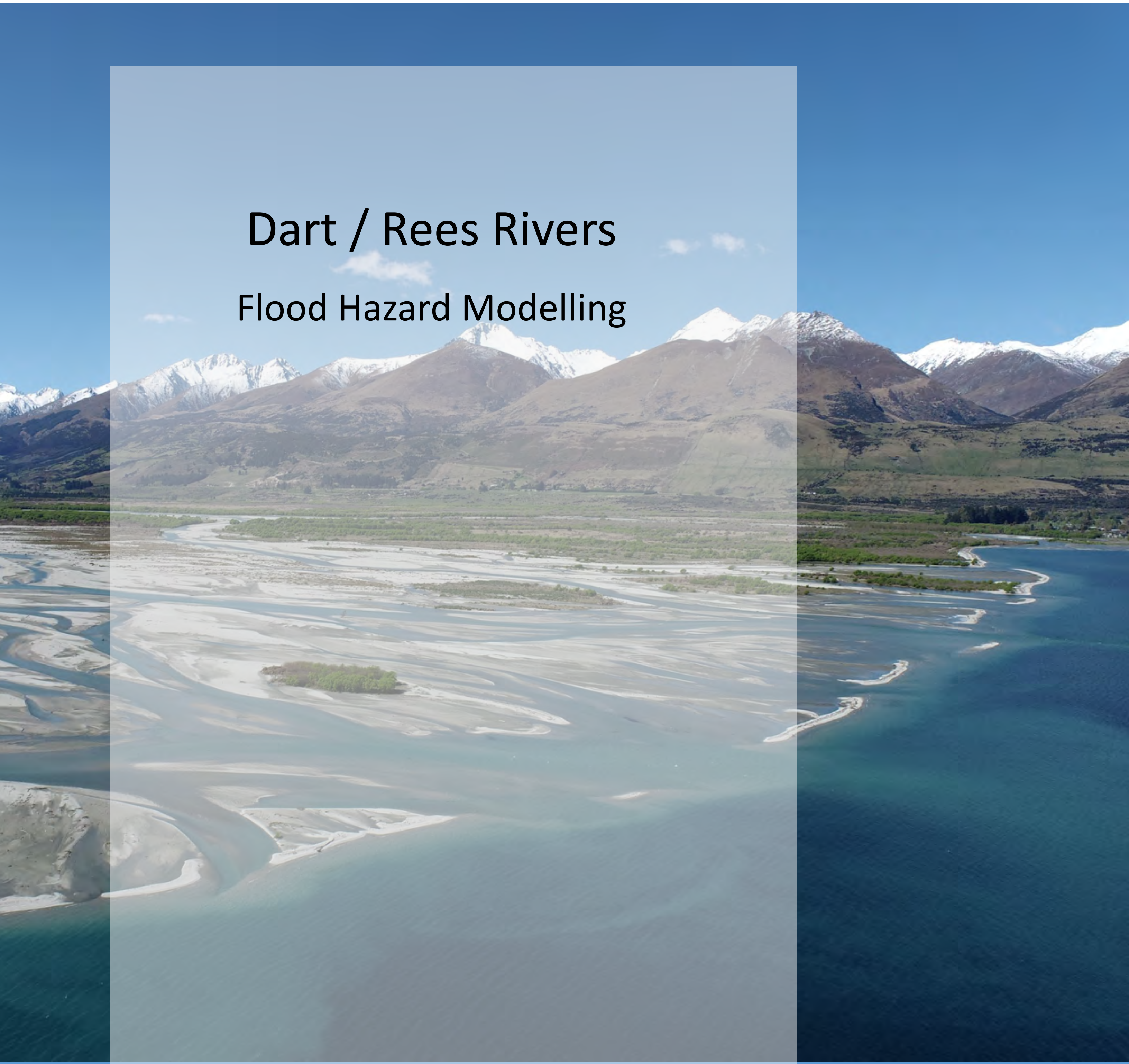


Dart / Rees Rivers

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

Author:	Matthew Gardner Water Resources Engineer, CMEngNZ, CPEng
Signature:	
Date:	1/06/2022
Revision:	06
Authorised by:	Tim Van Woerden
Signature:	
Organisation:	Otago Regional Council
Date:	

Land River Sea Consulting Limited
PO Box 27121
Shirley
Christchurch

M: +64 27 318 9527
E: matthew@landriversea.com
W: landriversea.com

TABLE OF CONTENTS

LANDRIVERSEA CONSULTING

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

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.

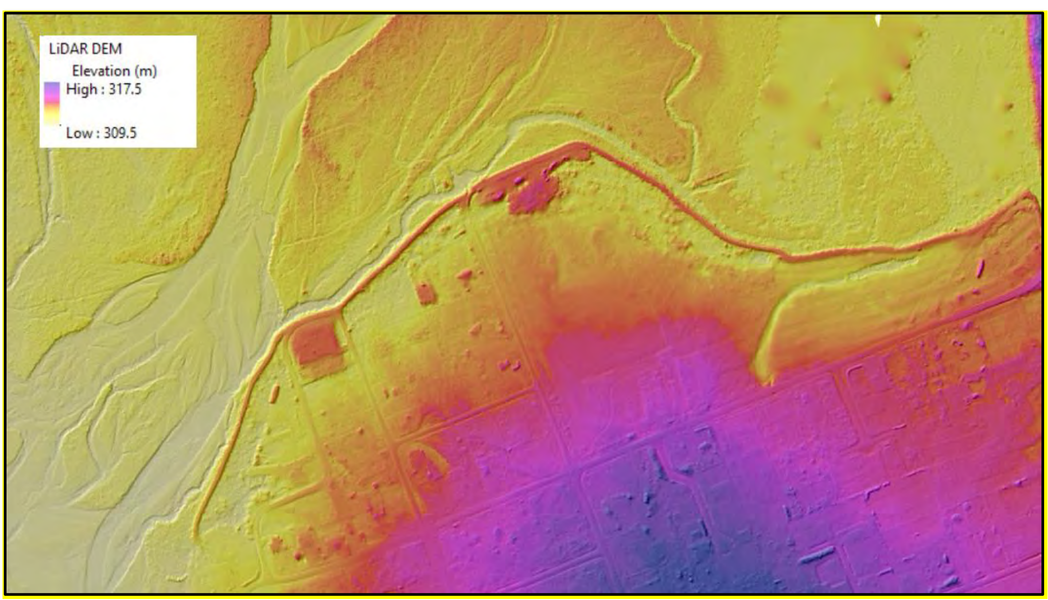


Figure 3-1 – Coloured hillshade visualisation of the LiDAR data in the area of the Rees River / Glenorchy

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

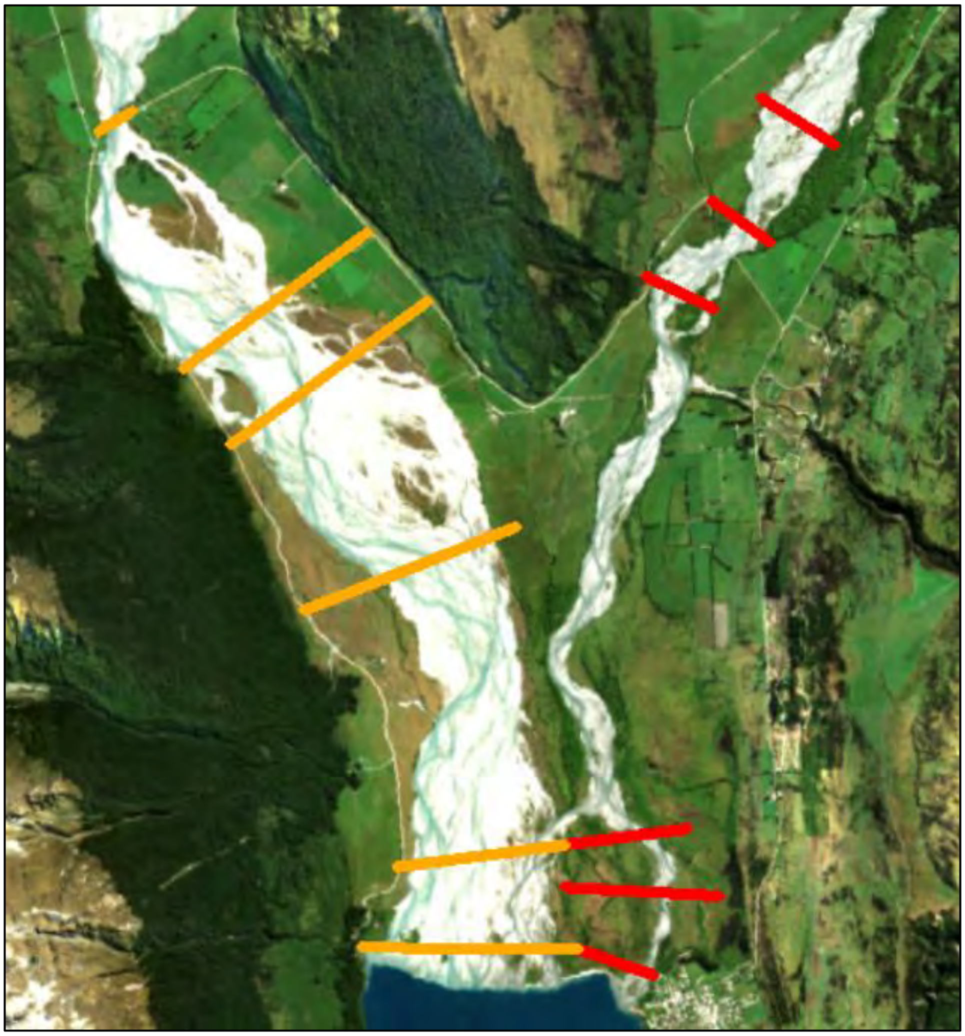


Figure 3-2 – Location of cross section surveys on the Rees and Dart Rivers (Orange lines – Dart River, Red lines – Rees River)

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.

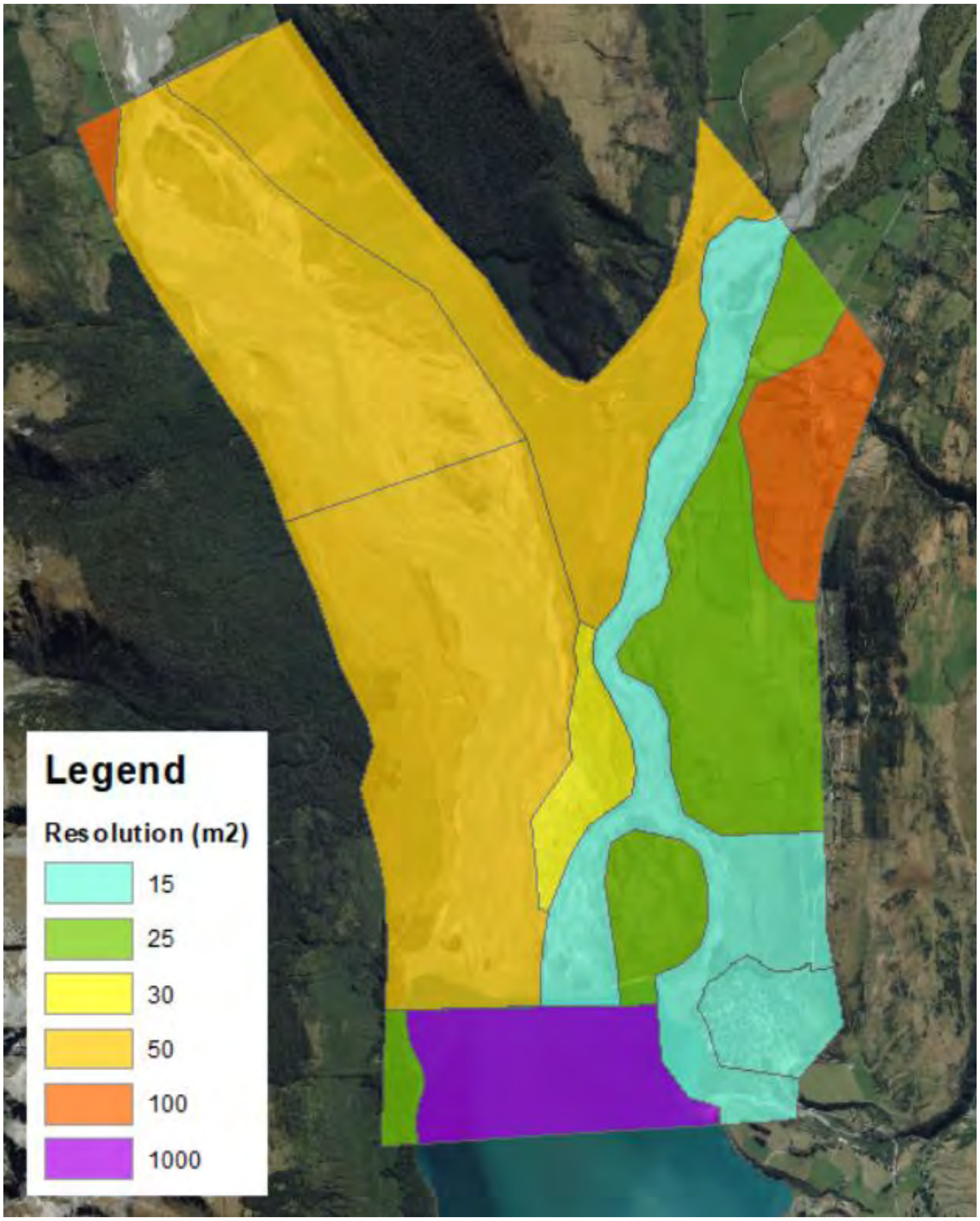


Figure 5-1 – Summary of assigned maximum mesh element resolution

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.

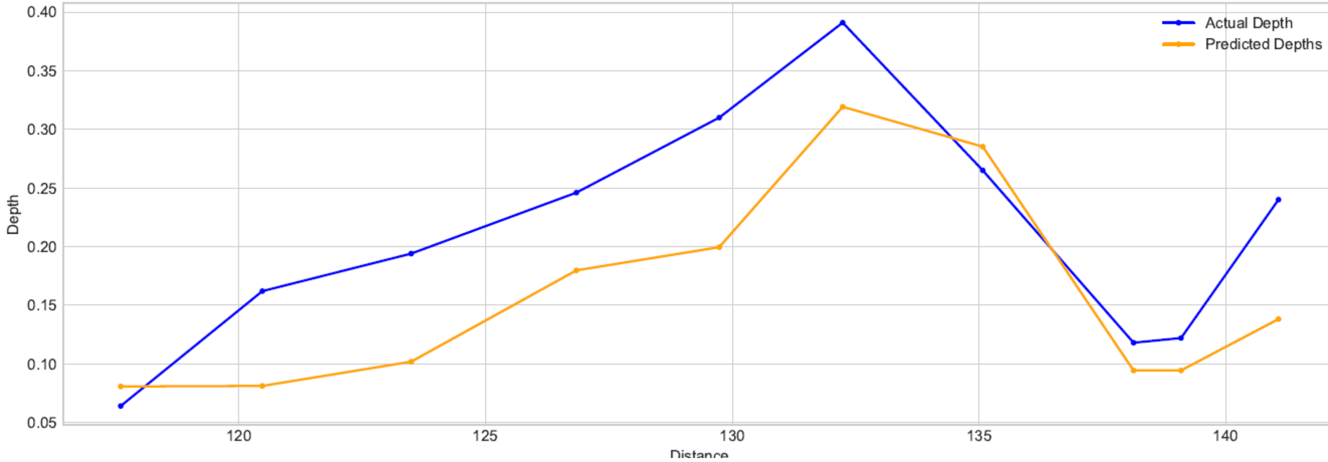


Figure 5-2 – Visualisation of interpolated 2D bathymetry

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

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.

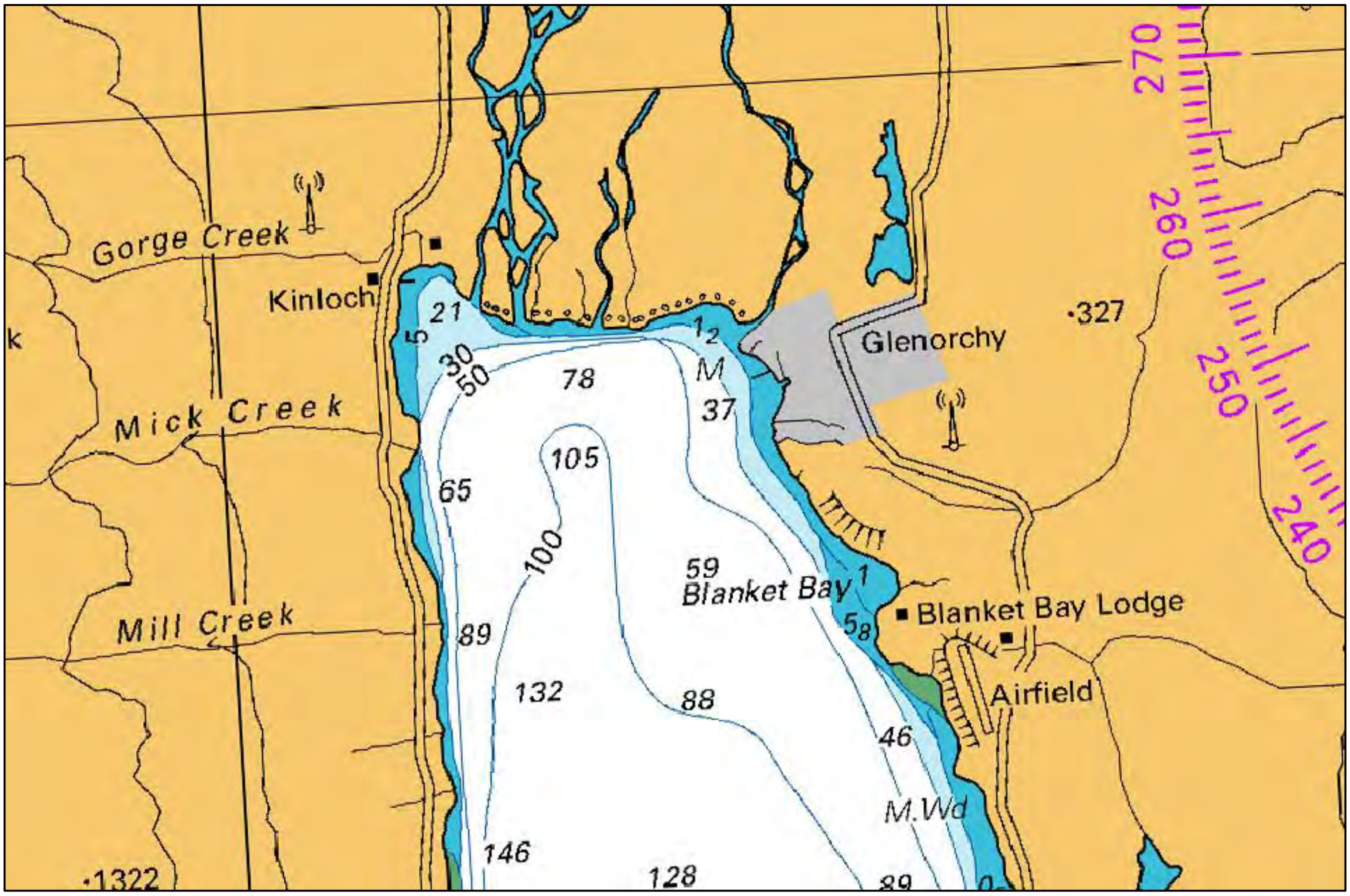


Figure 5-4 – Lake Wakatipu Bathymetric Contours obtained from LINZ

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

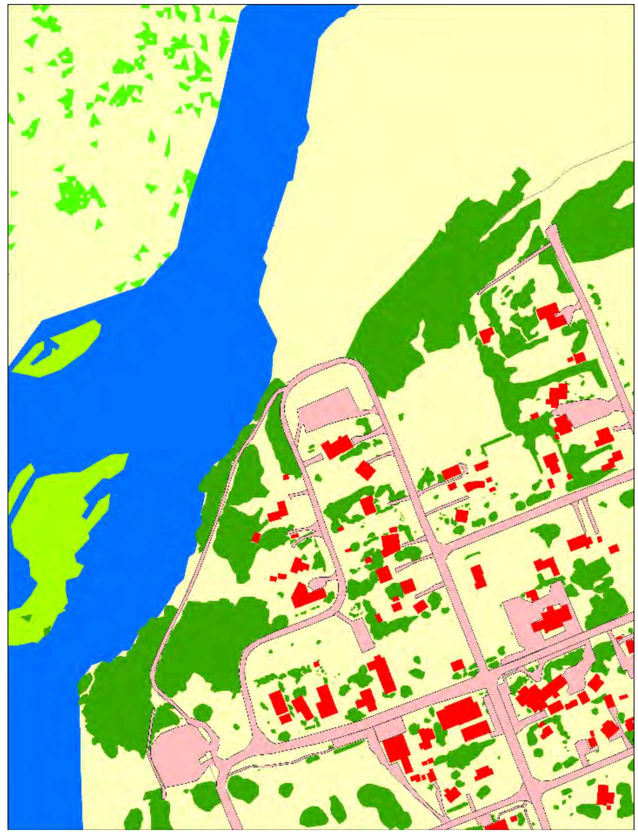


Figure 5-6 – Land use classification corresponding to the aerial imagery in Figure 5-5

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.

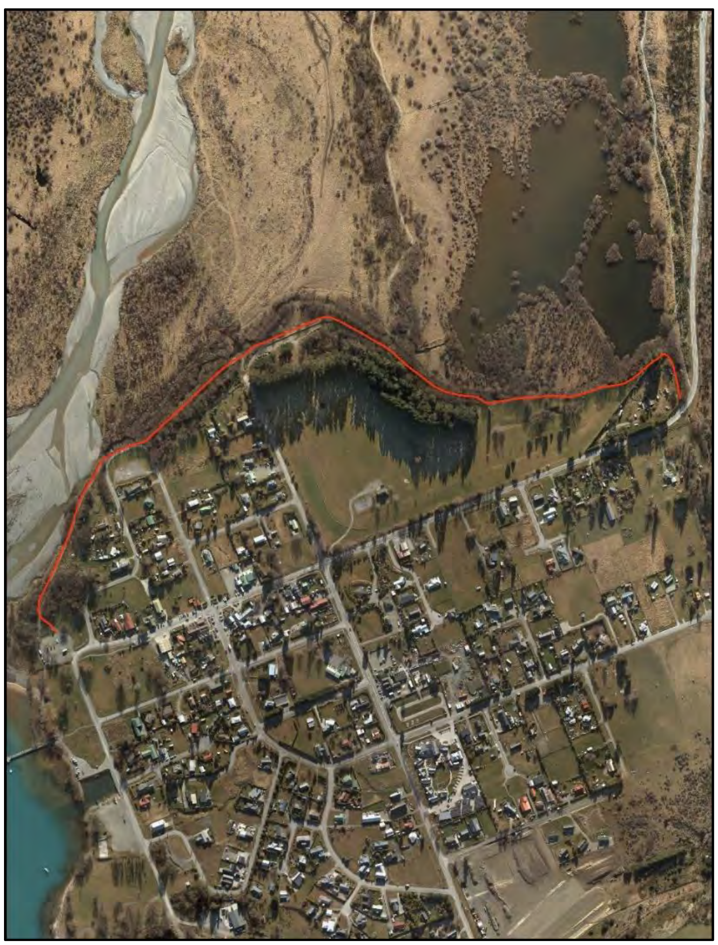


Figure 5-7 – Location of Glenorchy stopbank

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).

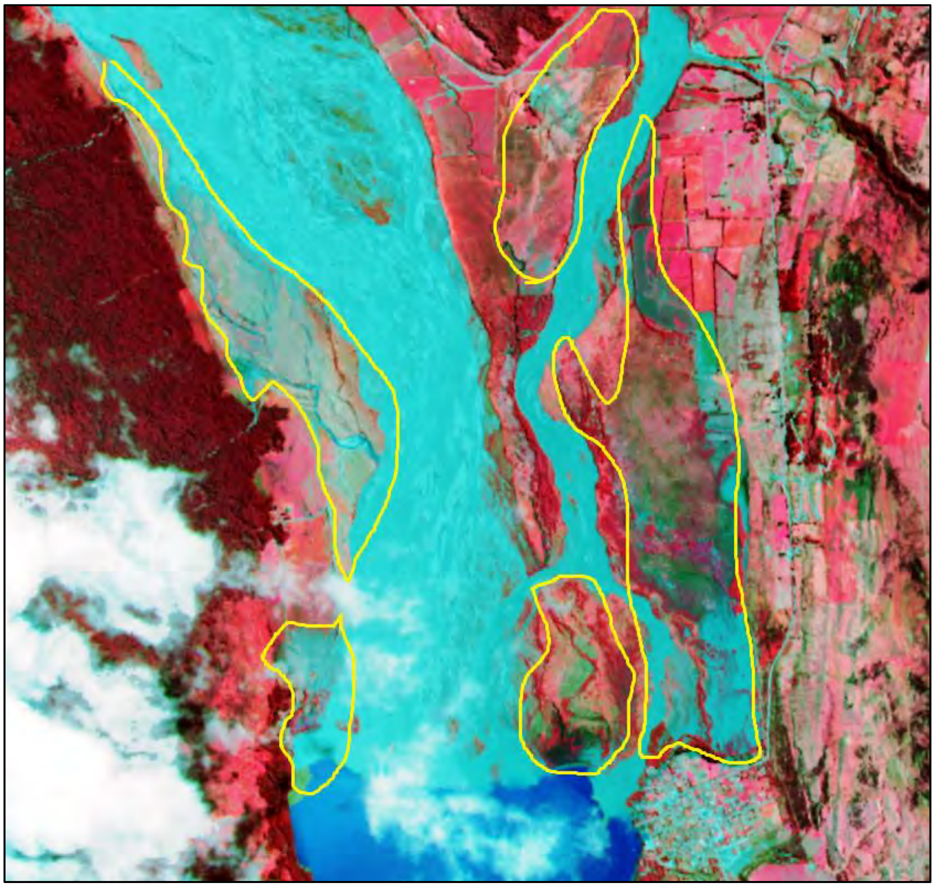


Figure 6-2 - Sentinel 2 Imagery taken on 4 Feb 2020 (UTC)

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.

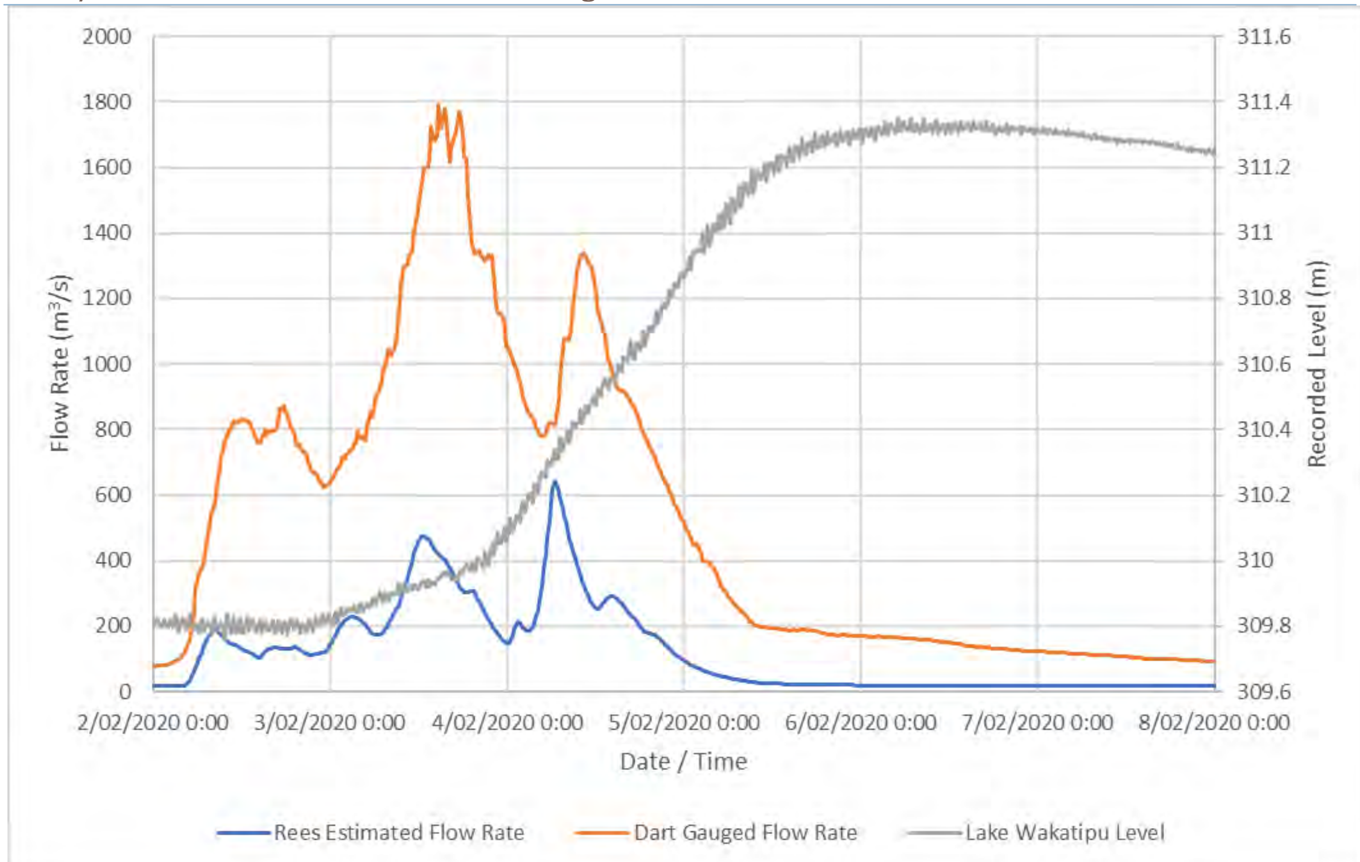


Figure 6-3 – Modelled hydrographs and lake levels for the 3/4 February 2020 validation event

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

LANDRIVERSEA CONSULTING

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.

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

LANDRIVERSEA CONSULTING

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.

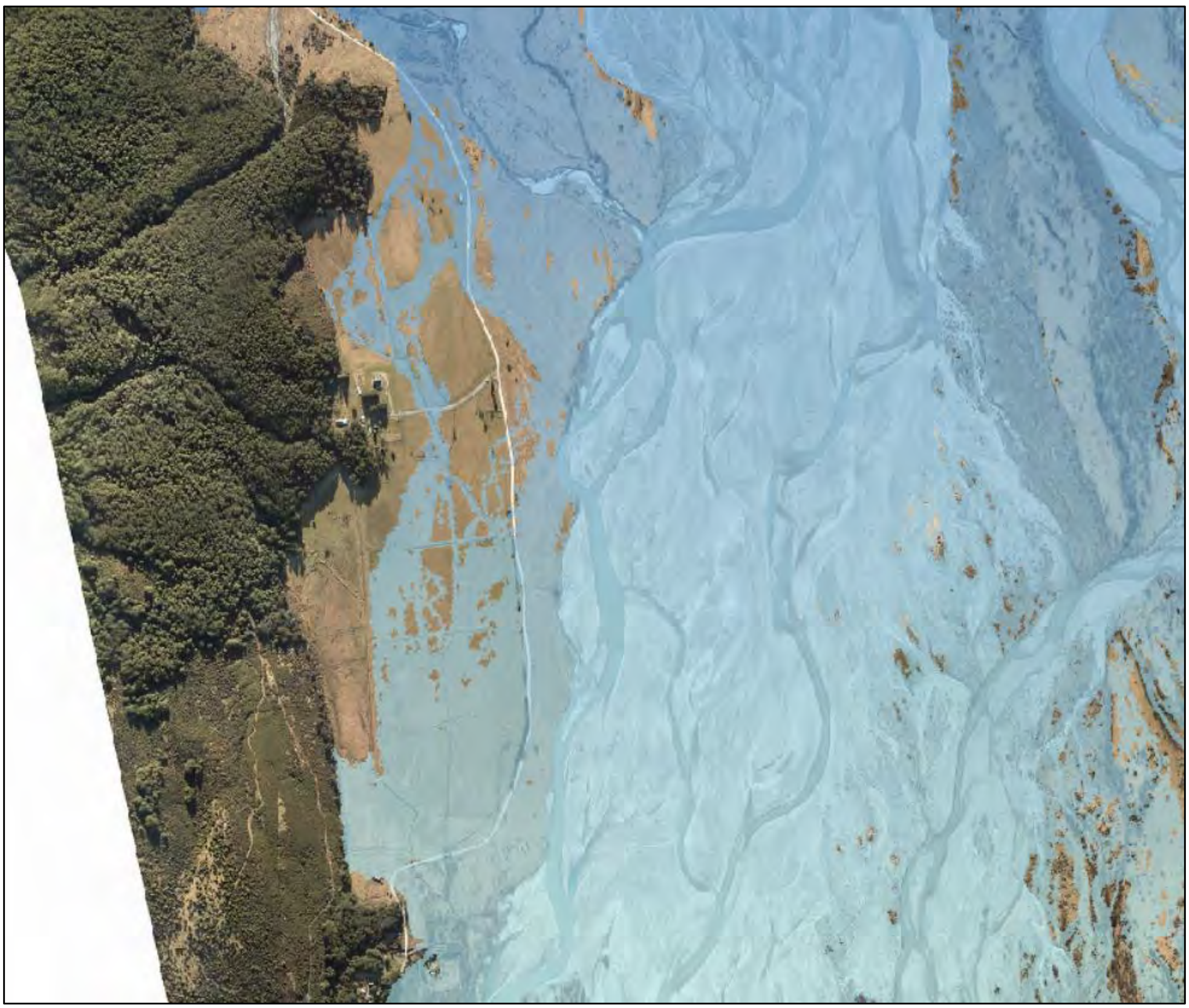


Figure 6-7 – Model flood extent at Kinloch Road

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.

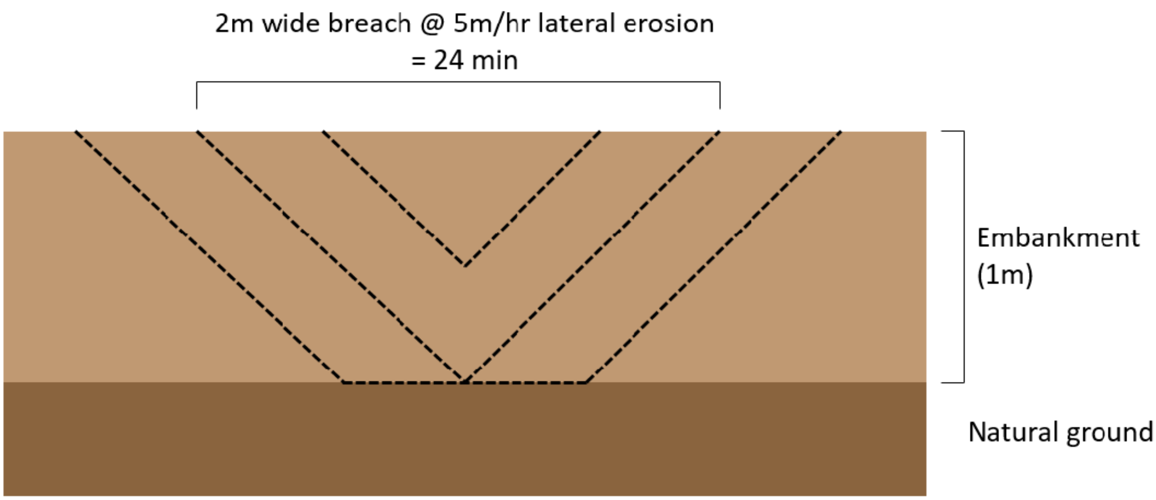


Figure 7-3 – Failure mechanism for overtopping failure (T&T, 2021)

[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.

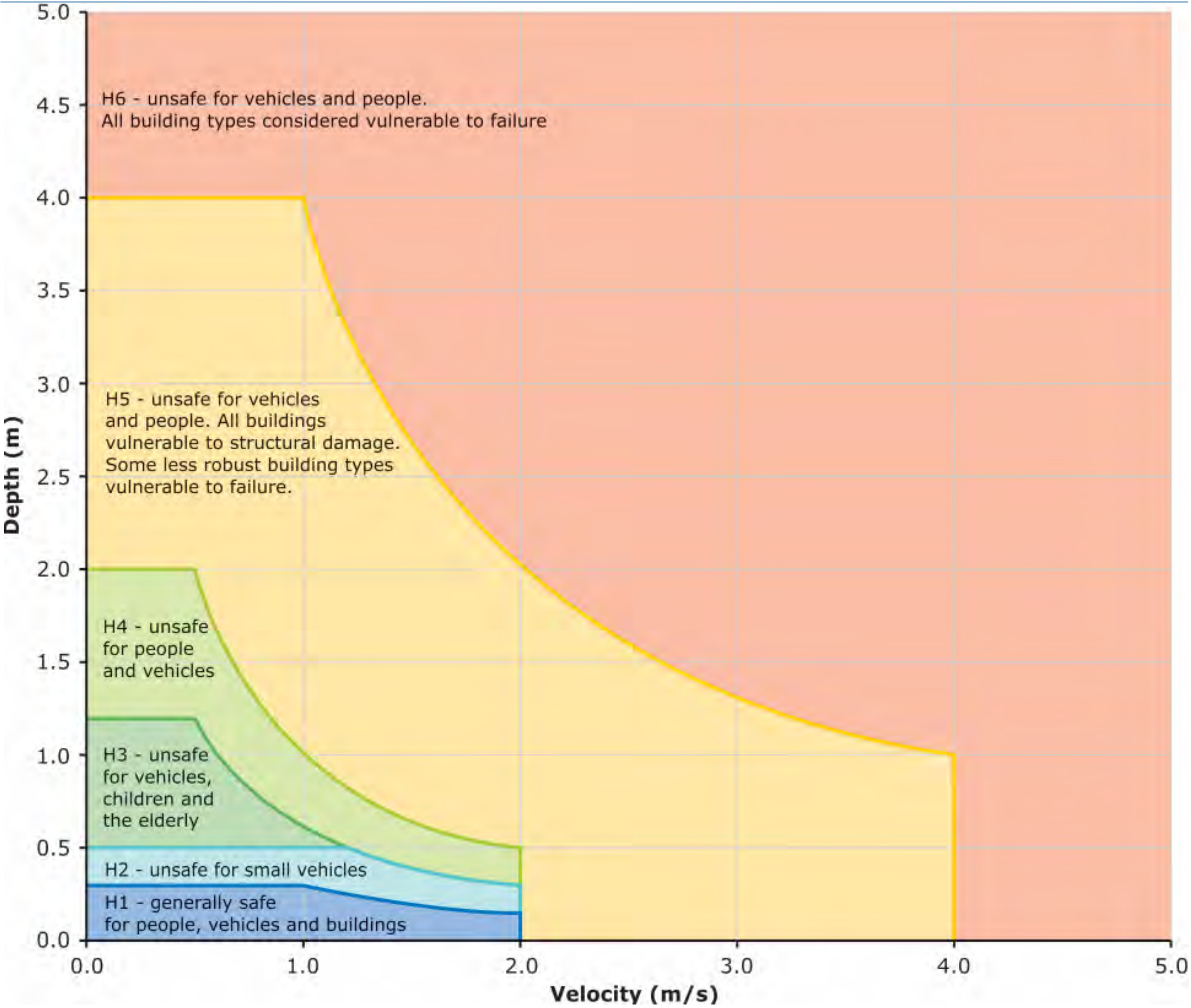


Figure 7-4 - Graphical representation of the Hazard Categories

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.

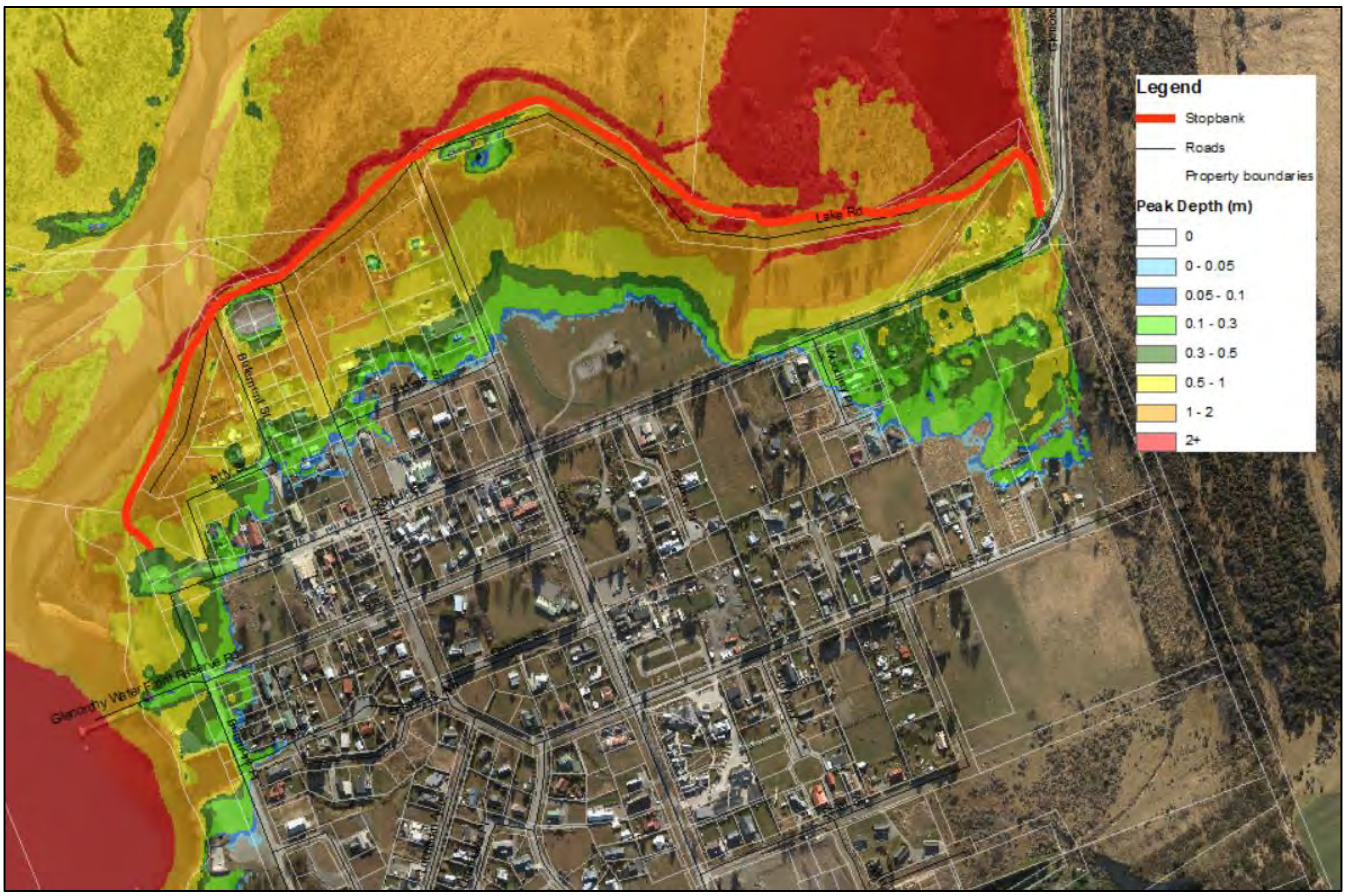


Figure 8-1 - Peak flood depth / extent for a 100-year ARI flood event combined with 10-year ARI Lake Level

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.

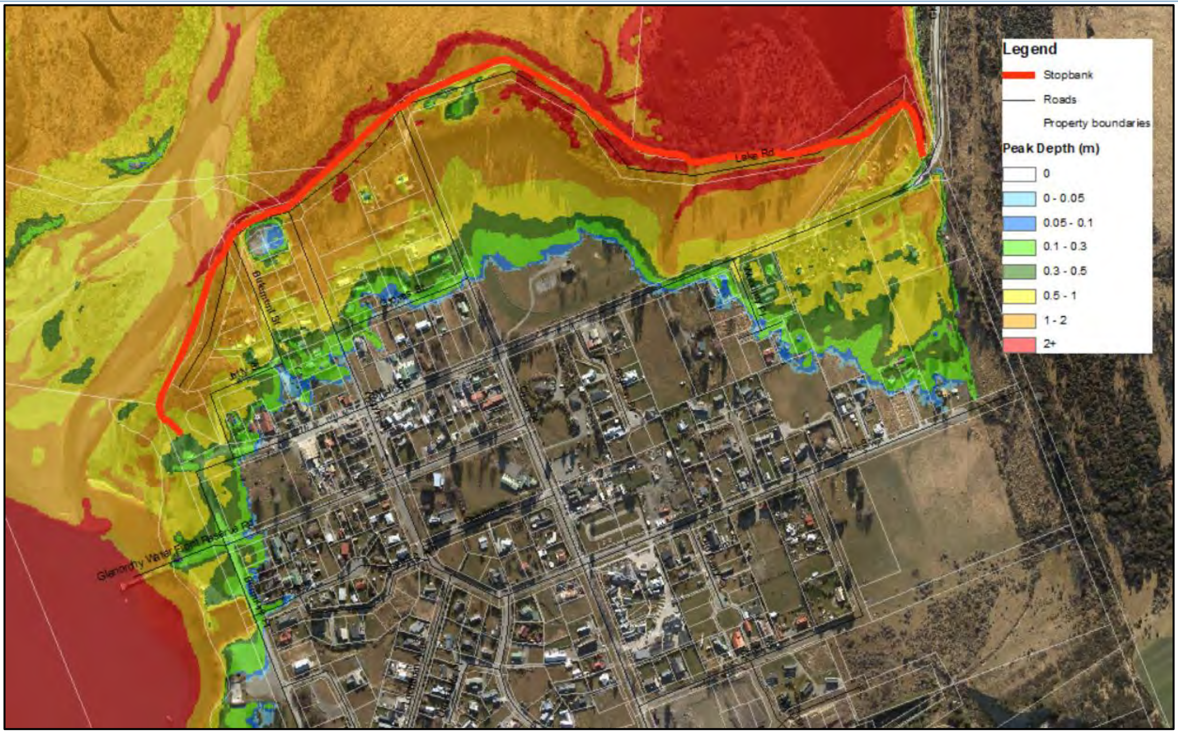


Figure 8-2 - Peak flood depth / extent for a 100-year ARI future climate (RCP8.5) flood event combined with 10-year ARI Lake Level combined with an avulsion in the Rees River

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.

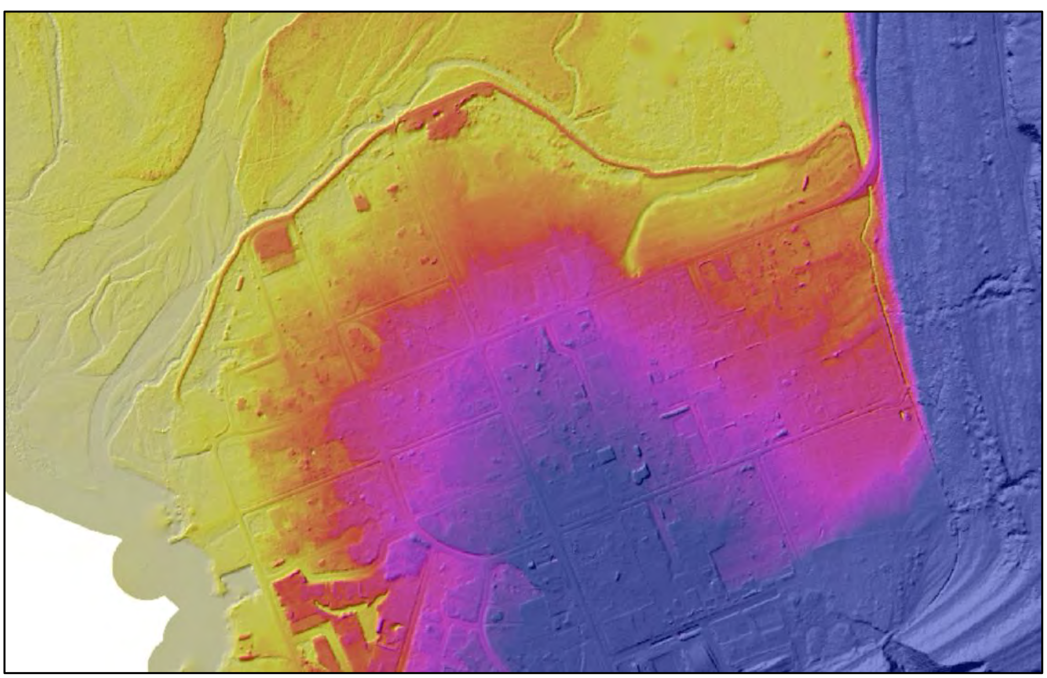


Figure 8-3 – Coloured hillshade representation of the topography in Glenorchy (Blue indicates high land, yellow indicates lower land)

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.

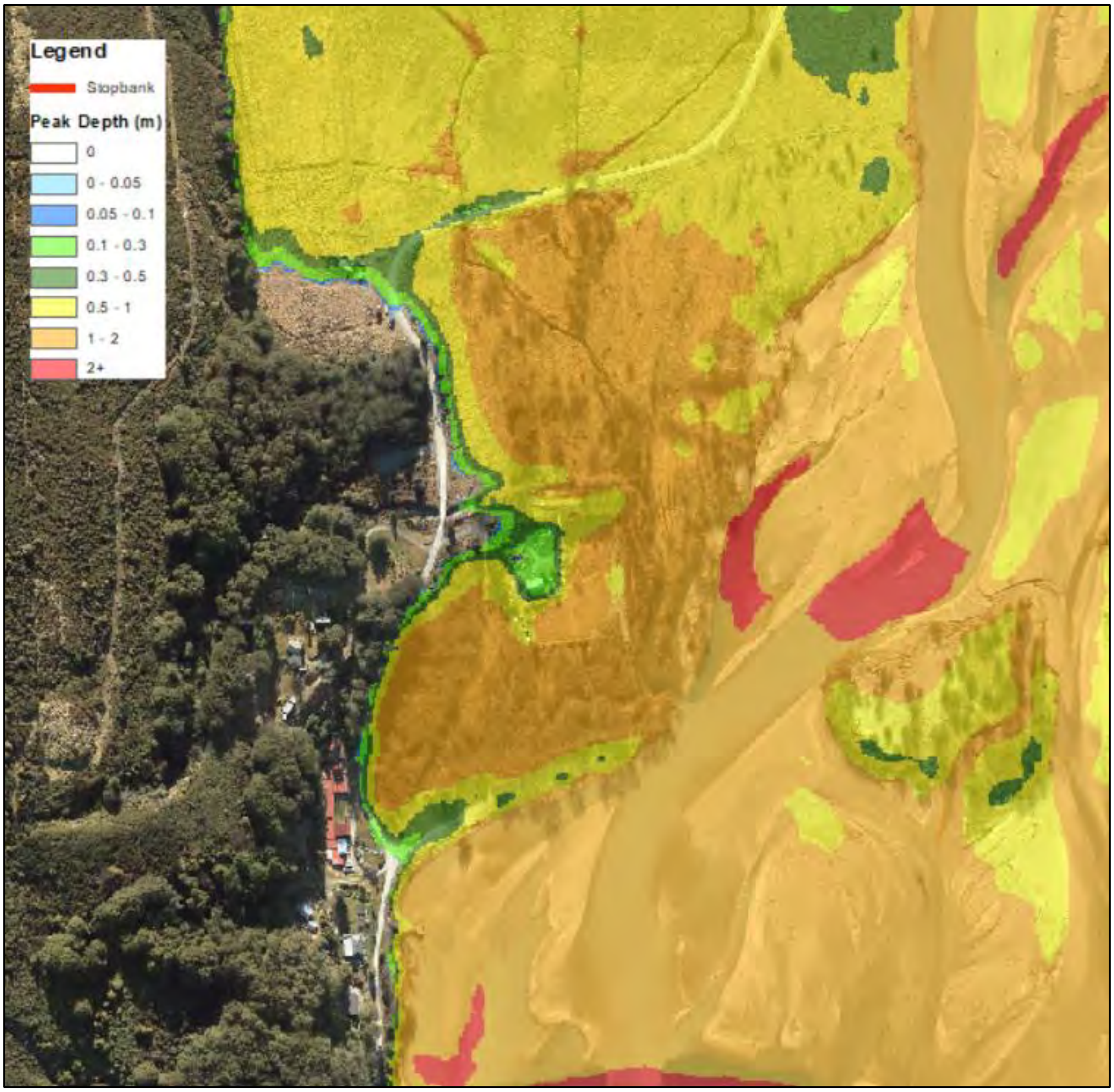


Figure 8-4 – Peak flood depth / extent for a 100-year ARI flood event combined with 10-year ARI Lake Level

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.

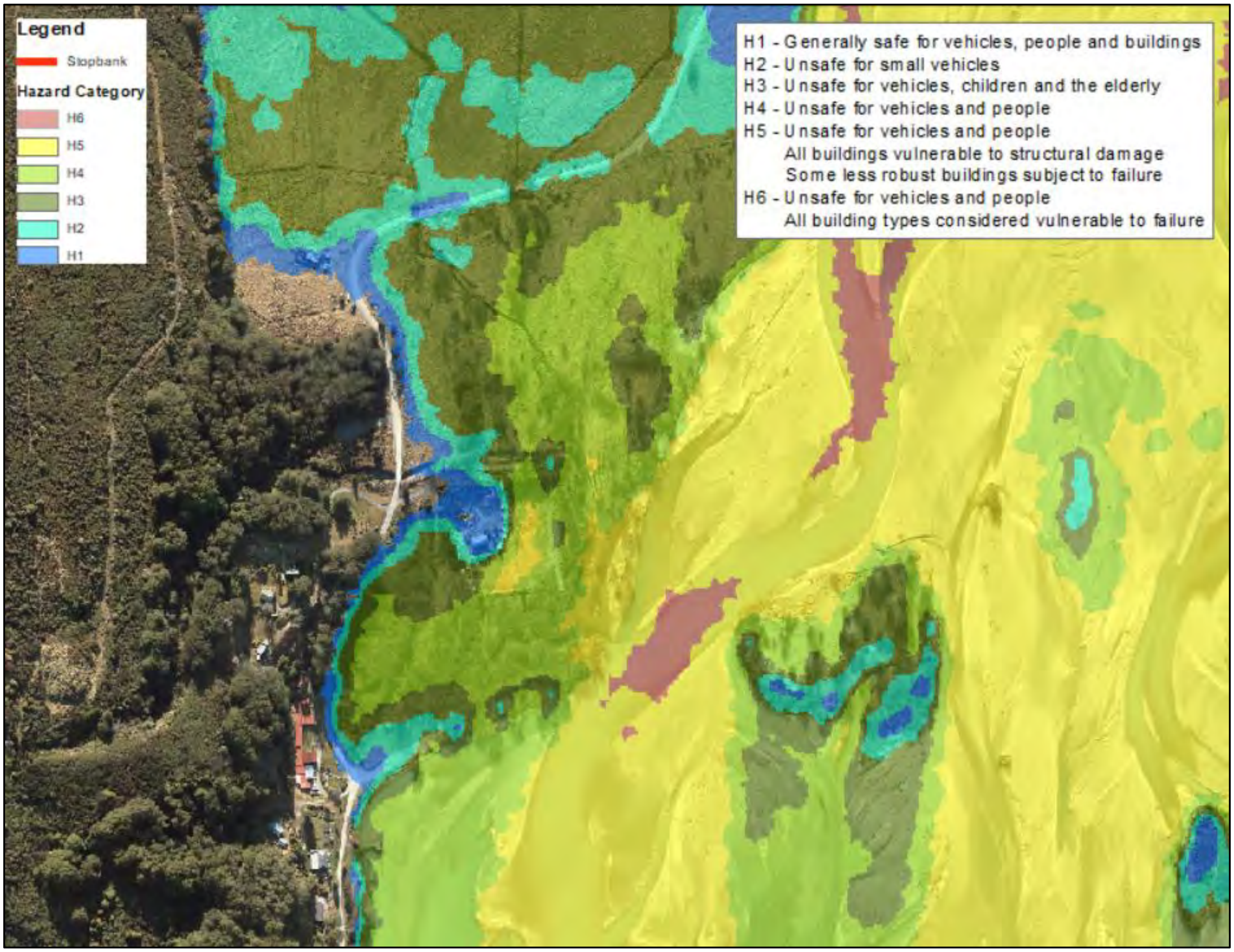


Figure 8-5 – Hazard map for a 100-year ARI flood event combined with 10-year ARI Lake Level in Kinloch

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.

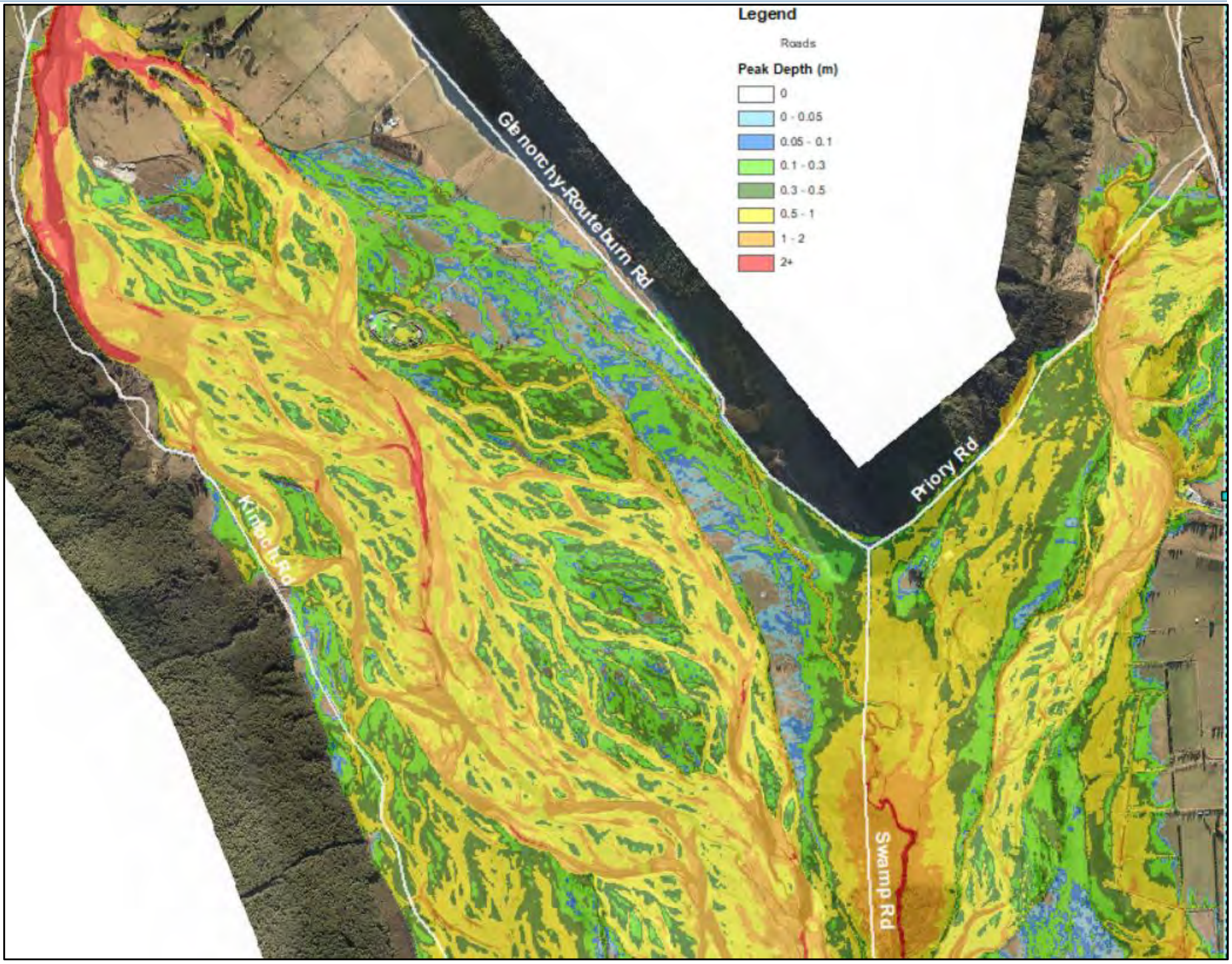


Figure 8-6 - Peak flood depth / extent for a 100-year ARI flood event highlighting road inundation

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.

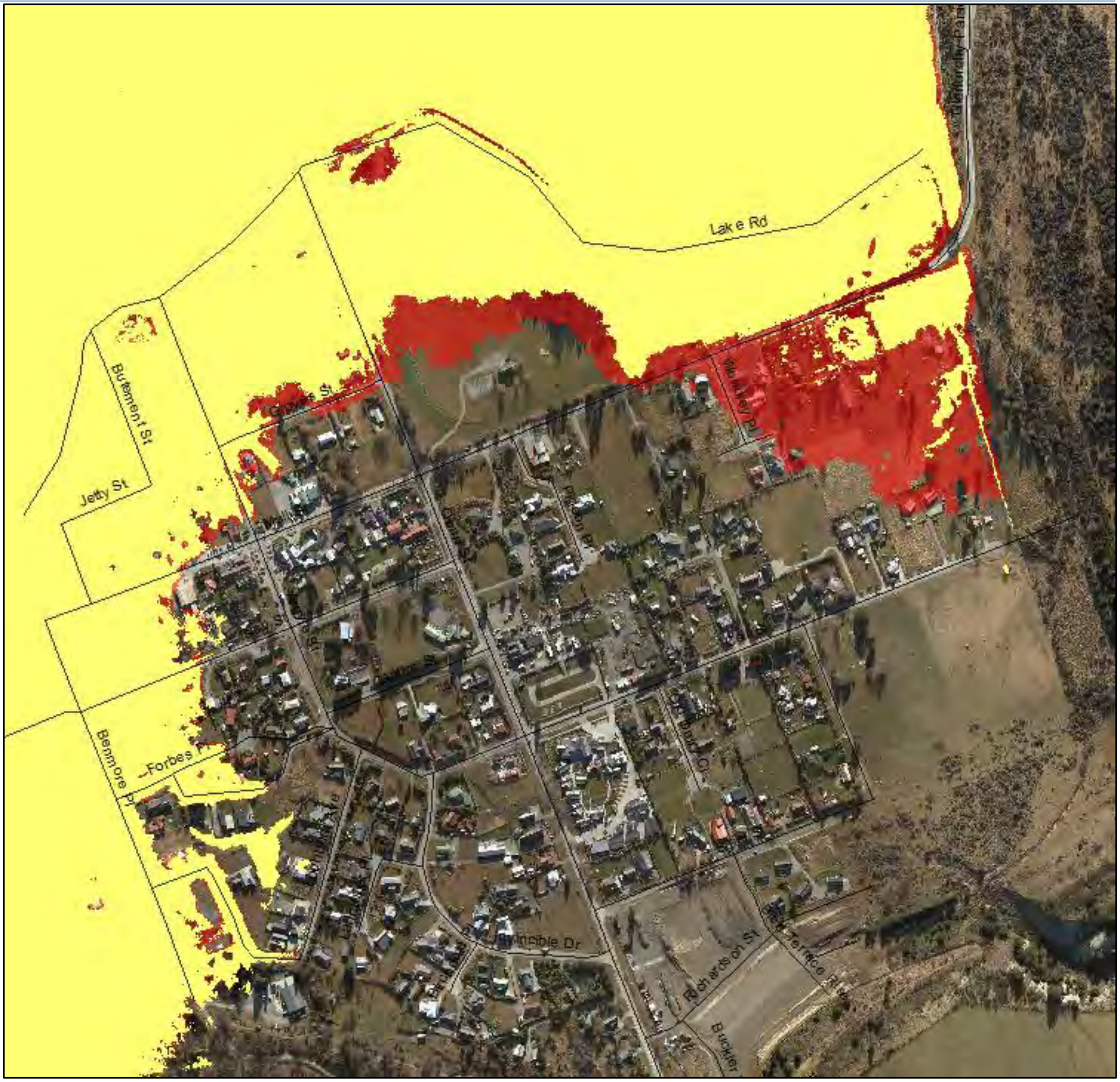


Figure 8-7 – Comparison of 100-year ARI lake level (yellow) with 100-year ARI river flood combined with a 100-year ARI lake level (red)

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

Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I. 2019. Australian Rainfall and Runoff - A Guide to Flood Estimation. [place unknown].

Crux Community Newsletter. https://crux.org.nz/community/glenorchy-homes-evacuated-qtown-lake-level-critical.

Mohssen M. 2021. Analysis of Flood Hazards for Glenorchy. Dunedin.

Whyte G, Ohlbock K. 2007. Glenorchy Floodplain Flood Hazard Study. Christchurch.

Williams R. 2014. Two-dimensional Numerical Modelling of Natural Braided River Morphodynamics. Otago.

van Woerden T. 2020. Review of the Feb 2020 Glenorchy flooding event. Otago.

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

Land River Sea Consulting Limited
PO Box 27121, Shirley, Christchurch 8640
Mob: 027 318 9527
matthew@landriversea.com
www.landriversea.com

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.

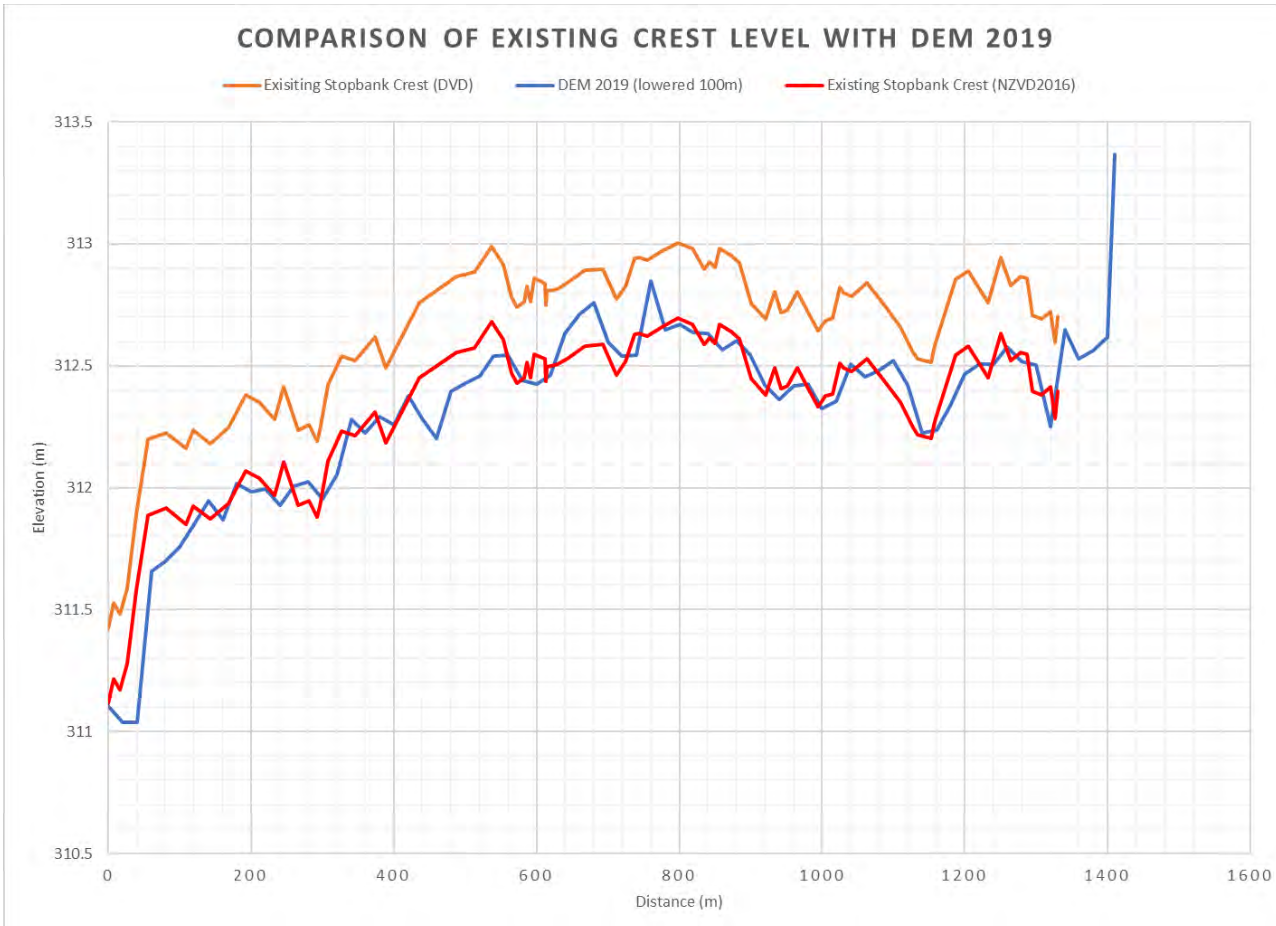


Figure 1 – Comparison surveyed crest level with 2019 LiDAR

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.

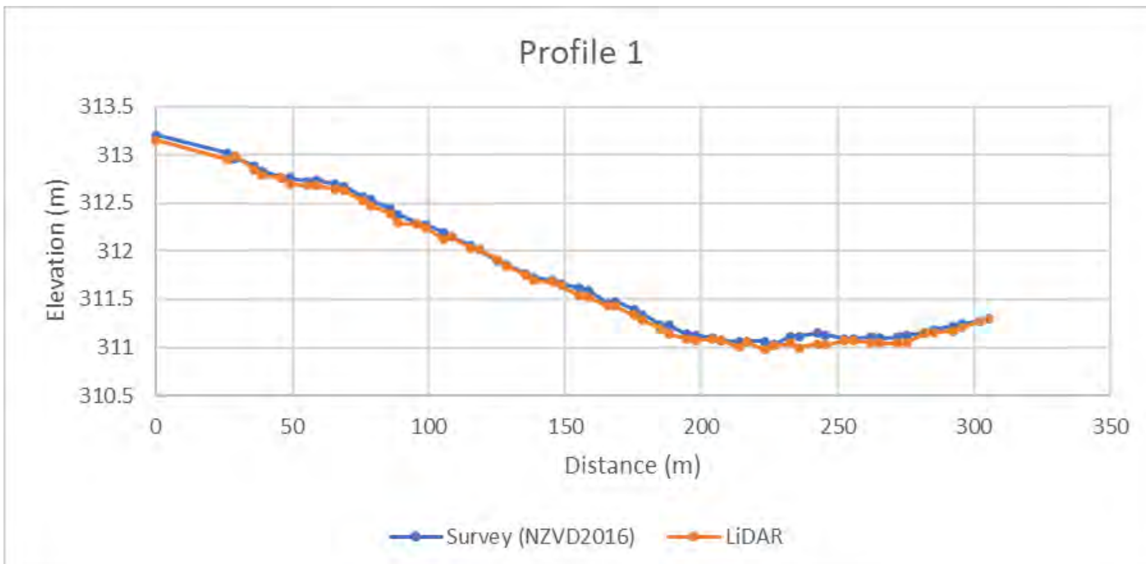
Professor James Brasington was set to be visiting Glenorchy on the 5th of October 2021, and I therefore requested that he collect some additional check data in reliable locations such as along road centrelines to allow us to confirm the datum shift.

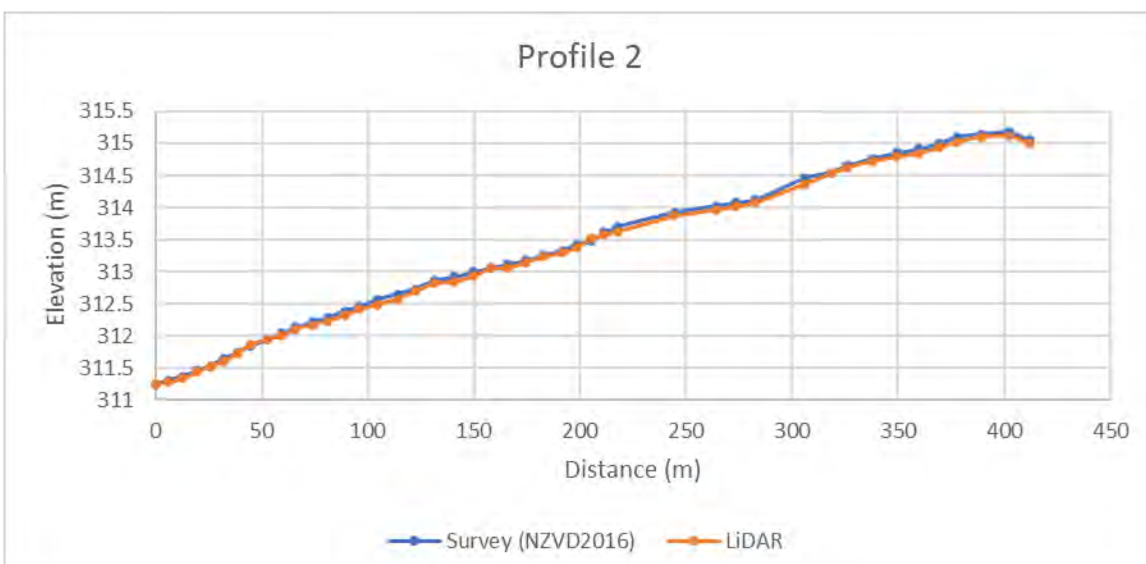
James collected a total of 354 points on hard road surfaces within Glenorchy township. Comparison of the survey data with the LiDAR data gives the following statistics:

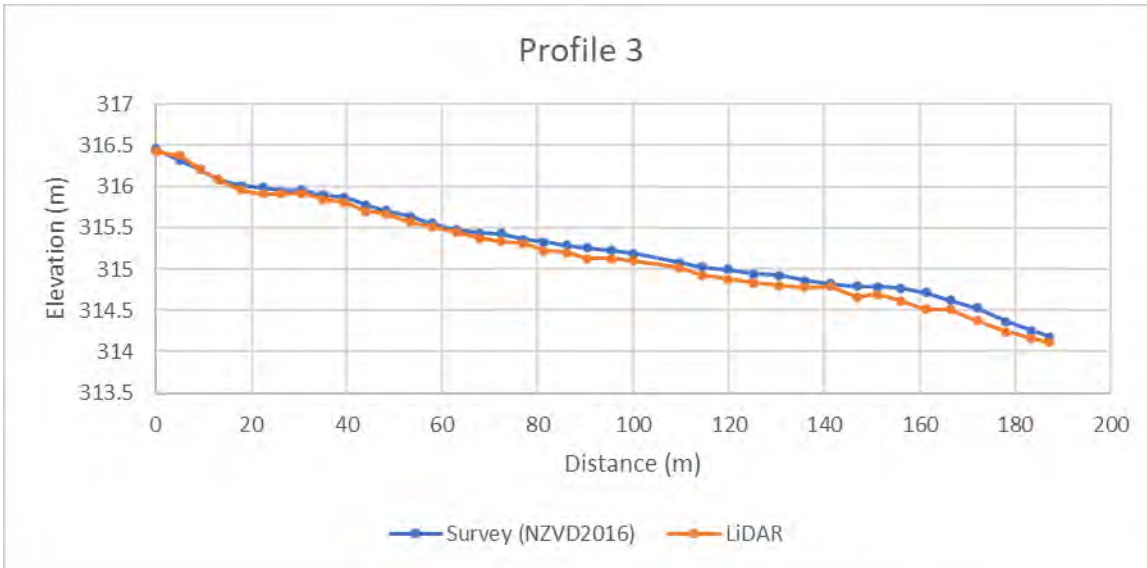
Average dz	-0.050
Minimum dz	-0.189
Maximum dz	+0.036
Average magnitude	0.052
Root mean square	0.064
Std deviation	0.039

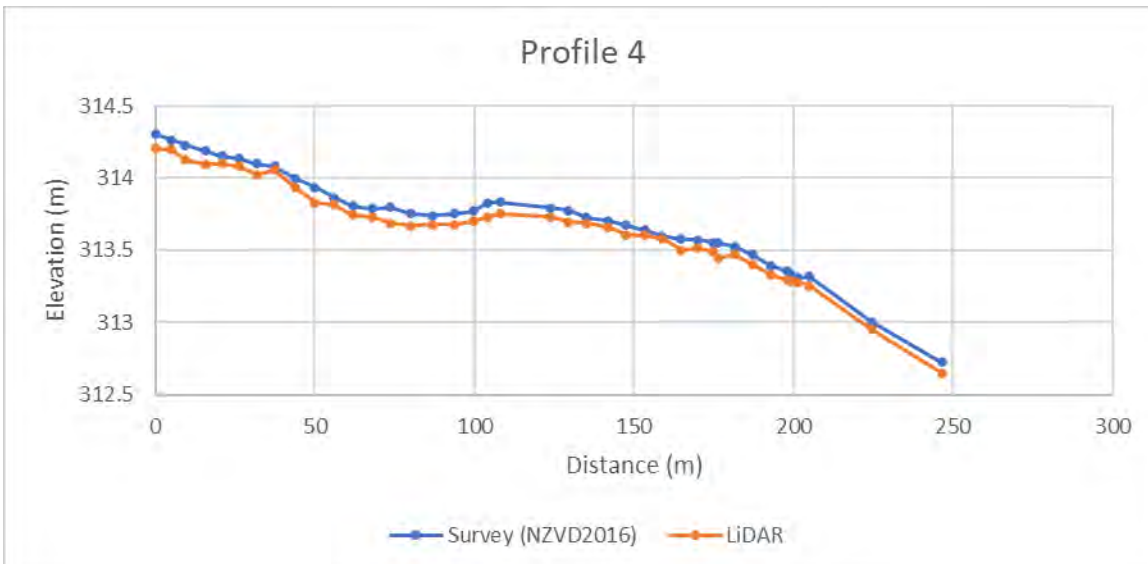
Five long section profiles have been plotted in order to visualise the difference between the LiDAR DEM and the survey data as per the location shown in Figure 2.

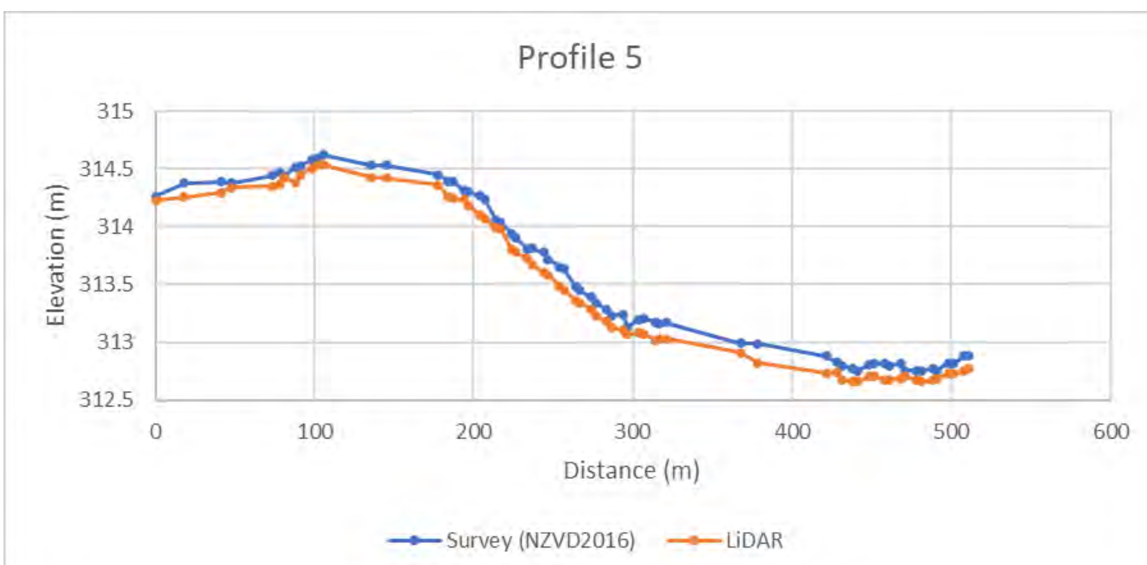
Figure 2 – Profile Locations






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,

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

Contents:

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.

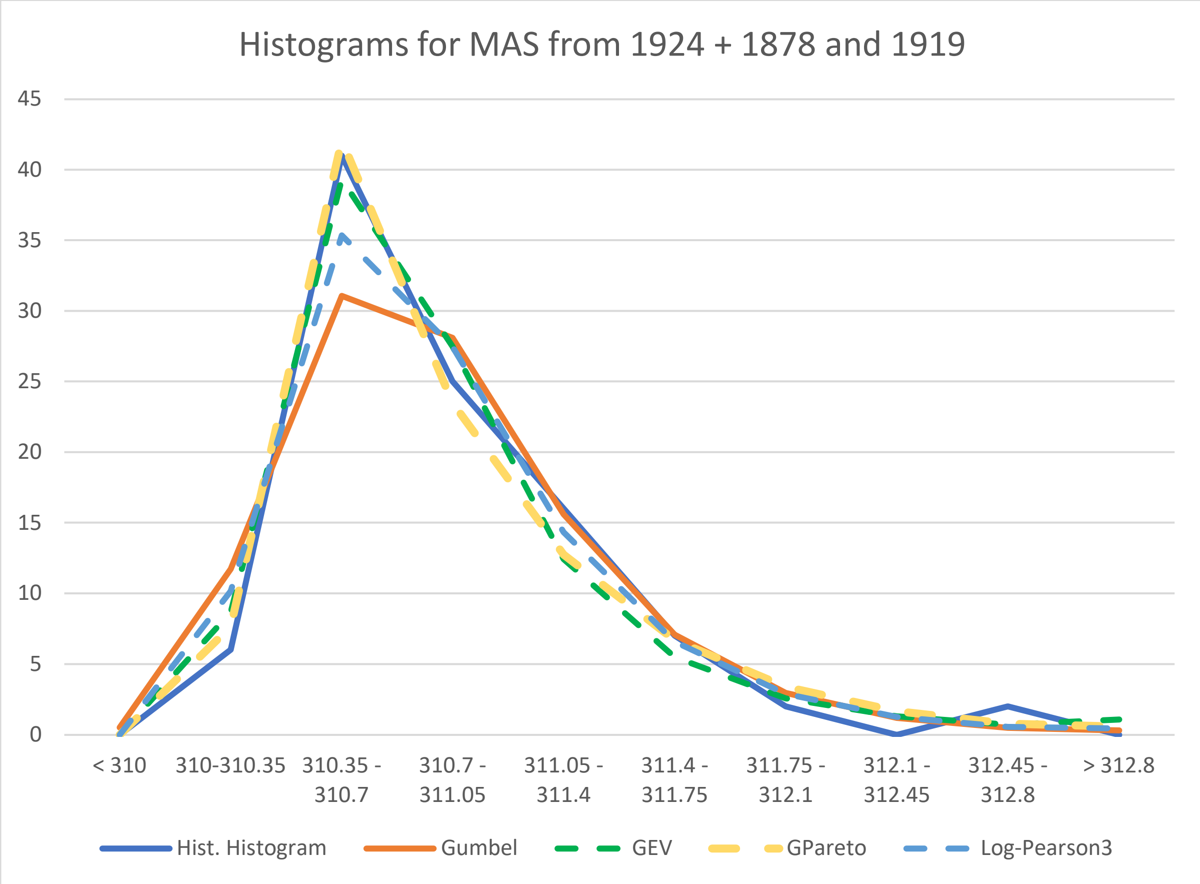


Figure 1 Histograms of Observed and MAS Modelled Peak L. Wakatipu Levels

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.

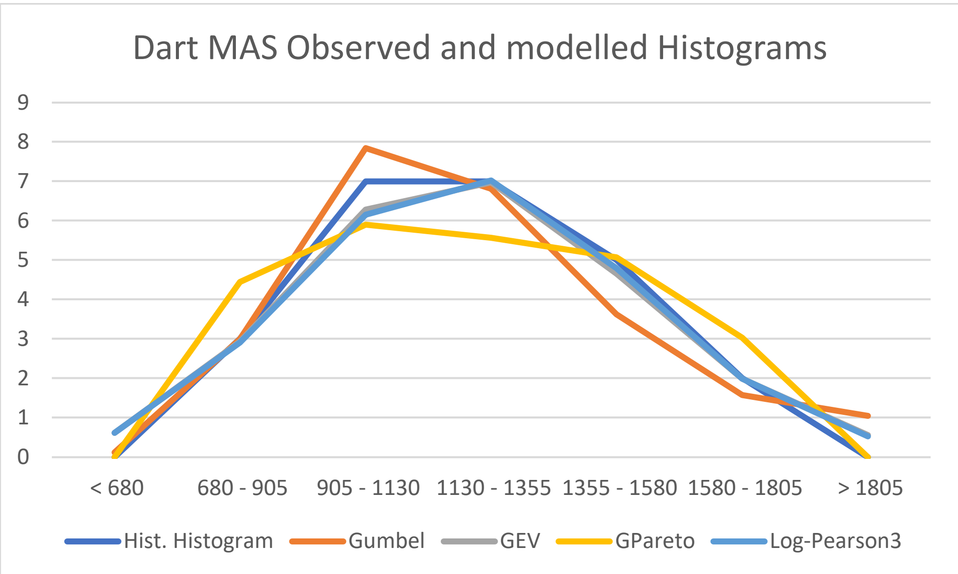


Figure 2 Dart MAS Observed and modelled Histograms

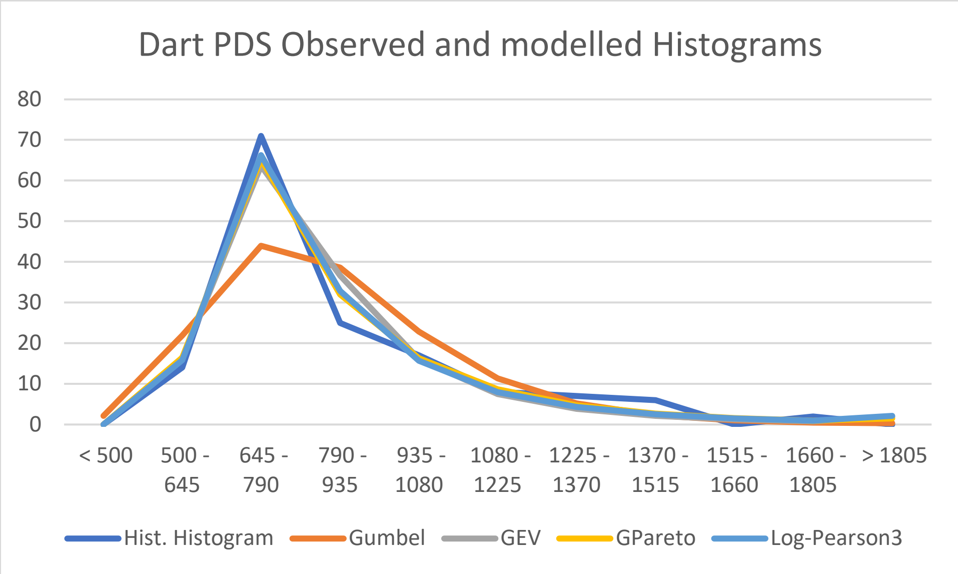


Figure 3 Dart PDS Observed and modelled Histograms

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.

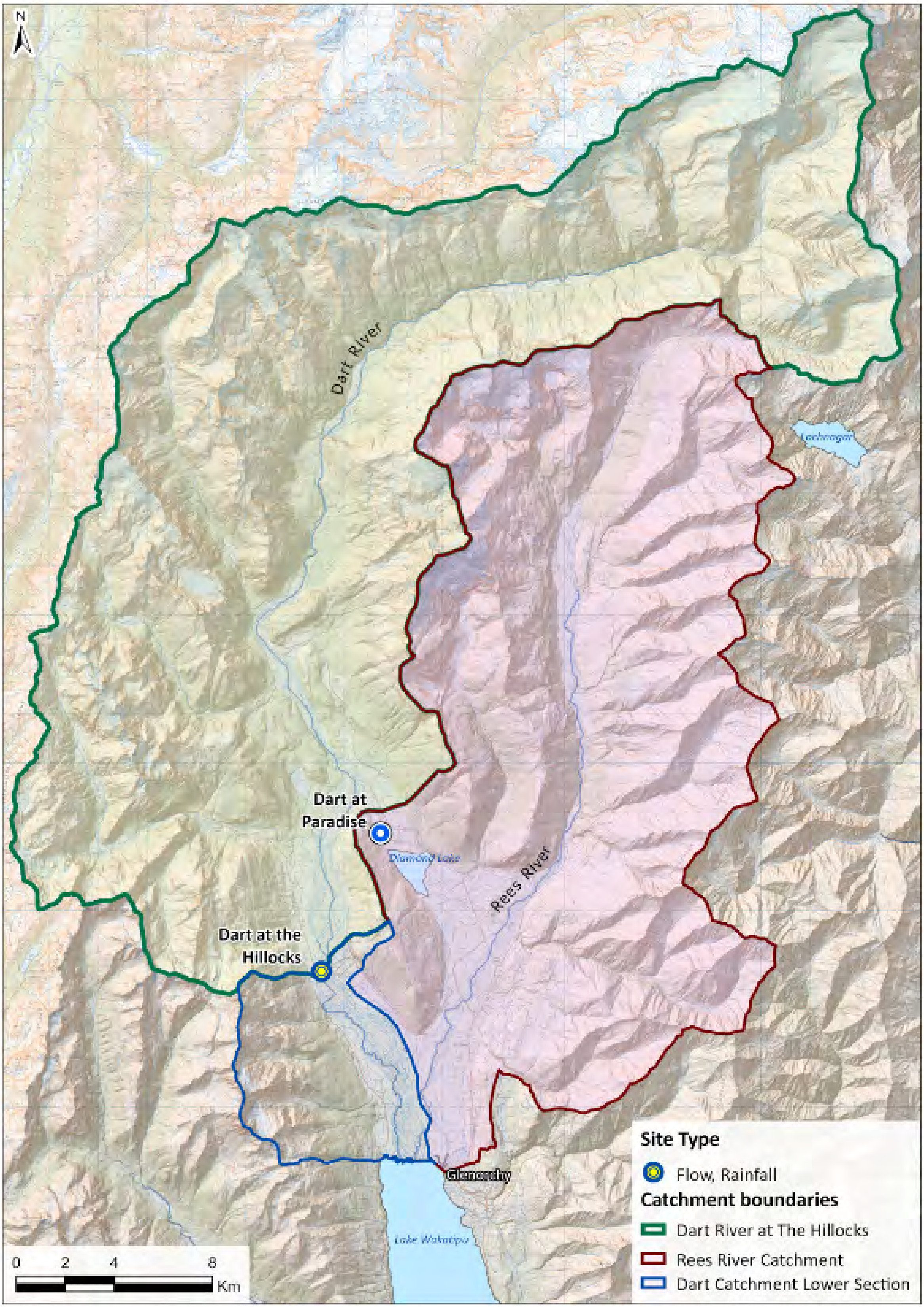


Figure 4 The Dart and Rees catchments

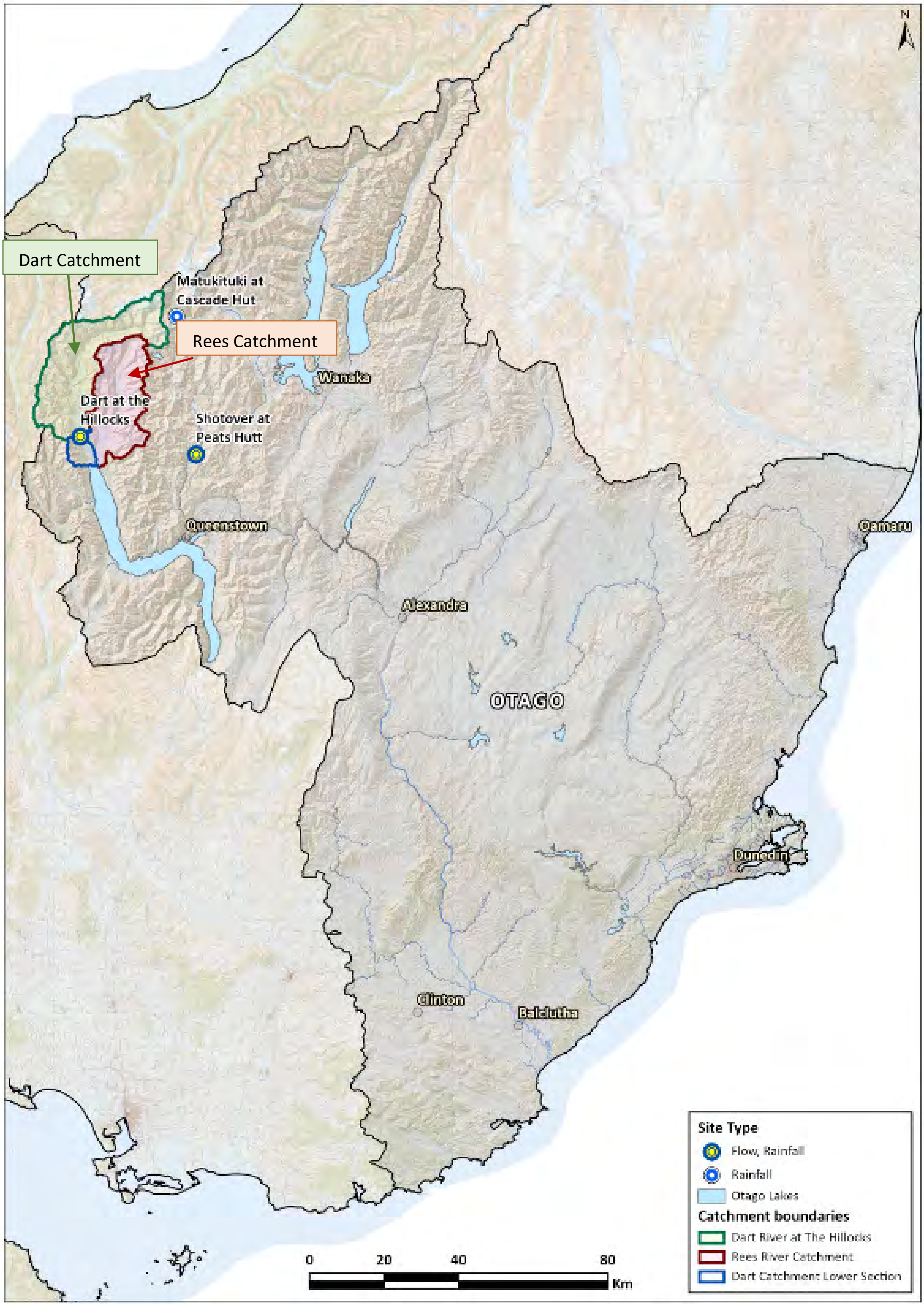


Figure 5 The Dart and Rees Catchments in Otago

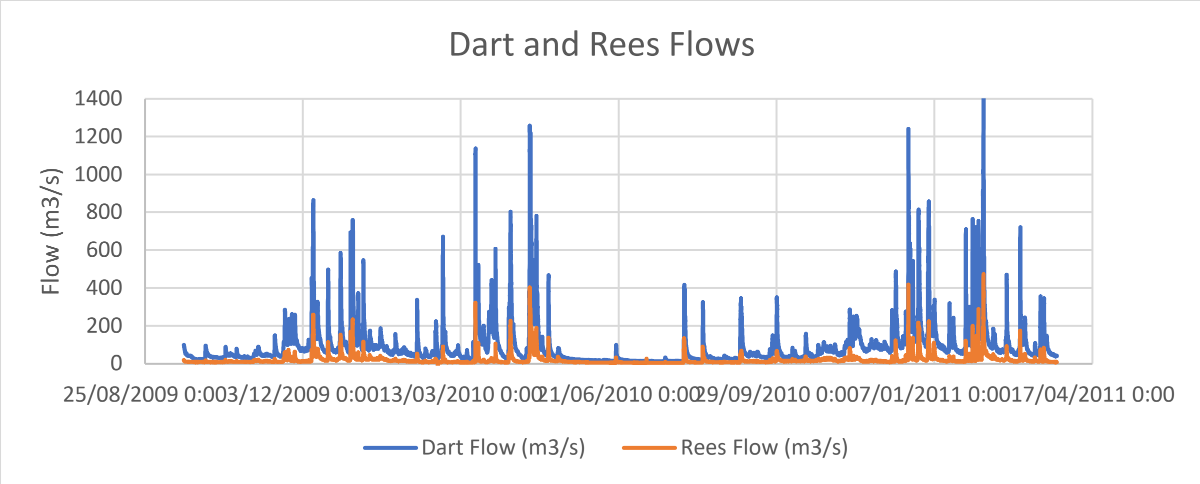


Figure 6 Dart and Rees flows during September 2009 to March 2011

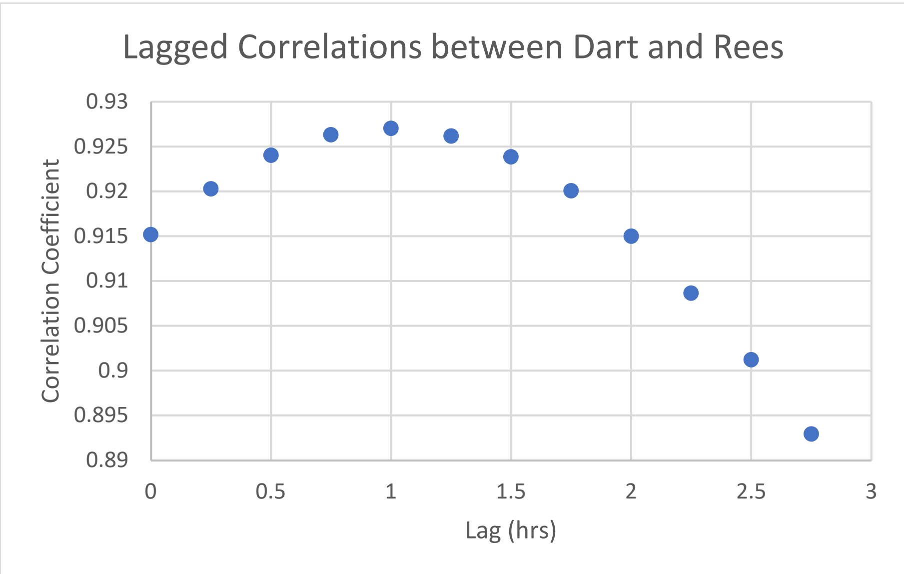


Figure 7 Lagged Correlations between the Dart and the Rees

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.

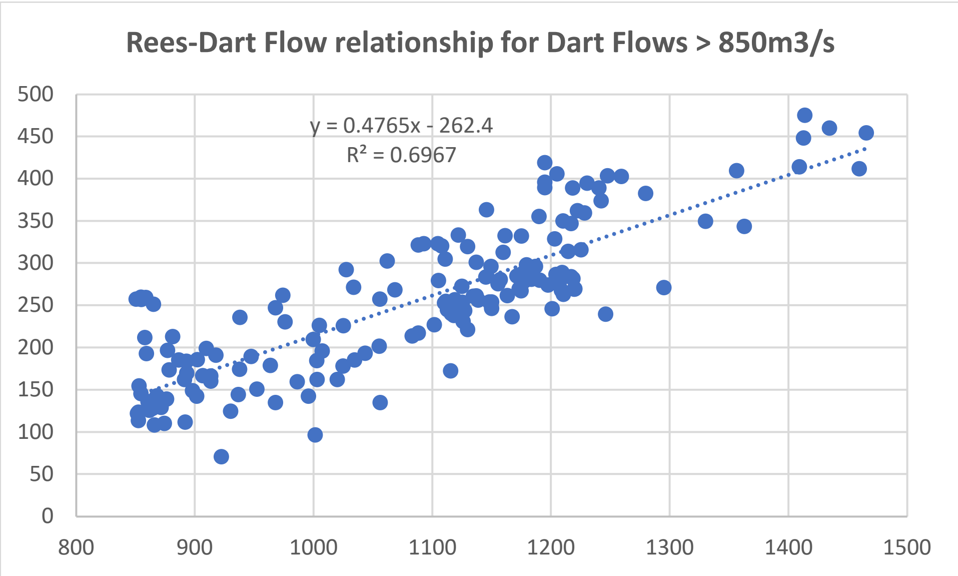


Figure 8 Rees-Dart Flow relationship for Dart Flows > 850m^3/s

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.

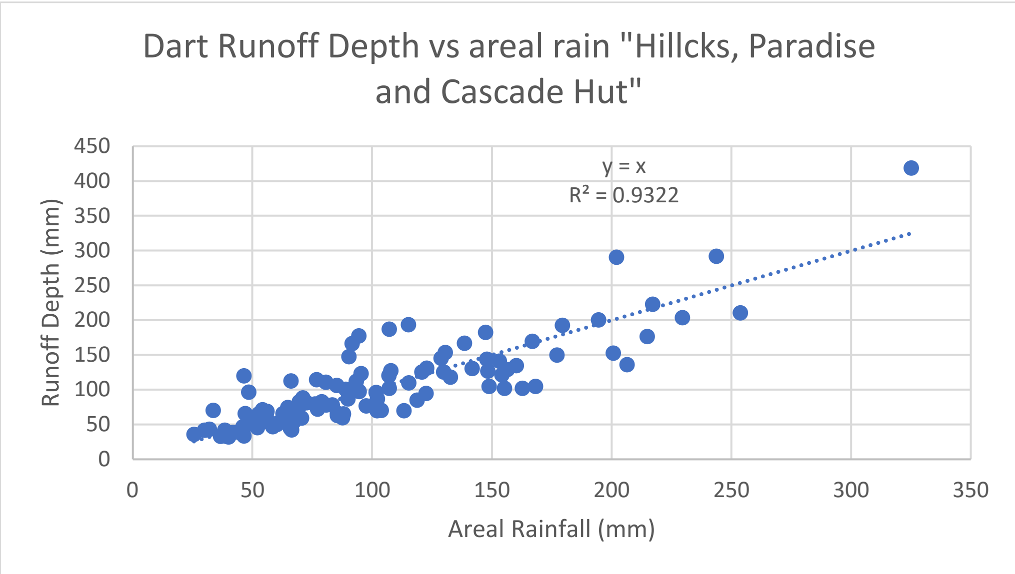


Figure 9 Dart Runoff Depth vs Areal rain from The Hillocks, Paradise and Cascade Hut

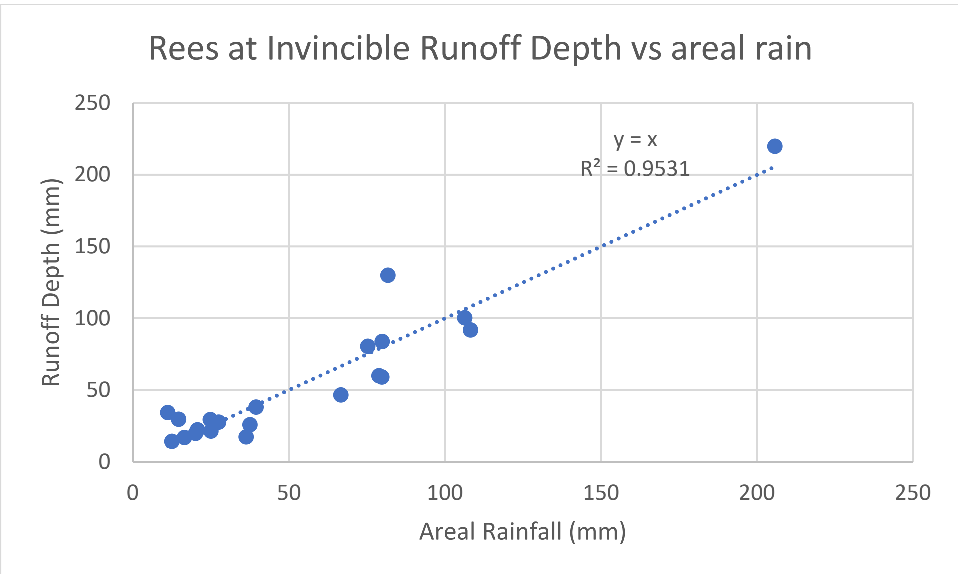


Figure 10 Rees at Invincible Runoff Depth vs Areal Rainfall

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.

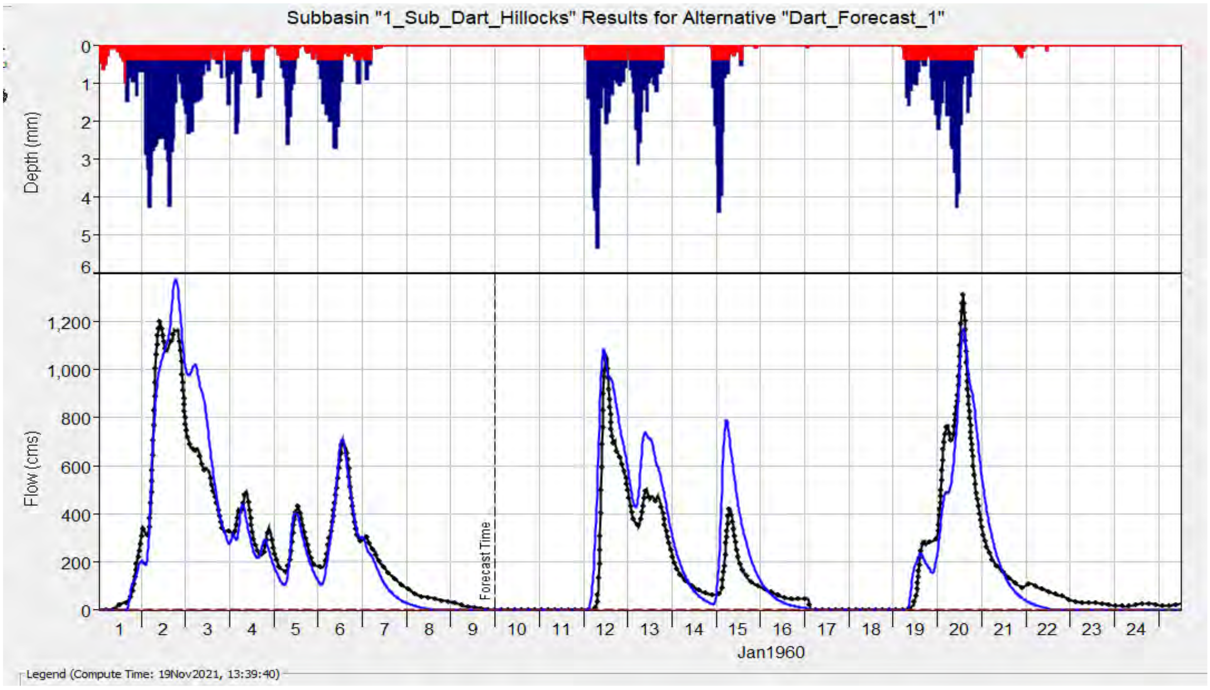


Figure 11 Dart at the Hillocks calibration to events 25 April 2010, 21 December 2010, 7 February 2011

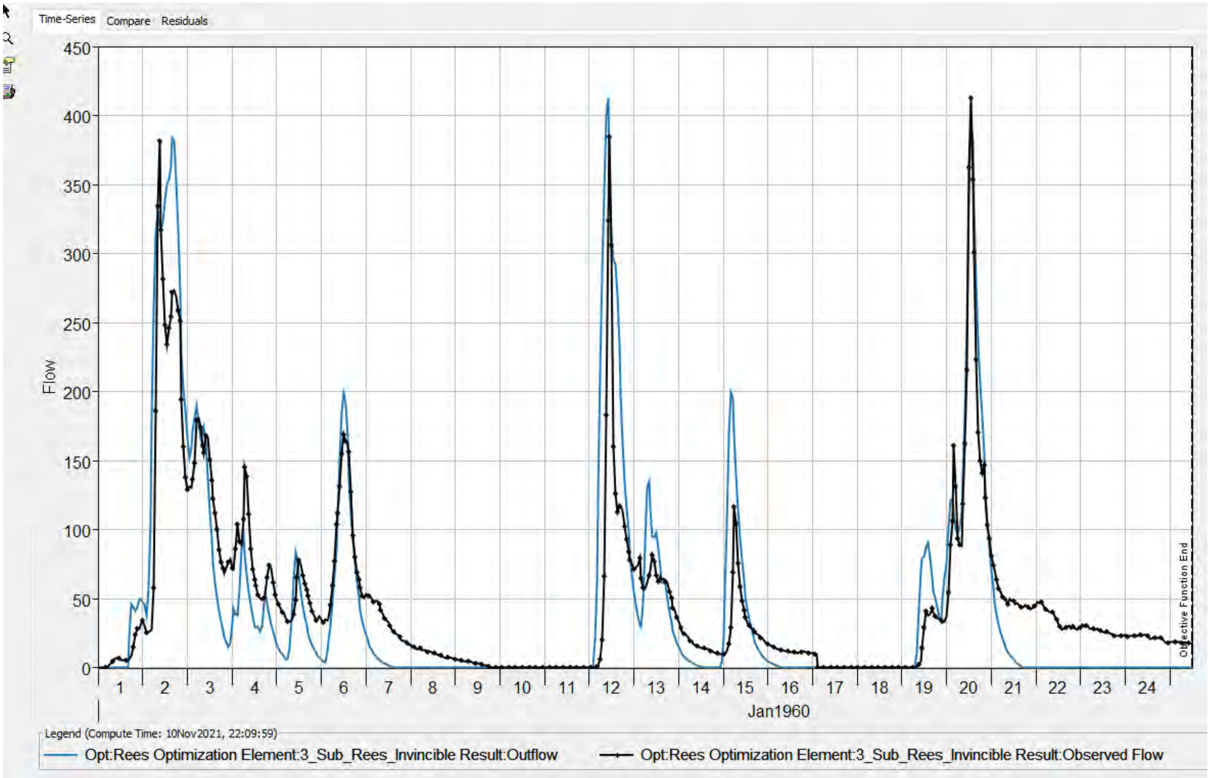


Figure 12 Rees at Invincible calibration to events 25 April 2010, 21 December 2010, 7 February 2011

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.

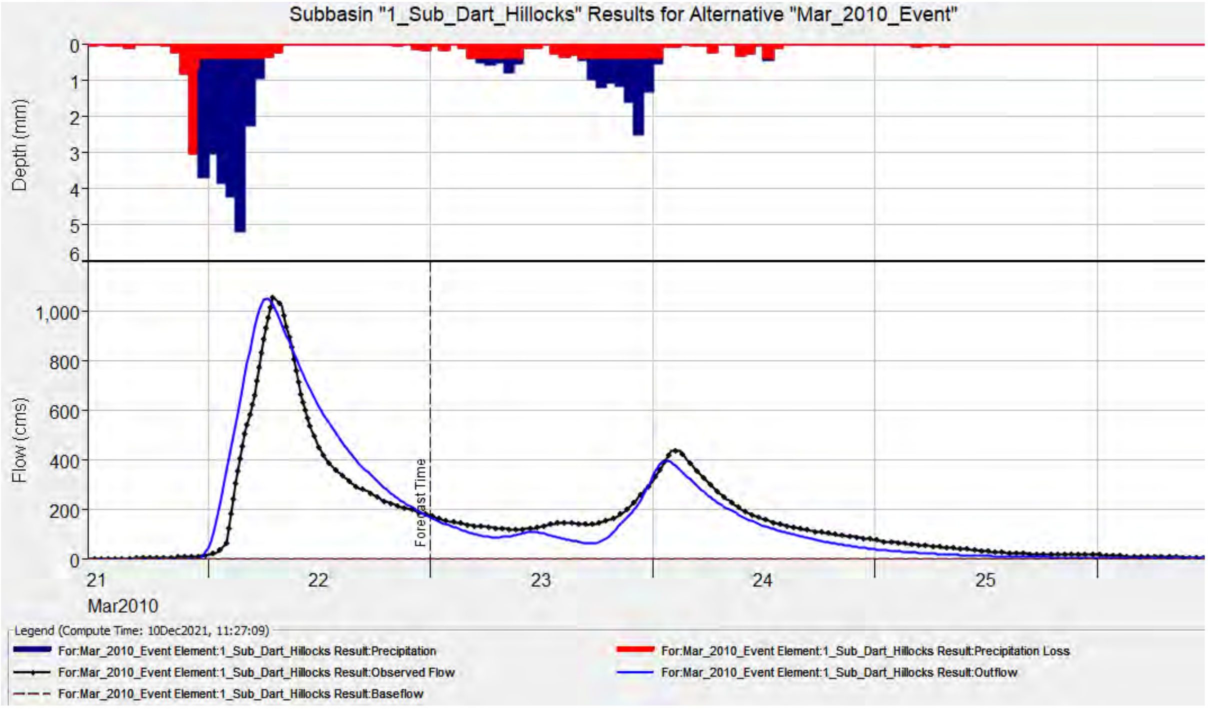


Figure 13 Simulation of the Dart flows for event March 2010

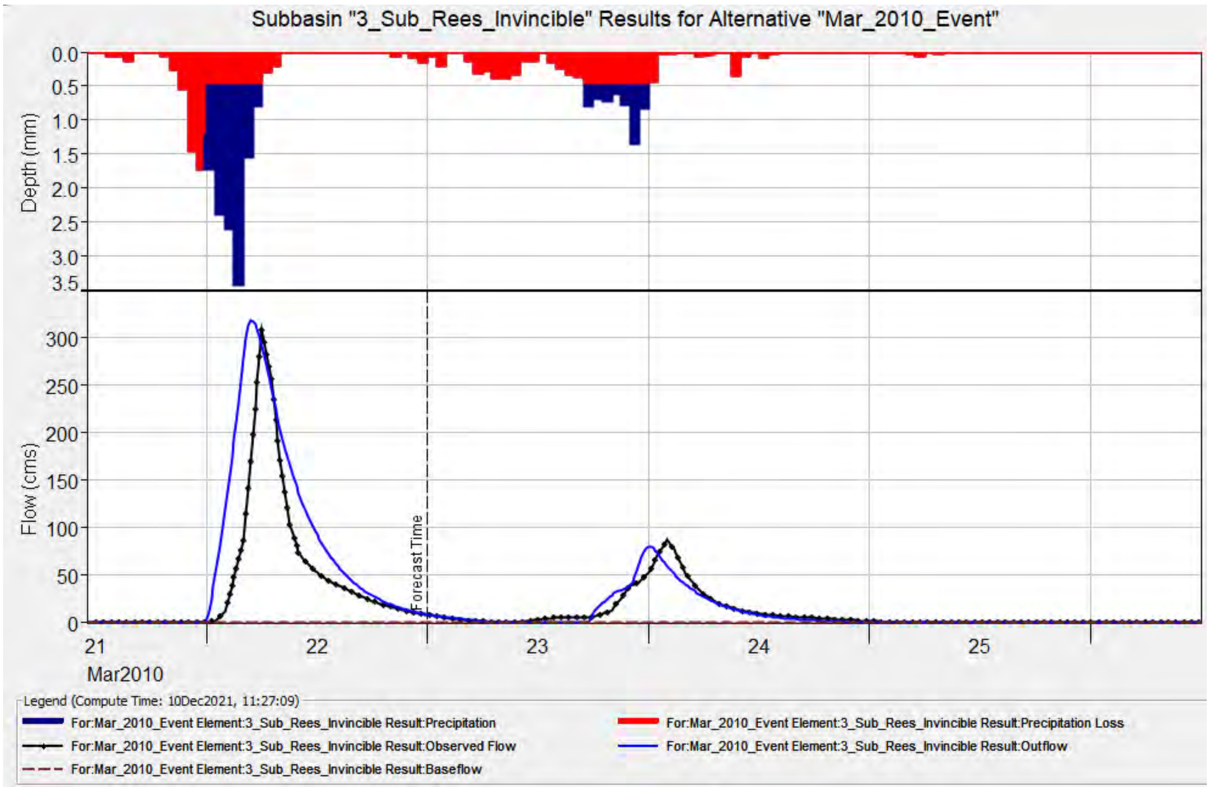


Figure 14 Simulation of the Rees Flows for event March 2010

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.

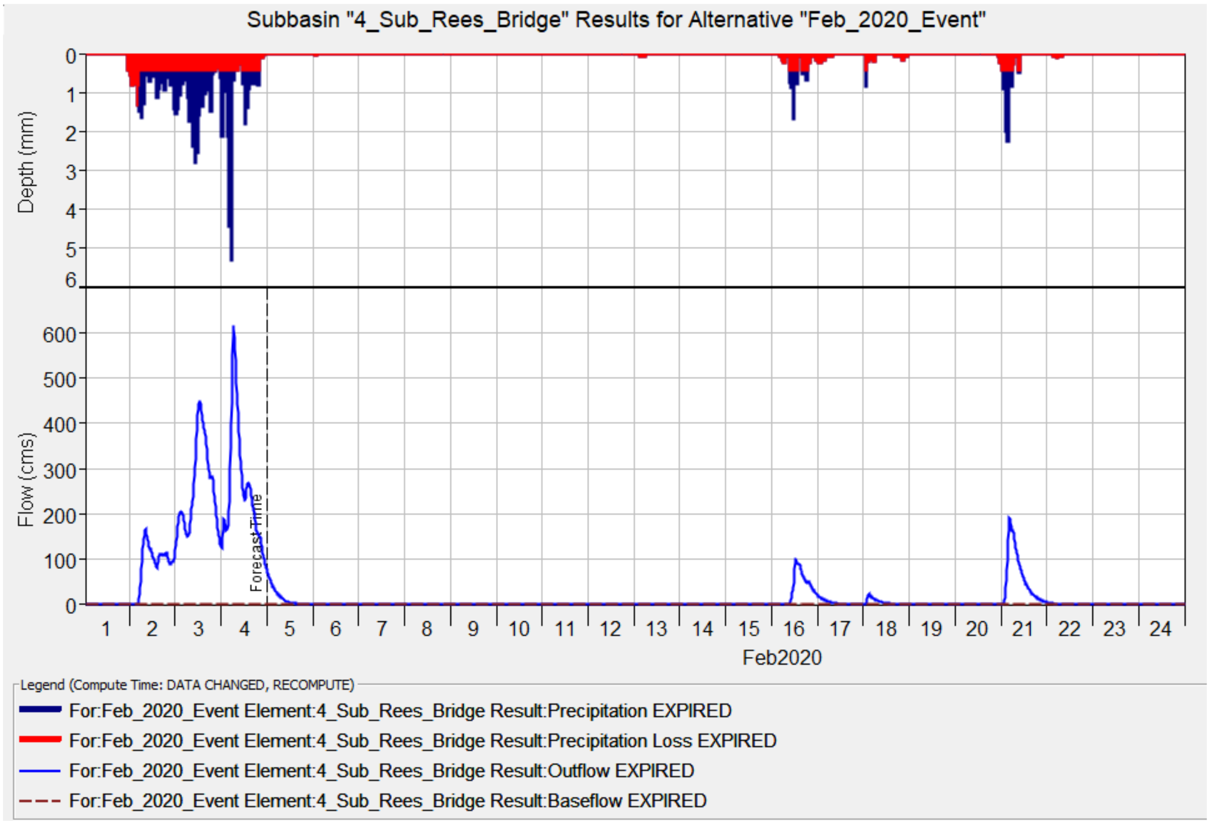


Figure 15 Rees at Bridge flow hydrograph for the Event February 2020

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.

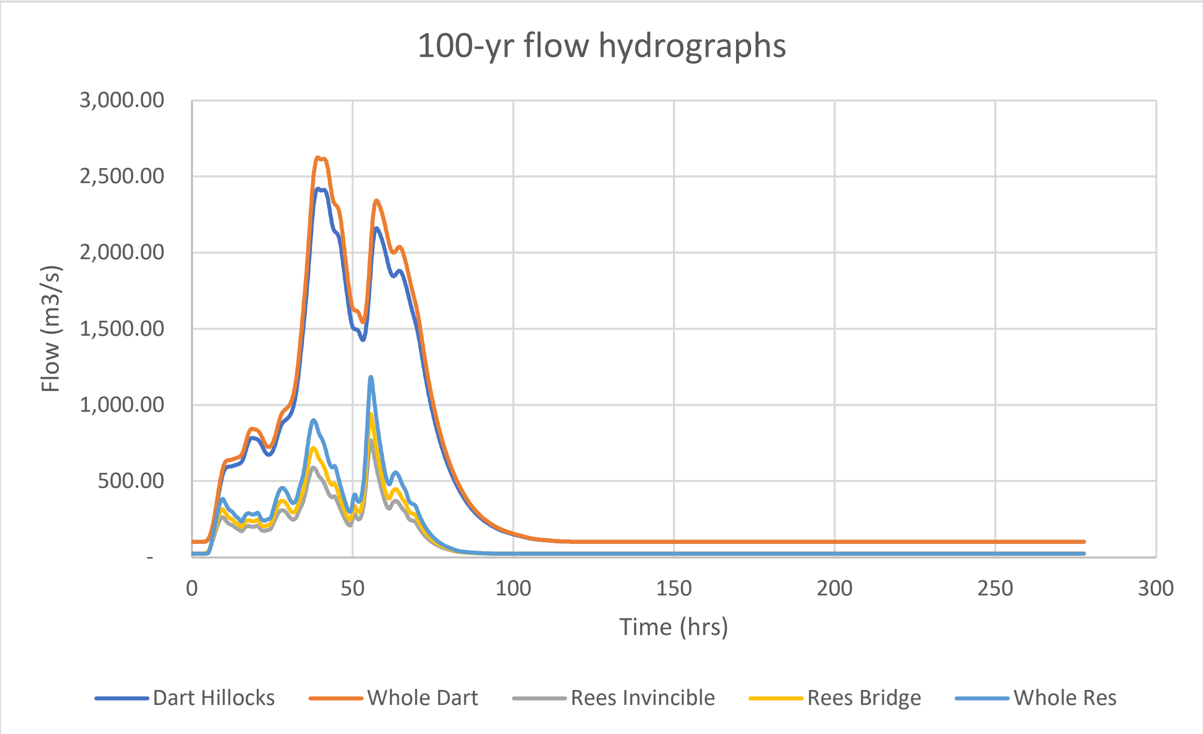


Figure 16 Design Flow Hydrographs for the Dart and the Rees

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.

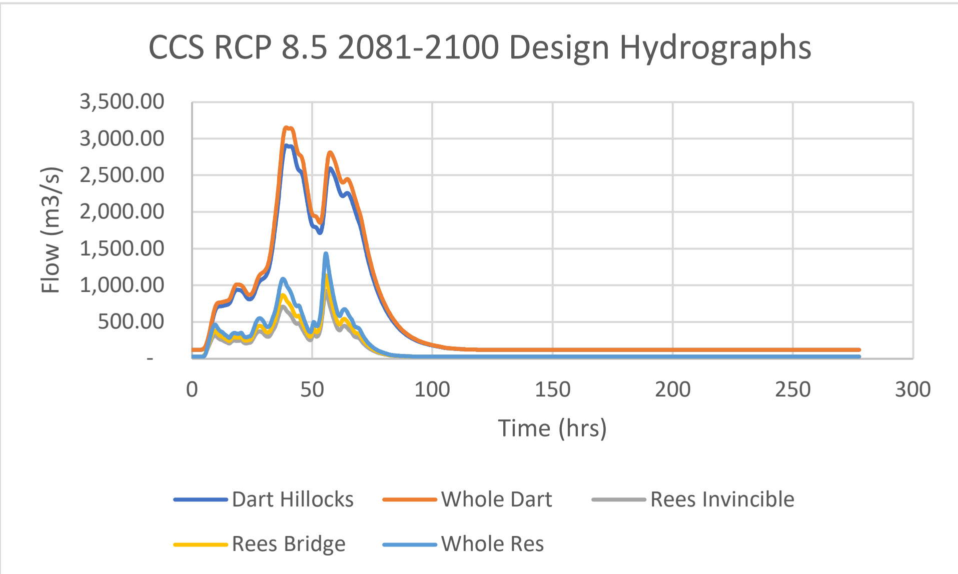


Figure 17 Design Flow Hydrographs for the Dart and Rees Rivers for CCS RCP 8.5 2018-2100

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.

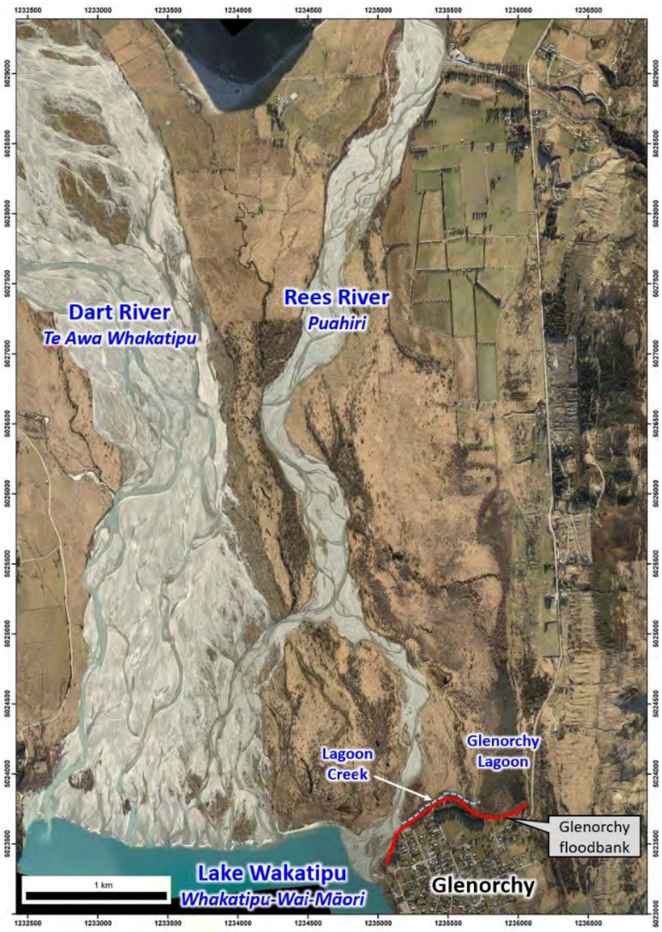


Figure 1 Site location plan (provided by ORC).

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.

[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.

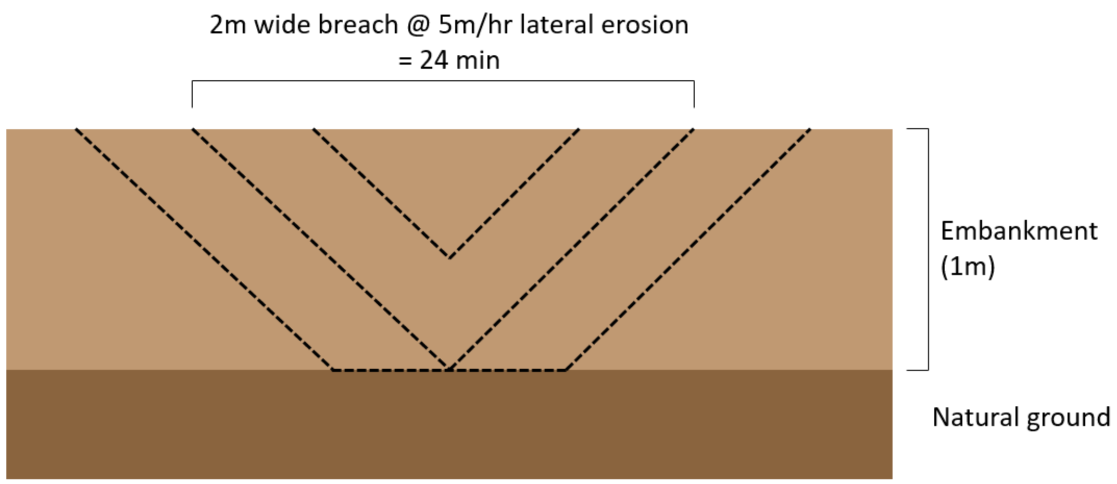


Figure 8 Illustrative diagram showing failure mode.

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:

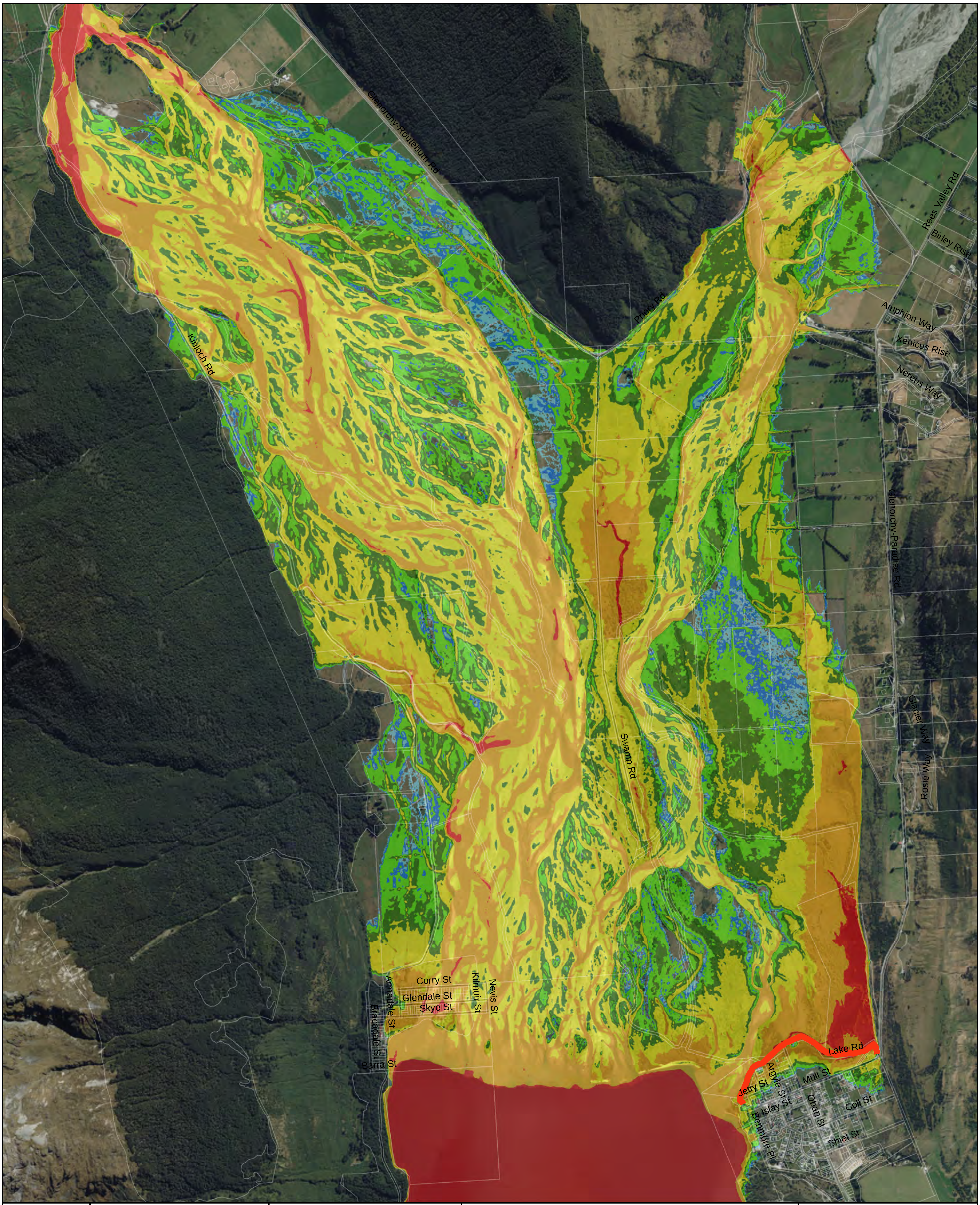
....

Sjoerd Van Ballegooy

Project Director

18-Nov-21
t:\christchurch\tt projects\1017916\1017916.1000\workingmaterial\2021.10.18.tgm.memo_daa_final_reissue.docx

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

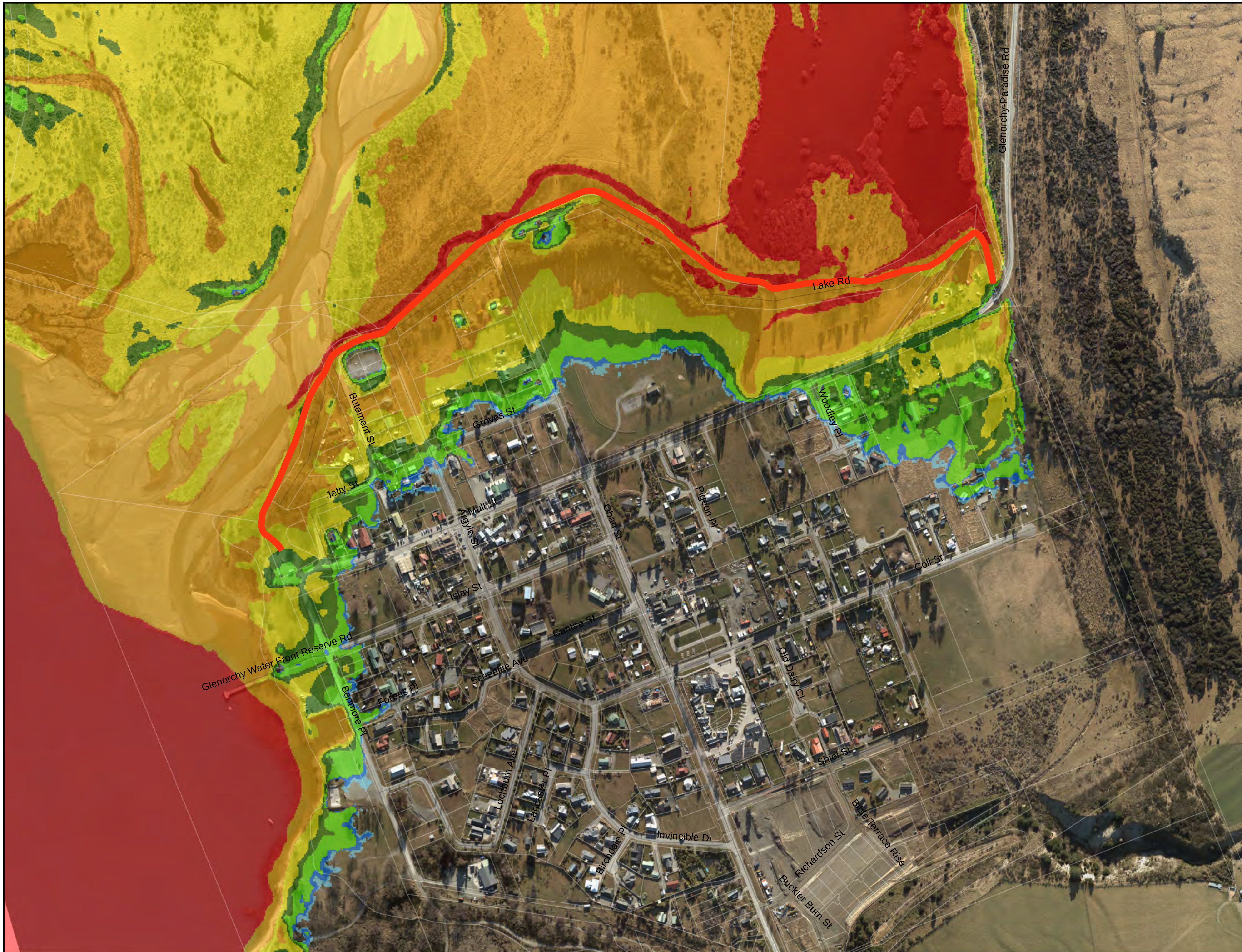
MAP TITLE

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

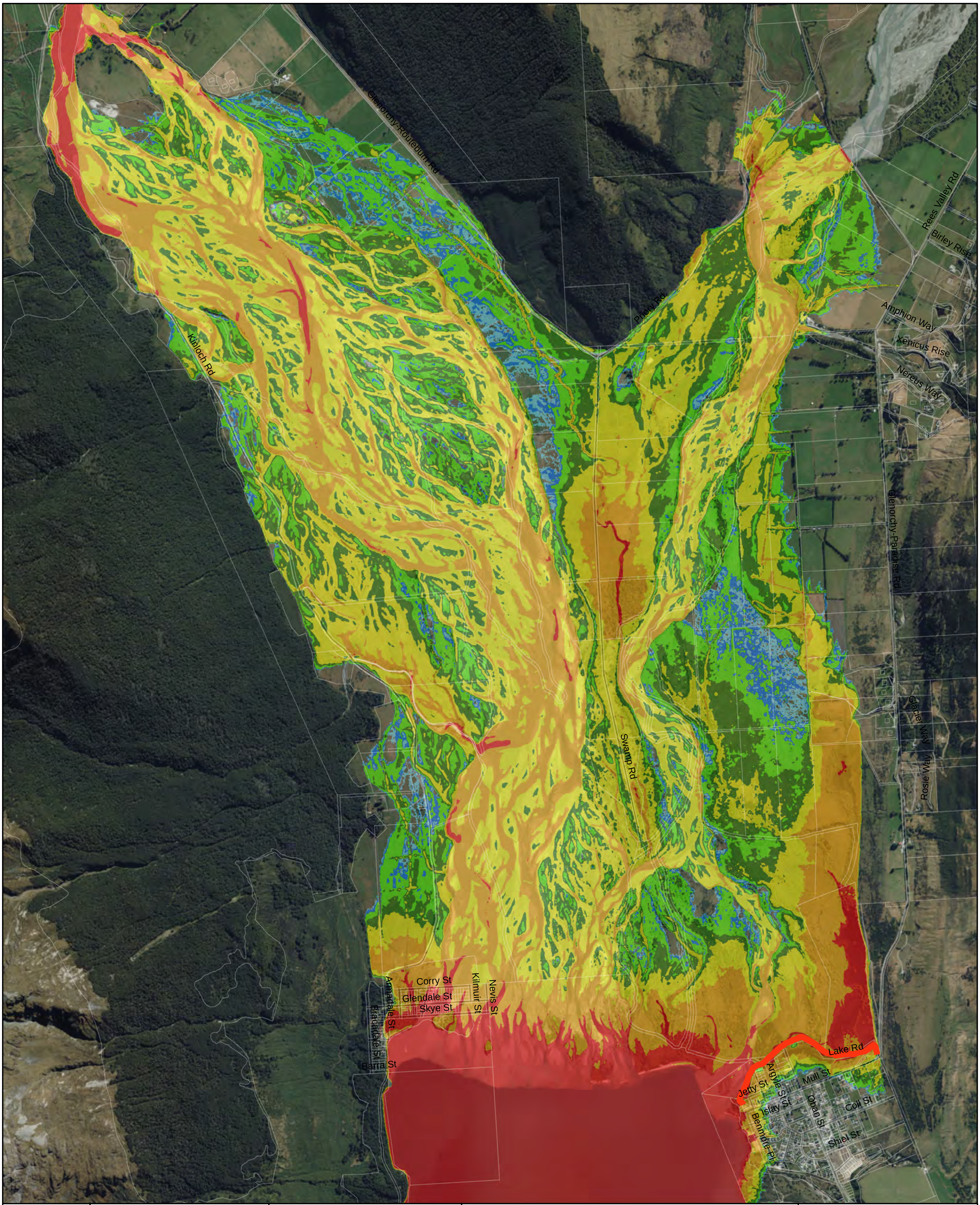
Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK DEPTH MAP
Scenario 1 – 100 year ARI flow (historic climate)
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**		



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

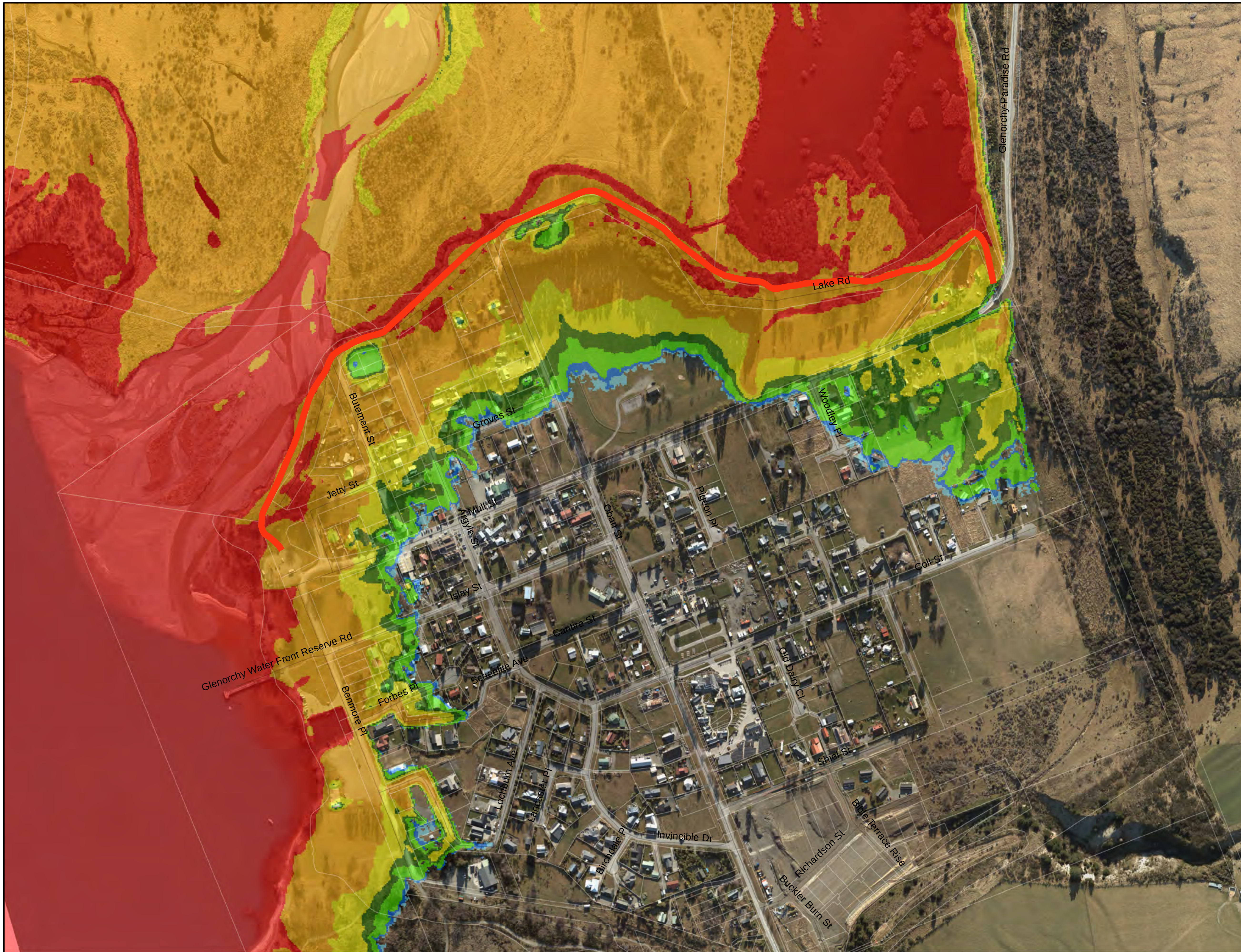
MAP TITLE

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

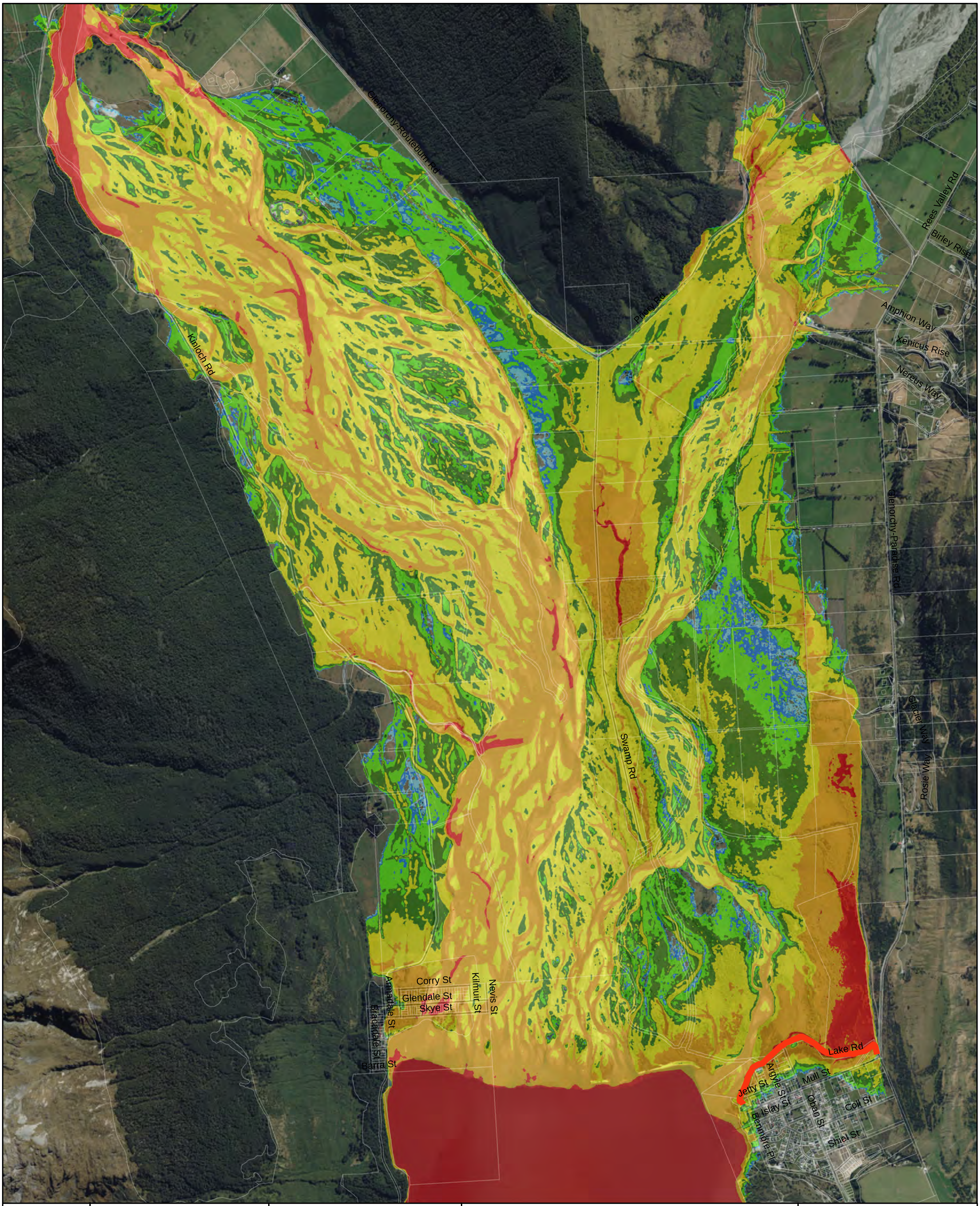
Otago Regional Council

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	MAP TITLE	REVISION 01	DATE	A3 SCALE	N
Glenorchy Flood Modelling	**PEAK DEPTH 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

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

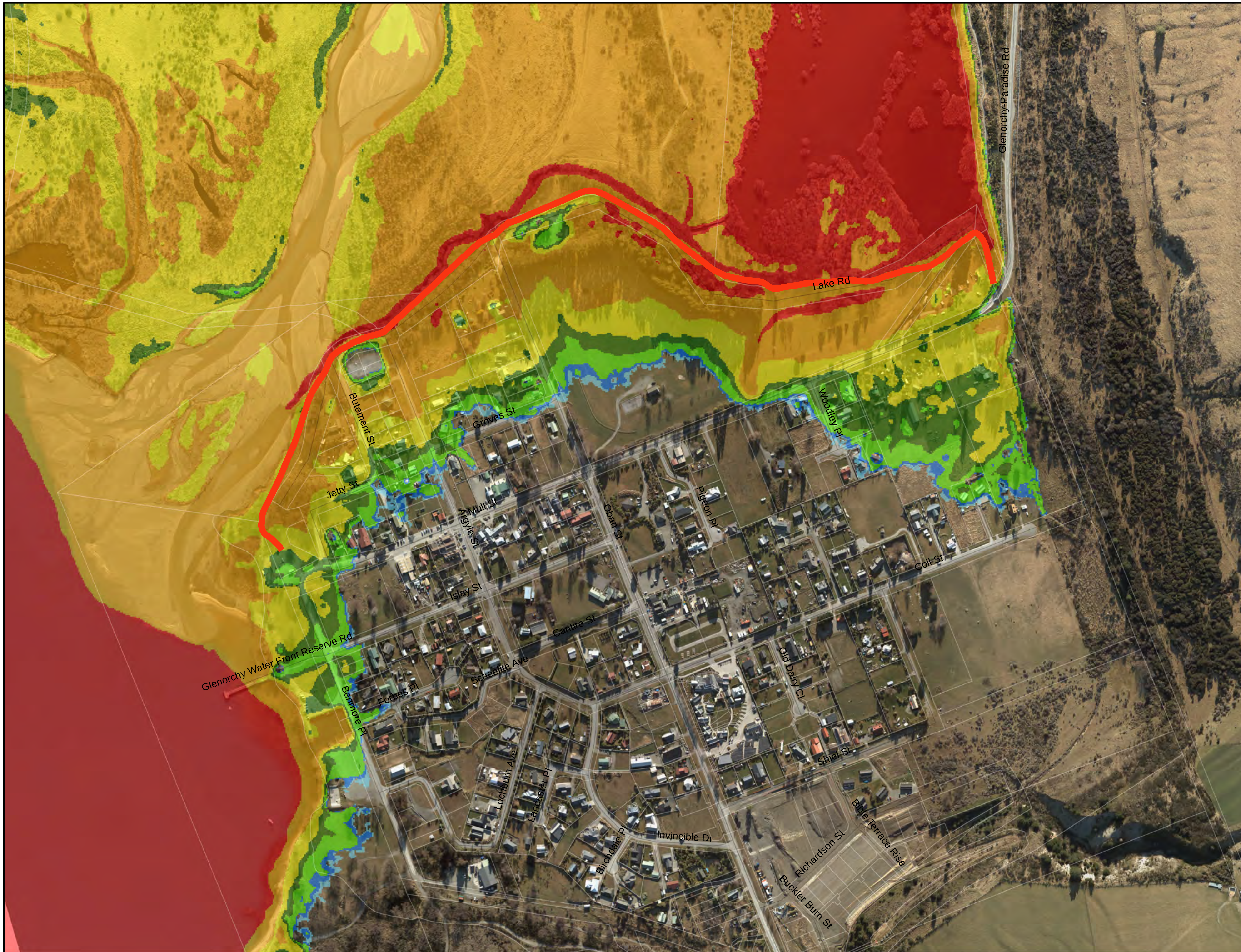
MAP TITLE

PEAK DEPTH OVERVIEW MAP
Scenario 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

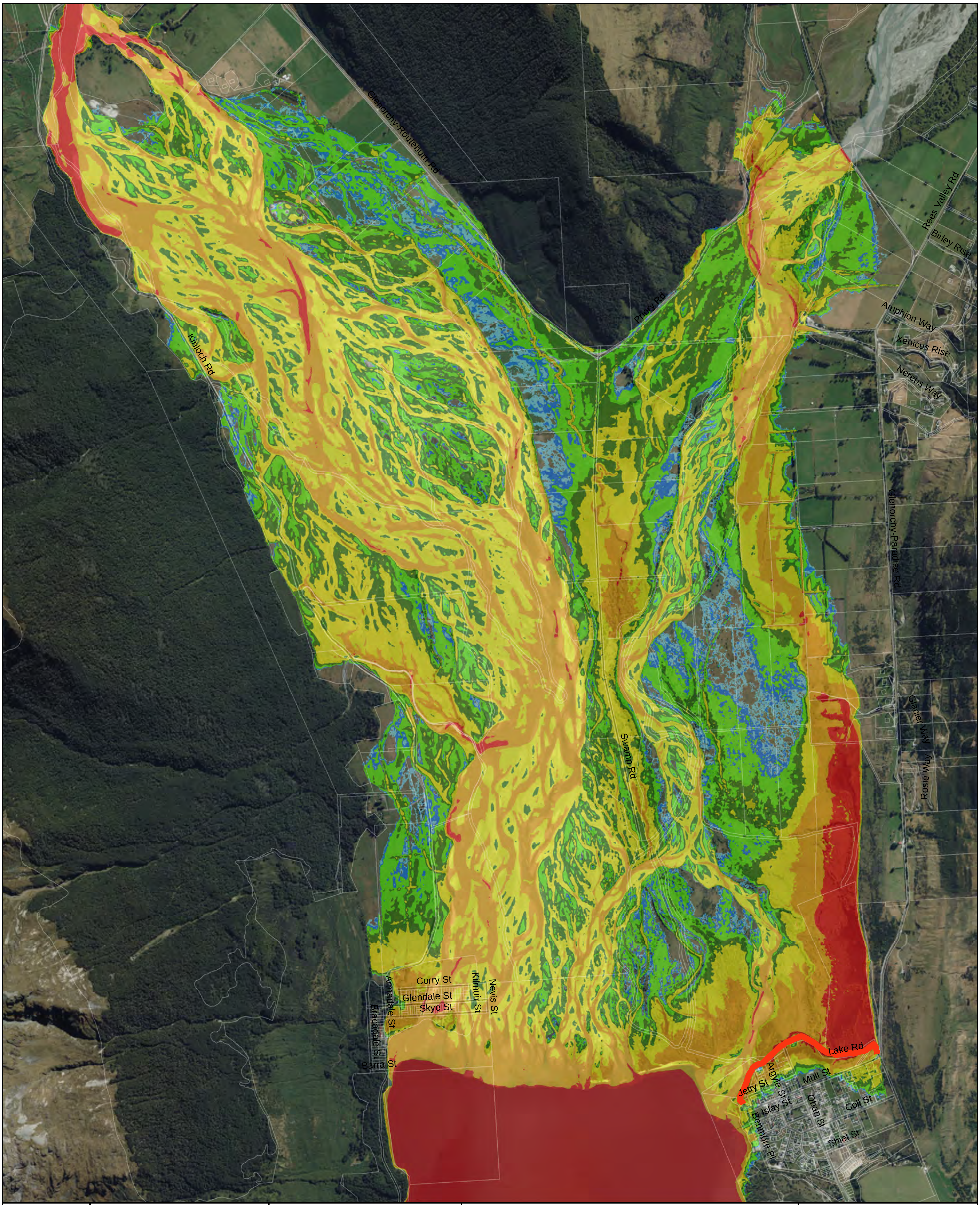
0 0.05 0.1 0.2
Kilometers

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



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)

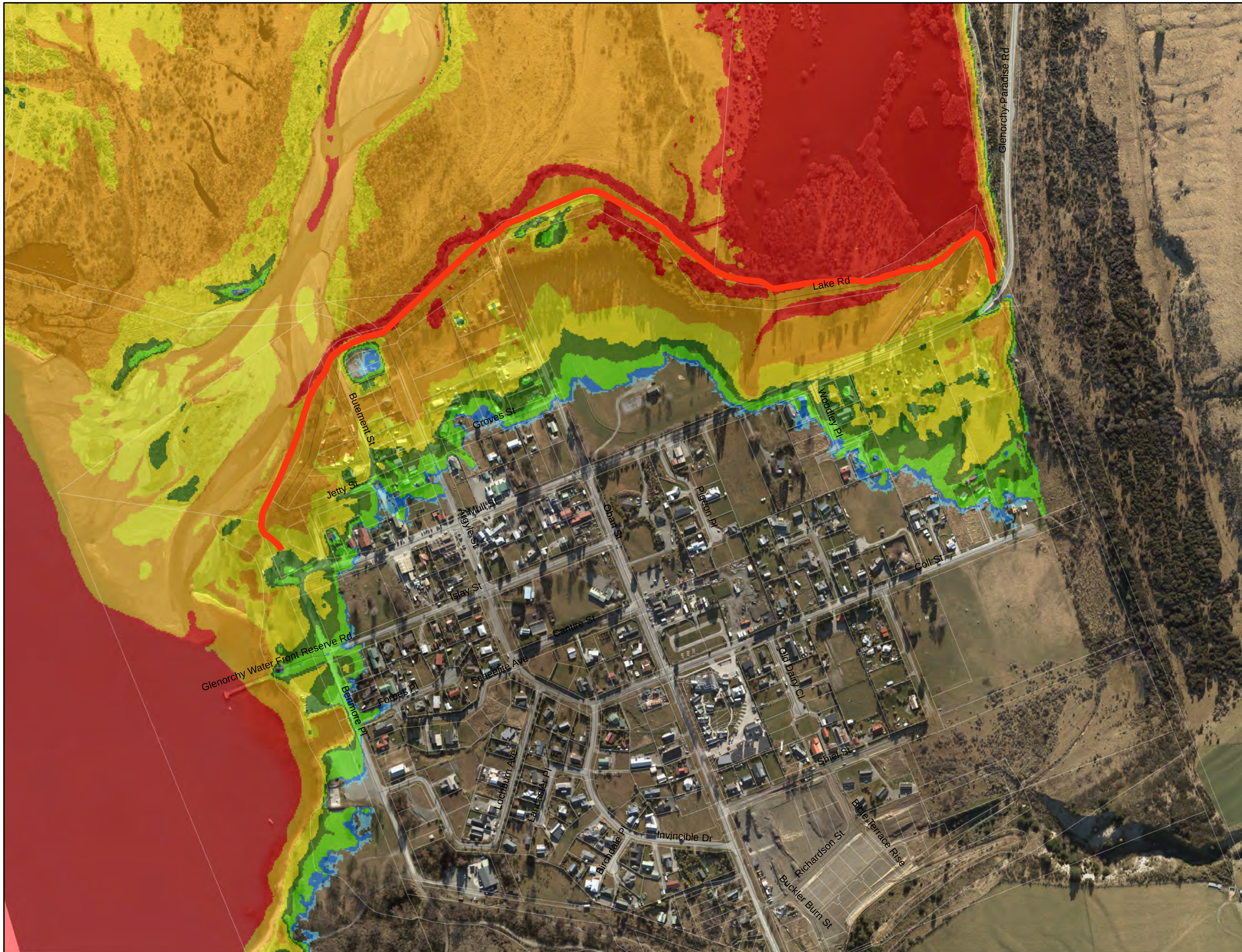
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK DEPTH OVERVIEW MAP
Scenario 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 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

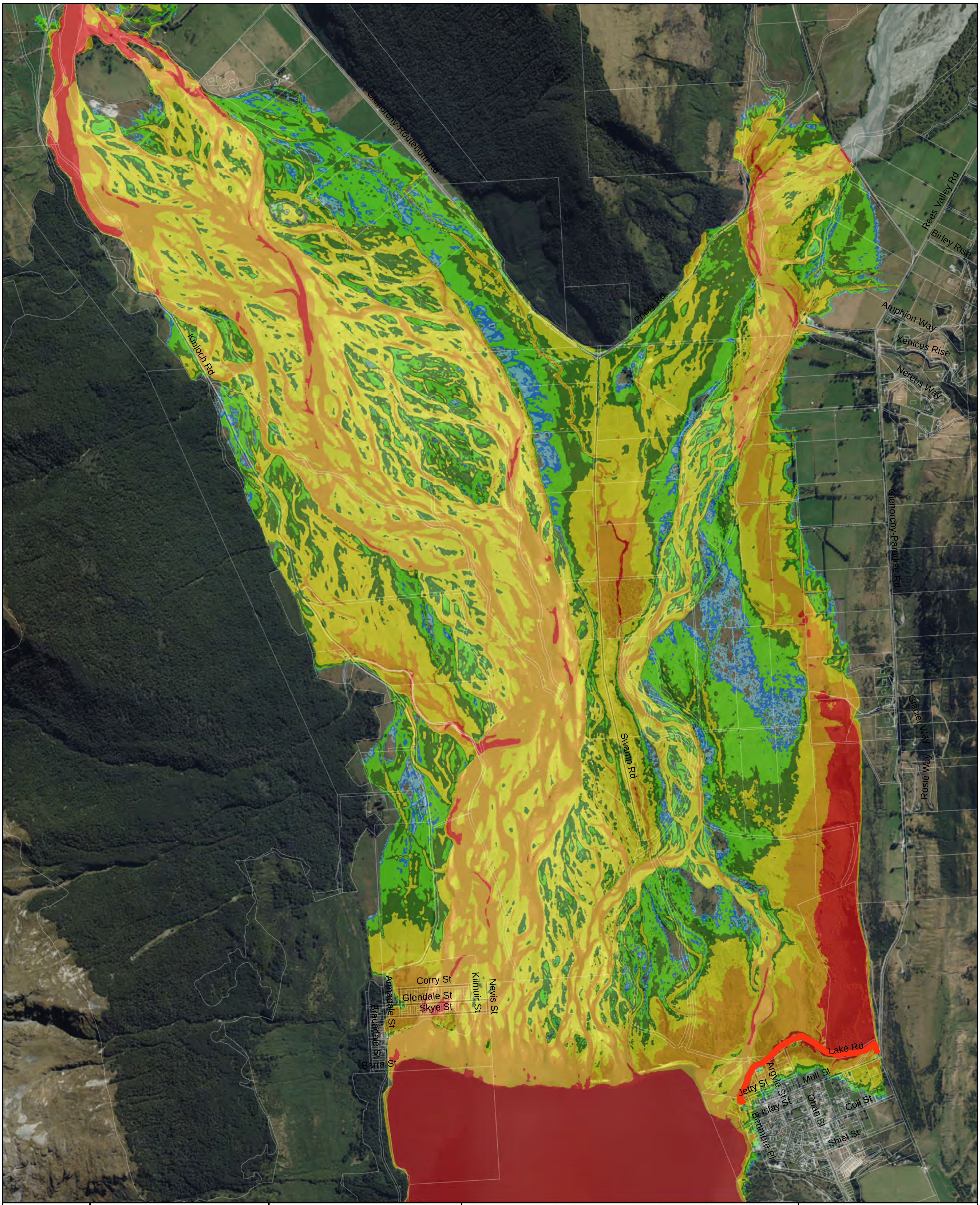
Otago Regional Council

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	N
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**		



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)

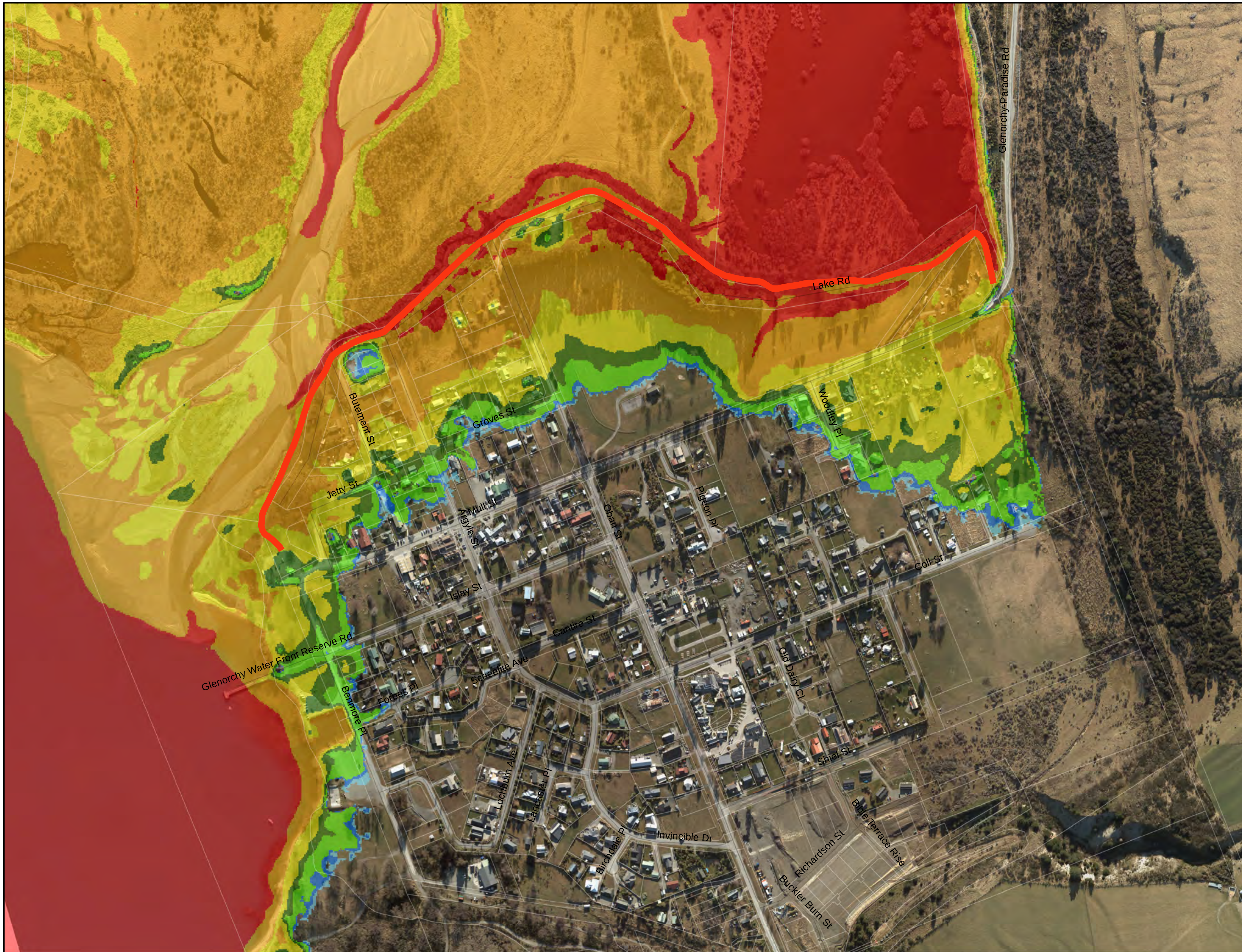
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK DEPTH OVERVIEW MAP
Scenario 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+

LANDRIVERSEA CONSULTING

Otago Regional Council

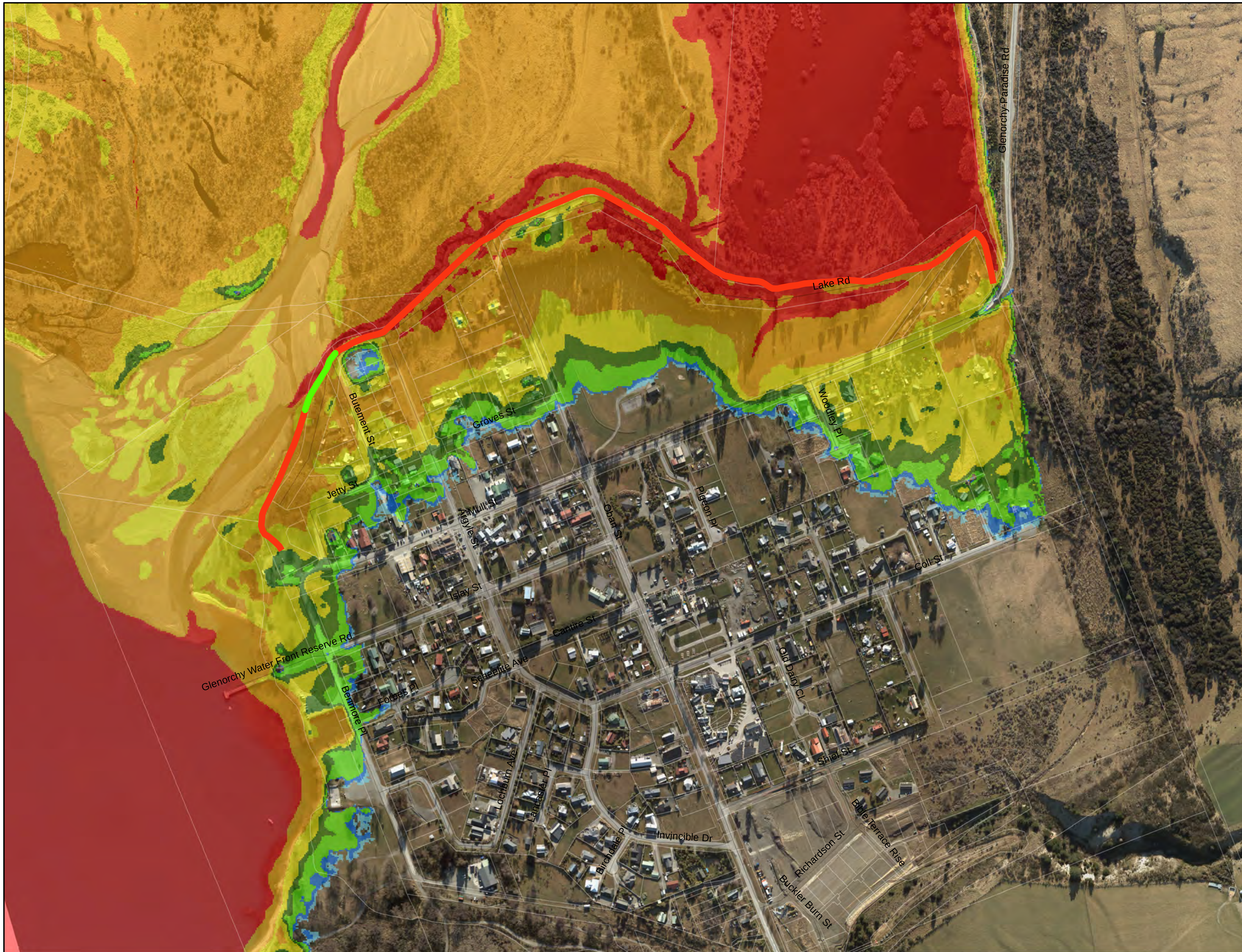
0 0.05 0.1 0.2
Kilometers

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 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 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

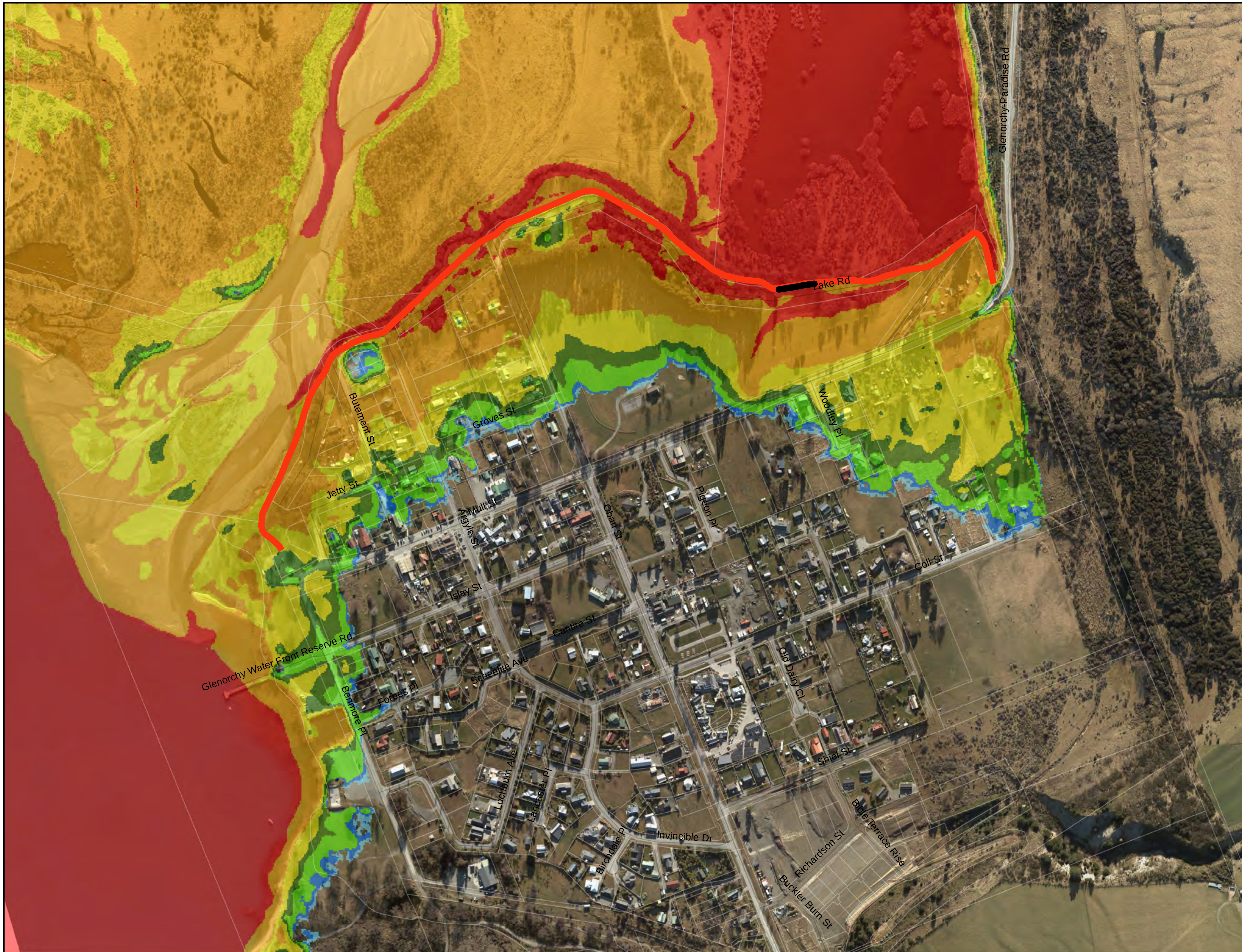
0 0.05 0.1 0.2
Kilometers

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 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 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

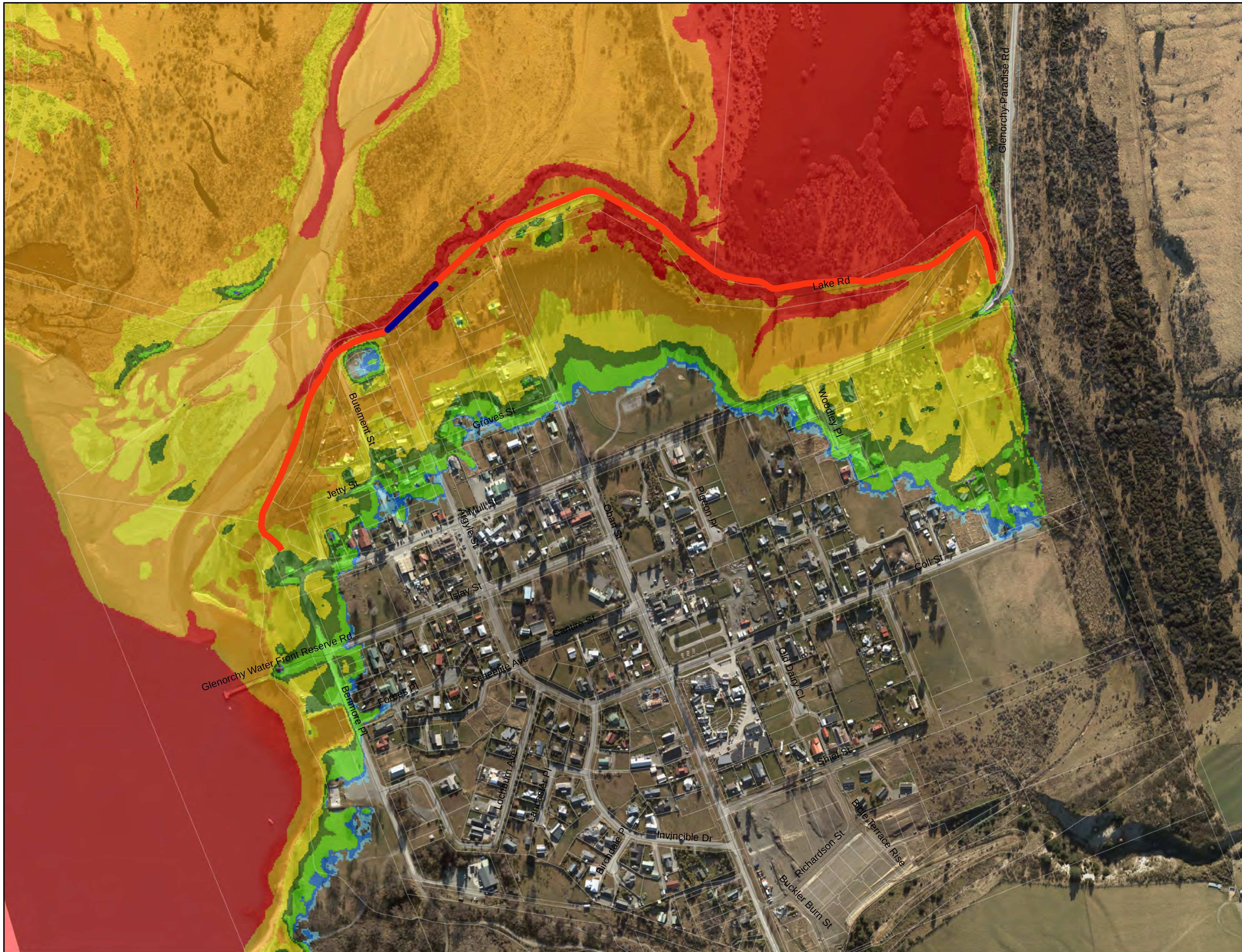
Otago Regional Council

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 7 - 100 year ARI flow ((Future Climate, RCP8.5) 10 year ARI lake level - Breach 2 (90m Wide) Avulsion towards lagoons	CREATED BY BSB	12/05/2022	1:5,000	N
		REVISED BY	AUTHOR Matthew Gardner		



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

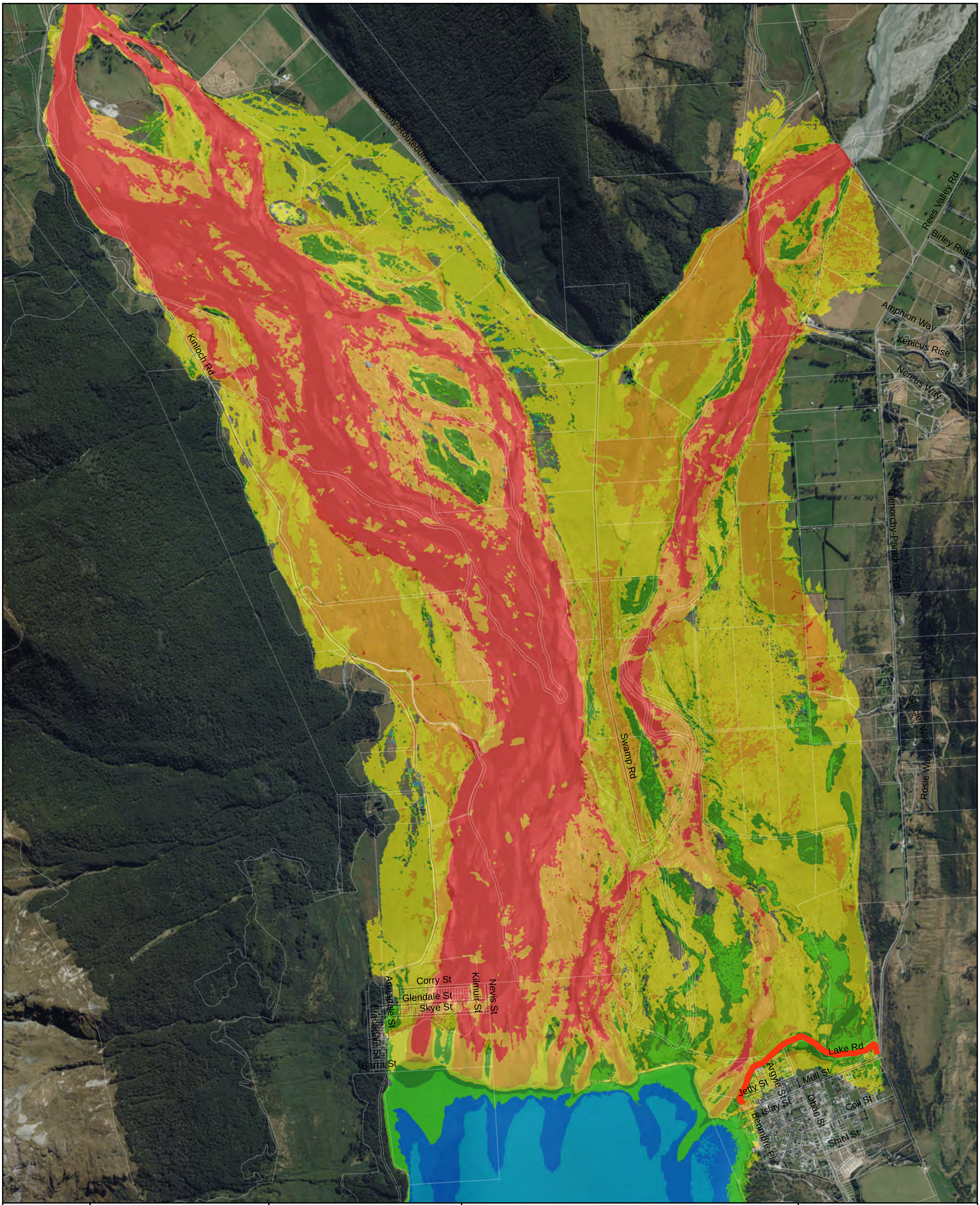
Model Information:
Coordinate System: New Zealand Transverse Mercator
Vertical Datum: DUN-1958

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
Glenorchy Flood Modelling	**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**	CREATED BY **BSB**	**12/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	

N

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

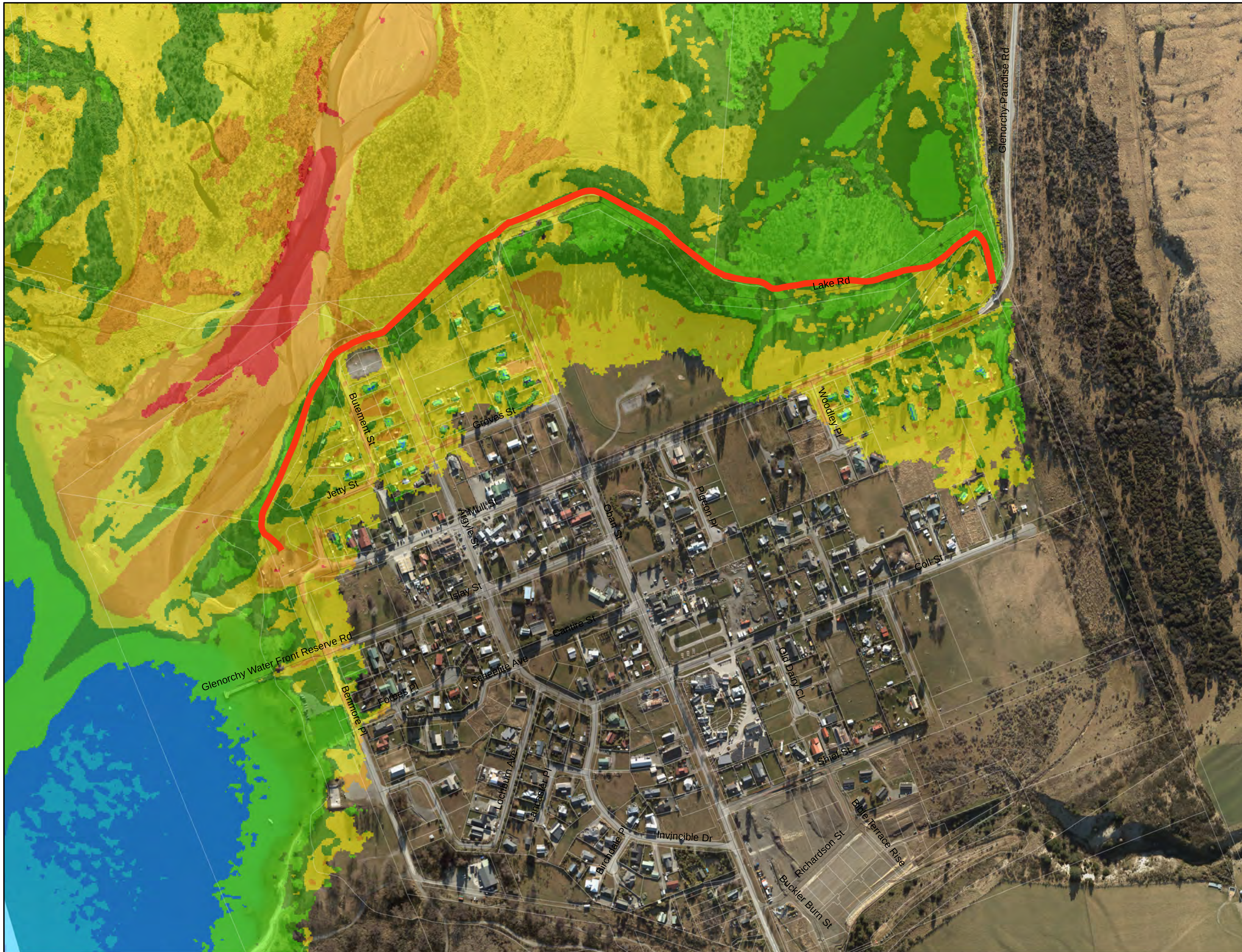
MAP TITLE

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

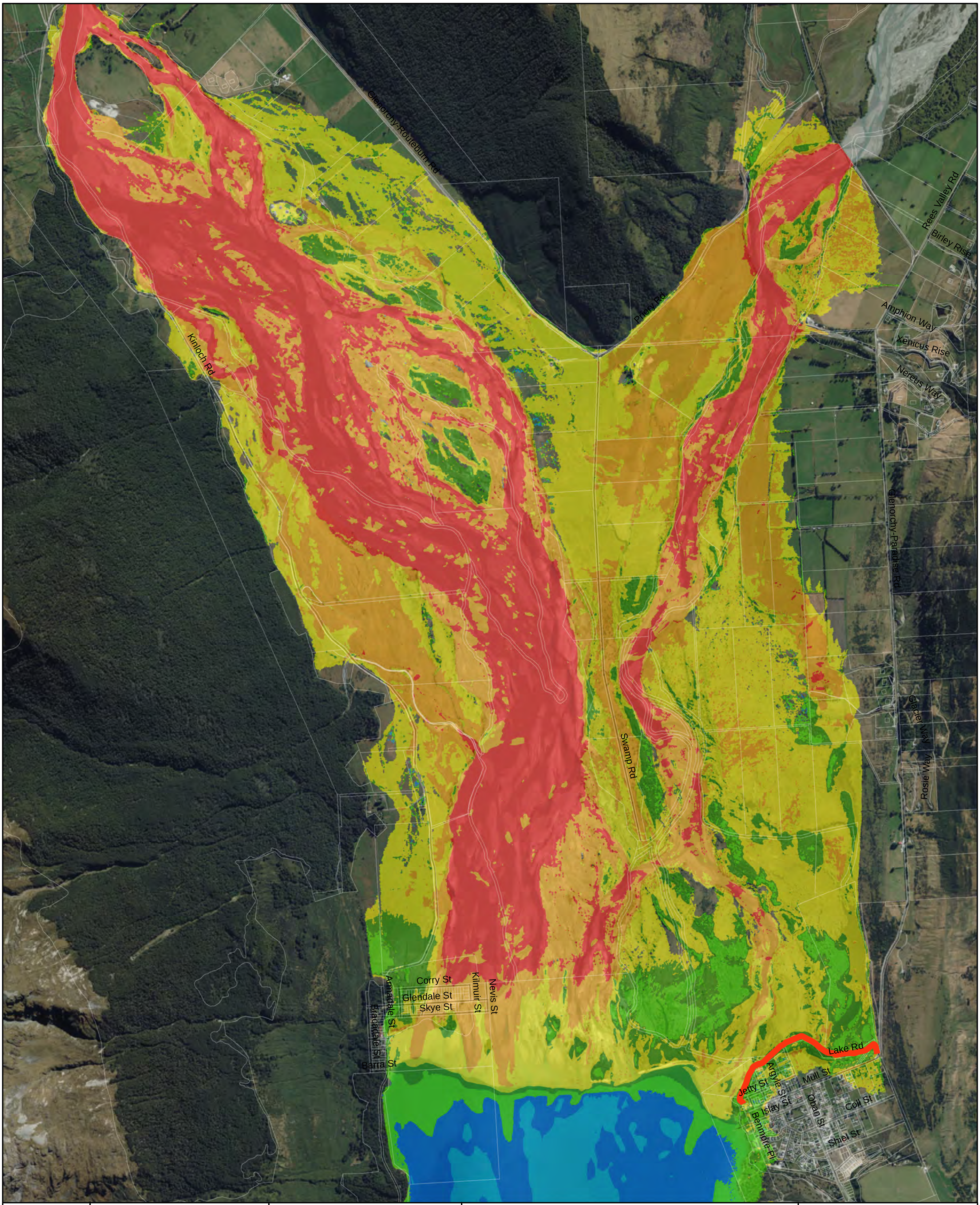
Otago Regional Council

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	MAP TITLE	REVISION 01	DATE	A3 SCALE	N
Glenorchy Flood Modelling	**PEAK SPEED 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**		



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)

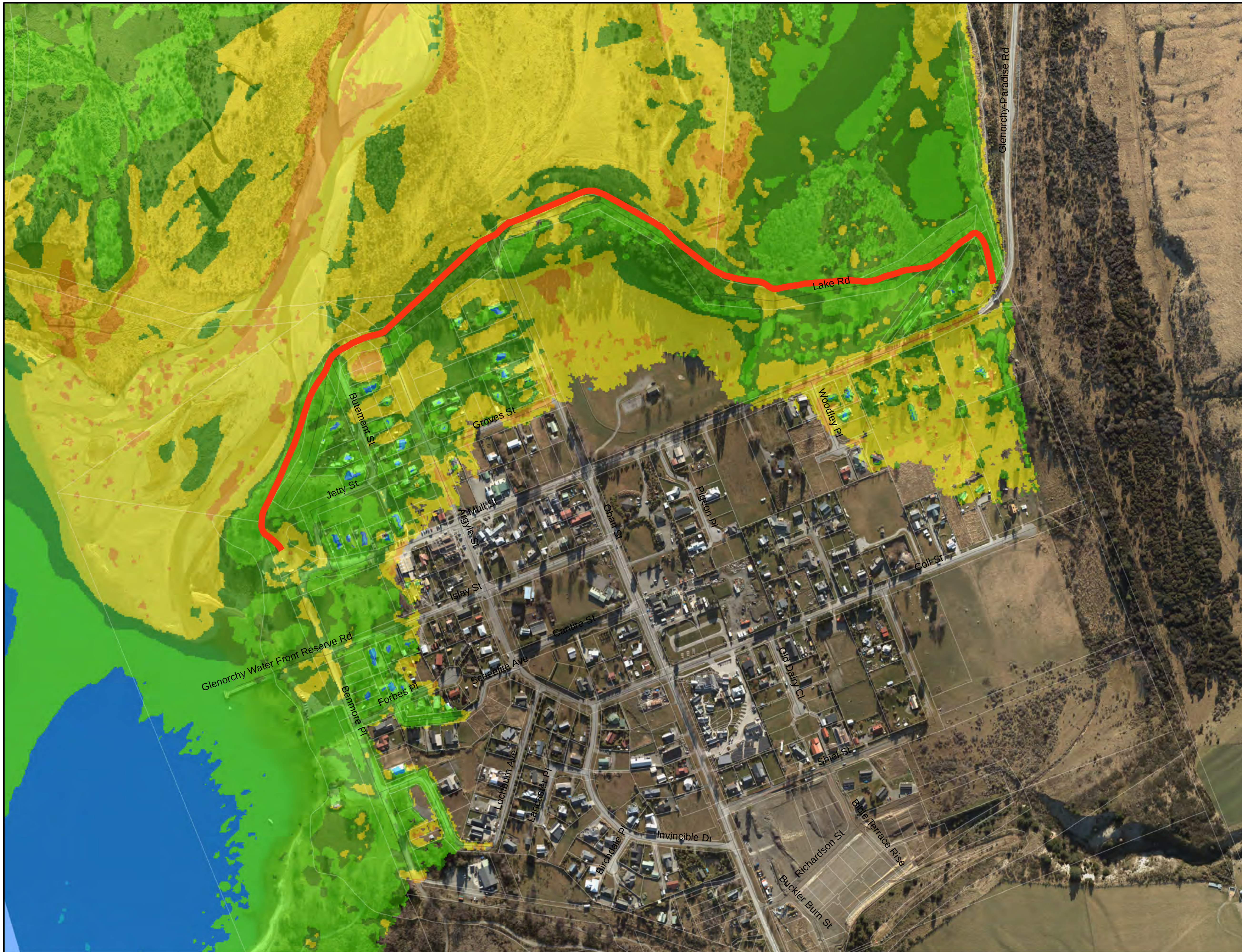
PROJECT
Glenorchy Flood Modelling

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

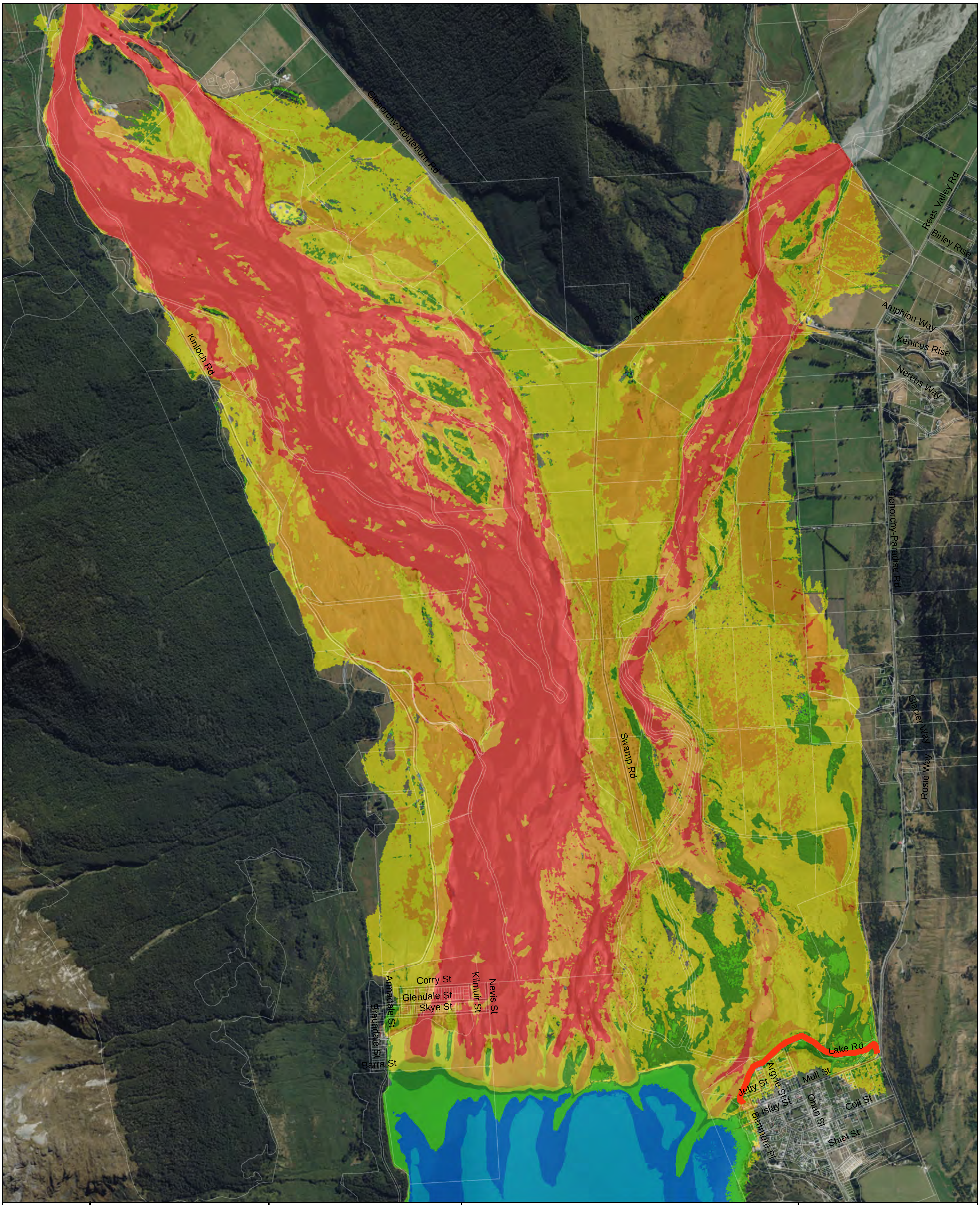
Otago Regional Council

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	N
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**		



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)

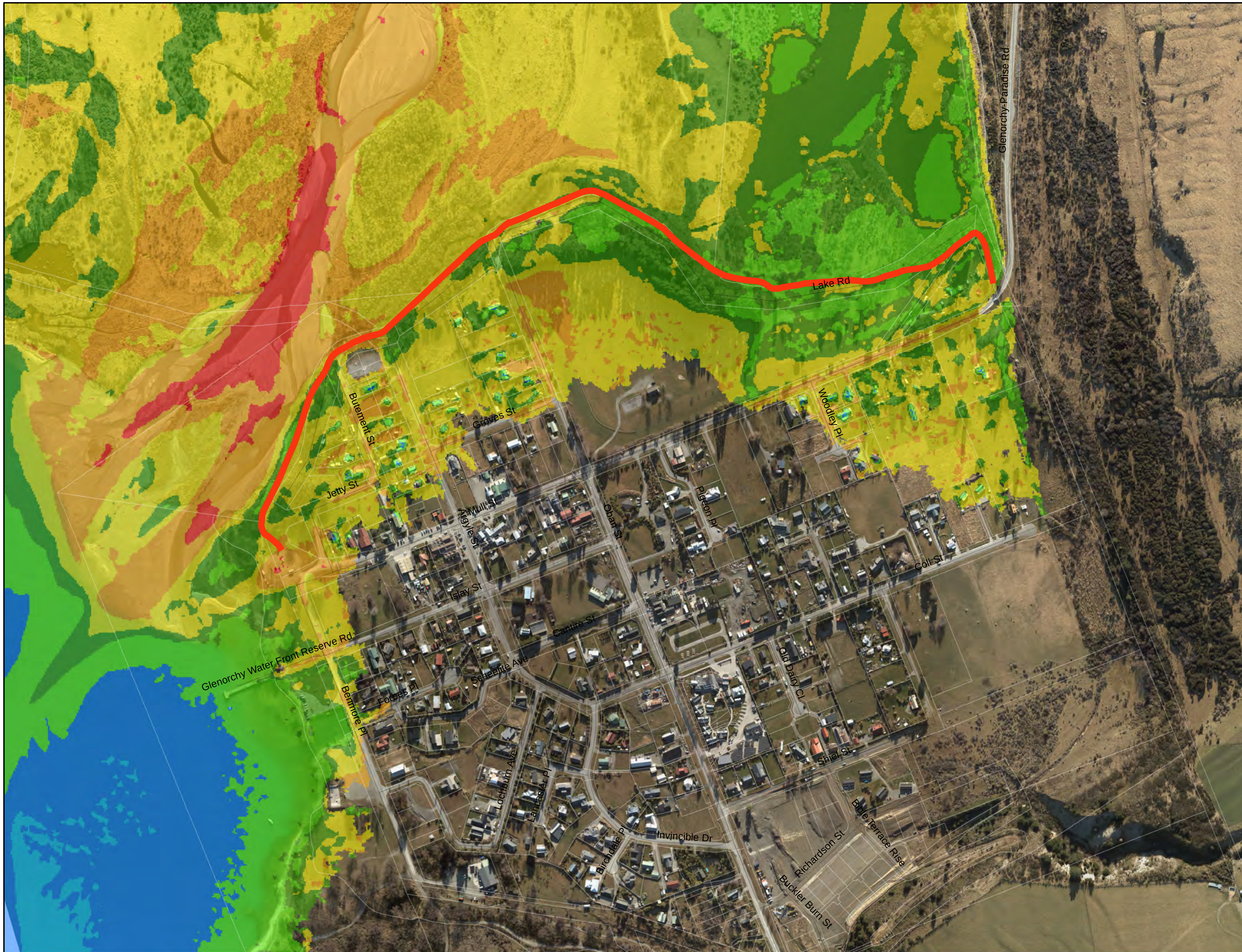
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK SPEED OVERVIEW MAP
Scenario 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

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

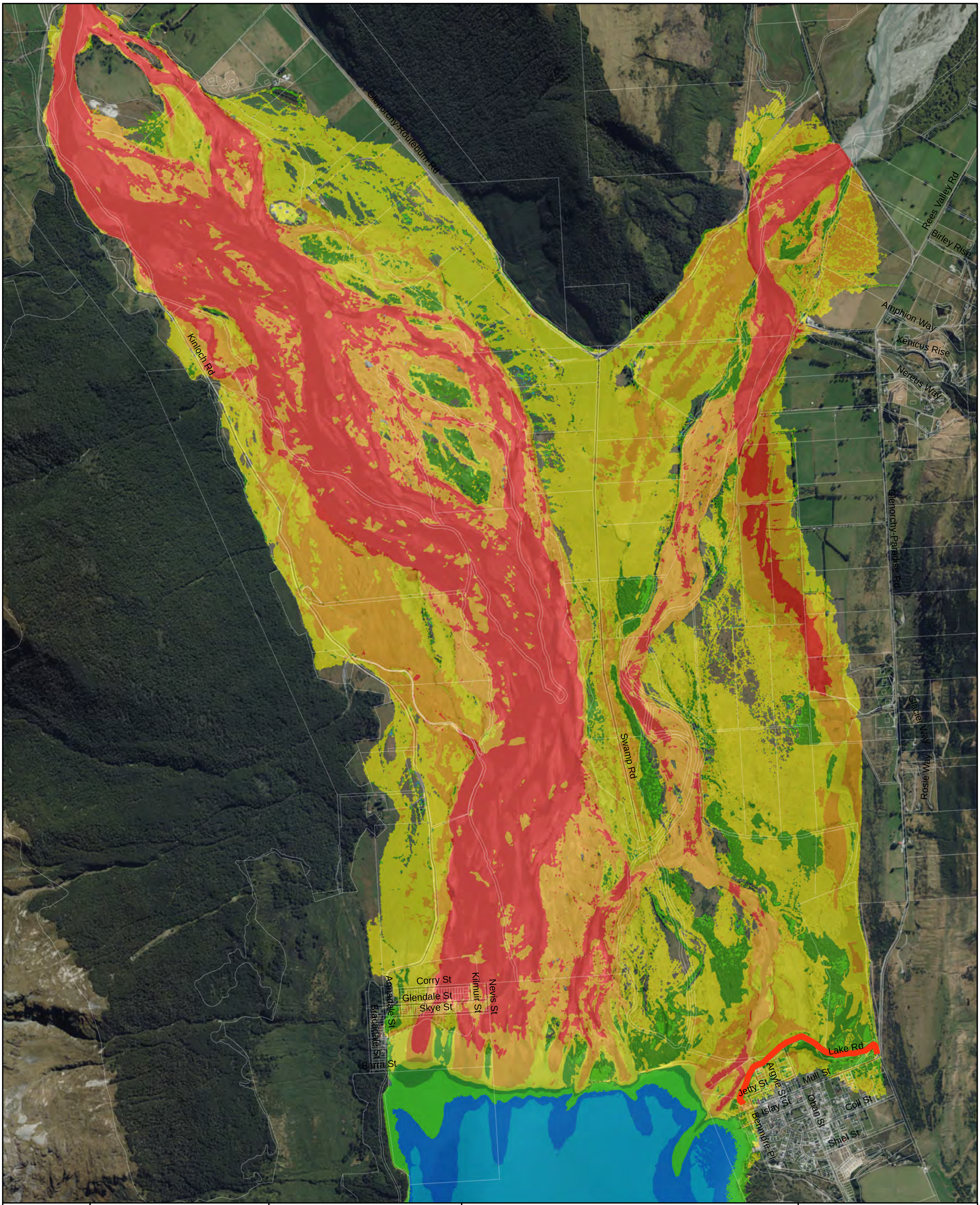
Otago Regional Council

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**
		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)

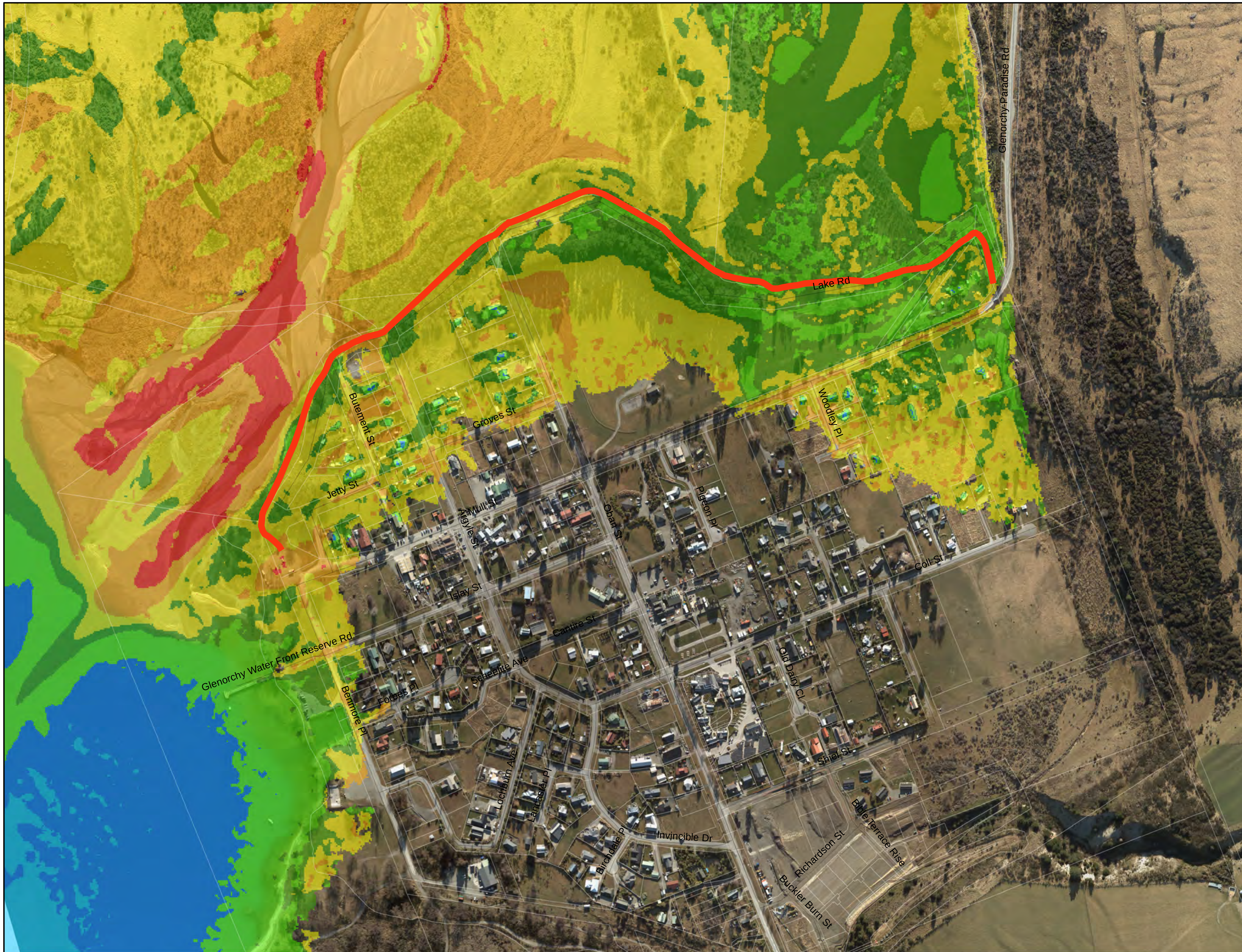
PROJECT
Glenorchy Flood Modelling

MAP TITLE
PEAK SPEED OVERVIEW MAP
Scenario 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

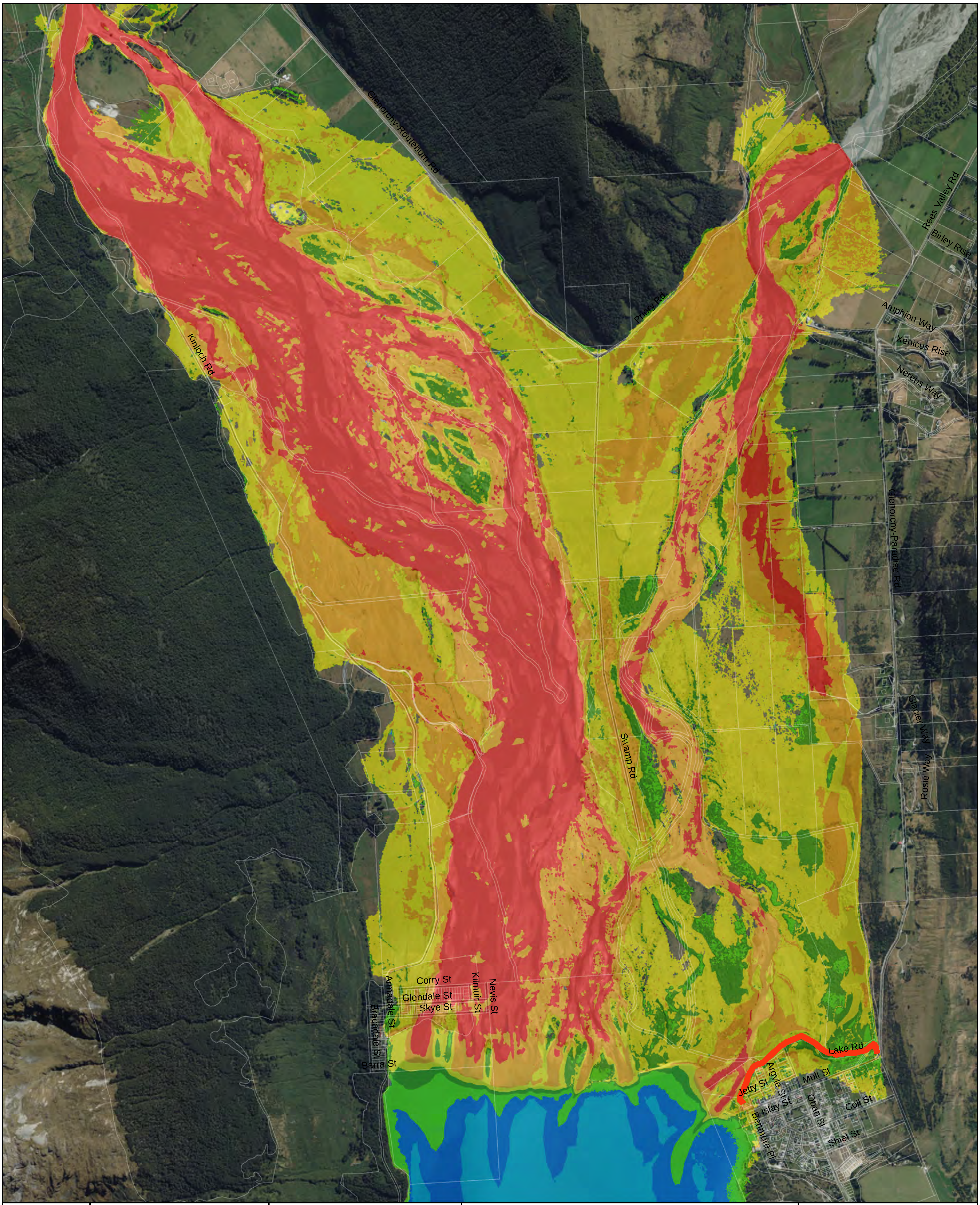
0 0.05 0.1 0.2
Kilometers

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

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION	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**	01	**13/05/2022**	**1:5,000**
		CREATED BY: **BSB**	AUTHOR: **Matthew Gardner**	
		REVISED BY		

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)

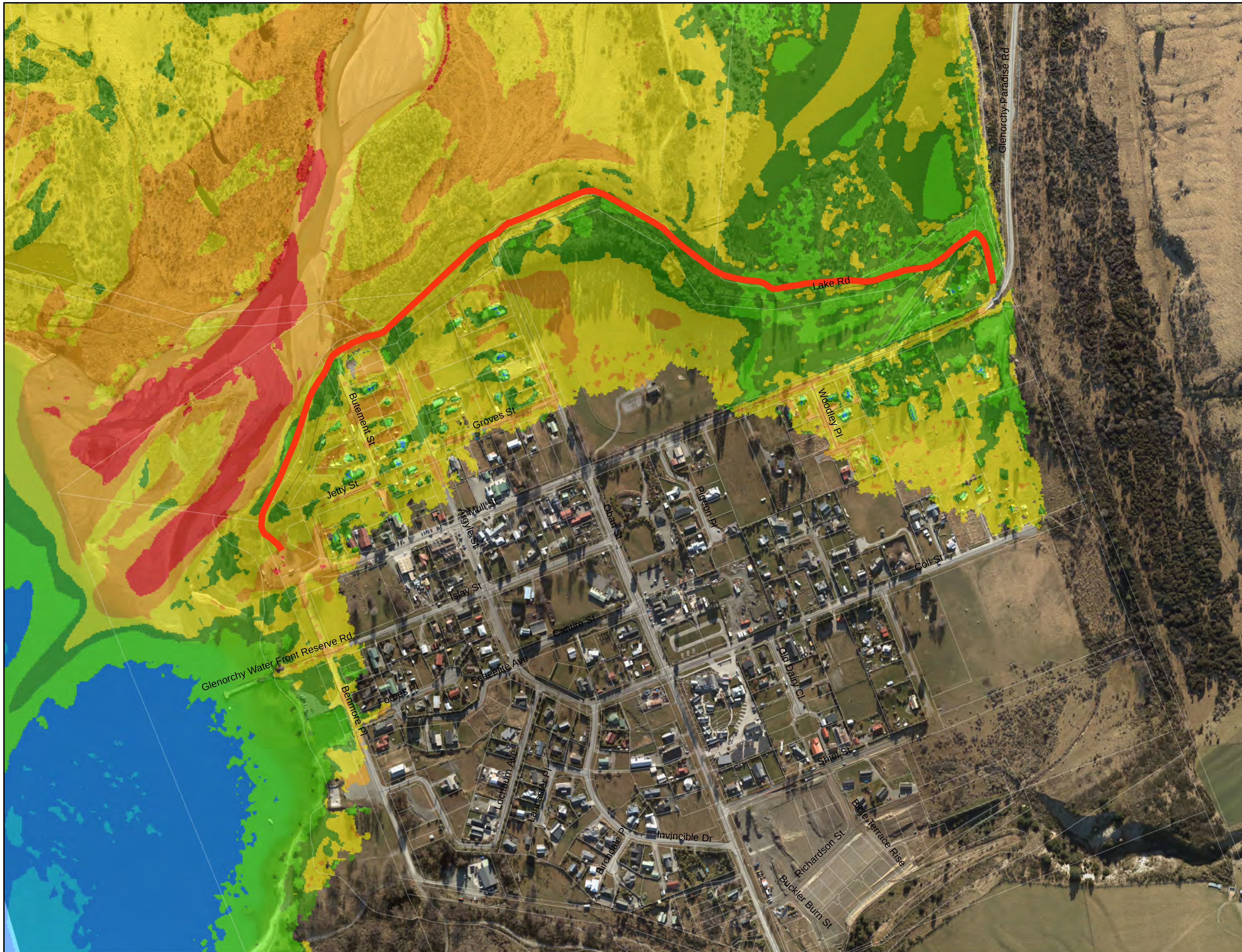
PROJECT
Glenorchy Flood Modelling

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

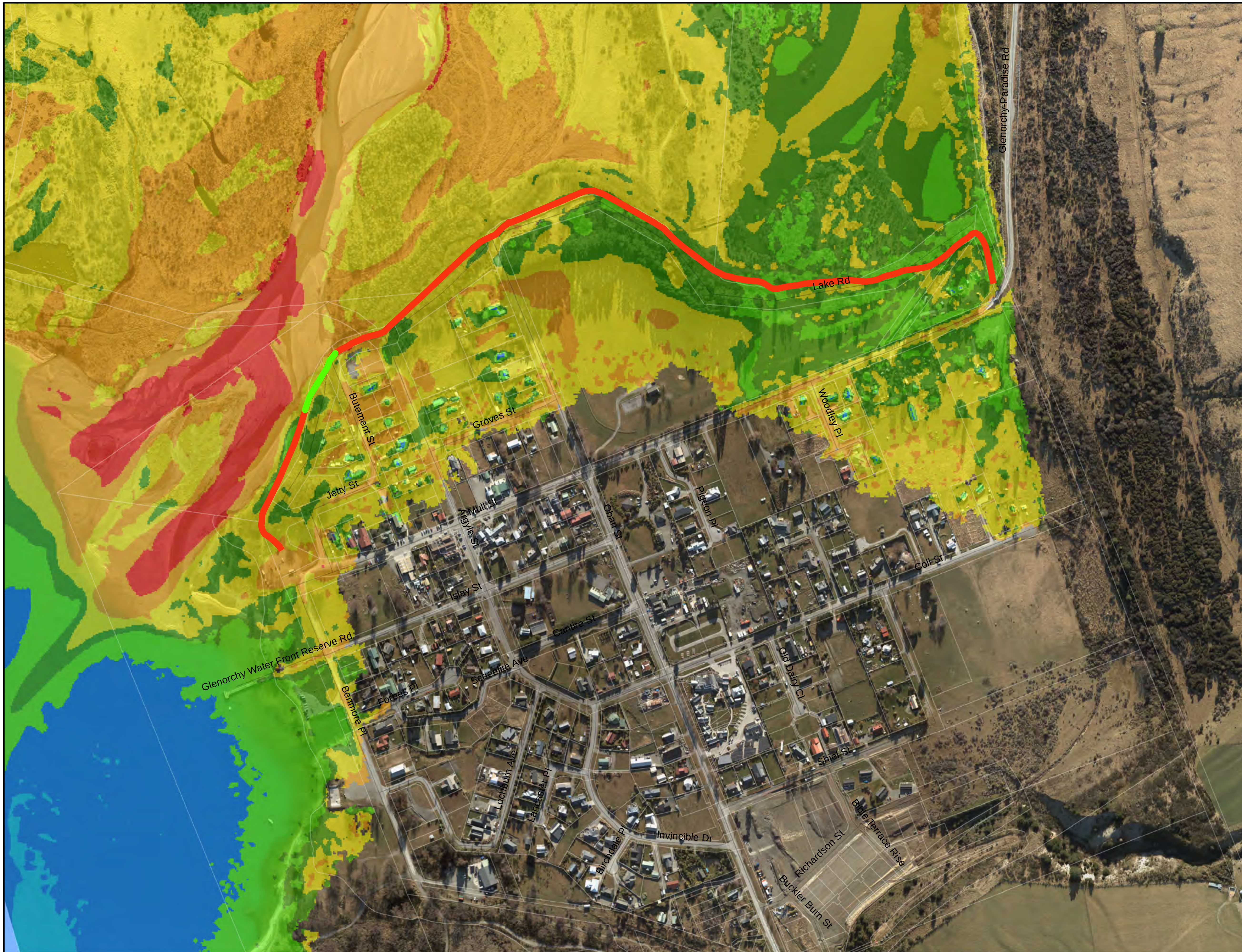
0 0.05 0.1 0.2
Kilometers

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

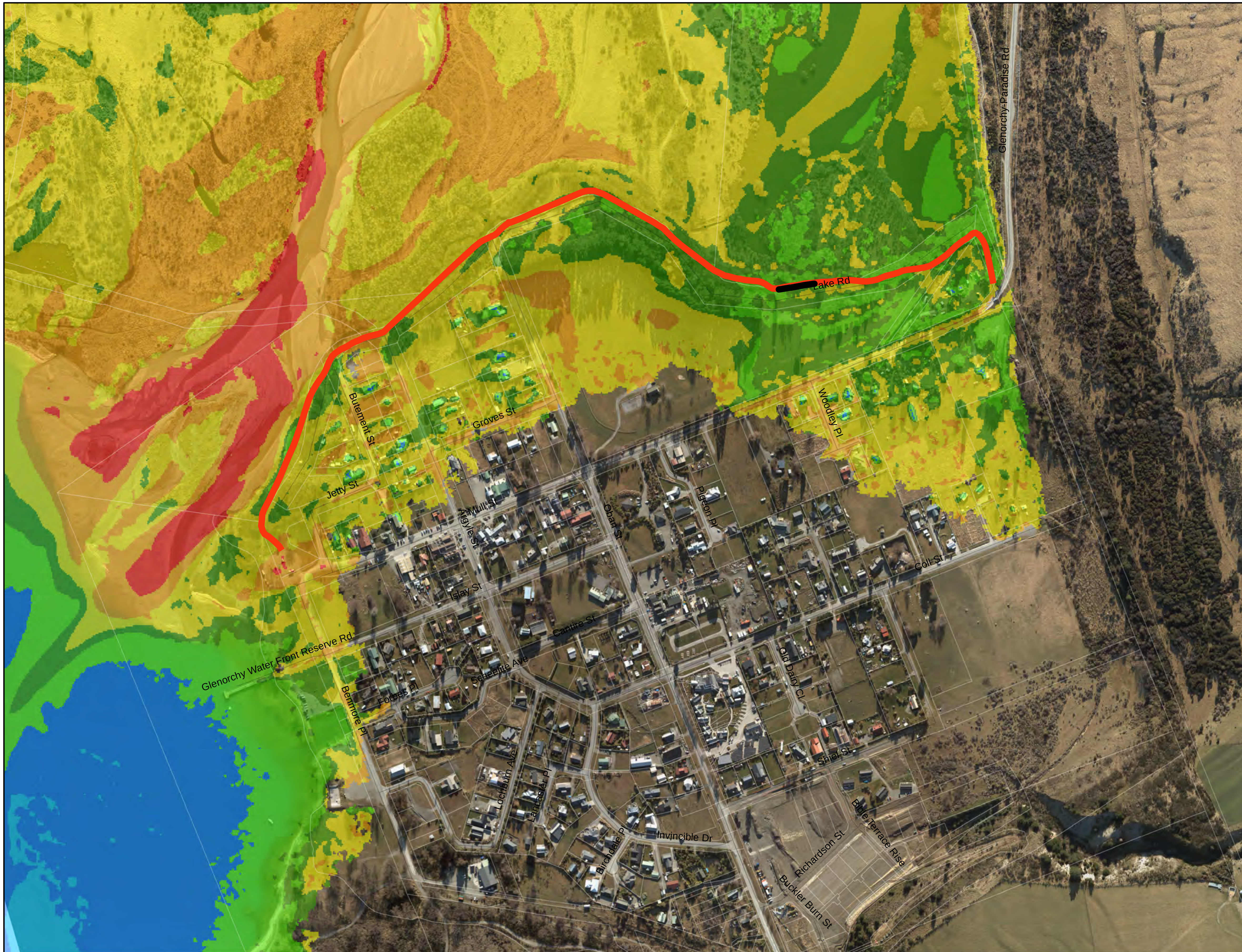
0 0.05 0.1 0.2
Kilometers

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+

LANDRIVERSEA CONSULTING

Otago Regional Council

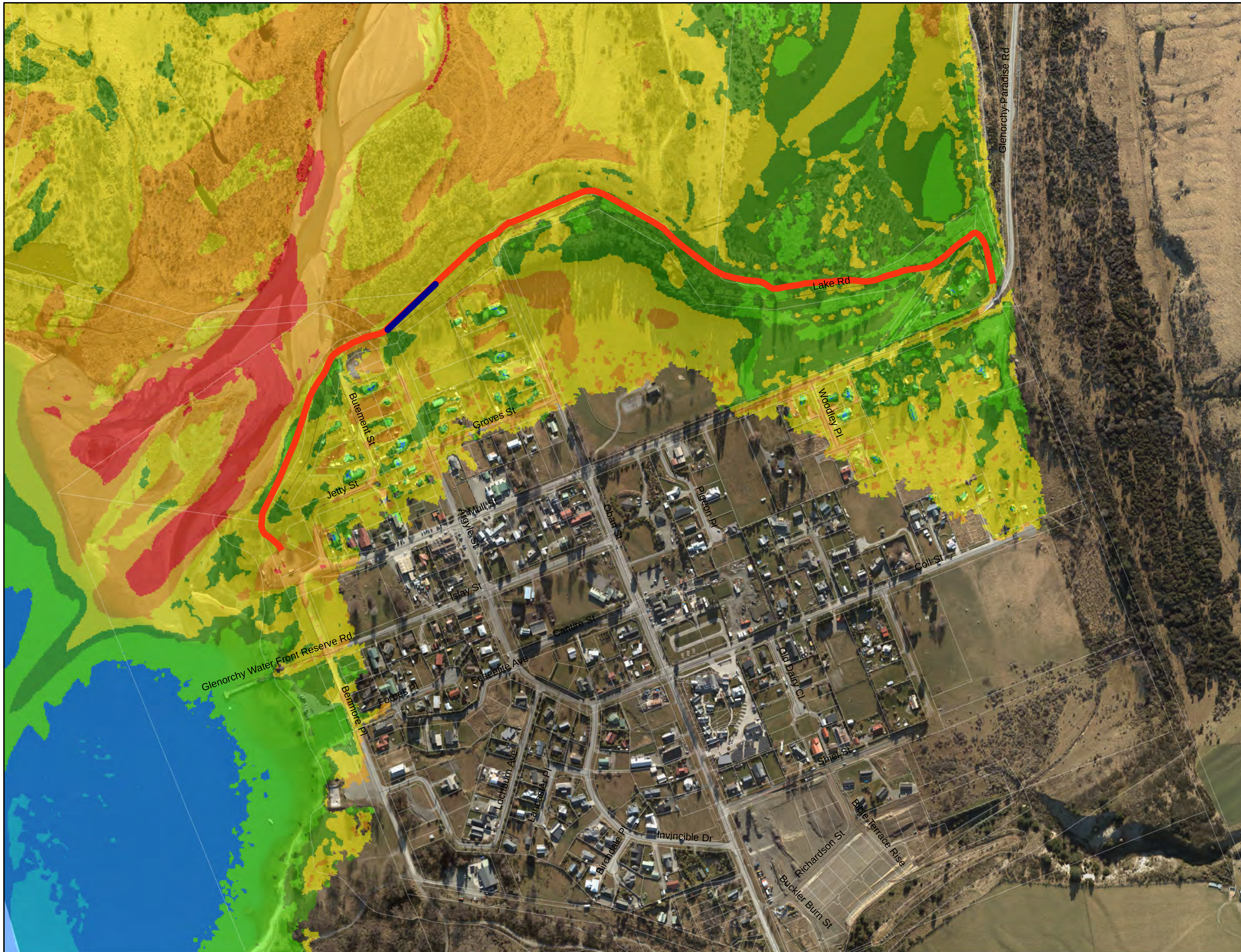
0 0.05 0.1 0.2
Kilometers

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 7 - 100 year ARI flow ((Future Climate, RCP8.5) 10 year ARI lake level - Breach 2 (90m Wide) Avulsion towards lagoons**	CREATED BY **BSB**	**12/05/2022**	**1:5,000**
		REVISED BY	AUTHOR **Matthew Gardner**	

N



Legend

- Breach 3
- 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

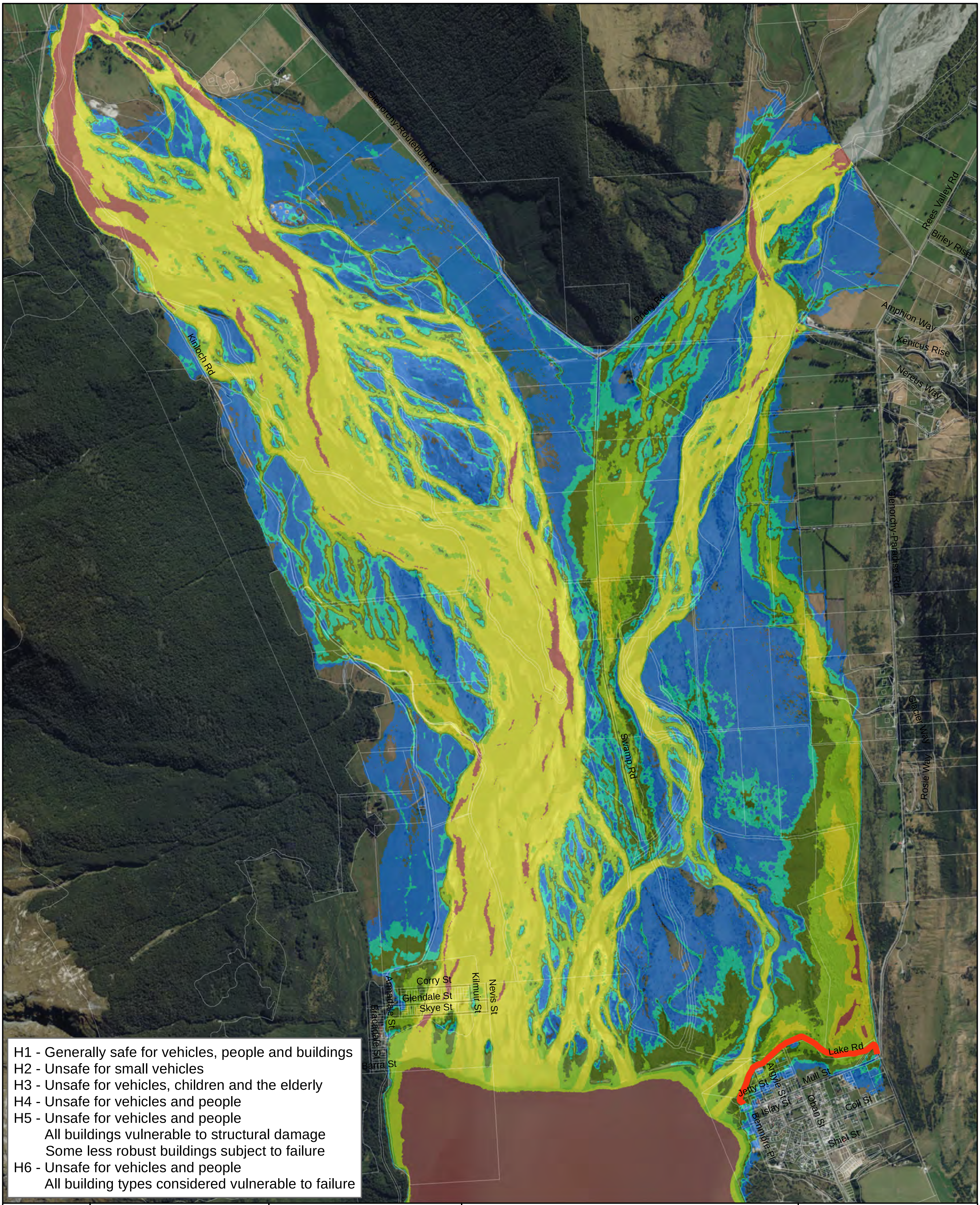
0 0.05 0.1 0.2
Kilometers

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

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE	N
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)

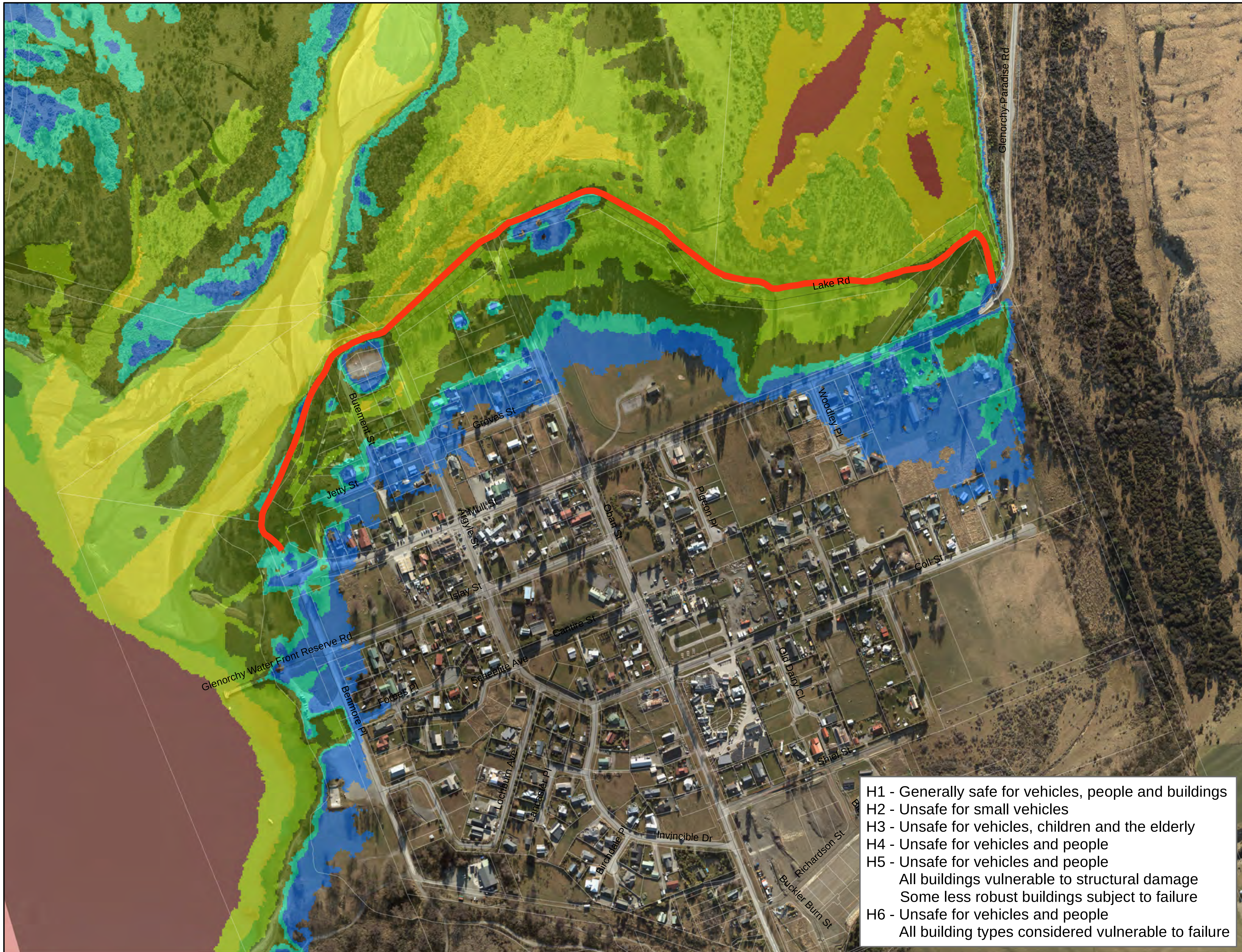
PROJECT
Glenorchy Flood Modelling

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



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

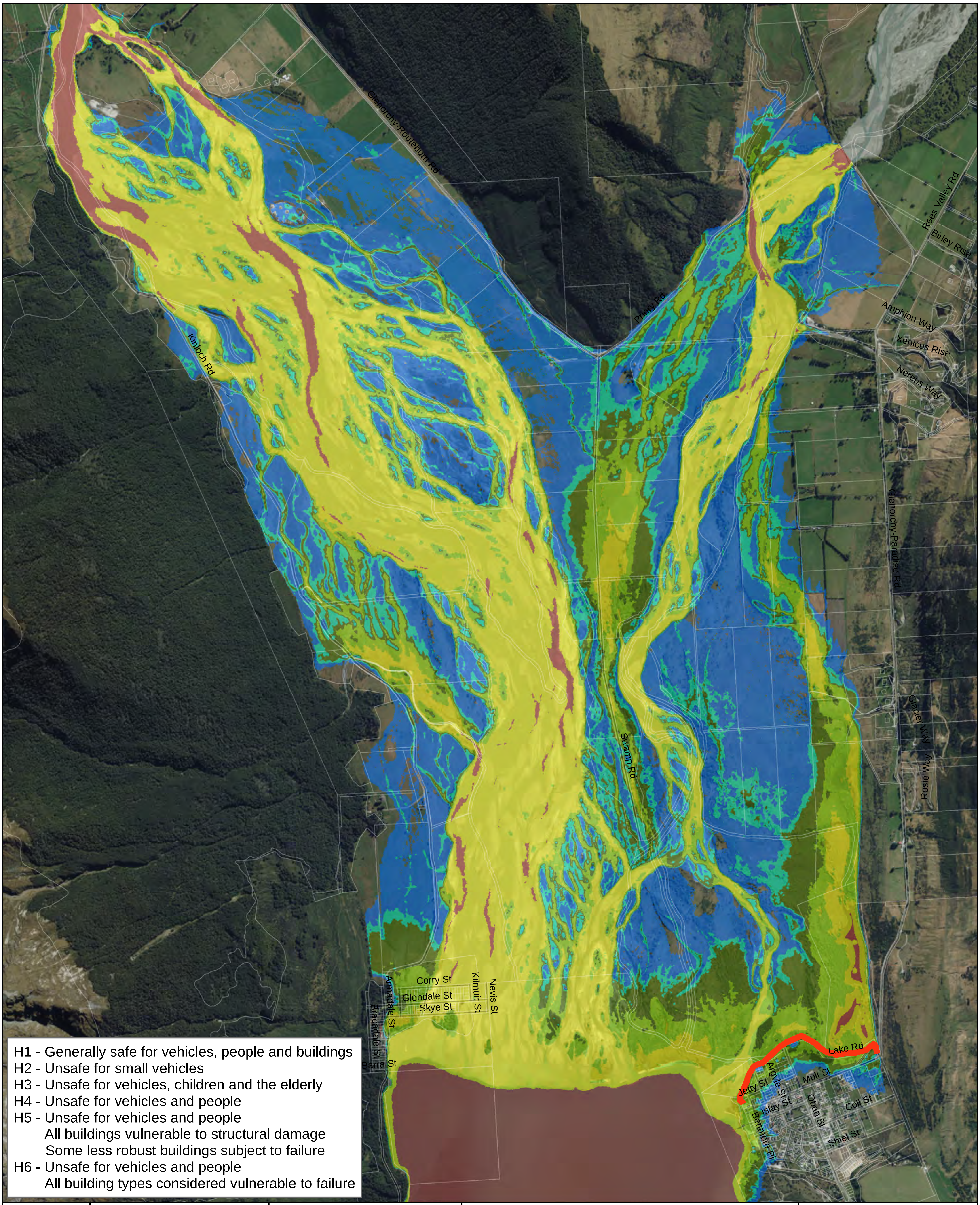
0 0.05 0.1 0.2
Kilometers

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

Model Completed: December 2021

PROJECT **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



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

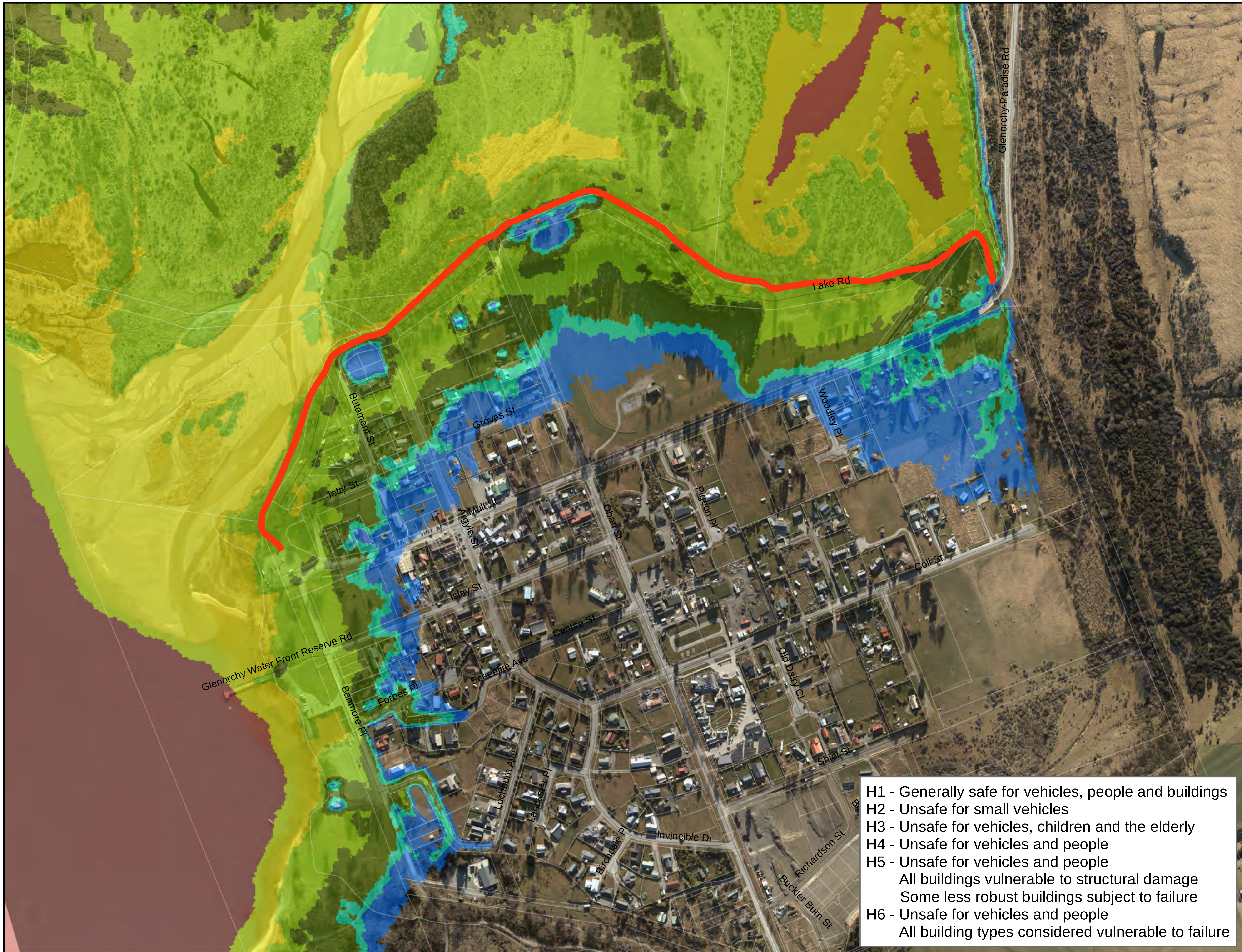
MAP TITLE

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



Legend

- Stopbank
- Roads
- Property boundaries

Hazard Category

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

LANDRIVERSEA CONSULTING

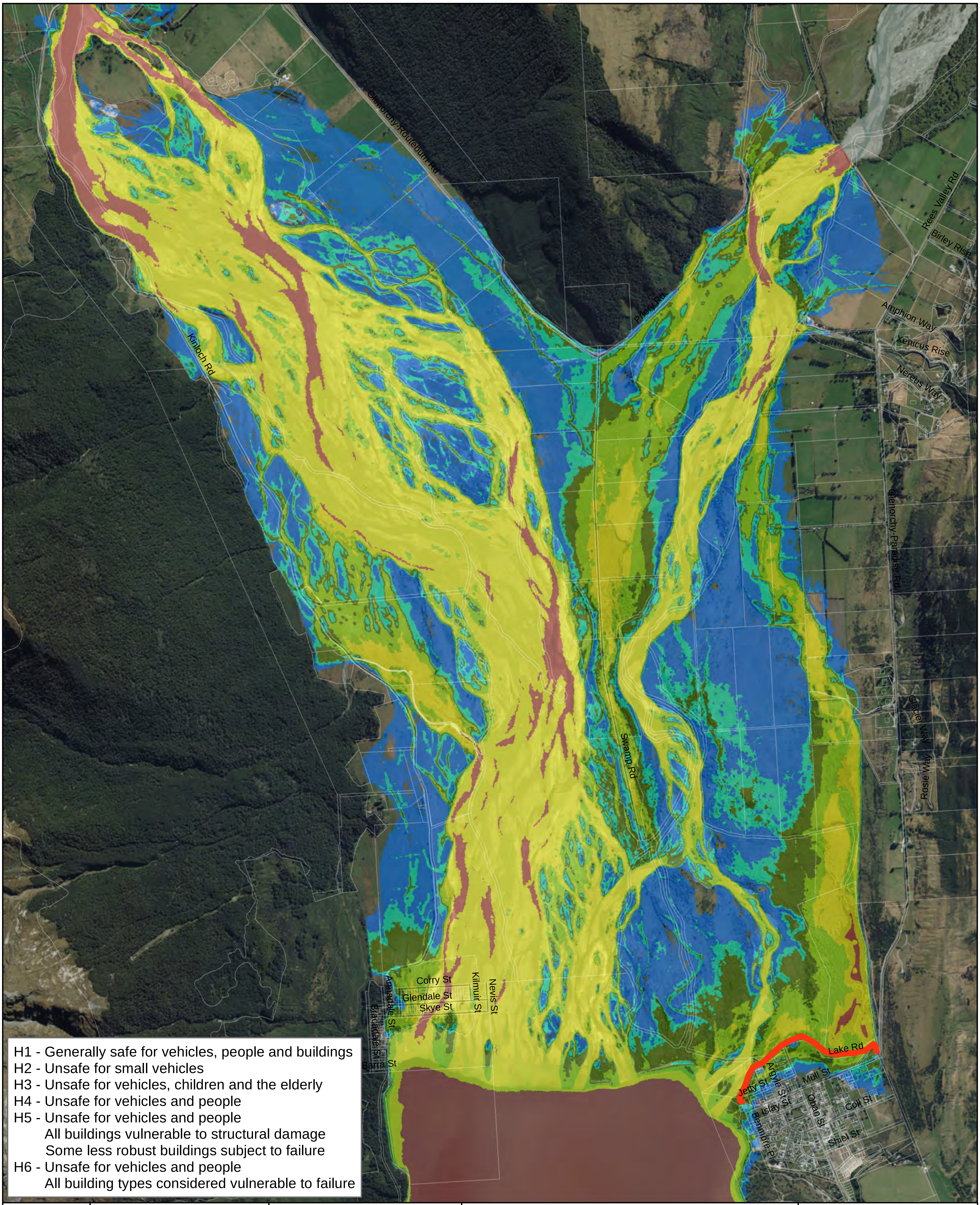
Otago Regional Council

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

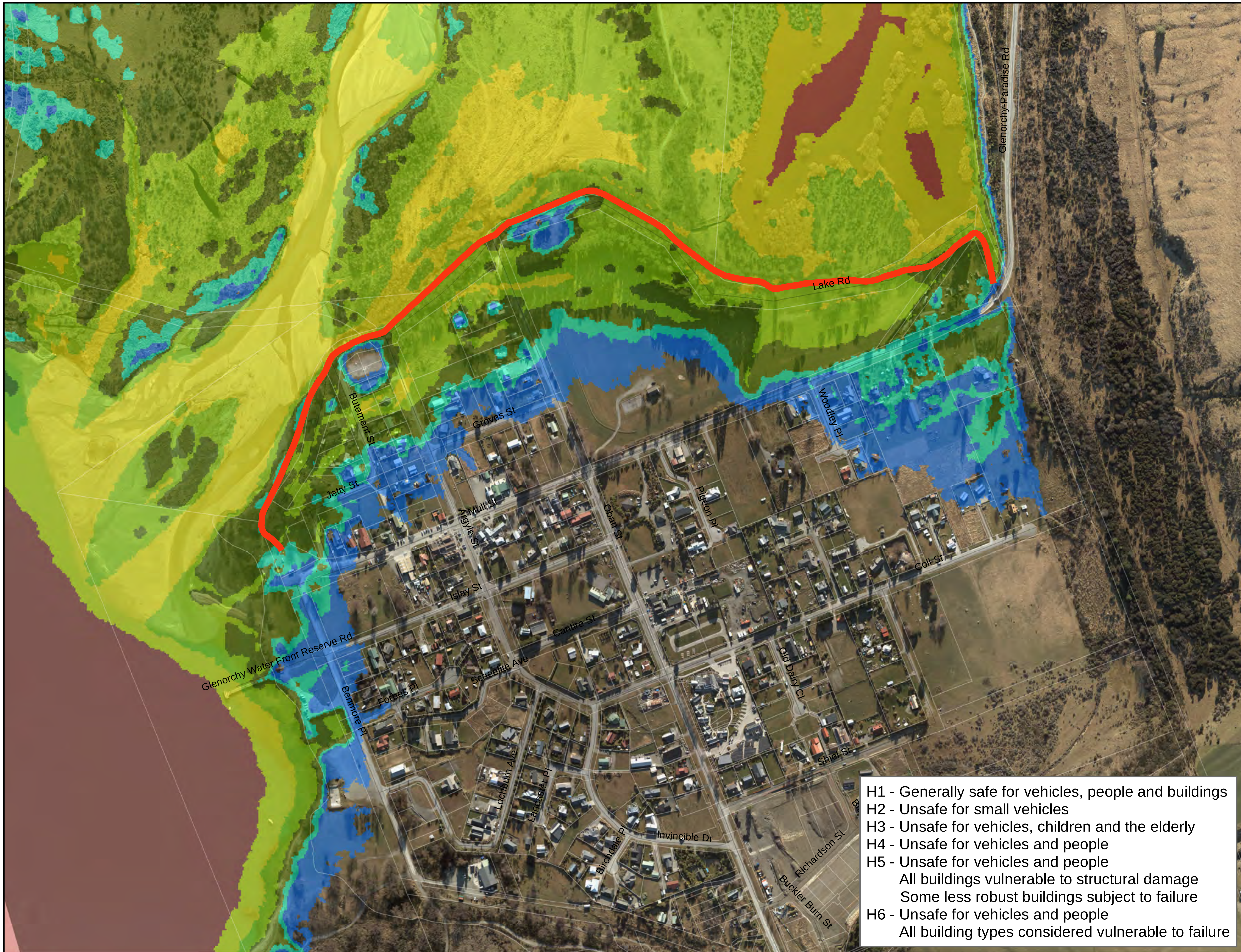
MAP TITLE

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



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

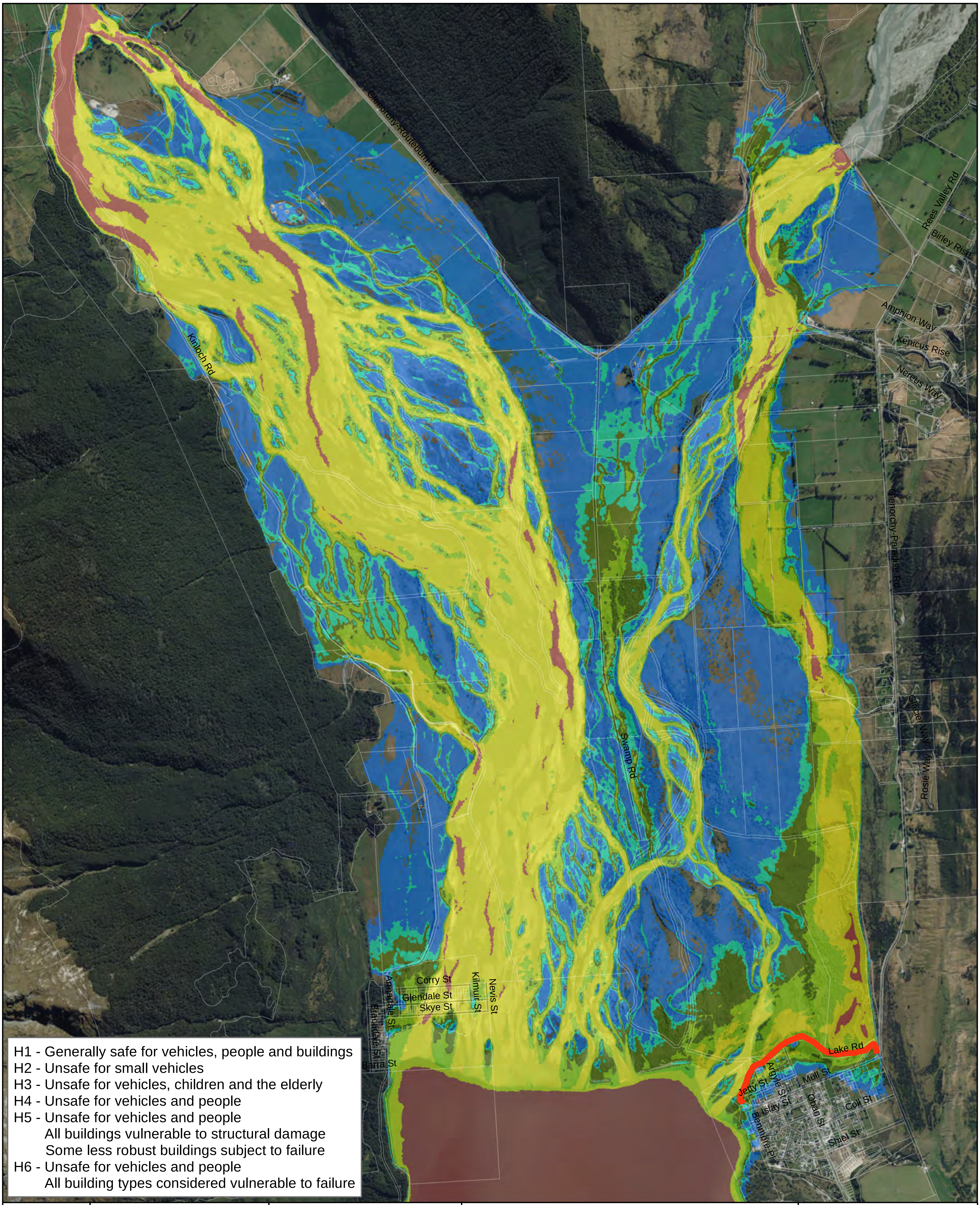
Otago Regional Council

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
Glenorchy Flood Modelling	**HAZARD 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



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

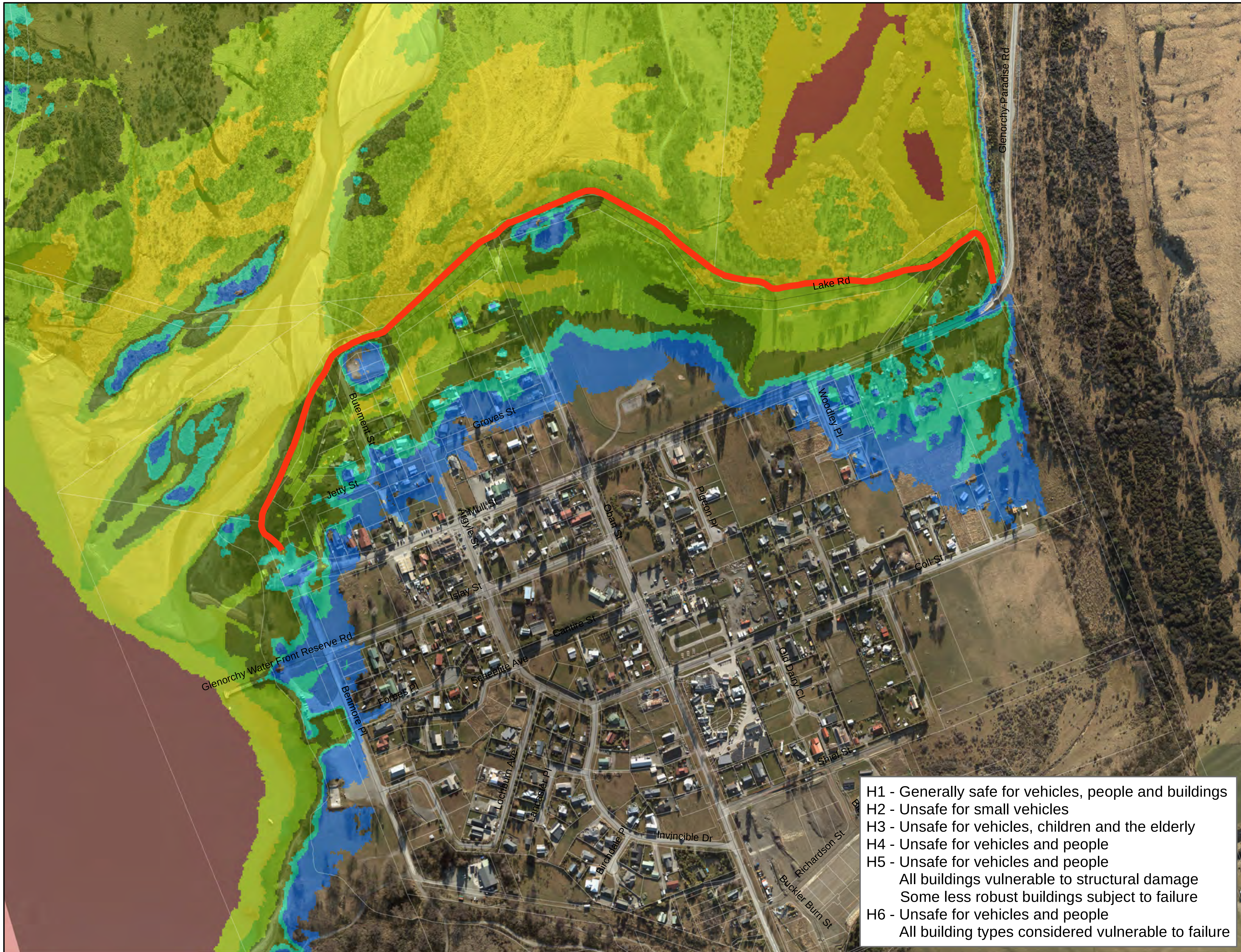
MAP TITLE

HAZARD OVERVIEW MAP
Scenario 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



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

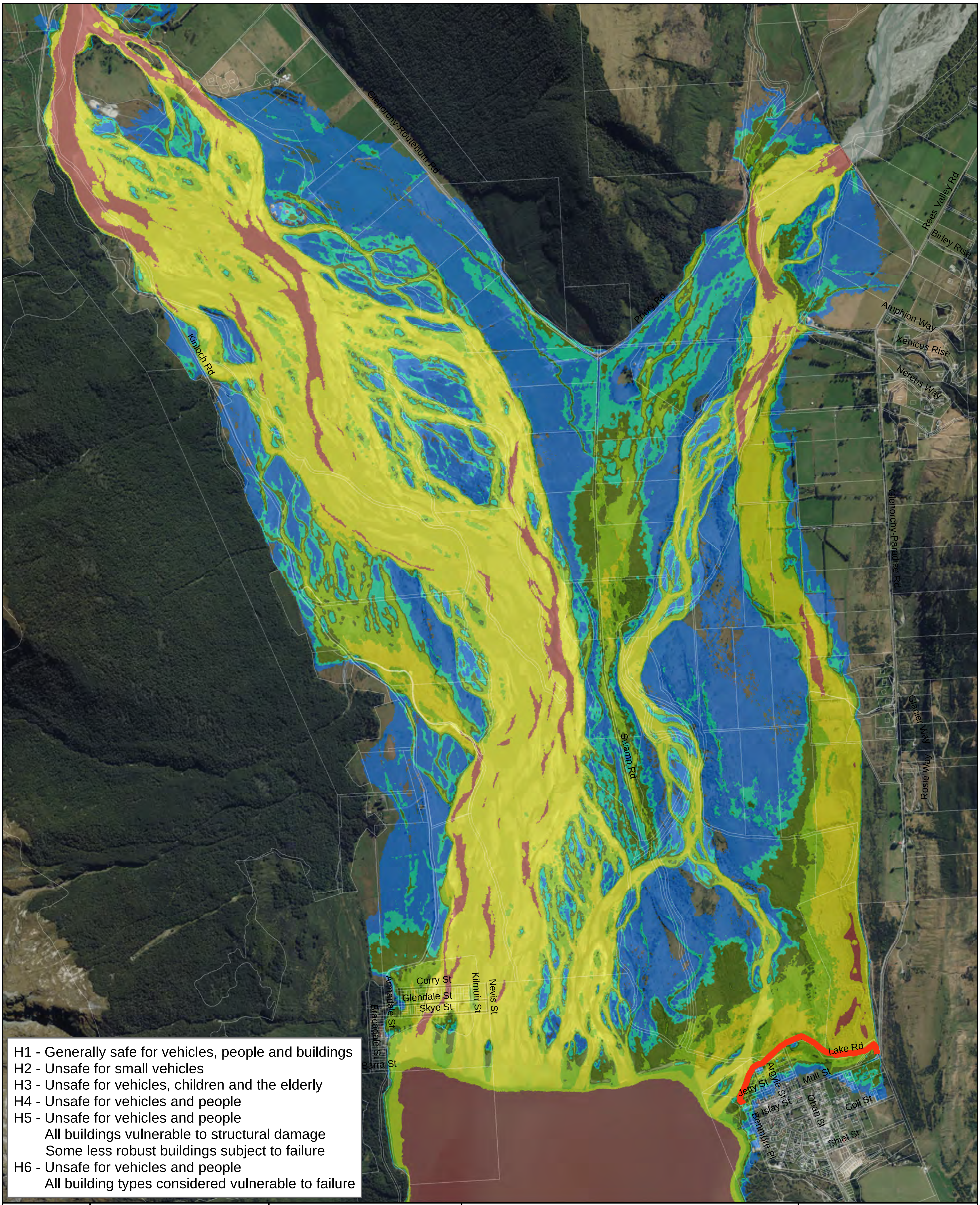
0 0.05 0.1 0.2 Kilometers

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

Model Completed: December 2021

PROJECT	MAP TITLE	REVISION 01	DATE	A3 SCALE
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

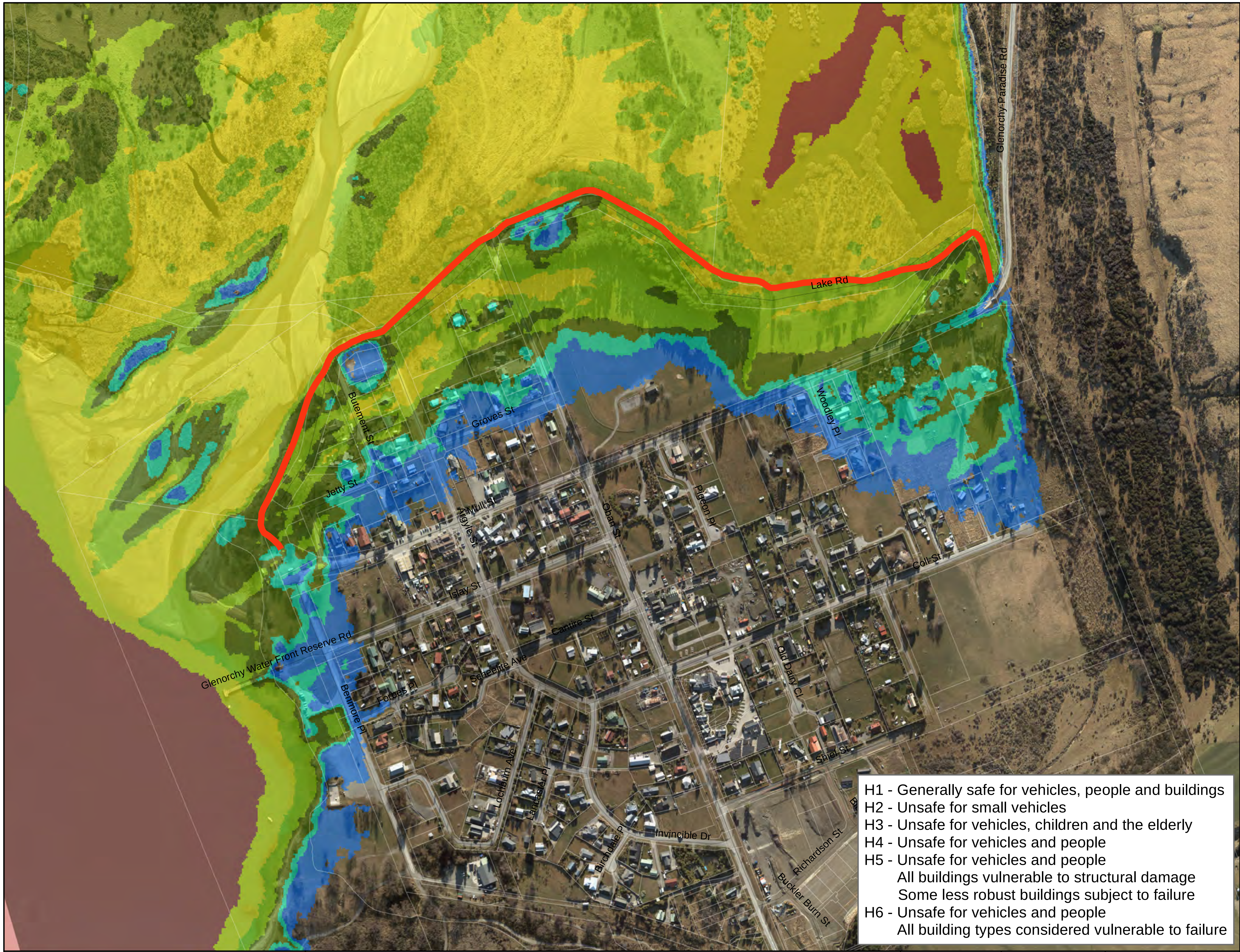
MAP TITLE

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



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

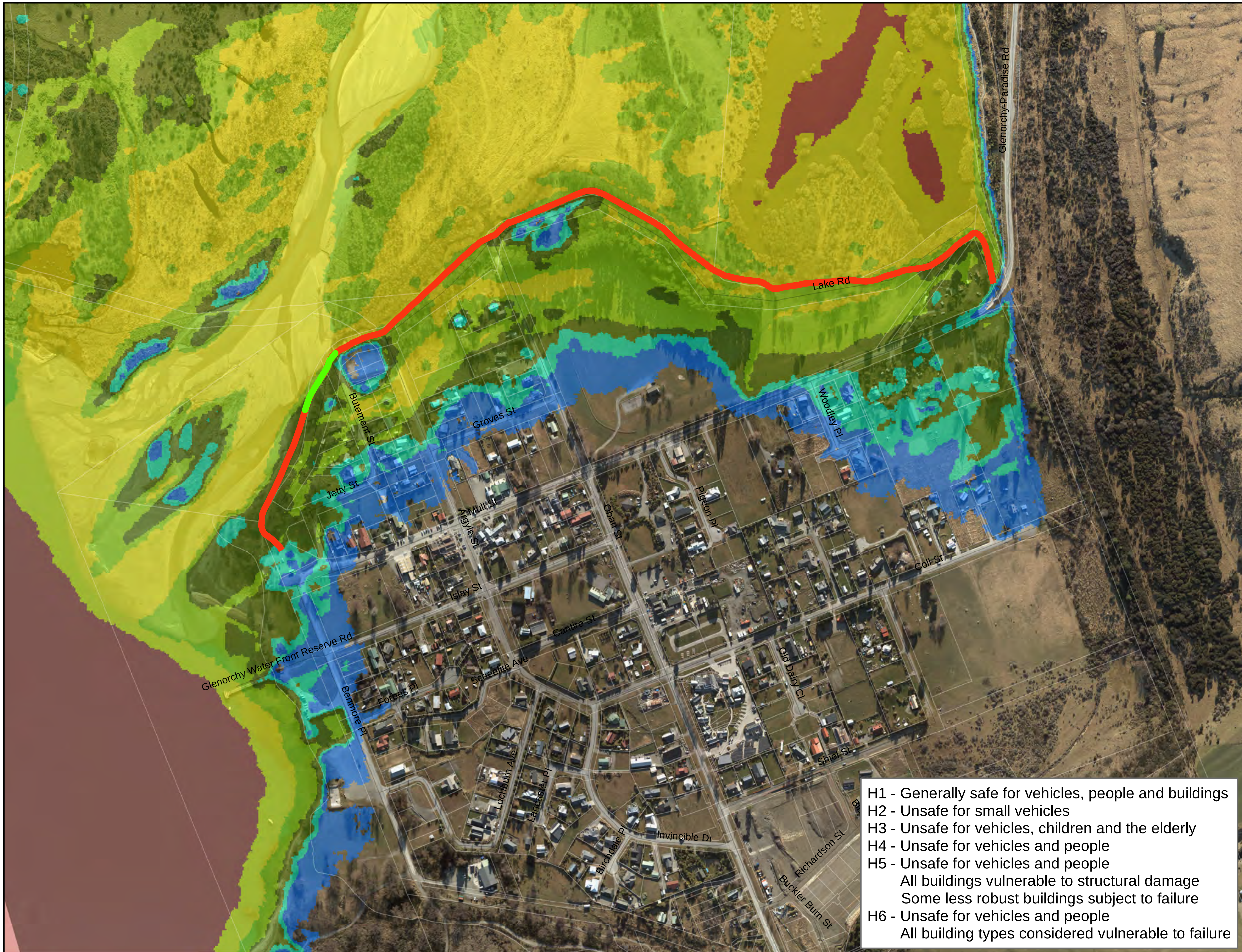
Otago Regional Council

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
Glenorchy Flood Modelling	**HAZARD 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

Hazard Category

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

LANDRIVERSEA CONSULTING

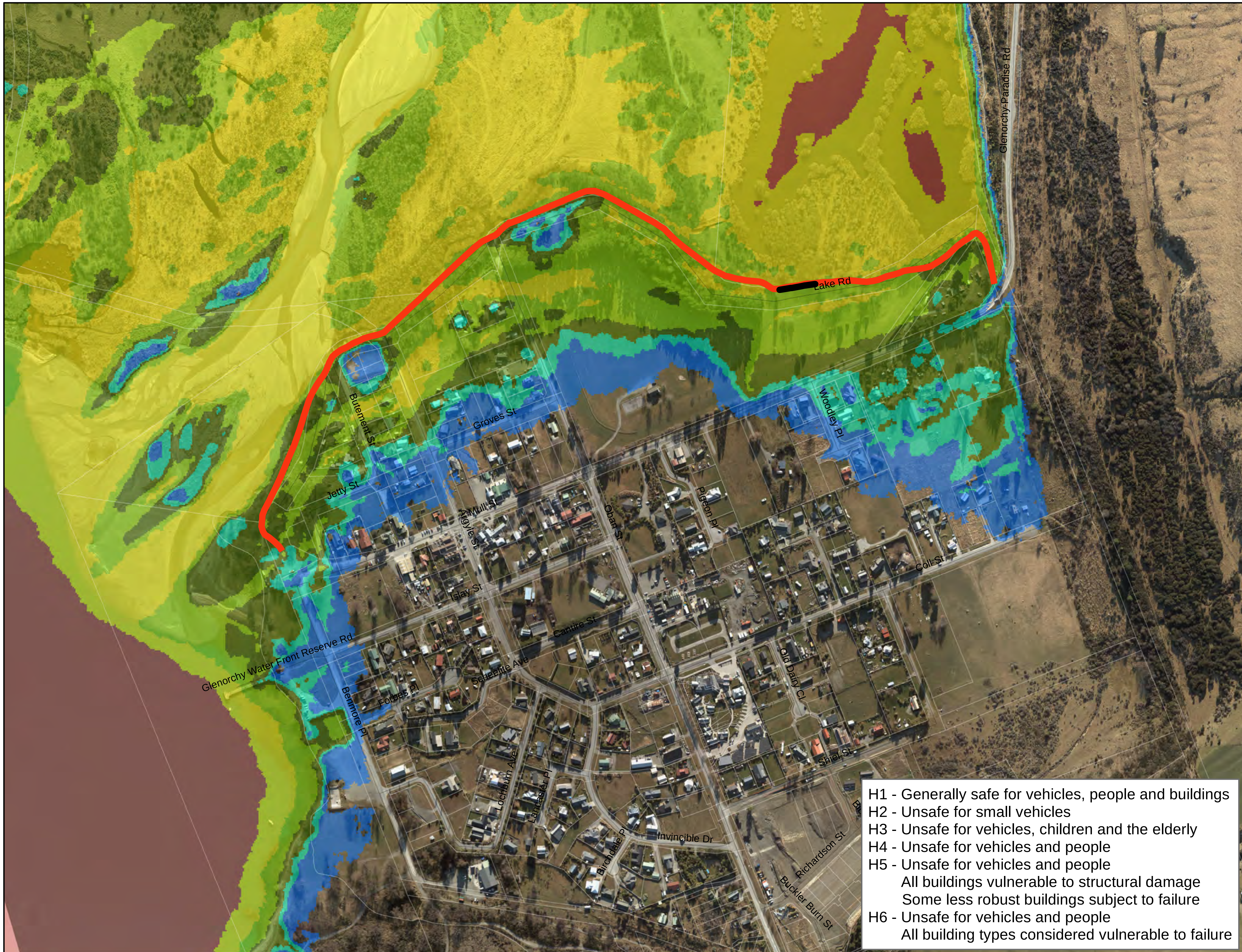
Otago Regional Council

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	N
		REVISED BY	AUTHOR Matthew Gardner		



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 2
- Stopbank
- Roads
- Property boundaries

Hazard Category

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

LANDRIVERSEA CONSULTING

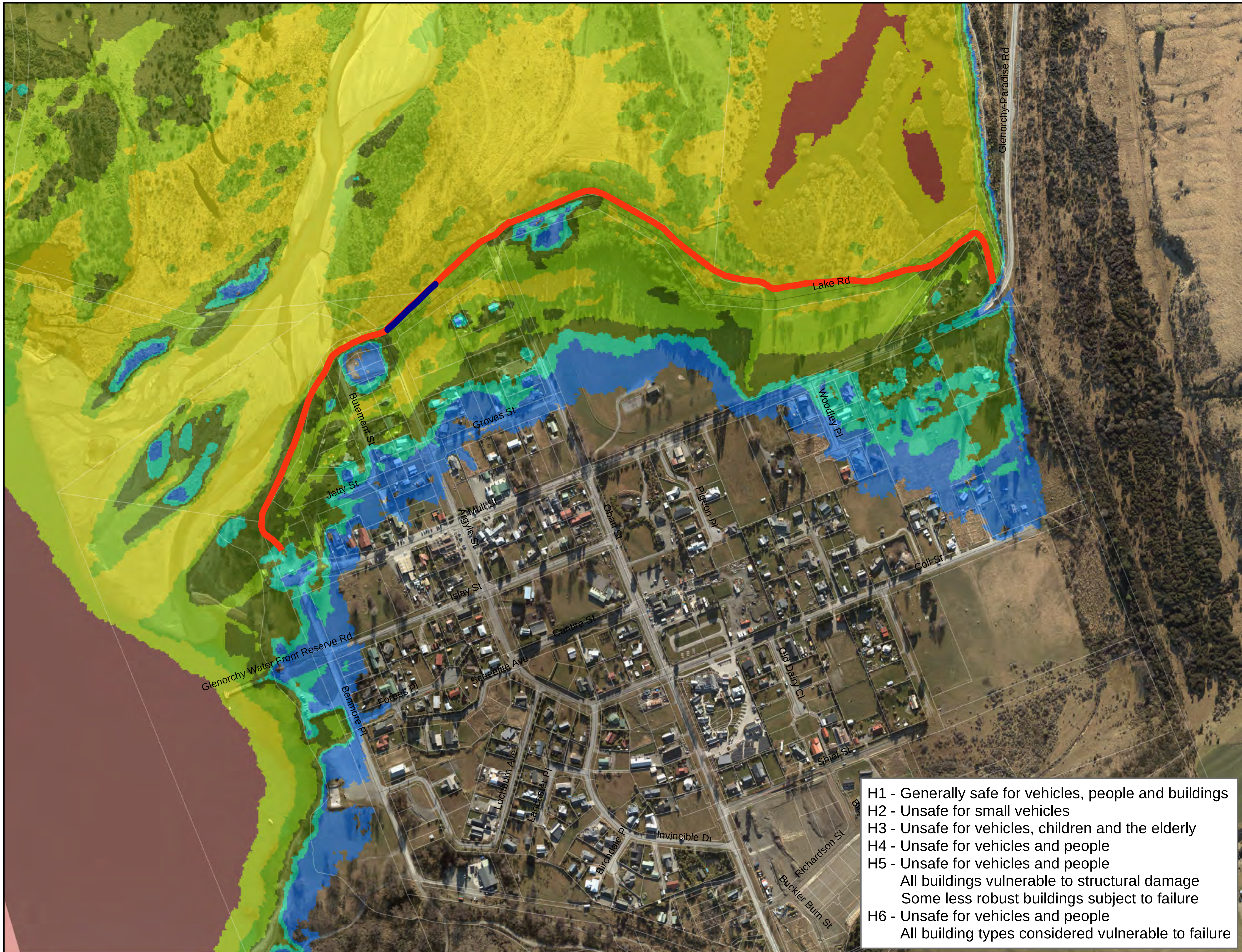
Otago Regional Council

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