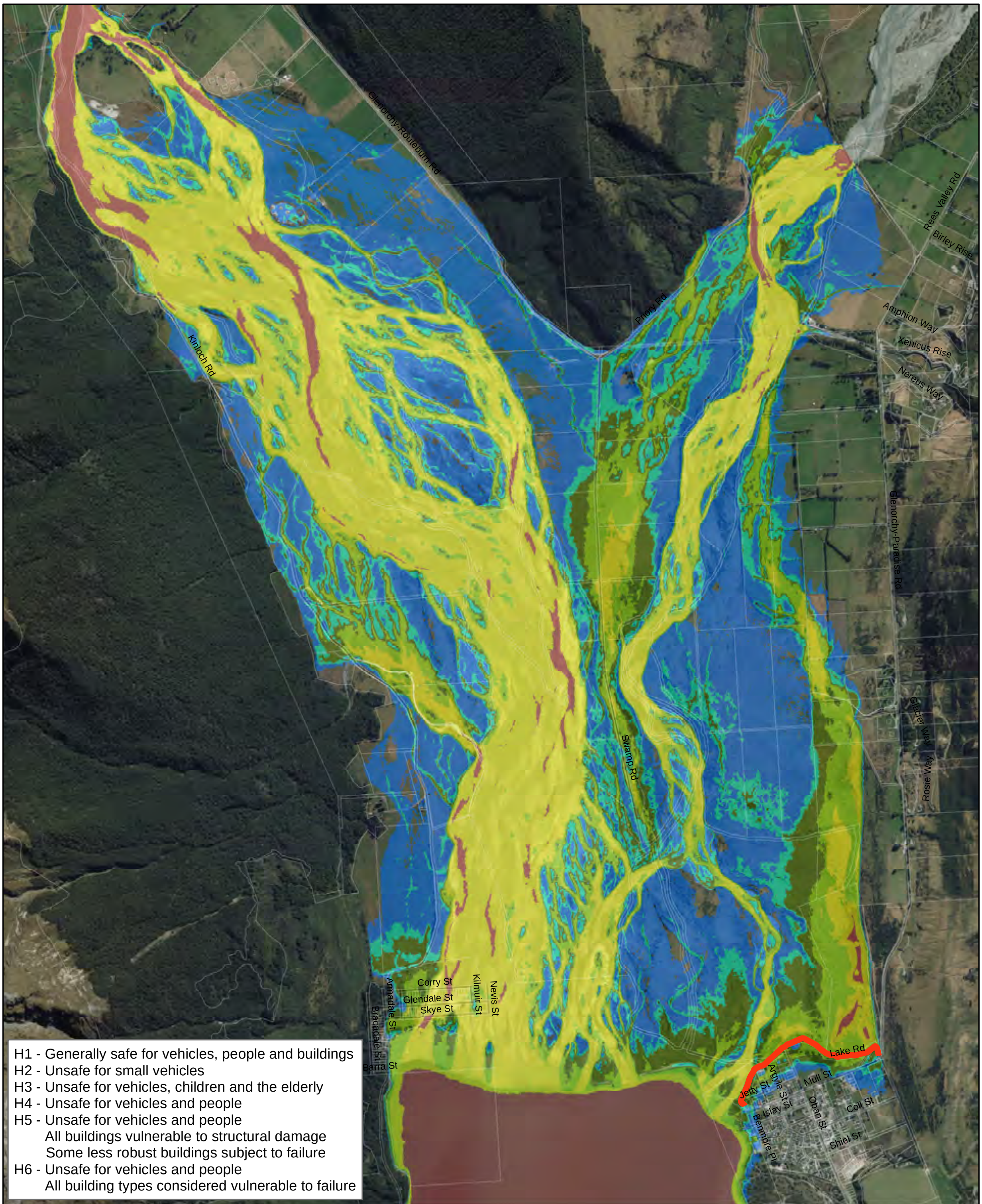


Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**PEAK SPEED MAP** **Scenario 8 - 100 year ARI flow (Future Climate, RCP8.5)** **10 year ARI lake level - Breach 3 (90m Wide)** **Avulsion towards lagoons**	CREATED BY **BSB**	**12/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	

APPENDIX G – HAZARD MAPS



Legend

- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

Otago Regional Council

0 305 610 1,220 Meters

A3 SCALE **1:25,000**

MAP (1 of 1)

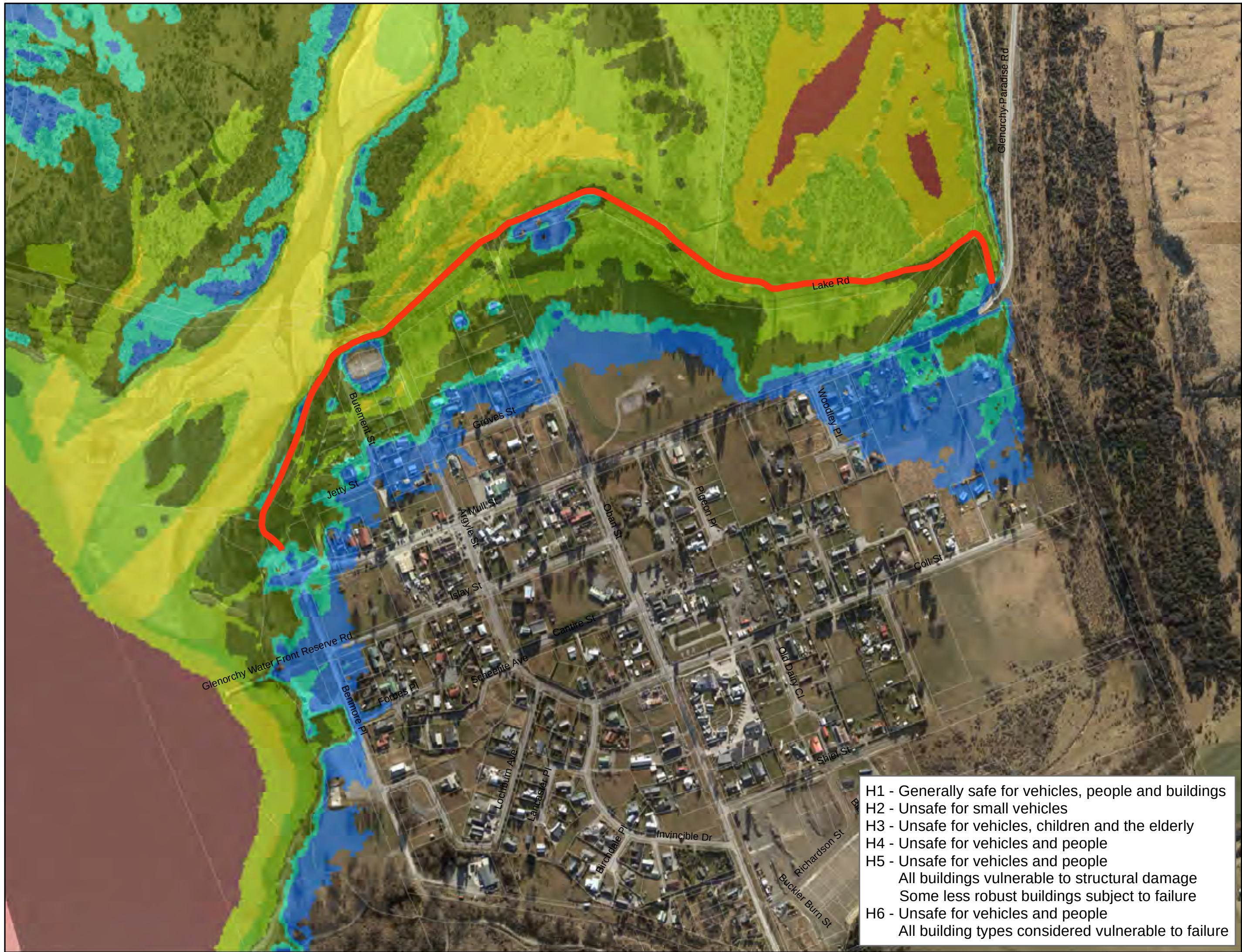
PROJECT
Glenorchy Flood Modelling

MAP TITLE
HAZARD OVERVIEW MAP
Scenario 1 – 100 year ARI flow (historic climate)
10 year ARI lake level

REVISION	01	Created By	PG	Reviewed By	MG	N
AUTHOR	Matthew Gardner		DATE	13/05/2022		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

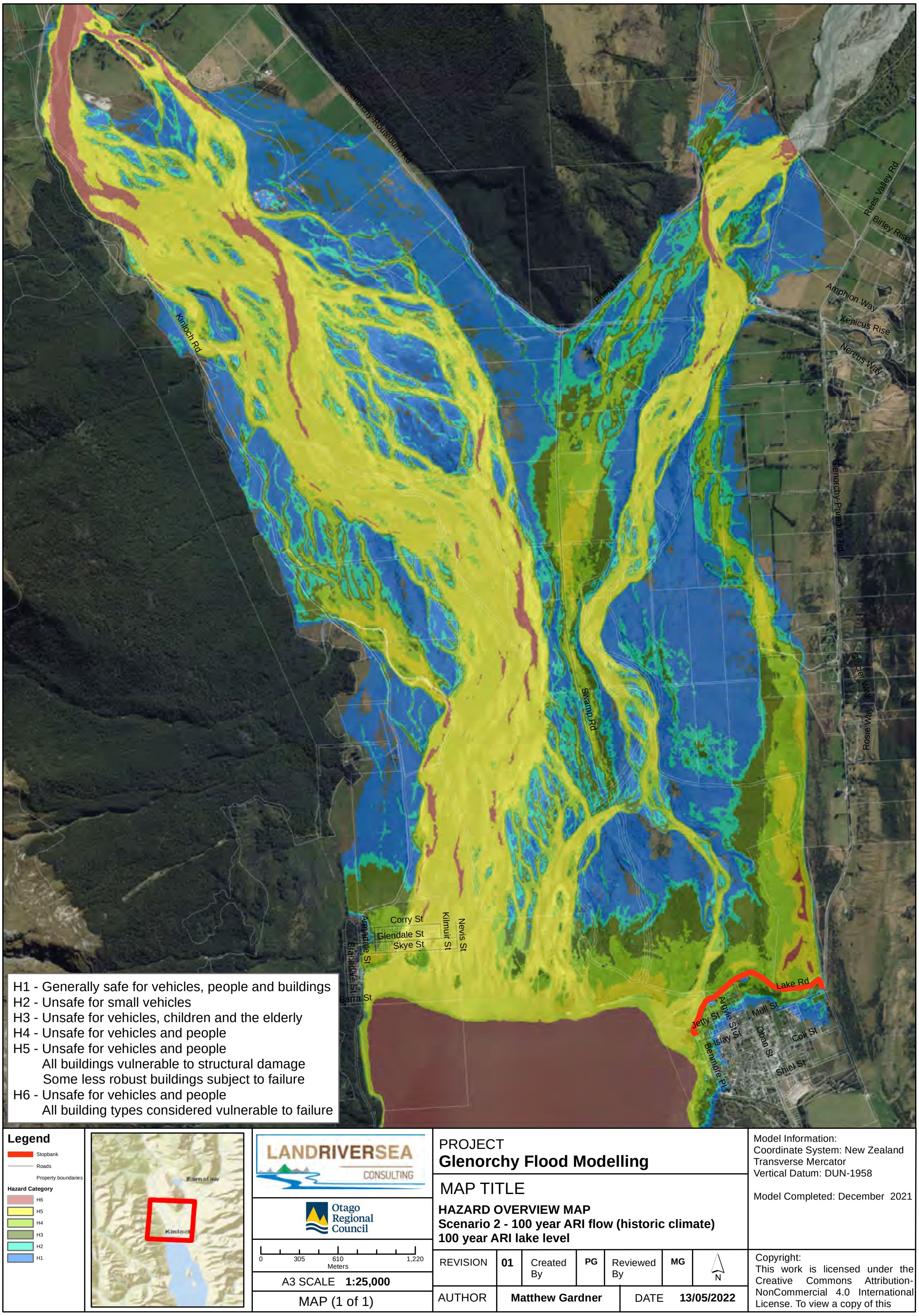
Otago Regional Council

0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **HAZARD MAP** **Scenario 1 – 100 year ARI flow (historic climate)** **10 year ARI lake level**	REVISION **01** CREATED BY **BSB** REVISED BY	DATE **13/05/2022** AUTHOR **Matthew Gardner**	A3 SCALE **1:5,000**	N


Glenorchy-Routeburn Rd
Kinloch Rd
Swamp Rd
Rees Valley Rd
Birley Rise
Amphion Way
Xenicus Rise
Nereus Way
Glenorchy-Paradise Rd
Rosie Way
Corry St
Glendale St
Skye St
Kilmuir St
Nevis St
Barra St
Lake Rd
Jetty St
Argyle St
Mull St
Islay St
Oban St
Coll St
Benmore Pl
Shiel St
H1 - Generally safe for vehicles, people and buildings
H2 - Unsafe for small vehicles
H3 - Unsafe for vehicles, children and the elderly
H4 - Unsafe for vehicles and people
H5 - Unsafe for vehicles and people
All buildings vulnerable to structural damage
Some less robust buildings subject to failure
H6 - Unsafe for vehicles and people
All building types considered vulnerable to failure
Legend
Stopbank
Roads
Property boundaries
Hazard Category
H6
H5
H4
H3
H2
H1
LANDRIVERSEA CONSULTING
Otago Regional Council
0 305 610 1,220 Meters
A3 SCALE 1:25,000
MAP (1 of 1)
PROJECT
Glenorchy Flood Modelling
MAP TITLE
HAZARD OVERVIEW MAP
Scenario 2 - 100 year ARI flow (historic climate)
100 year ARI lake level
REVISION 01 Created By PG Reviewed By MG N
AUTHOR Matthew Gardner DATE 13/05/2022
Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958
Model Completed: December 2021
Copyright:
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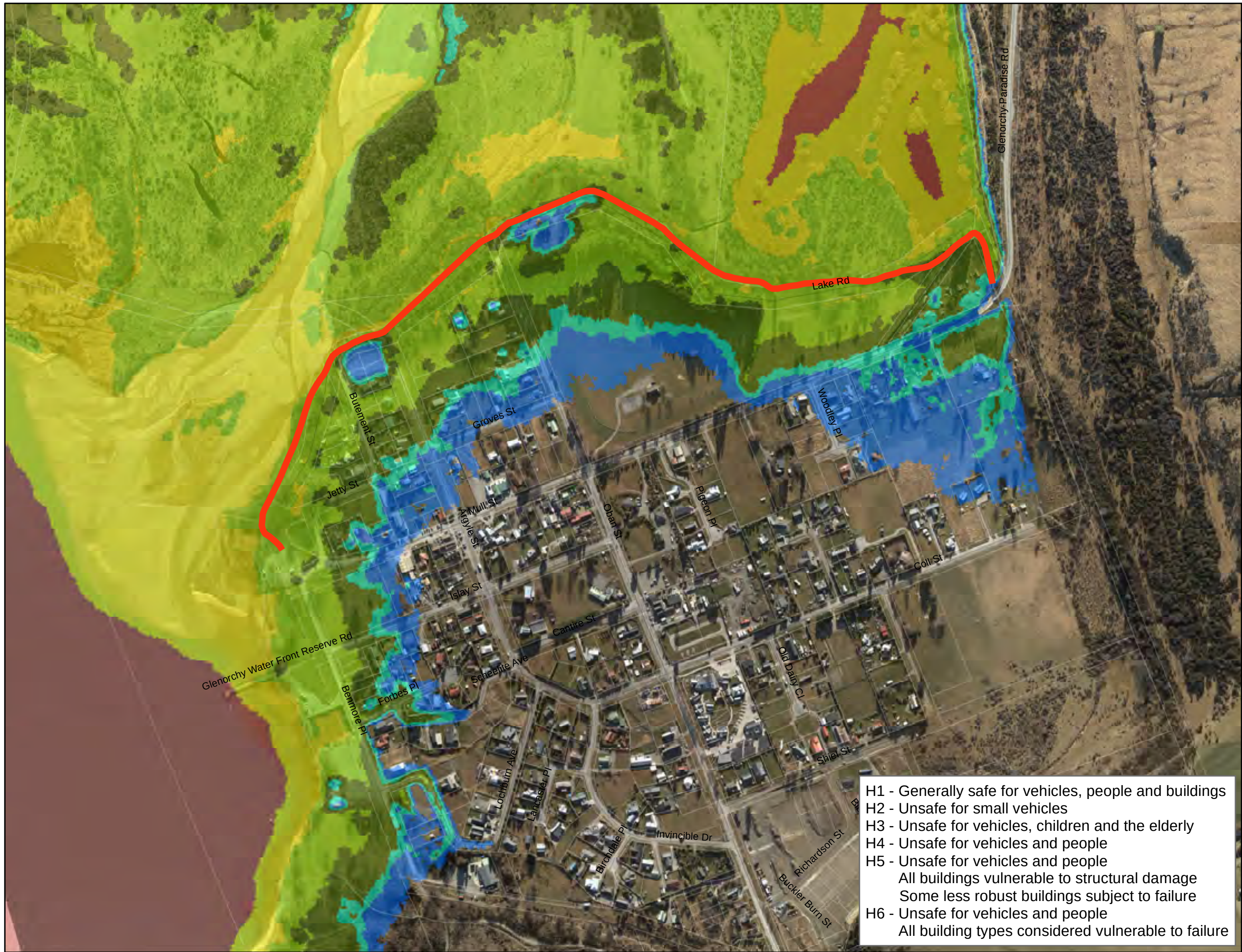


H1 - Generally safe for vehicles, people and buildings
H2 - Unsafe for small vehicles
H3 - Unsafe for vehicles, children and the elderly
H4 - Unsafe for vehicles and people
H5 - Unsafe for vehicles and people
All buildings vulnerable to structural damage
Some less robust buildings subject to failure
H6 - Unsafe for vehicles and people
All building types considered vulnerable to failure

Legend

- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

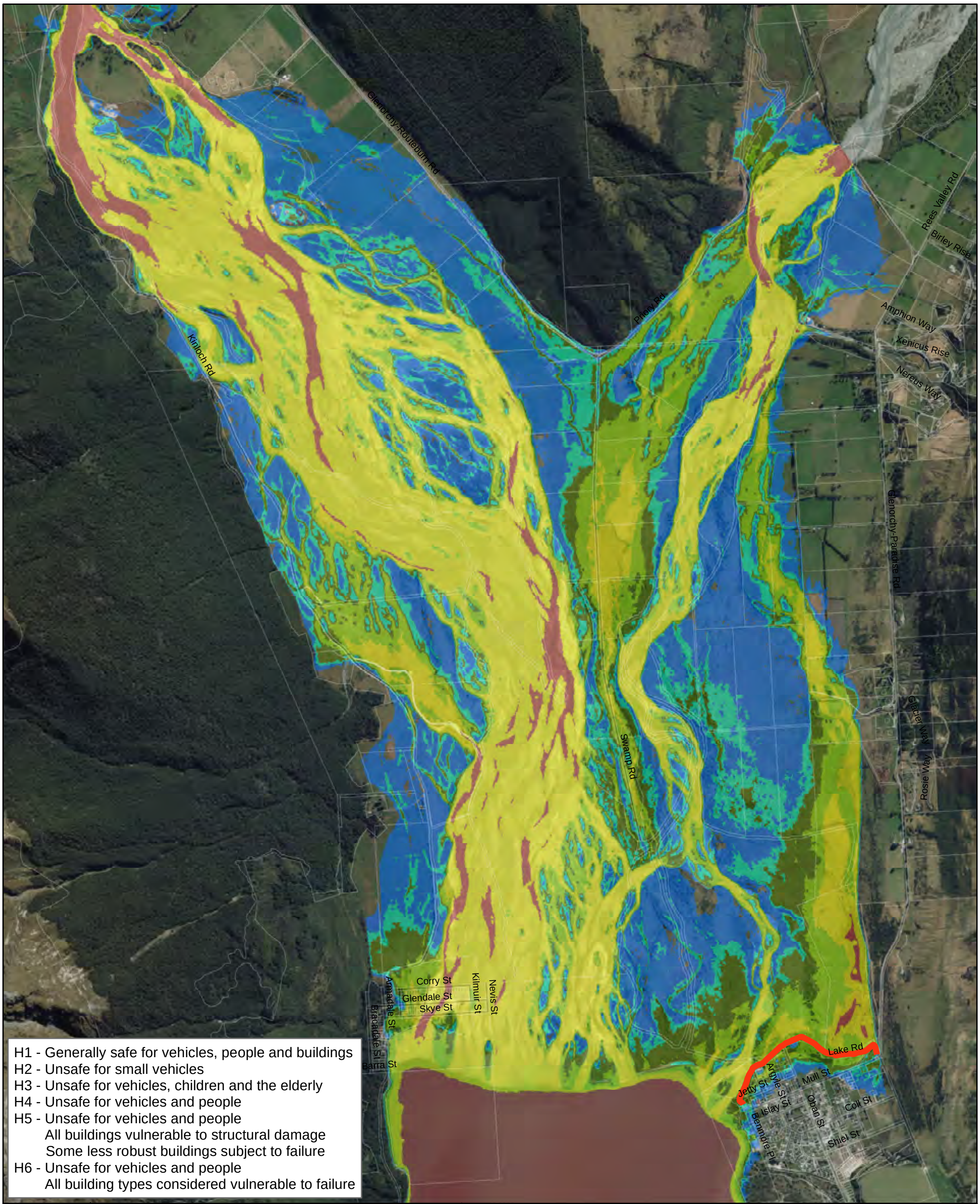
Otago Regional Council

0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE	N
Glenorchy Flood Modelling	**HAZARD MAP** **Scenario 2 - 100 year ARI flow (historic climate)** **100 year ARI lake level**	CREATED BY BSB	**13/05/2022**	**1:5,000**	
		REVISED BY	AUTHOR **Matthew Gardner**		



Legend

Stopbank
Roads
Property boundaries

Hazard Category
H6
H5
H4
H3
H2
H1

LANDRIVERSEA CONSULTING

Otago Regional Council

0 305 610 1,220 Meters

A3 SCALE **1:25,000**

MAP (1 of 1)

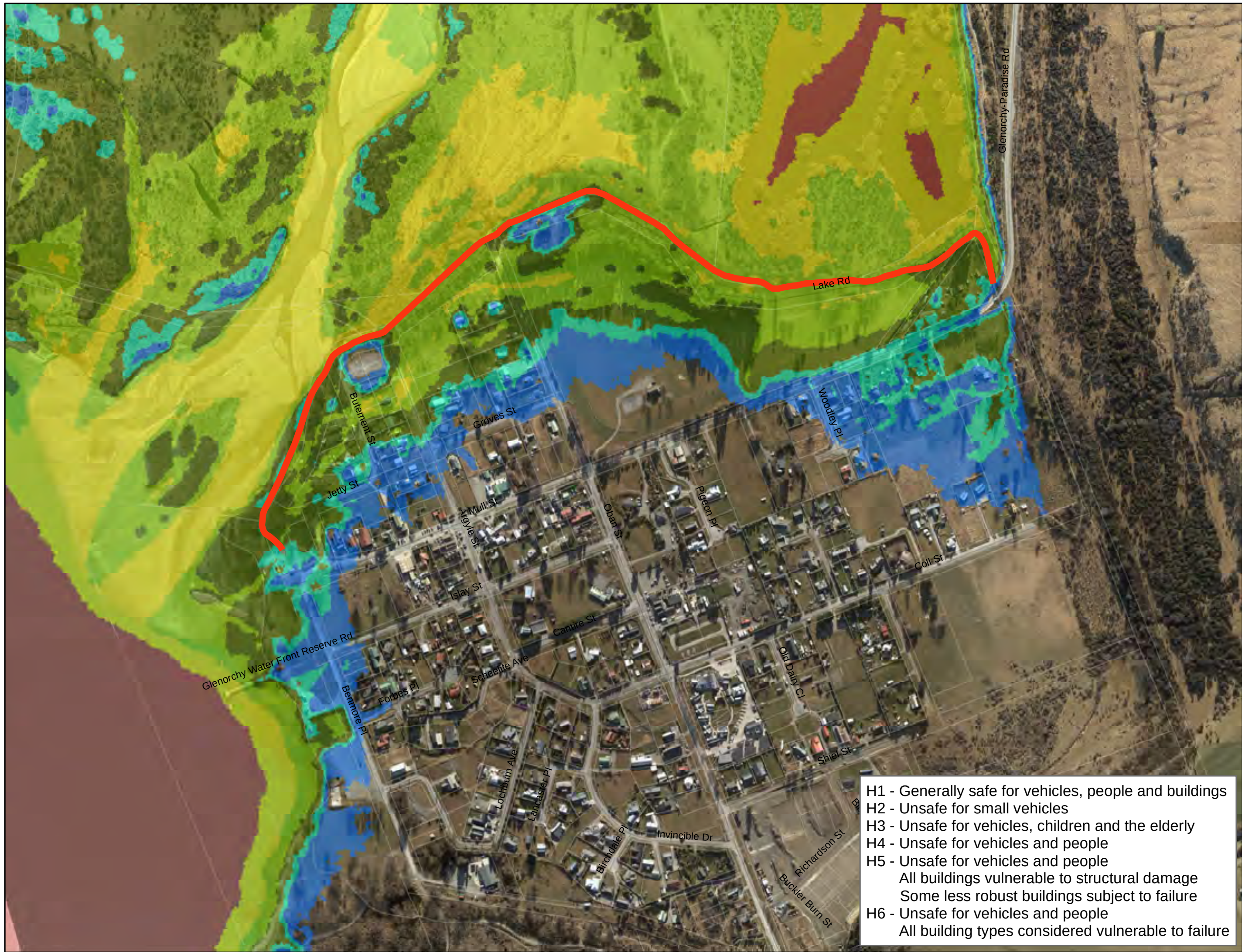
PROJECT
Glenorchy Flood Modelling

MAP TITLE
HAZARD OVERVIEW MAP
Scenario 3 – 100 year ARI flow
(Future Climate, RCP8.5) 10 year ARI lake level

REVISION	01	Created By	PG	Reviewed By	MG	N
AUTHOR	Matthew Gardner		DATE	13/05/2022		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

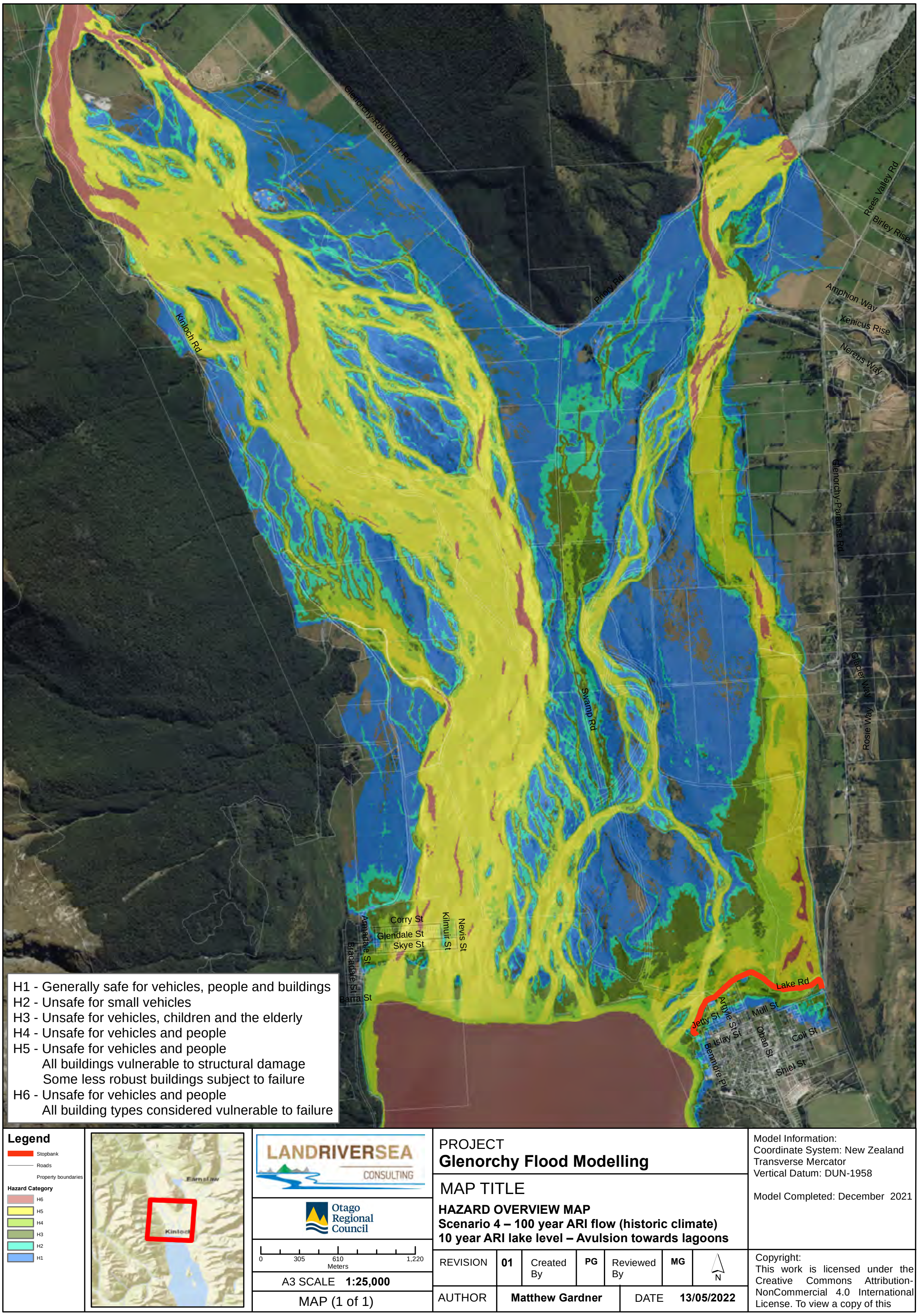
Otago Regional Council

0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **HAZARD MAP** **Scenario 3 – 100 year ARI flow (Future Climate, RCP8.5) 10 year ARI lake level**	REVISION **01**	DATE **13/05/2022**	A3 SCALE **1:5,000**	N
		CREATED BY **BSB**			
		REVISED BY	AUTHOR **Matthew Gardner**		


Glenorchy-Routeburn Rd
Kinloch Rd
Priory Rd
Rees Valley Rd
Birley Rise
Amphion Way
Xenicus Rise
Nereus Way
Glenorchy-Paradise Rd
Swamp Rd
Oban St
Rosie Way
Corry St
Glendale St
Skye St
Kilmuir St
Nevis St
Barra St
Lake Rd
Jetty St
Argyle St
Mull St
Islay St
Oban St
Coll St
Shiel St
Benmore Pl
H1 - Generally safe for vehicles, people and buildings
H2 - Unsafe for small vehicles
H3 - Unsafe for vehicles, children and the elderly
H4 - Unsafe for vehicles and people
H5 - Unsafe for vehicles and people
All buildings vulnerable to structural damage
Some less robust buildings subject to failure
H6 - Unsafe for vehicles and people
All building types considered vulnerable to failure
Legend
Stopbank
Roads
Property boundaries
Hazard Category
H6
H5
H4
H3
H2
H1
Kinloch
LANDRIVERSEA CONSULTING
Otago Regional Council
0 305 610 1,220
Meters
A3 SCALE 1:25,000
MAP (1 of 1)
PROJECT
Glenorchy Flood Modelling
MAP TITLE
HAZARD OVERVIEW MAP
Scenario 4 – 100 year ARI flow (historic climate)
10 year ARI lake level – Avulsion towards lagoons
REVISION 01 Created By PG Reviewed By MG
N
AUTHOR Matthew Gardner DATE 13/05/2022
Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958
Model Completed: December 2021
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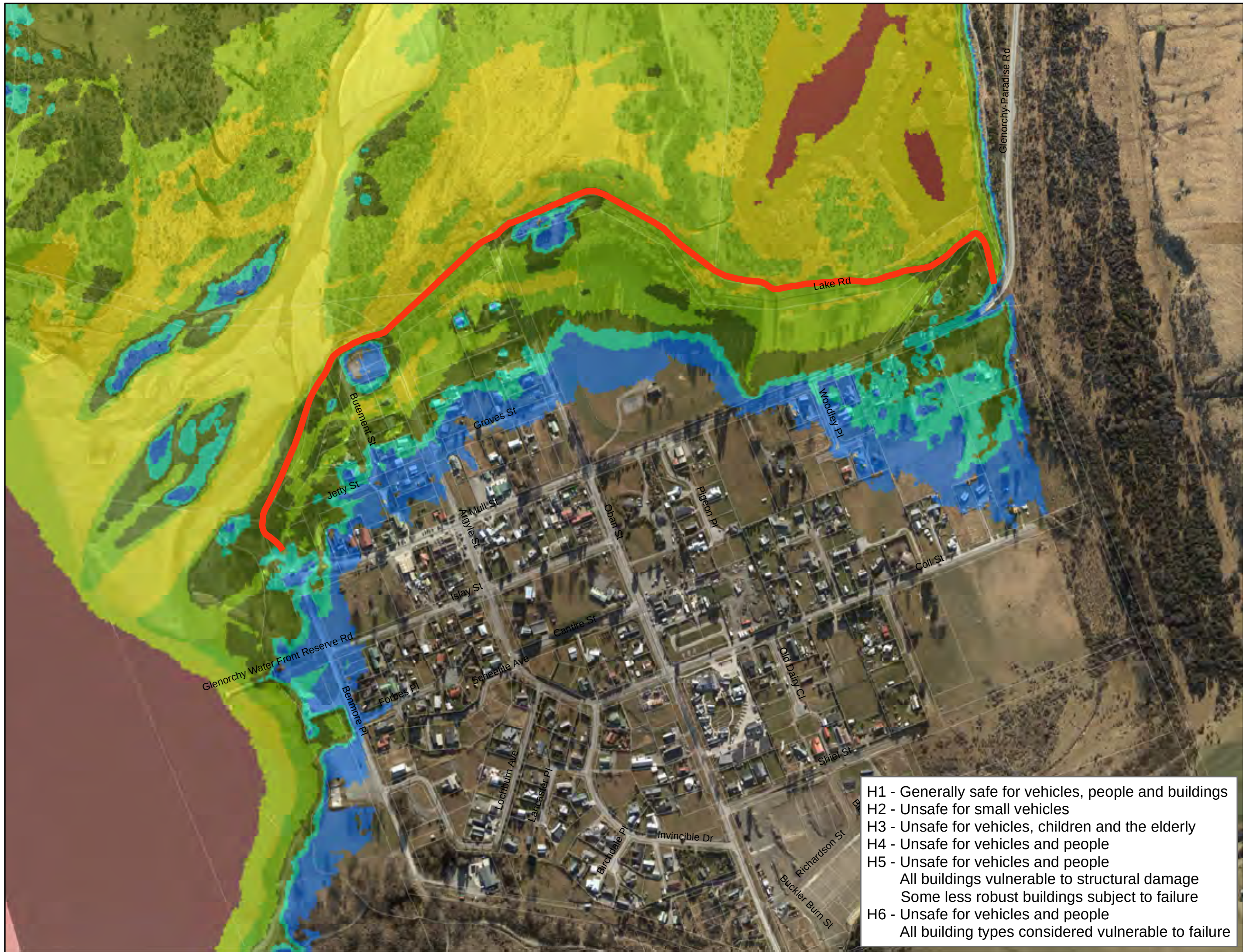


Legend

- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

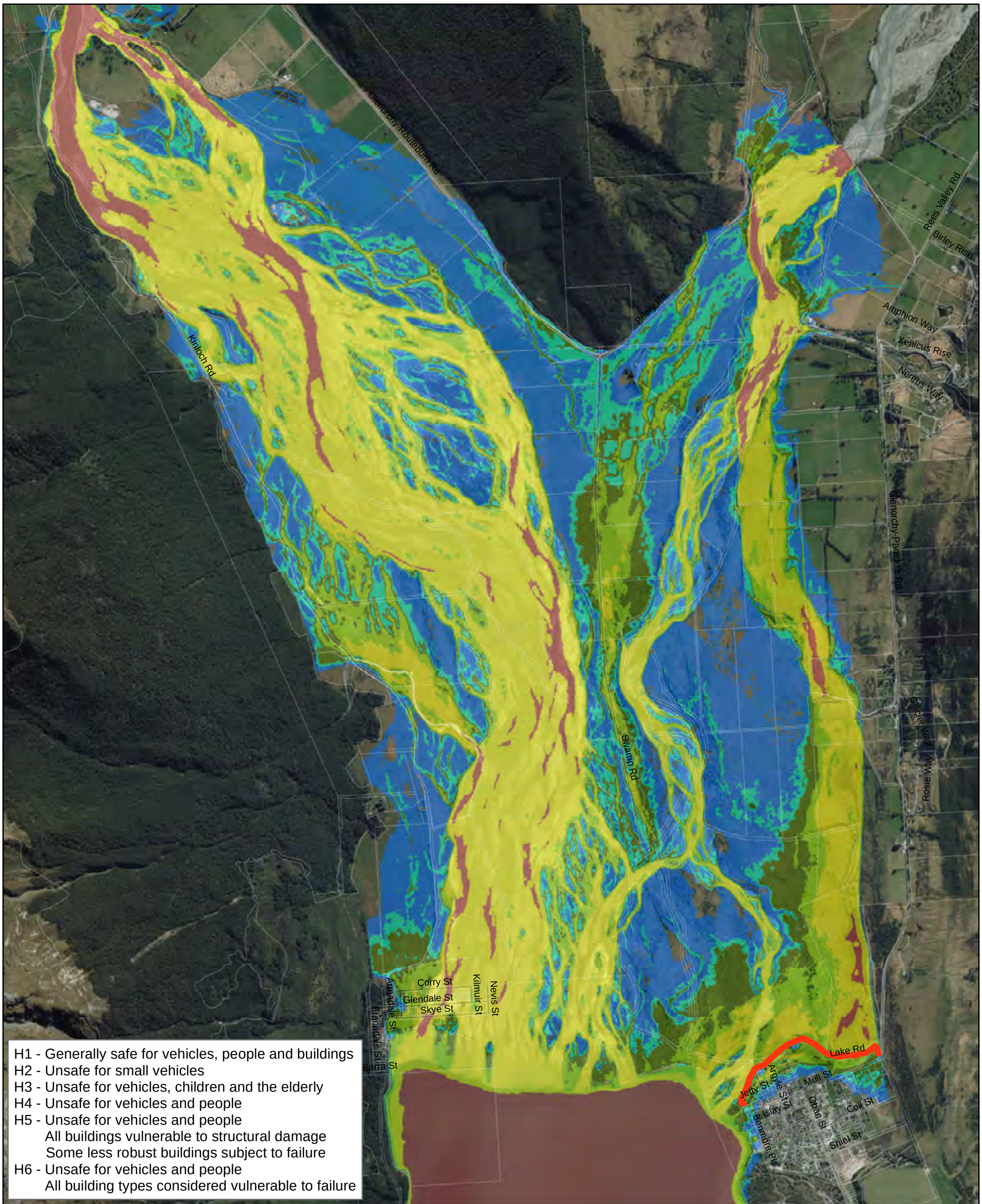
Otago Regional Council

0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**HAZARD MAP** **Scenario 4 – 100 year ARI flow (historic climate)** **10 year ARI lake level – Avulsion towards lagoons**	CREATED BY **BSB**	**13/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	N



Legend

- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

Otago Regional Council

0 305 610 1,220 Meters

A3 SCALE **1:25,000**

MAP (1 of 1)

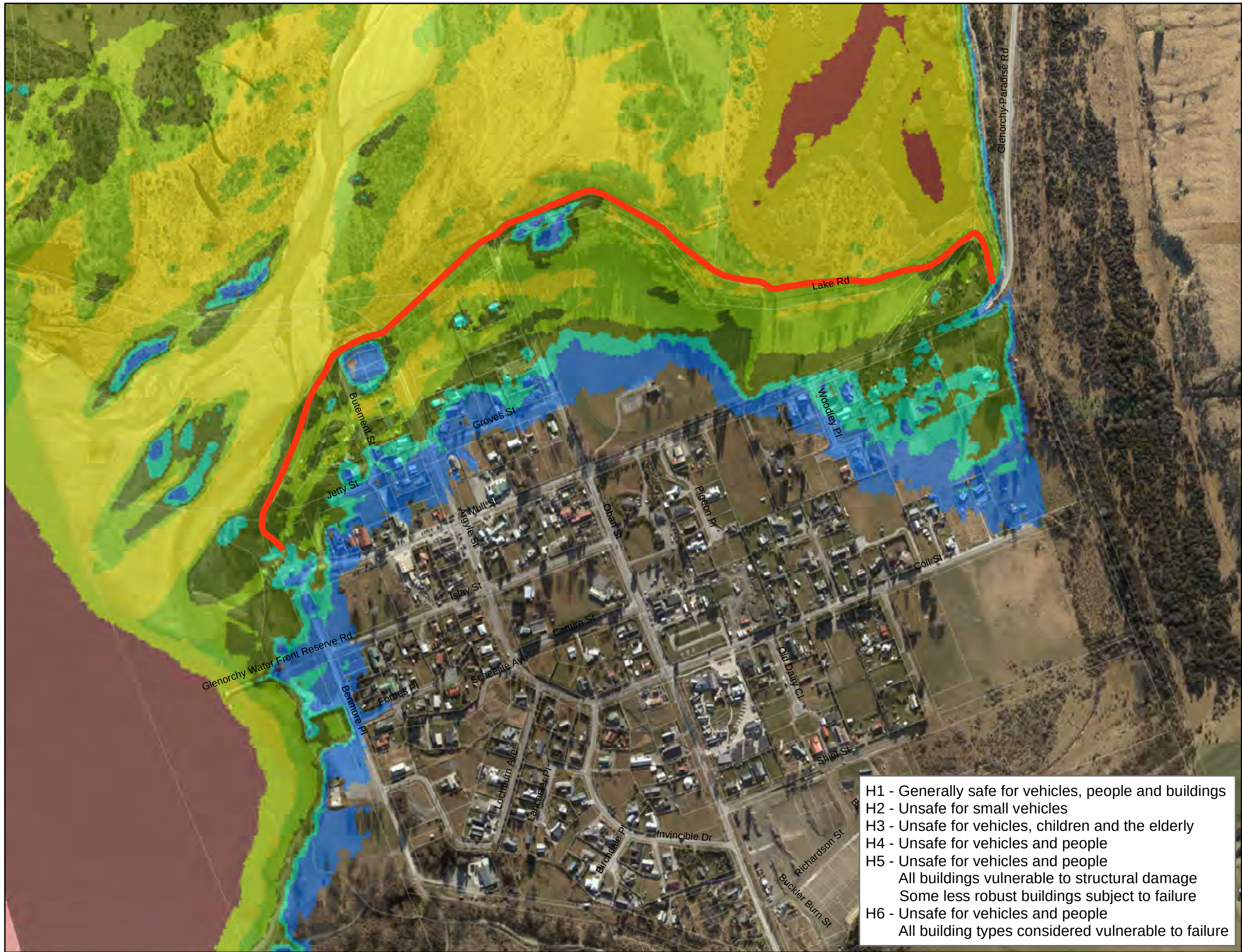
PROJECT
Glenorchy Flood Modelling

MAP TITLE
HAZARD OVERVIEW MAP
Scenario 5 – 100 year ARI flow
(Future Climate,RCP8.5) 10 year ARI lake level
Avulsion towards lagoons

REVISION	01	Created By	PG	Reviewed By	MG	N
AUTHOR	Matthew Gardner		DATE	13/05/2022		

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021



Legend

- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

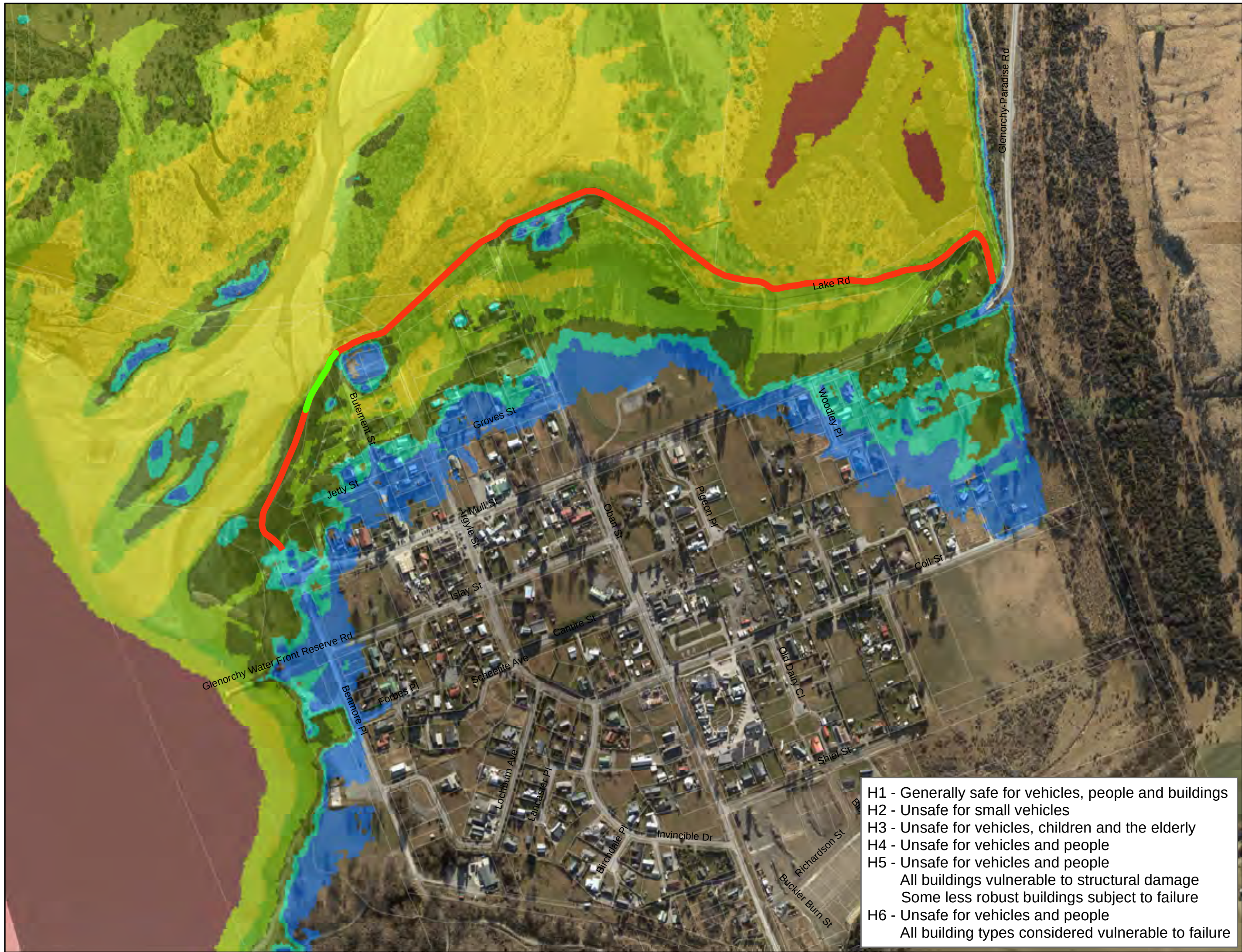
Otago Regional Council

0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **HAZARD MAP** **Scenario 5 – 100 year ARI flow (Future Climate, RCP8.5)** **10 year ARI lake level – Avulsion towards lagoons**	REVISION **01** CREATED BY **BSB** REVISED BY	DATE **13/05/2022** AUTHOR **Matthew Gardner**	A3 SCALE **1:5,000**	N



H1 - Generally safe for vehicles, people and buildings
H2 - Unsafe for small vehicles
H3 - Unsafe for vehicles, children and the elderly
H4 - Unsafe for vehicles and people
H5 - Unsafe for vehicles and people
All buildings vulnerable to structural damage
Some less robust buildings subject to failure
H6 - Unsafe for vehicles and people
All building types considered vulnerable to failure

Legend

- Breach 1
- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

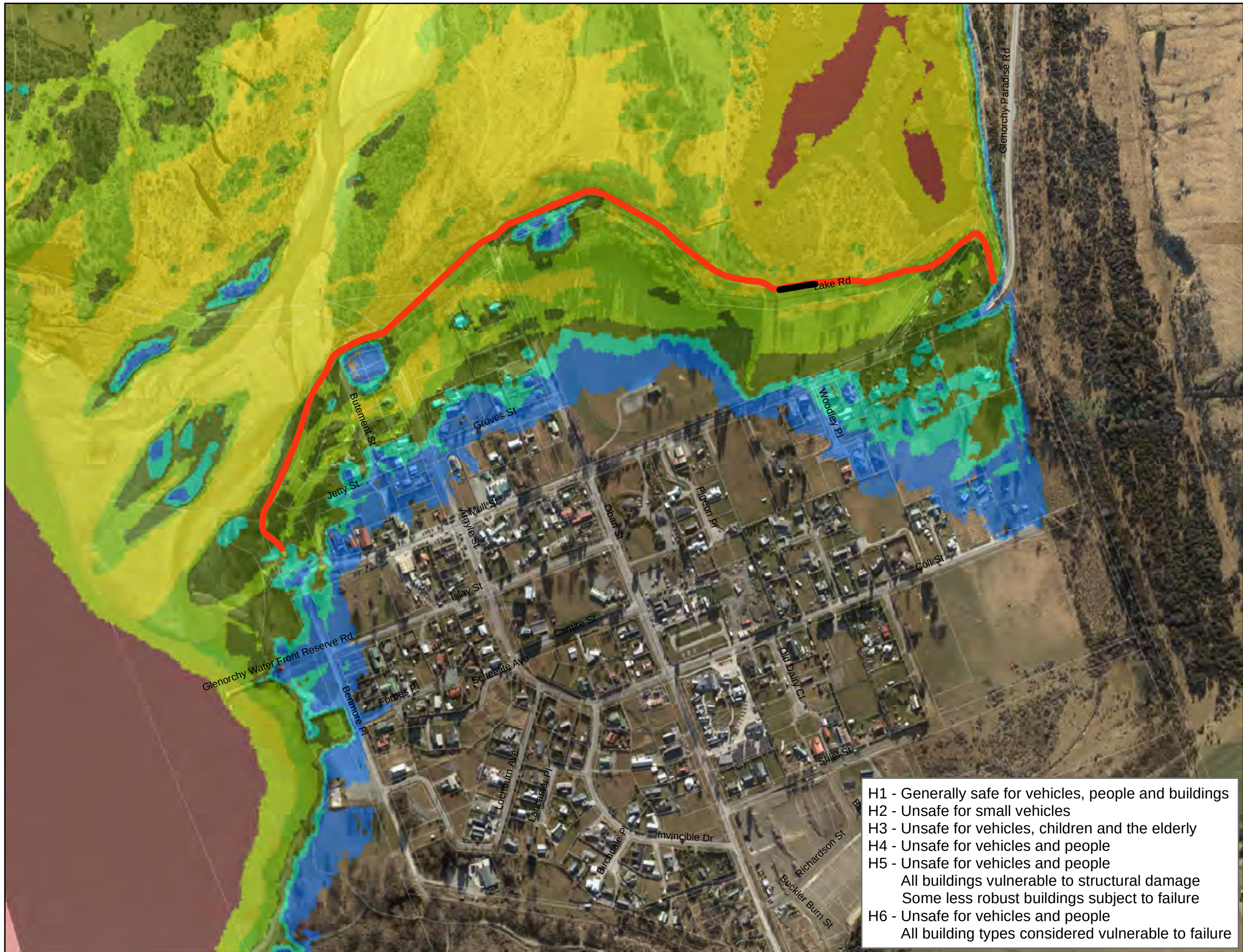
Otago Regional Council

0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**HAZARD MAP** **Scenario 6 - 100 year ARI flow (Future Climate, RCP8.5) 10 year ARI lake level - Breach 1 (90m Wide) Avulsion towards lagoons**	CREATED BY BSB	**12/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	N



Legend

- Breach 2
- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

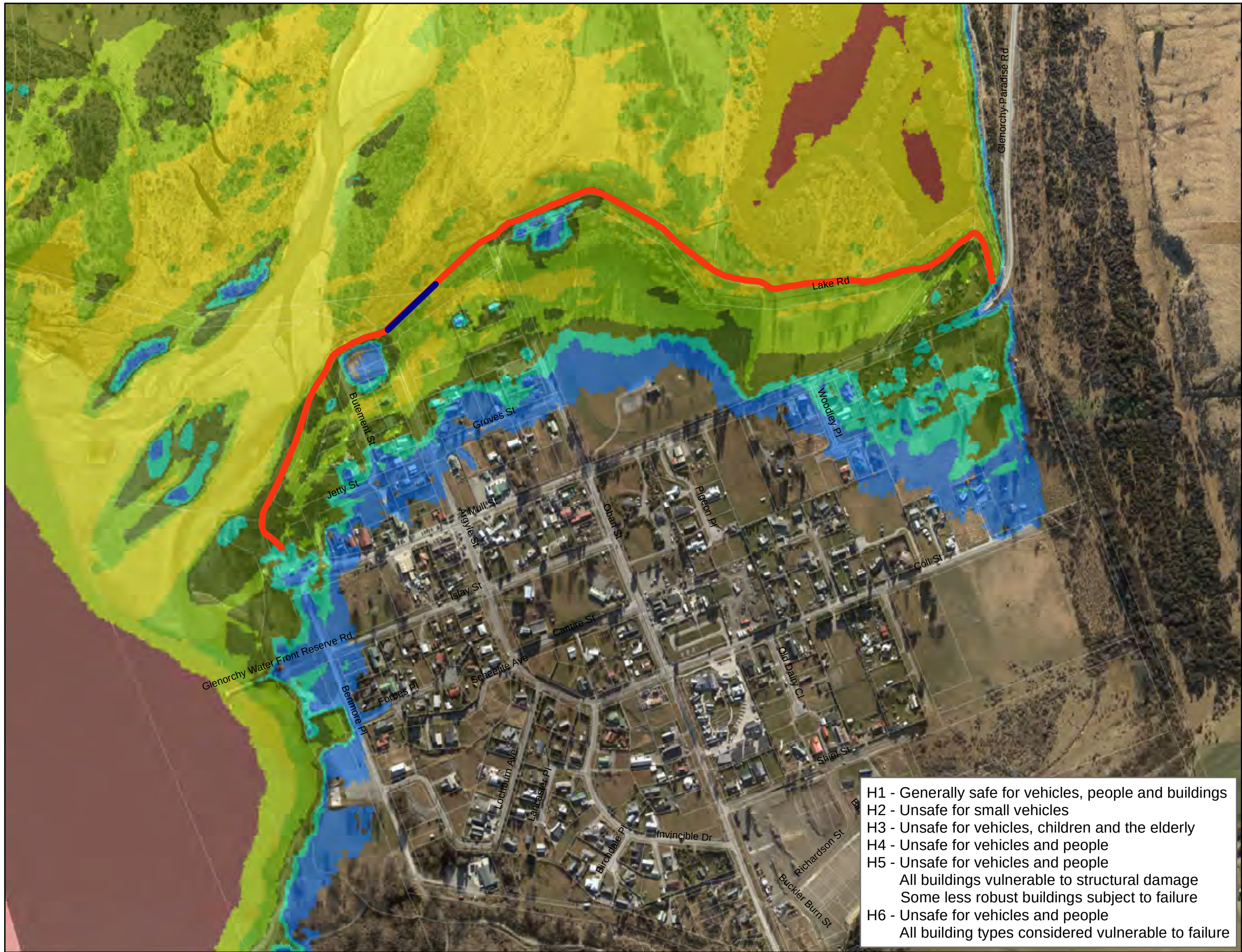
Otago Regional Council

0 0.05 0.1 0.2
Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT **Glenorchy Flood Modelling**	MAP TITLE **HAZARD MAP** **Scenario 7 - 100 year ARI flow ((Future Climate, RCP8.5)** **10 year ARI lake level - Breach 2 (90m Wide)** **Avulsion towards lagoons**	REVISION **01** CREATED BY **BSB** REVISED BY	DATE **12/05/2022** AUTHOR **Matthew Gardner**	A3 SCALE **1:5,000**	N



Legend

- Breach 3
- Stopbank
- Roads
- Property boundaries

Hazard Category

- H6
- H5
- H4
- H3
- H2
- H1

LANDRIVERSEA CONSULTING

Otago Regional Council

0 0.05 0.1 0.2 Kilometers

Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**HAZARD MAP** **Scenario 8 - 100 year ARI flow (Future Climate, RCP8.5) 10 year ARI lake level - Breach 3 (90m Wide) Avulsion towards lagoons**	CREATED BY **BSB**	**12/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	

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2 June 2022
Job No: 1015117.0150

Otago Regional Council
70 Stafford Street
Private Bag 1954
Dunedin 9054

Attention: Mr T van Woerden

Dear Tim

Dart-Rees Modelling: LRS Report Review

In accordance with our Letter of Engagement dated 12 May 2022, we are pleased to report on our review of the draft report for the Dart-Rees flood modelling project.

Land River Sea Consulting Ltd (LRS) has developed a computational hydraulic model of the Dart-Rees River system as it flows into Lake Wakatipu. The model has been used to investigate various modelling scenarios and outcomes as they may affect the flood hazard to Glenorchy and other locations in the vicinity of the Head of Lake Wakatipu.

We received by email (van Woerden/Bassett) on 23 May 2022, a link to a soft copy of the draft report prepared by LRS. We provided comments on the review, primarily annotated in the report document, to ORC by File Transfer on 25 May. Our technical specialist, Tom Bassett, discussed this review with Matt Gardner of LRS by phone on 31 May and 1 June. LRS subsequently provided a several revised draft report files.

The essential scope was a review of the draft modelling report and whether the completed work has met the objectives set out for it, including:

- The validity of the assumptions
- The validity of the conclusions
- The validity of the recommendations.

We set out our review conclusions below, which are based on the final draft of the 130-page report, Dart / Rees Rivers, Flood Hazard Modelling, by Matthew Gardner, Land River Sea Consulting for Otago Regional Council, dated 1 June 2022.

Modelling Assumptions

The model for the Dart-Rees river system has been developed using DHI MIKE21 software, incorporating 2019 LIDAR survey data of the terrain as well as available cross section survey data. This is a conventional approach to developing a computational flood model, based on widely used

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software. In the model terrain is defined using a variable mesh size enabling different degrees of resolution across the floodplain.

Hydraulic resistance in the model domain has been modelled by assigned roughness coefficients, depending on land cover.

Other input data to the model have been provided by third parties:

- Hydrology input hydrographs, by ORC
- Rees River avulsion scenarios, by Professor James Brasington
- Stopbank breach scenarios, by Tonkin+Taylor.

These inputs have not been scrutinised as part of this review.

Alternative parameter definition has been modelled to a limited extent to investigate sensitivity of model results. This includes:

- Viscosity
  - Modelling approach and selected parameters consistent with conventional practice
- Solution technique
  - Shown not to be critical for model results
- Roughness coefficient
  - A range of Manning's coefficients was tested for the gravel bed, and selected based on a good fit to the observed water levels as well as being within a sensible range based on the measured grain size
- Initial lagoon water level
  - Shown to have minimal effect on modelled flood extent
- Input hydrology
  - Early LRS modelling results provided to ORC during investigations to assist calibration of the hydrological model.

There are few observed data detailed and prolific enough to have enabled a robust calibration of the model. However, the model output has been validated by comparing model results (flood extent, etc) against observations (anecdotal and photographic) from the February 2020 flood event, principally in and around Glenorchy.

The modelling investigation has only considered the impacts of flooding on its own and has not considered the potential impact of cascading natural hazard scenarios (e.g. earthquake-induced liquefaction settlement in conjunction with flooding), nor has it considered longer-term aggradation of the Dart and Rees river beds and delta.

Review comment:

> The modelling approach, and parameters selected in development of the model, are soundly based, and reflect conventional practice. The model results for the February 2020 flood event provide validation of the model as a tool to investigate flooding processes and present-day flood hazards in the Head of Lake Wakatipu area.

Modelling Conclusions

LRS concluded that the model results provided a reasonable representation of the overall flood extent in relation to the February 2020 flood event.

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Subsequently the model was used to investigate the likely flood hazard for several input scenarios, including in combination:

- Bed configuration as defined by 2019 LiDAR survey
  - And a Rees River avulsion scenario directing more flow along the left bank towards the Glenorchy lagoon
- Lake level
- Present-day and 2100 future climate as they affect flood hydrograph inputs to the model
- Glenorchy stopbank breaches.

LRS concluded:

- The low-lying areas in Glenorchy are at particular risk of flooding from both the river as well as the lake, with properties closest to the stopbank and the lake most exposed
- The Glenorchy stopbank is prone to overtop in small to medium sized flood events
- Should a stopbank breach occur, the extent of flooding is unlikely to increase due to the current topography controlling the flood extent
- The impact of increased flows due to climate change as well as an avulsion in the Rees River will send more water towards the lagoons and increase the depth and extent of flooding at the upstream end of the stopbank, however, the flood extent closer to the lake remains largely unchanged
- Whilst existing buildings in Kinloch will remain above the flood level, access to the settlement will be severed due to inundation, with velocities sufficient to erode the road surface
- There will be significant issues with road access in the wider catchment area, with the Glenorchy-Routeburn Road, Priory Road, Swamp Road and Kinloch Road access all likely severed during a 100-year ARI event.

Review comment:

> The modelling results for the various scenarios provide useful guidance to the Head of the Lake community regarding flooding exposure at various frequencies (return periods) and river/stopbank scenarios, and the flood hazard in various locations particularly in and around Glenorchy for the existing river systems.

Modelling Recommendations

LRS notes that "*if future and more reliable calibration data becomes available then it would be worthwhile refining and upgrading the model*" to provide more confidence in the model results.

Review comment:

> We concur that more and accurate monitoring data of future flooding (including rainfall across the Dart-Rees catchment, river flows, and observed flooding extent) will assist refinement of the model. Nonetheless we consider that the model is presently appropriate and fit for purpose to assess flood hazard from the Dart-Rees river system at the Head of the Lake. In due course the model could also be amended/used to investigate possible cascading hazard scenarios, e.g. widespread liquefaction and lateral spreading resulting in significant ground surface subsidence following a large earthquake, and/or longer term aggradation of the Dart-Rees braided river channels and delta.

We trust that this meets your requirements. Please contact Tom Bassett at tbassett@tonkintaylor.co.nz if you require clarification or elaboration of this review report.

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This T+T review was a form of peer review, undertaken on a level-of-effort basis, to provide additional assurance to Otago Regional Council as to the quality of the modelling. The responsibility for the modelling remains fully with the Principal Consultant (LRS), and T+T's review does not constitute a means by which that modelling responsibility can be passed on to T+T. This report has been prepared on behalf of, and for the exclusive use of ORC, and is subject to, and issued in accordance with, the provisions of the contract between T+T and ORC. T+T accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon, this report by any third party.

Yours sincerely

Dr Sjoerd van Ballegooy
PROJECT DIRECTOR

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Communication and Engagement

1.1 Context

The community of Lake Wakatipu, particularly Glenorchy and Kinloch, will be aware of the studies and the findings due to come out of the flood hazard and liquefaction studies, though not the detail of the impact.

The findings of studies will give residents the important information about how to 'live with these hazards' and enable decisions about their future and livelihood, however, as NIWA's Paula Blackett said in the recent South Dunedin Future adaptation councillors' workshop, this kind of information is hard to get your head around and into.

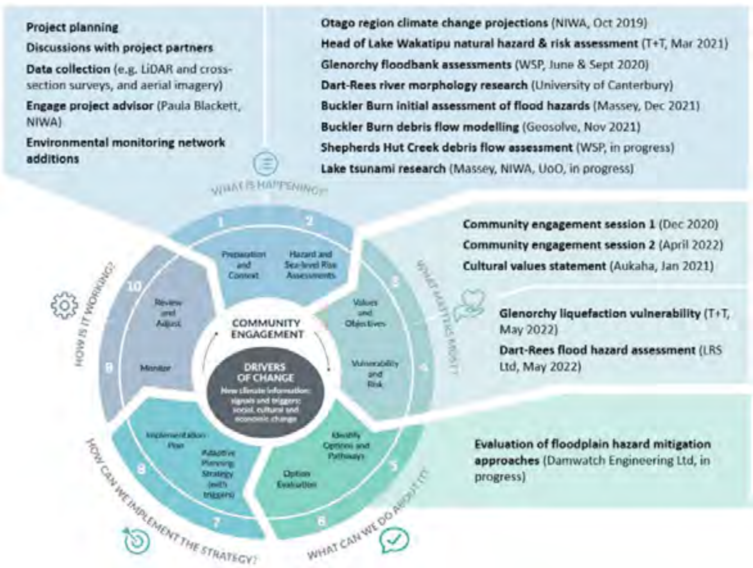
Being at the head of lake Wakatipu, a tourism hot spot and well-known film location, and the gateway to some of the New Zealand's great walks, the report findings will attract local and national media interest.

Often times, reading negative news about your 'backyard' can be upsetting. This level of detail and the media coverage may be discomforting, and we need to try to manage that.

1.2 Purpose

A broader Head of The Lake communication and engagement plan includes objectives, approach, key messages (and ownership), key timelines and risk analysis and mitigation as well as key channels.

The plan has ensured support for staff to have ongoing engagement with this community (see below) for many years, as part of an adaption cycle process (as illustrated by the purple shading across the Dynamic adaptive policy pathways or DAPP).



This is a critical point before we move from step 4 to the 5th and 6th step of the cycle.

This *micro* plan is focused on ensuring the Head of Lake Wakatipu community is given opportunity to receive and digest the recently completed research (report findings) about the natural hazards in the head of Lake Wakatipu area, ensure they feel prioritized, supported and involved in making ongoing decisions about their future options.

1.3 Approach

Due to the level of engagement needed, this micro plan identifies the best means and timing to engage with communities and media, focused over four weeks.

We will use existing channels including the well-read monthly newsletter and updates on the ORC website, online and face-to-face community sessions, alongside media engagement.

Our Head of the Lake newsletter has around 60 subscribers. The newsletter is timed to go out on the day of the Glenorchy Community Association meeting, and is designed for them to discuss the information.

The presentation

We will present the findings via an online meeting on 2 June (a date we have checked with key contacts in Glenorchy), where consultants will share the presentations, and we will answer questions.

This will be facilitated by David Cooper, with a welcome by Clr Forbes. We will invite attendees to be involved with questions via chat that will be monitored and referred to or speaking. Q&As are built into the presentation, but we are also setting time aside for additional Q&As afterwards. We will emphasis that the community can get in touch with us at any time during or after the meeting.

Follow up

Following the online community meeting, the website will be updated. By Friday 3 June, it will have the recorded meeting online, an easy-to-read summary of both reports, links to the reports (when available) and media release as well as a raft of questions and answers (that we can update as they come in).

We will send the details and links to the Head of the Lake newsletter subscriber base on Friday 3 June.

Throughout we are strongly emphasizing that we are available;

- We will have follow up sessions (as many as needed) with the community throughout this adaptation process.
- These will be opportunities to discuss findings and let us know your feedback – we value your input.
- We have a dedicated email address - Headofthelake@orc.govt.nz. We will provide responses to any emailed questions and facilitate answers from our consultants or QLDC if needed.