Technical Committee - 21 March 2019 Attachments

Otago Regional Council

Minutes of a meeting of the Technical Committee held in the Council Chamber, Phillip Laing House, 144 Rattray Street, Dunedin on Wednesday, 30 January 2019, commencing at 10:59 am

Membership

Cr Andrew Noone	*(Chairperson)*
Cr Ella Lawton	*(Deputy Chairperson)*
Cr Graeme Bell	
Cr Doug Brown	
Cr Michael Deaker	
Cr Carmen Hope	
Cr Trevor Kempton	
Cr Michael Laws	
Cr Sam Neill	
Cr Gretchen Robertson	
Cr Bryan Scott	
Cr Stephen Woodhead	

Welcome

Cr Noone welcomed Councillors, members of the public and staff to the meeting. The meeting was adjourned at 11:00am and re-adjourned at 11:20am.

1. APOLOGIES

2. LEAVE OF ABSENCE

3. ATTENDANCE

Sarah Gardner	*(Chief Executive)*
Tanya Winter	*(Director Policy, Planning and Resource Management)*
Peter Fitzjohn	*(Acting, Director Stakeholder Engagement)*
Gavin Palmer	*(Director Engineering, Hazards and Science)*
Peter Winder	*(Acting, Director Environmental Monitoring and Operations)*
Sally Giddens	*(Director People and Safety)*
Ian McCabe	*(Executive Officer)*
Kim Wainscott	*(Acting, Committee Secretary)*
Mike Roesler	*(Manager Corporate Planning)*
Neil Thomas	*(Groundwater Service Leader, Pattle Delamore Partners Ltd)*
Rachel Ozanne	(*Environmental Resource Scientist)*
Jean-Luc Payan	*(Acting Manager Resource Science)*

4. CONFIRMATION OF AGENDA

The agenda was confirmed as tabled.

5. CONFLICT OF INTEREST

No conflicts of interest were advised.

6. PUBLIC FORUM

No public forum was held.

7. PRESENTATIONS

No presentations were held.

8. CONFIRMATION OF MINUTES

Resolution

That the minutes of the Technical Committee meeting held on 28 November 2018 be received and confirmed as a true and accurate record.

Moved: Cr Noone
Seconded: Cr Lawton
CARRIED

9. ACTIONS

Status report on the resolutions of the Technical Committee.

Report	Meeting Date	Resolution	Status
An assessment of the Clean Heat Clean Air program's effectiveness	13/6/18	That this report be used to inform the review of ongoing financial incentives for Air Quality, proposed for 2018/19 in the 2018-2018 Draft Long-Term Plan	OPEN
Lake Hayes Restoration	1/8/18	That the consultant report by Castalia be re-framed into a more public intelligible document.	CLOSED
Lake Snow technical workshop recommendations	18/10/18	The CE engage on the with CEs at the regional CEOs meeting on 8 November 2018 on the primary objectives from the workshop. Invite Regional Councils and MPI to formally endorse and support the proposed research programme and to discuss funding arrangements.	IN PROCESS

10. MATTERS FOR NOTING

10.1. Director's Report on Progress

The report provided an update on the following matters:

[1] Lake Hayes water quality remediation;
[2] Lower Waitaki River Control Scheme;
[3] November 2018 Otago Flood, and;
[4] Leith Flood Protection Scheme;

The committee noted that Dr Palmer will provide a revised budgetary report for Lake Hayes at the March Technical Committee meeting.

The committee asked for information regarding community engagement regarding the Leith Flood Protection Scheme and were advised that the Otago Regional Council Communications Team is very involved with the University and community who are affected, providing updates, letterbox drops and signage.

Resolution

That the Council:

1) ***Receives*** *this report.*
2) ***Notes*** *this report.*

Moved: Cr Noone
Seconded: Cr Lawton
CARRIED

Cr Laws left the meeting at 11:30 am.
Cr Laws returned to the meeting at 11:33 am.
Cr Bell left the meeting at 11:35 am.
Cr Bell returned to the meeting at 11:40 am.
Cr Laws left the meeting at 11:41 am.

10.2. Recreational Water Quality monitoring in Otago

[1] The report provided a brief update on current recreational water quality monitoring in Otago's rivers, lakes and coastal waters. Monitoring is undertaken at a suite of sites at weekly intervals over the summer months and focuses on human health risks relating to faecal contamination and/or potentially toxic cyanobacteria.

[2] New provisions in the National Policy Statement for Freshwater Management (NPS-FM) mean that the current programme will need to be revisited once Council identifies primary contact recreation sites in an update of the Regional Plan: Water (Water Plan). State of the Environment (SoE) river and lake sites that will be used to monitor progress towards achieving freshwater objectives established in the Water Plan relating to human health will also need to be identified.

Discussion was held on a possible pilot on one of the river flows; and more proactive information for, and engagement with, the community.

Resolution
That the Council:

*1) **Receives** this report.*

*2) **Notes** the summer monitoring programme.*

*3) **Requests** that a paper be provided on opportunities regarding forecasting in priority areas, and best practice for communication options for informing the public regarding contamination of recreational swimming sites with the aim for implementation by next summer.*

Moved: Cr Woodhead
Seconded: Cr Noone
CARRIED

Cr Laws returned to the meeting at 11:55 am.

10.3. Contact Recreation Results 2018-2019

[1] The report provided a brief update on 2018/2019 recreational water quality monitoring results in Otago's rivers, lakes and coastal waters.

[2] The report is an addendum to the paper 'recreational water quality monitoring in Otago' presented to the Technical Committee on 30-Jan-19.

The committee noted the need for discussion on budgetary issues, and the communication approach, during the annual plan process.

Resolution
That the Council:

*1) **Receives** this report.*

Moved: Cr Noone
Seconded: Cr Lawton
CARRIED

10.4. Wanaka Basin-Cardrona Gravel Aquifer Groundwater Model Report

The report detailed the results of a groundwater model developed by Pattle Delamore Partners ('PDP') that simulates the effect of groundwater abstraction on surface water flows and recommends an appropriate allocation approach. The findings from the study are included in the Wanaka Groundwater Model Report (*Attachment 1*).

The committee noted the importance of disseminating this report and the communication between staff and those receiving it.

Resolution
That the Council:

*1) **Notes** this report.*

*2) **Notes** that the Wanaka Groundwater Model Report will be made publicly available and will be provided to Cardrona catchment water users.*

Moved: Cr Lawton
Seconded: Cr Bell
CARRIED

11. NOTICES OF MOTION

No Notices of Motion were advised.

12. CLOSURE

The meeting was declared closed at 12:20 pm.

Chairperson

Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept

client / project name: OTAGO REGIONAL COUNCIL
drawing name: **FORTH STREET TO HARBOUR - OVERALL PLAN**
designed by: Dave Compton-Moen / Mike Moore
original issue date: 17 MAY 2018
scales: 1:4000 @ A3

revision no:	amendment	approved	date
-	DRAFT OPTION	DCM	17.5.18
A	DRAFT OPTION	DCM	25.5.18
B	DRAFT FINAL OPTION	DCM	26.5.18
C	FINAL OPTION	DCM	27.5.18
D	FINAL ISSUE	DCM	28.5.18
E	OPTION 2 ADDED	DCM	29.5.18
F	OPTION 2 AMENDED	DCM	21.6.18

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project no / drawing no: **2018_020 - MIKEMOORE-LEITHWORKS_ FORTHSTHARBOUR_CONCEPT_100**
revision: F

Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept

client / project name: OTAGO REGIONAL COUNCIL
drawing name: **FORTH STREET TO HARBOUR - FORTH STREET - ANZAC AVENUE PLAN**
designed by: Dave Compton-Moen / Mike Moore
original issue date: 17 MAY 2018
scales: 1:1000 @ A3

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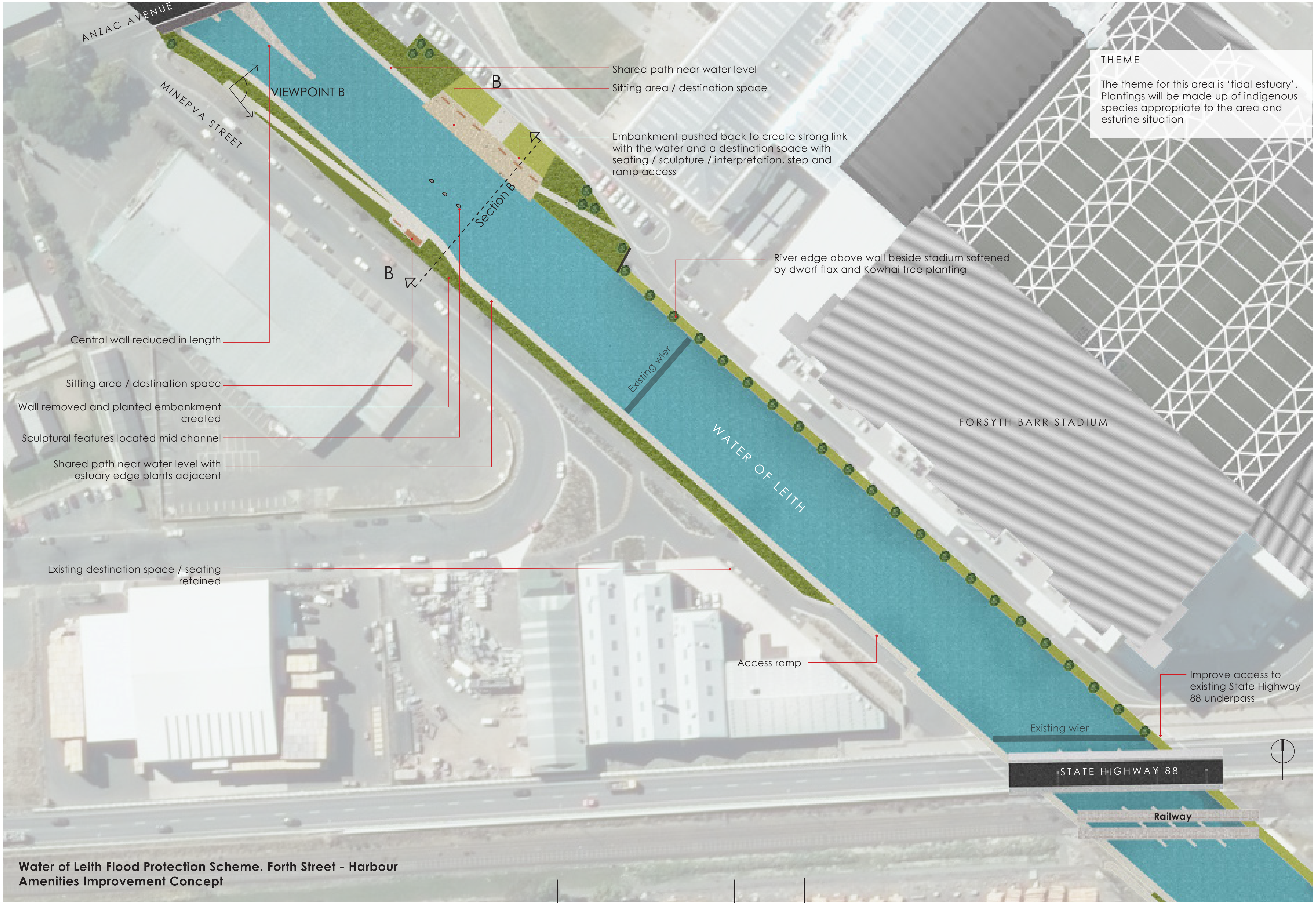
revision: E



Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept

client / project name: OTAGO REGIONAL COUNCIL
drawing name: **FORTH STREET TO HARBOUR - ANZAC AVENUE - STATE HIGHWAY 88 PLAN**
designed by: Dave Compton-Moen / Mike Moore
original issue date: 17 MAY 2018
scales: 1:1000 @ A3

revision no:	amendment	approved	date
-	DRAFT OPTION	DCM	17.5.18
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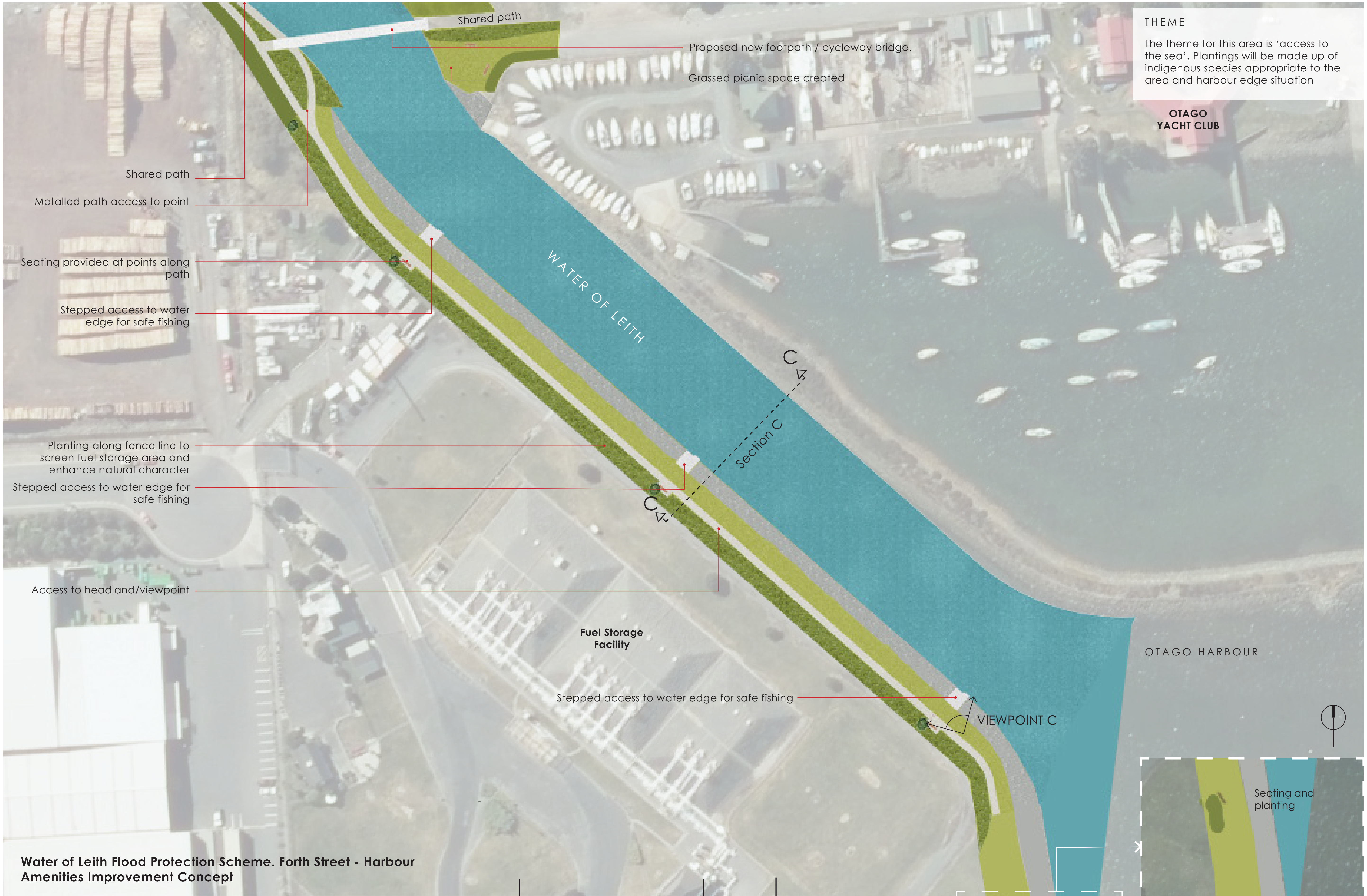
revision: **F**



Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept

client / project name: OTAGO REGIONAL COUNCIL
drawing name: **FORTH STREET TO HARBOUR - STATE HIGHWAY 88 - OTAGO HARBOUR**
designed by: Dave Compton-Moen / Mike Moore
original issue date: 17 MAY 2018
scales: 1:1000 @ A3
project no / drawing no: **2018_020 - MIKEMOORE-LEITHWORKS_ FORTHSTHARBOUR_CONCEPT_100**

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Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept

client / project name: OTAGO REGIONAL COUNCIL
drawing name: **FORTH STREET TO ANZAC AVENUE - PERSPECTIVE A**
designed by: Dave Compton-Moen / Mike Moore
original issue date: 17 MAY 2018
scales: NTS

revision no:	amendment	approved	date
-	DRAFT OPTION	DCM	17.5.18
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project no / drawing no: **2018_020 - MIKEMOORE-LEITHWORKS_ FORTHSTHARBOUR_CONCEPT_100** revision: F

Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept

client / project name: OTAGO REGIONAL COUNCIL
drawing name: **FORTH STREET TO ANZAC AVENUE - PERSPECTIVE A- OPTION 2**
designed by: Dave Compton-Moen / Mike Moore
original issue date: 17 MAY 2018
scales: NTS

revision no:	amendment	approved	date
-	DRAFT OPTION	DCM	17.5.18
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revision: F

Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept

client / project name: OTAGO REGIONAL COUNCIL
drawing name: **ANZAC AVENUE TO STATE HIGHWAY 88 - PERSPECTIVE B**
designed by: Dave Compton-Moen / Mike Moore
original issue date: 17 MAY 2018
scales: NTS

revision no:	amendment	approved	date
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F	OPTION 2 AMENDED	DCM	21.6.18

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project no / drawing no: **2018_020 - MIKEMOORE-LEITHWORKS_ FORTHSTHARBOUR_CONCEPT_100**
revision: F

Forsyth Barr Stadium

Proposed new footpath / cycleway bridge (indicative)

Planting along fenceline to screen fuel storage area and enhance natural character

Seating provided at points along path

Metalled path - semi permeable surface

Stepped access to water edge for safe fishing

Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept

client / project name: OTAGO REGIONAL COUNCIL
drawing name: **STATE HIGHWAY 88 TO OTAGO HARBOUR - PERSPECTIVE C**
designed by: Dave Compton-Moen / Mike Moore
original issue date: 17 MAY 2018
scales: NTS

revision no:	amendment	approved	date
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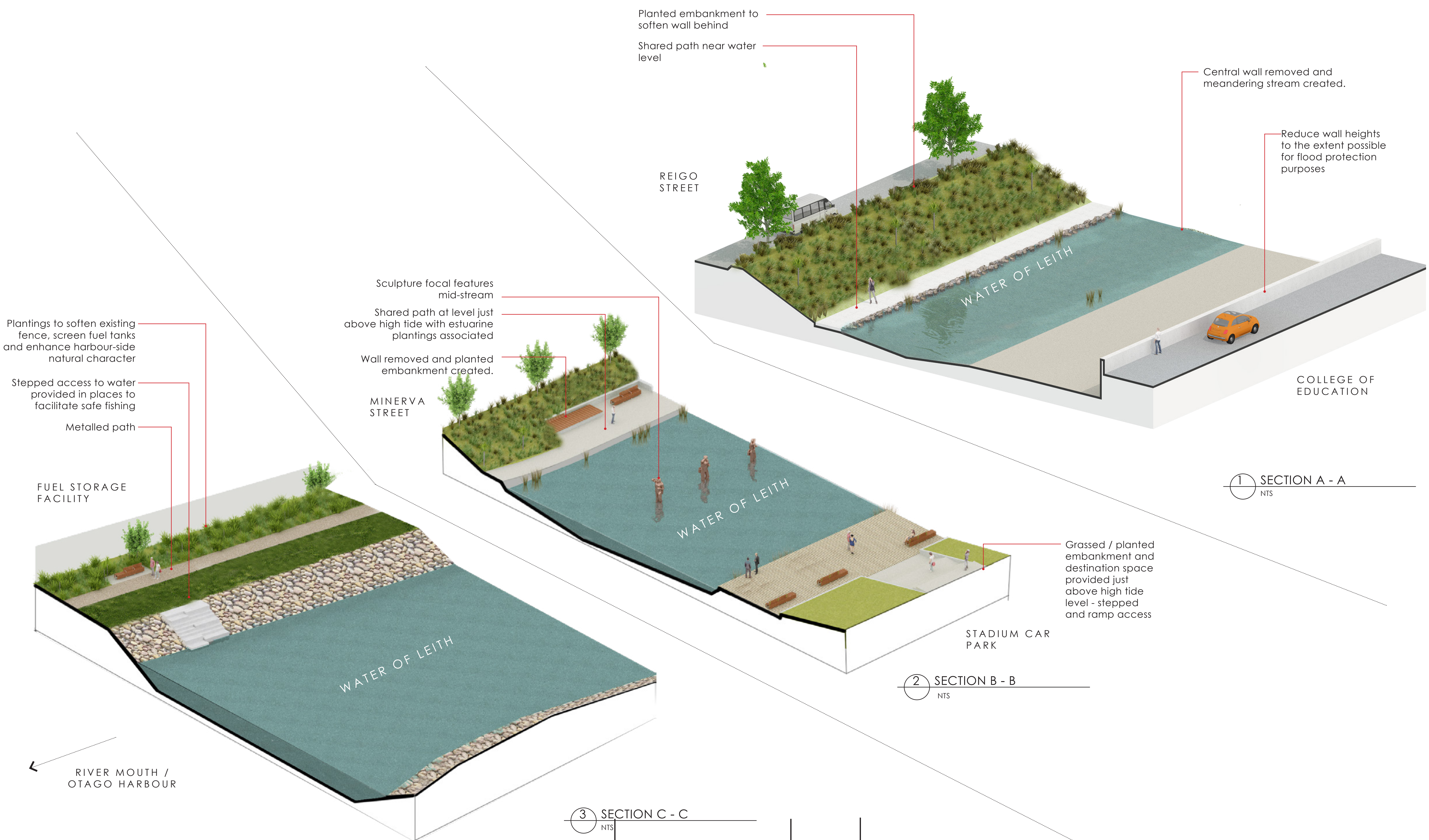

client / project name: OTAGO REGIONAL COUNCIL
drawing name: **FORTH STREET TO HARBOUR - CROSS SECTION**
designed by: Dave Compton-Moen / Mike Moore
original issue date: 17 MAY 2018
scales: NTS

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revision: F

Leith Project Working Group Final Report

October 2018

Executive summary

The Leith Project Working Group presents their Final Report for the Otago Regional Council's (ORC) consideration. This report details the Final Design Concept, the reasoning behind each section of the project and illustrates the recommendations with the attached drawings from the landscape architect.

The Final Concept Design incorporates the key stakeholders' requirements and recommendations, the input from neighbouring business owners and the wide-ranging suggestions, recommendations and endorsements from both rounds one and two of 'Love Your Leith' - the community engagement project. The Working Group noted the significant consistency of the inputs from each of these contributing groups and the high level of stakeholder and community support for what is proposed; with an approval rating in excess of 80%.

In considering each of the suggestions for inclusion, the Working Group used a three-level framework to assess the potential contribution to the project:

- Does it meet the technical requirements of the ORC's Workbook?
- Does it contribute to the guiding principles detailed below?
- Does it add to the design consideration's developed?

Within that framework, the Working Group's guiding principles further refined the project:

- Aiming to return the Leith to a more natural state while meeting flood protection, accessibility and health and safety considerations.
- Recreating areas representing a natural stream and a length of tidal estuary.
- Improving shared pathway access along both banks of the Leith and increasing opportunities to access the water level for recreation.
- Enhancing the water quality and ecology of the area to encourage the return of wildlife.
- Creating spaces for un-defined and flexible recreation purposes, for temporary and or permanent art installations or performances and for presenting the historical and cultural aspects of the Leith such as Kāi Tahu stories, cultural values, names and traditions.

The final design detailed in this report creates a long-term plan to achieve three, themed areas which are aligned to the three distinct sections from Forth St to the harbour:

1. Forth St – Anzac Av: **Natural stream**
2. Anzac Av – State Highway 88: **Tidal estuary**
3. State Highway 88 – Harbour: **Connect the city to the sea**

Background

The Leith Project Working Group was established by the ORC in December 2017 to provide key stakeholder collaboration and input into the Leith Amenity Project, for the Forth St to Harbour section of the Leith, as one of the last stages of the Leith Flood Protection Scheme.

The Working Group was formed with representation from:
Dunedin City Council (DCC),
Otago Polytechnic,
University of Otago,
Kai Tahu contract advisors Aukaha
Otago Regional Council (ORC).

An independent Facilitator was appointed by the ORC to plan and organise the Working Group process. Individual representation from each organisation changed throughout the project, but the Working Group shown in Appendix K, page 20, details those who created this final report.

Objectives

The initial briefing paper to the Working Group outlined the main objectives:

- To review community feedback and to develop concepts for enhancement of amenity, public access and ecology
- To understand the physical limitations of flood conveyance, accessibility and ecological and financial limitations
- To collaborate to produce a final design concept that meets public, stakeholder and ORC expectations.

At the Working Group's first formal meeting on 18 December 2017, members were provided with Workbook prepared by ORC which detailed the key background information required to guide decision making. Section 6 of this booklet did not include a budget for the project and consequently the Working Group members have focussed on providing creative solutions within the technical constraints detailed. It is understood that the totality of this plan will exceed the funds currently available and the Working Group recommends that the project is staged, and constructed as ORC and potential partners', funds become available. This draft report does provide a suggested priority ranking for the works as Appendix J, page 18.

Guiding Principles

The Working Group established a set of guiding principles to under-pin their deliberations. These were to:

- Consider a holistic view of the project and links to the prior Leith developments
- Aim for creating the most natural state possible
- Provide for enhanced natural planting
- Give access to the harbour
- Improve public access to the waterway
- Create/maintain fish access
- Minimise sediment deposit
- Follow Workbook cultural principles

Design Considerations

Based on the Guiding Principles, the Working Group created a list of 12 Design Considerations to provide a practical framework to connect the suggested enhancements, the guiding principles, and the ORC Workbook requirements. These were to:

1. **Maintain flood protection** while considering sea level rise

2. **Improvements must be flood resistant**, with minimal post-flood reinstatement costs.

3. Create **natural characteristics and natural habitat** – but may use modern methods

4. Ensure all enhancements meet **safety, security and regulatory** requirements.

5. **Ecology restoration** is preferred to "landscaping".

6. **Water quality** to be improved

7. **Access should be provided** along the length of the project, on both banks and ideally this access should reflect the current working agreement between the University, Polytechnic and DCC with the Tertiary Precinct Group (TPG). Any works should integrate with the existing street networks and any TPG proposed upgrades.

8. **Centre island should be removed** unless needed for bridge support.

9. **Consider Leith in three sections and themes**
   - Above Anzac Avenue bridge, design to reflect a stream
   - Below Anzac Avenue bridge, design to reflect an estuary
   - From Forth Street to harbour, design to connect the city to the sea

10. **Construct project from the top down**, maintaining a continuous improvement flow. The meeting acknowledged the potential for this to be a project staged over some years.

11. Allow for flexible spaces to be available for **art/ sculpture/performance/recreation** development.

12. Project should **link to the Polytechnic's plan** to rebuild the old Teacher's College building.

The detailed considerations, design iterations, and reflections on each of the many, many suggestions received are detailed in the eight Workshop Reports which record the Working Group's progress through this project

Design planning

Beginning with a full-day workshop, and guided by the design frameworks created, the Working Group held a site visit which covered the entire length of the project along both banks.

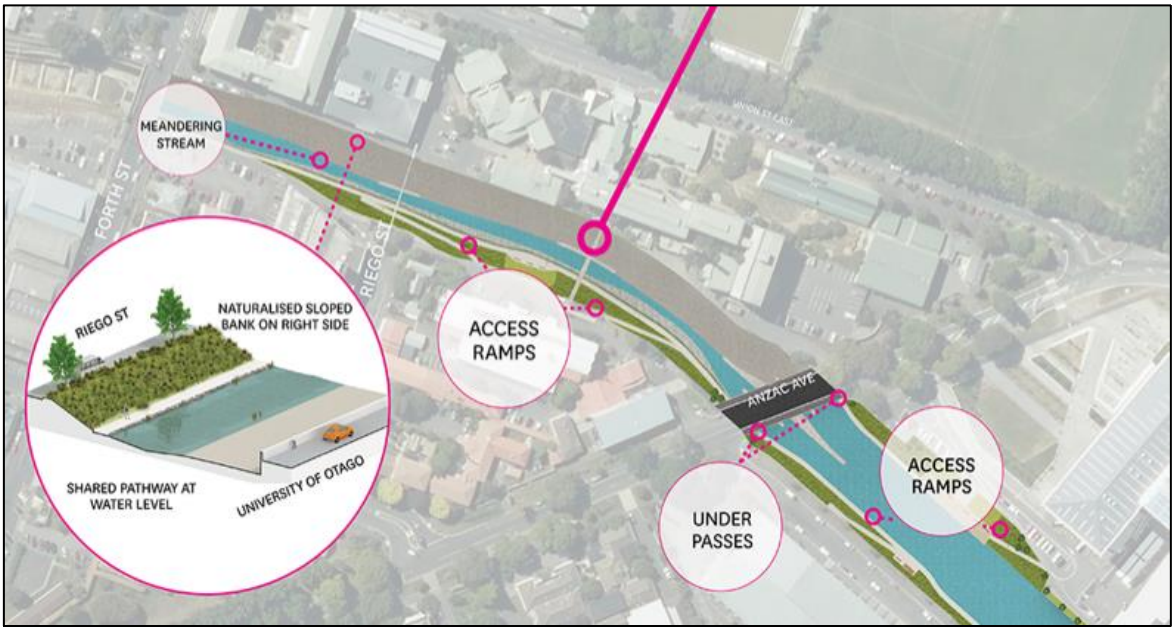
This was followed by a series of workshops where the Working Group suggestions and initial input from the Community Engagement project were located on large scale aerial plans to develop an initial view of the possibilities offered by the project. These were detailed in the Working Group report dated 7 March 2018 which lists each of the suggestions received and locates them on a series of overlays. The recommendations in that report were subsequently checked by the ORC staff to ensure they met the hydraulic, accessibility and safety requirements, and minor amendments were made to achieve compliance. From there, a document was prepared to brief the Landscape Architect to produce the draft Design Concepts drawings.

These drawings were used as the basis for the creation of display panels, which, along with the ORC's online tools, presented the Working Group's recommendations to the community for their feedback. This further stage of community engagement gave the Working Group a high level of support for the proposals, while suggesting further fine-tuning and enhancements which have been incorporated into this report.

Key Project recommendations

The recommendations below – and the attached plans, cross-sections and artistic impressions from the landscape architect show the three areas of development. It must be stressed that the artistic diagrams attached do represent a stylised representation of the Working Group's recommendations and we would expect the final, as-built project to be less formal, more natural and to include more plant diversity, as shown in the example below of the development upstream to this project.

Forth Street to Anzac Avenue *– Appendices A, B, C*



1. This section of the Leith should be returned to as "natural" stream state as possible, mirroring the project works completed above the Forth St bridge.

2. Centre channel wall to be removed where possible in this area to enhance natural stream appearance by including floodable plantings, water-level shared pathways and by adding meanders in the stream bed.

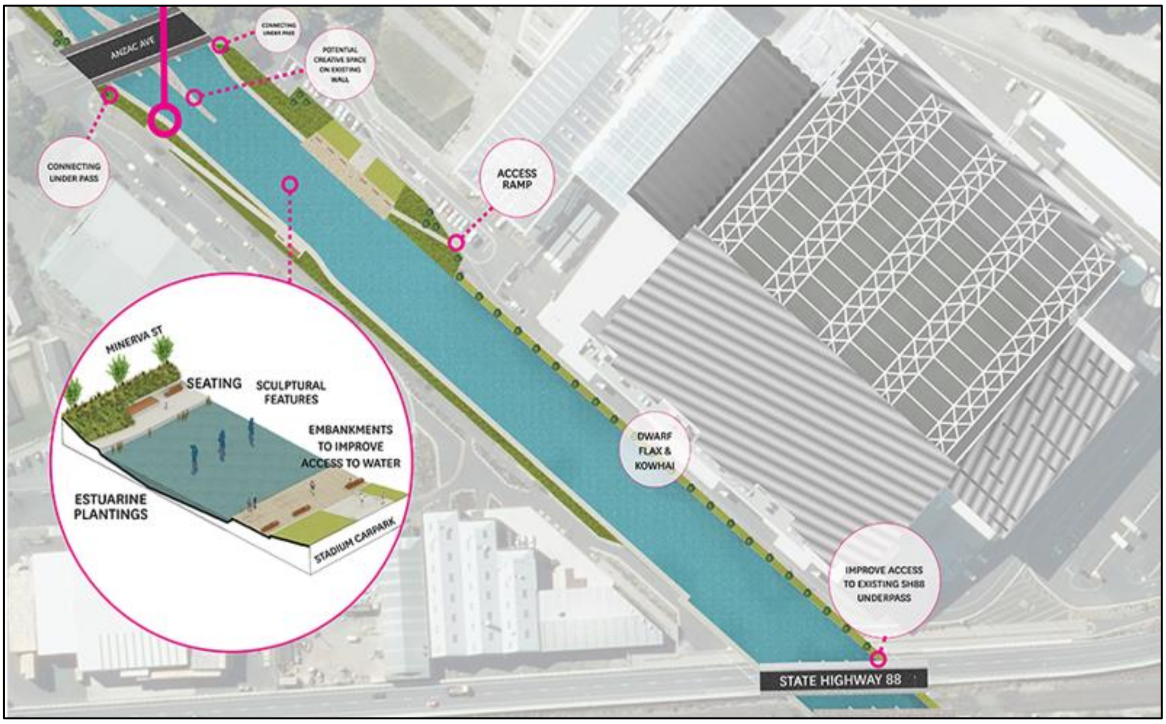
3. The right bank should be developed in conjunction with the Otago Polytechnic redevelopment plan for the area. It is considered a priority for the two projects to work together to achieve:
    a. Improved access to the water level and flexible-use "destination" places
    b. Improved access to the existing footbridge.
    c. Improved non-vehicle links to longitudinal access.

4. On the left bank, sloping banks should be created to the extent possible by the hydrological cross-section limitations. At a minimum, the project should include a naturalised stream bed and "floodable", above tide-level walkways to give longitudinal access to the water and minimise the need for safety rails.

5. Consideration should be given to developing the remaining left-bank concrete channel walls into a feature area, including representational panels describing the historical and cultural aspects of the area. The obsolete pipe-work on the true left channel wall can be removed.

6. It is important this project links to the walkways existing above the Forth Street bridge to allow access without the need to cross the road. There is a wider potential for this project to support the Tertiary Precinct Group project underway between the DCC, University and Polytechnic.

Anzac Avenue to SH88 – *Appendices D, E, F*



1. This area of the Leith has been designed to reflect its estuarine state at the usual limit of tidal inflows; planting and construction should enhance a tidal estuary theme.

2. The plan provides options for pedestrians/cyclists to cross Anzac Avenue, by developing water-level walkways under the bridge on both banks as a priority.

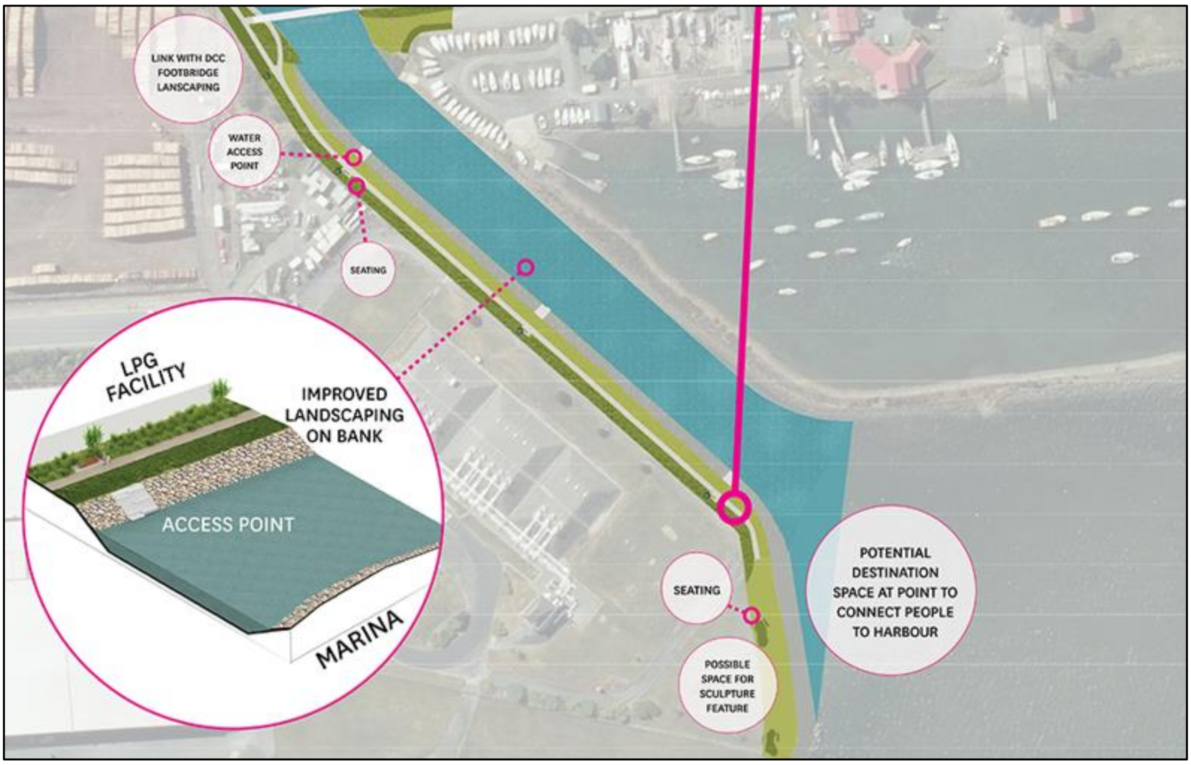
3. On the true right, the design continues the Otago Polytech redevelopment and links to the Minerva Street section. It enhances the DCC access already created by sloping the bank from the grassed area into water and by creating flexible use destination points.

4. The Working Group has identified an opportunity to enhance visual appeal of Stadium while improving event-day access by creating a walkway along the left bank to provide a link from the Stadium under Anzac Avenue.

5. The design creates a feature area, alongside current Stadium carpark, which would remain above water at high tide and give access to the water for picnics, fishing or swimming.

6. The recommendations open access from Stadium to the existing path under SH88

SH88 to the sea – Appendices G, H, I



1. This project links to the DCC landscaping proposed for the new shared-pathway bridge currently under development.

2. The design improves access to the water by the yacht storage, to give swimming and family boating opportunities and to include picnic and exercise areas.

3. The plan improves links to planned and existing cycleways/paths on both banks.

4. In response to significant demand, the plan opens access to a new “to the sea” path on true right, along the existing grassed area and uses native plantings to screen the wood and gas storage areas.

5. It also creates fishing access points and develops the largest area possible at the end of the walkway for picnics and city viewing.

Potential Project Partnerships

The process has identified several areas of significant opportunity to join this Leith Amenity Project to existing projects:

- This project has the potential to be linked to the current DCC project constructing a pedestrian/cycle bridge across the Leith downstream of SH88. The DCC's landscaping and amenity plans for their project should be combined with the recommendations in this project to achieve improved outcomes with shared costs.
- This project has the potential to be linked to the existing DCC, University, Polytechnic Tertiary Precinct Group project to enhance pedestrian/cycling access within the tertiary area.
- This project has the potential to be linked to the existing Polytechnic plan to redevelop their properties alongside Riego Street and joint funding of the amenities enhancement is possible.
- This project has the potential to link to the Forsyth Barr Stadium requirements for access enhancements to the Stadium and road safety improvements already suggested for Anzac Avenue.
- The project has the potential to partner with the Polytechnic's public art commissioning plan and with the DCC's public art framework to provide flexible spaces to house such art.

The Working Group recommends that the ORC develop formal project relationships with the organisations noted above to explore opportunities to work collaboratively by building on the partnerships identified in this project.

General information

The Community Engagement projects collected a considerable number of small-scale suggestions which are captured in the Engagement Reports. It is recommended that the ORC review each of these suggestions as construction planning is begun for each section, to judge the practicality, cost and value of their inclusion. These suggestions range from decorative lighting displays under the bridges through to the arm-rest design for any seating provided and these, together with the partnership opportunities identified above, have the potential to enhance the project and strengthen community input and involvement.

The project also noted the calculated potential long-term flooding resulting from sea level rise and the value of informing property owners alongside the Leith of this possibility, to assist with their capital planning.

Construction priority

The Working Group recommends that the project is developed progressively, starting at Forth Street, once the current works above the bridge are complete, and working downstream as funding permits. This priority represents the recommendations of all stakeholders and the community engagement.

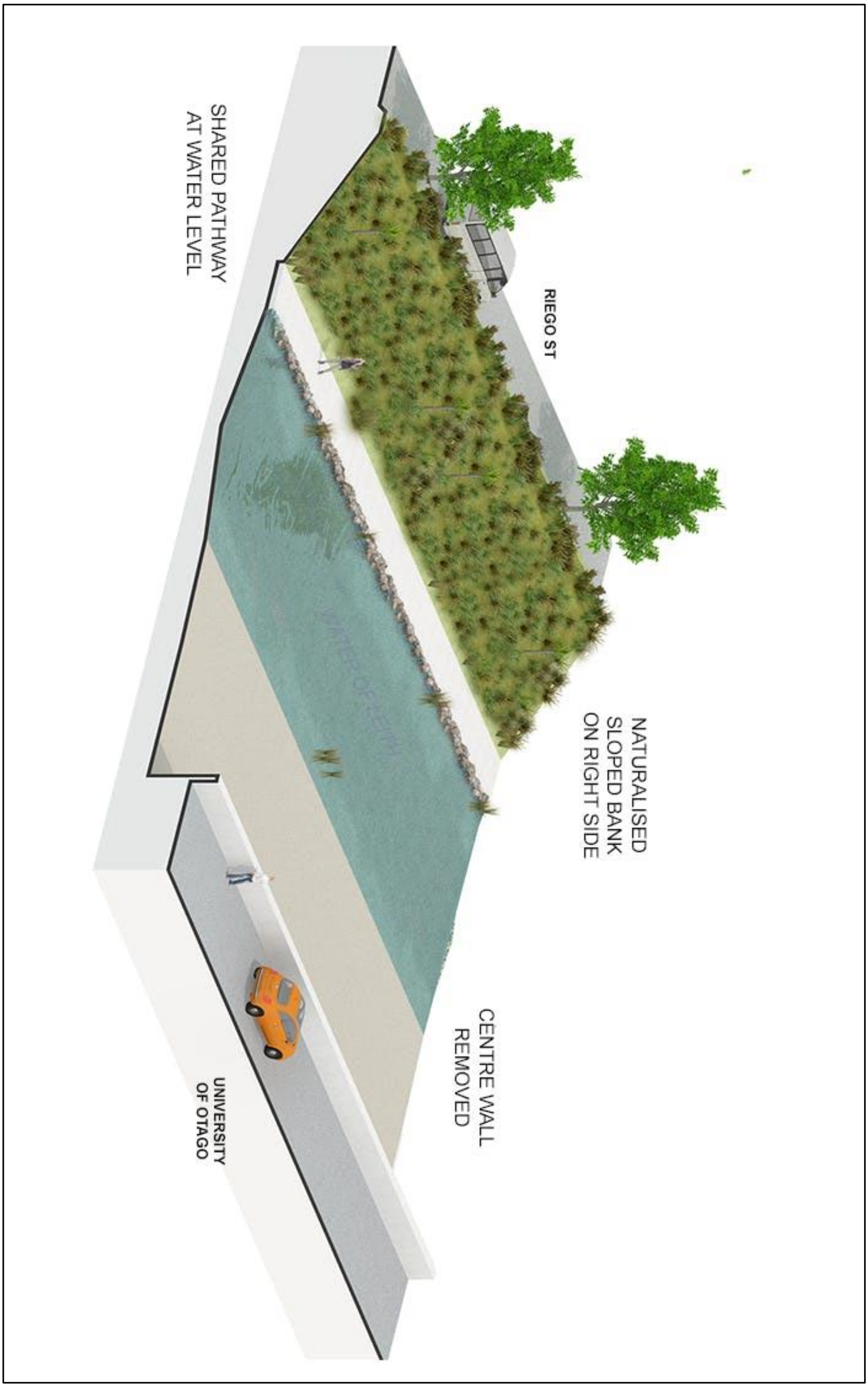
There are two, low cost features which could enhance the area immediately and it is recommended that they be constructed as part of Stage One;

- the joining of the existing Stadium access path to the DCC walkway under the SH 88 bridge by ramping through the walled garden area.
- opening access to the sea on the right bank from SH88 to the sea, using low-cost pathway construction to link the new DCC walk-bridge to the sea.

A more detailed Priority Plan was created, and this is attached as Appendix J.

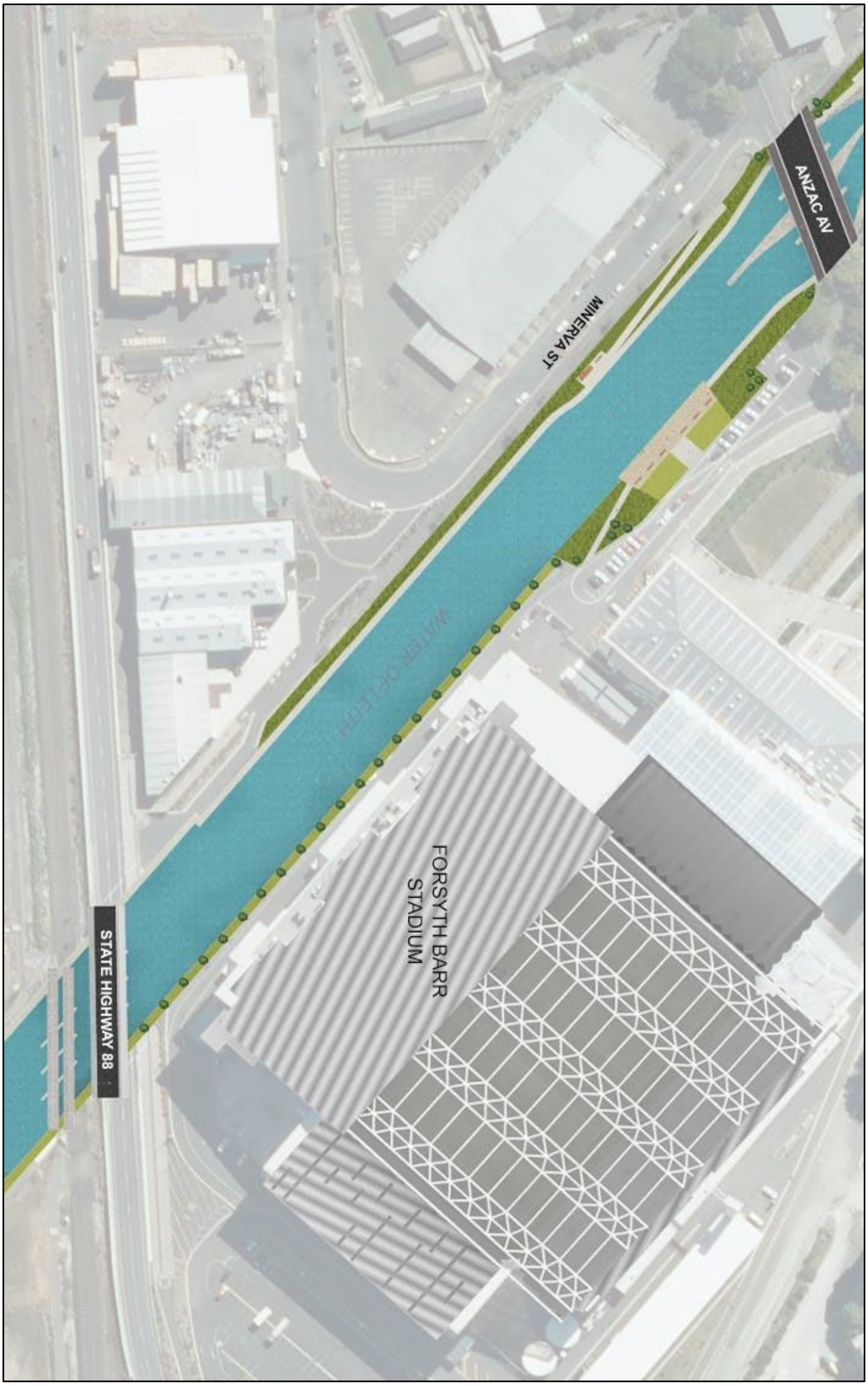
APPENDIX A – Plan of Forth Street to Anzac Avenue

APPENDIX B – Cross-section of Forth Street to Anzac Avenue

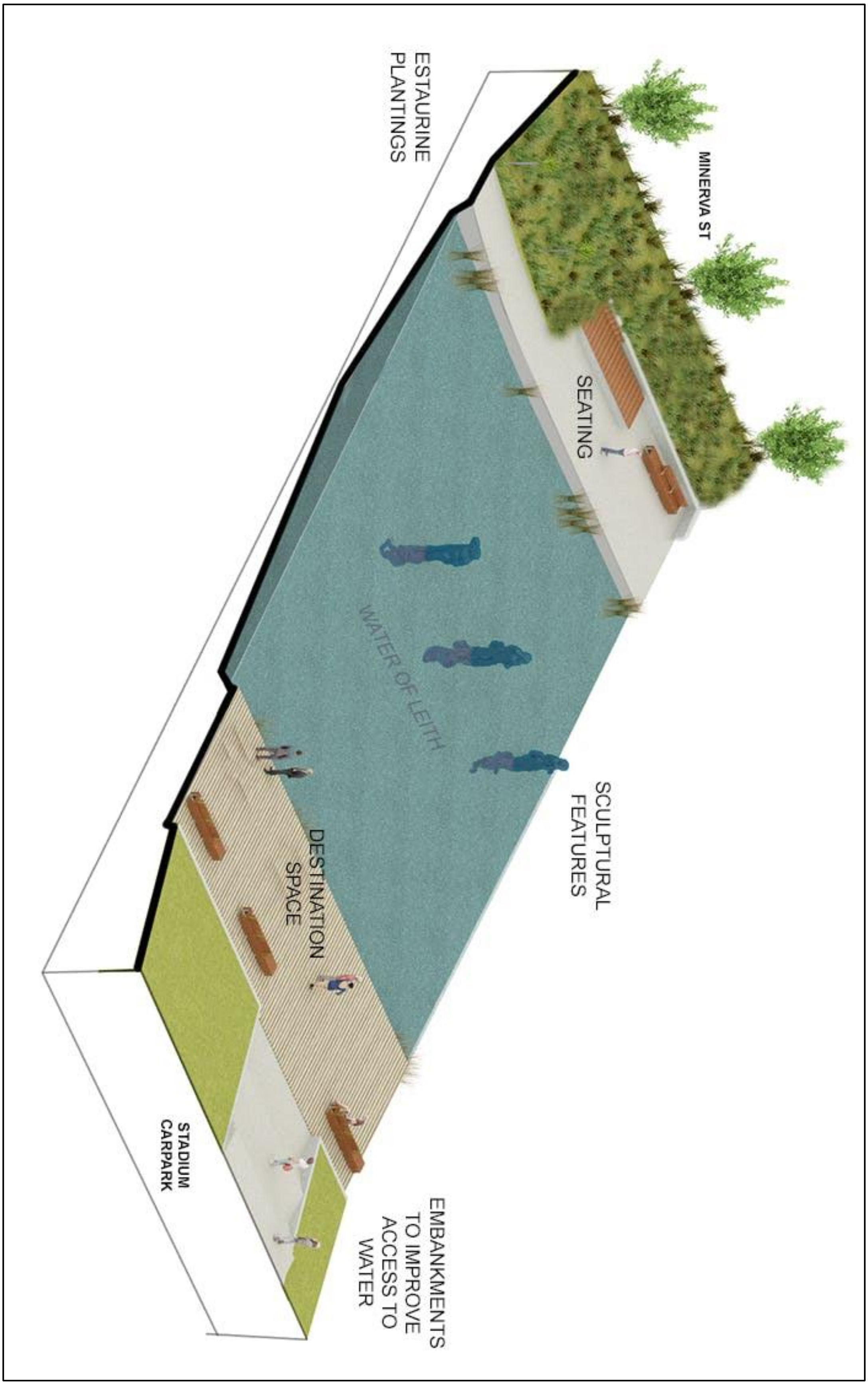


APPENDIX C – Artistic impression of Anzac Avenue to SH88.

APPENDIX D – Plan of Anzac Avenue to SH88.

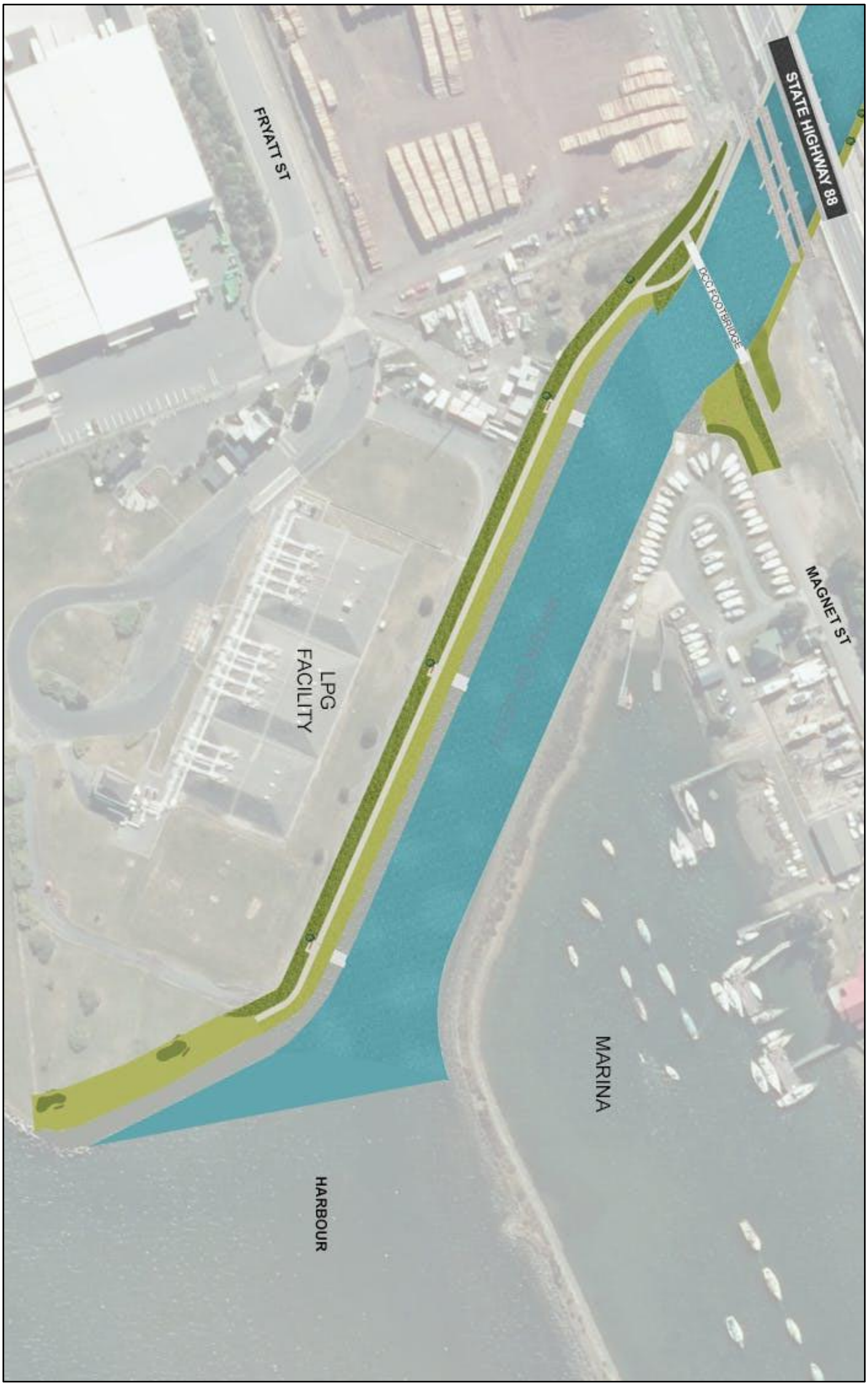


APPENDIX E – Cross section of Anzac Avenue to SH88.

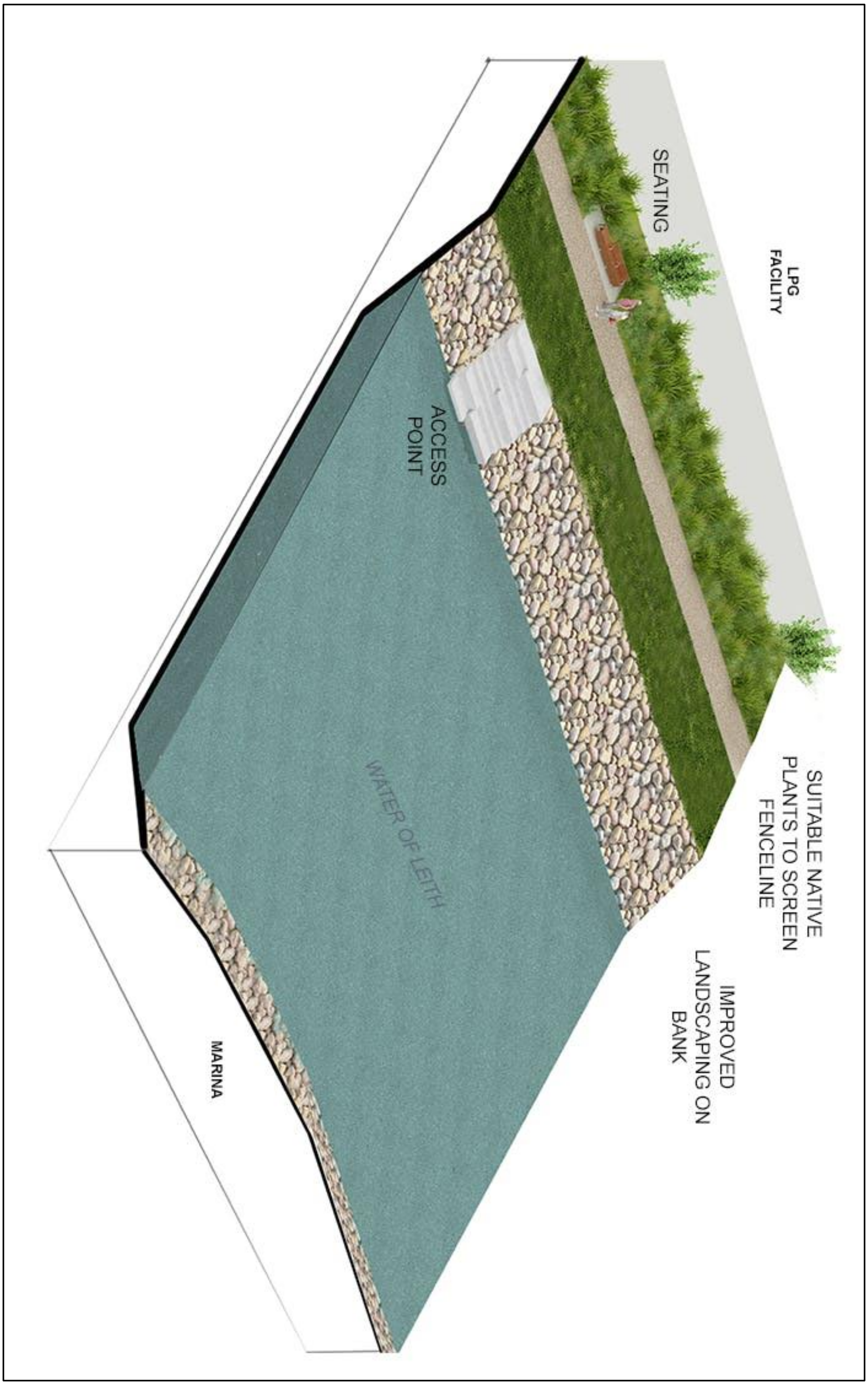


APPENDIX F – Artistic impression of Anzac Avenue to SH88.

APPENDIX G – Plan of SH88 to the sea.



APPENDIX H – Cross section of SH88 to the sea.



APPENDIX I – Artistic impression of SH88 to the sea.

APPENDIX J – Recommended construction priority.

1. **Forth Street to Anzac Avenue -** This section of the Leith should be returned to as "natural" stream state as possible, mirroring the project works completed above the Forth St bridge.

1.1 Centre channel wall to be removed where possible in this area to enhance natural stream appearance by including floodable plantings, water-level shared pathways and by adding meanders in the stream bed.

2. **SH88 to the Sea – Stage one**

2.1 Open access from Stadium to the existing path under SH88

2.2 Create a simple pathway on the true right from the new DCC footbridge to the sea.

3. **Forth Street to Anzac Avenue** The right bank should be developed in conjunction with the Otago Polytechnic redevelopment plan for the area. It was considered a priority for the two projects to work together to achieve:

3.1 Improved access to the water level and flexible-use "destination" places

3.2 Improved access to the existing footbridge.

3.3 Improve non-vehicle links to longitudinal access

3.4 The left bank in this area should be developed into sloping banks (to the degree allowed by the design cross-section) and should include "floodable", above water level walkways to give longitudinal access to the water and minimise the need for safety rails.

3.5 It is important to link to the walkways existing above the Forth Street bridge to allow access without the need to cross the road.

3.6 The project should work with the Tertiary Precinct Group project underway between the DCC, University and Polytechnic.

3.7 The obsolete pipe-work on the true left channel wall can be removed.

4. **Anzac Avenue to SH88 -** This area of the Leith has been designed to reflect its estuarine state as we reach the usual limit of tidal inflows; planting and construction should enhance a tidal estuary theme.

4.1 On the true right, the design continues the Otago Polytech redevelopment and links to the Minerva Street section. It enhances the DCC access already created by sloping the bank from the grassed area into water and by creating flexible use destination points.

4.2 The Working Group has identified an opportunity to enhance visual appeal of Stadium while improving event-day access by creating a walkway along the left bank to provide a link from the Stadium under Anzac Avenue.

4.3The design creates a feature area, alongside current Stadium carpark, which would remain above water at high tide and give access to the water for picnics, fishing or swimming

4.4 The plan provides options for pedestrians/cyclists to cross Anzac Avenue, by developing water-level walkways under the bridge on both banks as a priority.

5. **SH88 to the sea Stage Two -** This project links to the DCC landscaping proposed for the new shared-pathway bridge currently under development. The plan improves links to planned and existing cycleways/paths on both banks

5.1 The design improves access to the water by the yacht storage, to give swimming and family boating opportunities and to include picnic and exercise areas.

5.2 In response to significant demand, the plan further develops access to the "to the sea" path on true right along grassed area and uses native plantings to screen the wood and gas storage areas. It also creates fishing access points and develops the largest area possible at the end of the walkway for picnics and city viewing

APPENDIX K – Working Group membership

Leith Amenity Project
Working Group Membership

Otago Regional Council

NAME	ORGANISATION	CONTACT DETAILS
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Lindsay Smith
Facilitator
October 2018

Love Your Leith

Round 1 and 2 Community engagement report for the Leith Amenity Project for Forth St to Harbour

ROUND 1

CONTENTS

EXECUTIVE SUMMARY

A working group, online engagement and in-person focus groups were methods conducted to gather community feedback. The online engagement platform utilised three engagement tools: a survey, an interactive mapping tool, and a storytelling tool. There were a total of Walking is the most common activity respondents do around the river and improving accessibility to the river is the most popular change respondents would like to see. The community idea of creating shared, connected pathways from the harbour through to University campus is strongly supported by the Leith Project Working Group and other key stakeholders, including Forsyth Barr Stadium. Another key concept is the removal of the centre wall from Forth St to Anzac Av, and to return the river to a natural state, a similar concept achieved by earlier flood protection works.

SUMMARY OF SURVEY

- Over 75% respondents use the Leith
- Walking is the main activity
- Other activities include cycling, picnicking, use pathways, fishing, running
- Adds character to the city
- Beautiful on campus, ugly further down
- There is too much rubbish in the Leith
- The lower reaches need love
- Access is the number one thing respondents requested to change (improve access to the river)
- Top three values (Q6) are **accessibility, visual amenity, and native plantings**

QUOTES FROM FEEDBACK

"During my PhD journey, I would walk along the Leith or sit there peacefully to gain perspective and clear my head. I was based nearby when construction was on-going near the Clocktower Building, which was disruptive but worth it for the end result." – Q2

"I don't like that it looks so industrial, it's a stream it should look more natural and I hate the amount of rubbish that you see in it sometimes! It's so grey and unappealing at the moment." – Q4

"It's so cool to have a body of water flowing through the city and university. It adds significant aesthetic value pretty much everywhere it is. The developed parts, like around the university are really nice, it's great to be able to go down and sit by the river." – Q3

"This last part of the Leith is just plain ugly. Even though birds use it, it's not very welcoming for wildlife and certainly not for humans either." – Q4

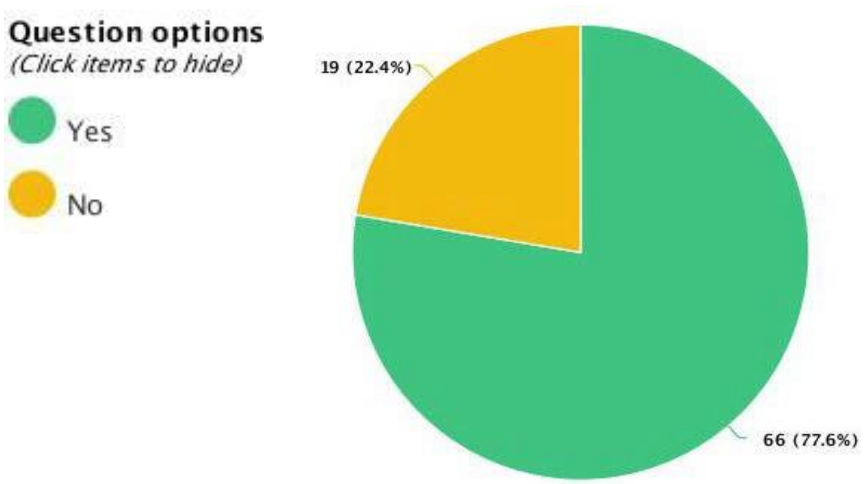
"Have more of it connected to park-like areas for public use and continuous walk/cycle way along at least one side of it." – Q5

"Much more access... people can't love what they can't reach." – Q5

SURVEY RESPONSES

A values-based survey was conducted to capture key themes. There were 85 survey submissions.

Q1: Do you use the Water of Leith?



Q2: If you answered yes to this question, what activities do you do?
Walking and biking. Last year my family and I did the Love the Leith trail walk which was so great, we found out lots of interesting facts about the Leith which we wouldn't have known otherwise.
Walk from work to town during lunch break, and back again.
If my youngest with me (ie. during school holidays), we dawdle in newer section "under the road" - skimming stones, wading in water.
Walk around it
I walk along the riverside often at lunch.
walk alongside
Eat lunch riverside on campus most days.
Walking along the riverside.
I work at the University and every day during the semester i park on Minerva or Perry Street and walk all the way along the side of the Leith to my office.
walk along the riverside/new paths in the uni campus
Walk next to it and admire it
Walking, enjoying, commuting.
Walk and run beside. Sit beside and rad
Walking alone the riverside
Walk along it every day, overlook it etc.
Fishing.
Watching trout and salmon spawn.
Annual trout & salmon spawning surveys.
Walking alongside, sitting nearby picnicking
Walk along the river through the university, and from the uni to the stadium area.
walking, paddling, swimming

walking along the riverside
As a lover of rivers and a whitewater enthusiast, I appreciate the opportunity to enjoy the river in high water and low. I work around the Uni and spend a lot of time in the area.
Walk and explore along the pathways on both sides.
Walk along side, watch duck families having fun
Fishing
Walk along the river, hang out there and eat.
Watch the salmon
Leith run
Walking by, selwyn bath run
Walk along the riverside
Walk alongside to uni
Walked past the river
Walking along riverside
Walking
Cycling along/over on work commute every day
walking
During my PhD journey, I would walk along the Leith or sit there peacefully to gain perspective and clear my head. I was based nearby when construction was on-going near the Clocktower Building, which was disruptive but worth it for the end result.
Living in NEV and working in town, I like to walk to work when I can. This means that I cross over the Leith on my walk - either on George St or at the Botanic Garden. It's always a moment along my walk that grounds me, and I love looking along the river toward the backdrop beyond.
Walk alongside it
Walk along it
Walking along the Leith
Walking alongside
Walk by it. Look at it.
Walking along the side, sit by the river to take a rest or sunbathing
Walking alongside
Walk
Sight seeing
Walking past
Walking past
Swimming
Walk past it for some chill time
Walk around the Leith
Walk and enjoy the view
Walk around
Walks along it, wading
I walk beside the Leith to get to uni everyday
Walk past it
Walking along the riverside/bridge
Walking
Walking
Run up the tracks
Last year did activities with hall walking and swimming down

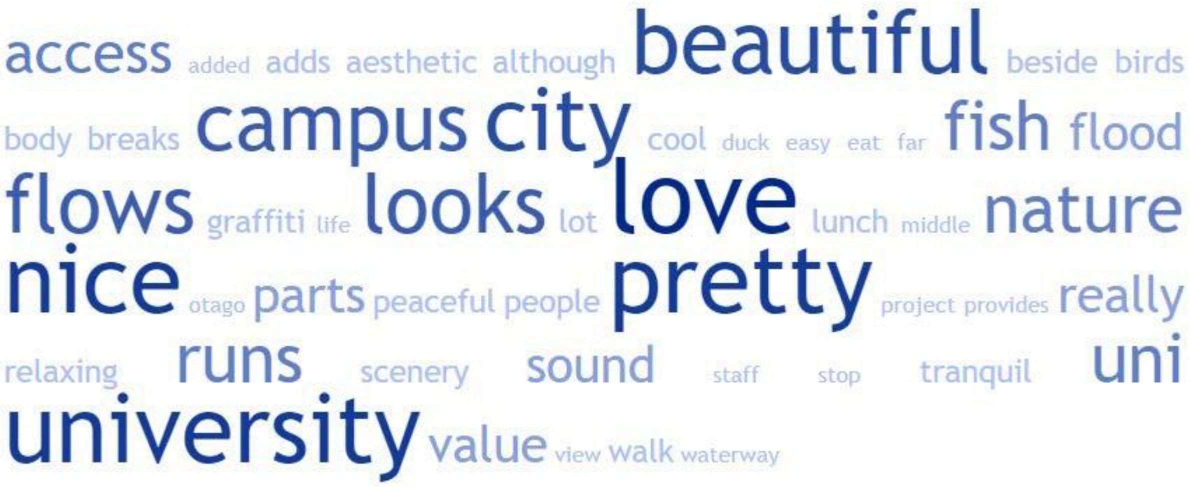
Walk past
Fishing
Walk along the river, hang out there and eat.
Watch the salmon
Leith run
Walking by, selwyn bath run
Walk along the riverside
Walk alongside to uni
Walked past the river
My office in the Owheo building looks out over the river and I walk by it or cycle over it every day. I watch the birds that spend time out there and greatly enjoyed the elephant seal visit last year!
Walking along riverside
Walking
Relaxation and meditation on a daily basis. Our university department depends on the Leith for our mental health!
Walking alongside it. Admiring and being pacified by its ripply charm.
Kayaking at the mouth. Walking along it.

Q3: What do you love about the Leith? Why?
I love it flows right through the middle of Dunedin. I love the new look it has around the University area - people can interact with it more, have a paddle, eat their lunch beside it.
Breaks up the buildings of the campus with a bit of nature.
Able to access quite close to water's edge - nice landscape to eat lunch beside.
Local history - eg. students using as kayaking route.
It’s so cool to have a body of water flowing through the city and university. It adds significant aesthetic value pretty much everywhere it is. The developed parts, like around the university are really nice, it’s great to be able to go down and sit by the river
I love the many different birds that can be spotted there and looking out for the occasional eel or trout. Ducklings in the springtime are a highlight.
Easy to access, pretty, esp thru the uni campus now
I love how it is a central part of the university campus. It connects the students and staff directly to nature.

Its so peaceful to walk along, i love the sound of the water flowing, and the fish and bird life that you see. Although i dont like the big concert walls i do like the graffiti i think that it livens it up a lot and shows people trying to reclaim a space and make it their own.
a beautiful accessible waterway in the city, the birdlife attracted
It's part of the University culture. I love the greenery on part of it and how it is a centrepiece for our beautiful university.
I appreciate that these new amenity projects have been put in place, although just near the staff club I question the conveyance ability of the flood control where one of the cement walls just stops. The new project overall has improved the value of the campus, and the stream itself. Although I still write negatives below, overall it is a much more positive change then what we previously had.
The peace in a busy area.
How beautiful it looks in the Woodhaugh gardens and that it flows through the university
That it flows through the uni and provides a tranquil type environment with the sound
I love that is runs through the university and is pleasing to the eye.
I love that it has good access for fishing.
It's beautiful and it's right by campus. Connects you to nature while at uni, gives you a break.
Flowing water! And a lot of it! It's lovely to have water running through campus, and healthy looking water at that.
cool water in summer, habitat for fish, birds, invertebrates
it's nice to have a body of water running through the city
It is a very special waterway through the city and campus - I love the sound of the water, it is very relaxing. It is great for wildlife, ducks, fish and insects. Parts of it are really beautiful and tranquil, other parts are artistic - such as the graffiti by the Forth Street Bridge. I could be interested in fishing but there don't seem to be many safe places to do this. Over the years I have seen many kayakers in floods - looks very impressive. I cross the Leith everyday coming to work!
I love the look of the water The graffiti is also great.
Its possibilities
It has so much potential to be more than a drainage ditch.
Essential to flood protection of city (re flood in 1930's). can be a great amenity for the city. Love what has been done through Uni.
It's a relaxing spot to stop and ponder life. I love watching the duck activity. Waiting to see the salmon (miss this every year)
The parts of the river where you can actually go and sit down beside it, put your feet in on a hot day when having lunch etc.
it is in the middle of town and has so much potential
I love its natural strength, that it exists within our urban core.
It’s very scenic and breaks up the city
It’s beautiful, pretty
It’s presence, it’s variability under different weather
Water
A river is always nice in a city
Location
Tranquil. Nice to look at.
Feel comfortable
Clean and good scenery
Iconic
Length, branches out far

The scenes
It goes through the uni so something nice to look at
It’s polluted
The calm atmosphere it creates for the people walking
The nice beautiful view
That it’s Dunedin’s own river. And adds character to our beautiful city.
It’s beautiful and peaceful
Scenic
It flows right through the city adding to the scenery and is a great way to cool down without going far.
I appreciate any body of water
It’s a river
Relaxing
It looks pretty nice, adds a natural appearance to the city
When the Leith is really full
Beautiful
It’s pretty nice looking
It runs through the campus and looks appealing
I love that it runs all the way through the Otago uni campus and right up through to where I’m flatting. The sound of running water is the best especially when it’s clean
The scenery
Pretty
Pretty
It makes the university look nice
It looks nice by the University
Lots of fish
Aesthetic value, upstream is really nice.
It’s pretty
The views
Pretty
It is pretty
So beautiful and serene
Very pretty
Pretty
Looks mean
Pretty pleasant walk
Added value to the landscape of the beautiful Otago University
It flows through the University
Looks nice
The fact it flows through the whole university.
The aesthetics.
Makes campus look nice
I love the wildlife it attracts and the easy access to nature it provides.
The tranquillity and joy it brings to all. It welcomes people to stop during their busy days.
It's a Dn icon. It may not be pretty like the Avon in Chch but it is functional in terms of containing water.

95% of the time it’s tiny, sparkly and innocent. Within 24hrs it can turn into a roaring monster. I love both incarnations.
Body of water in the heart of the city that could be even more beautiful



Q4: What don't you like about the Leith? Why?
The thing I don't like about he Leith now is the section you are asking for feedback on. It looks horrible, dirty, too much concrete.
People abusing it - rubbish, unsafe activities.
Tagging - although artful, tasteful graffiti ok.
Pretty much the whole way down the river is extremely ugly concrete. From the graffiti covered George street part to the mossy shallow parts where it looks barely like drainage to the remaining concrete jungle. Even the nice parts around the university are tainted by the ugly, mossy wall as a backdrop.
It's occasionally smelly and often rubbish seems to collect (or be thrown) on the banks.
I don't like how inaccessible parts of it are.
I don’t like that it looks so industrial, it’s a stream it should look more natural and I hate the amount of rubbish that you see in it sometimes! It’s so grey and unappealing at the moment
the lower part behind the college of education is ugly and not easily accessible
The lower reaches are grey and concretey
The weirs (especially the large one outside the Clocktower) is a barrier to fish migration. At this same location, with the stairs leading down to the stream, it is unsustainable/expensive/unsightly to constantly be fixing the handrail in large flood events when the sediment strikes it. The water quality is still an issue, last month there was a large spike of algae at this site. The urban stormwater and the rural catchment that drains the Leith Lindsay Catchment still had management issues that needs addressed-this has ramifications for those who recreate or 'users' of this common space.
It looks disgusting and not NZ or Dunedin.
All the rubbish that gets dumped in it. The concrete bits by the highway where I’ve seen fish get beaches. How vulnerable the Leith street flats are to flooding.
Often full of road cones and trash which isn’t nice to look at. Big concrete walls in some places too.
The amount of rubbish that is thrown into it from mainly students.
The water quality is bad.
Not enough fine gravels to enhance trout & salmon spawning.

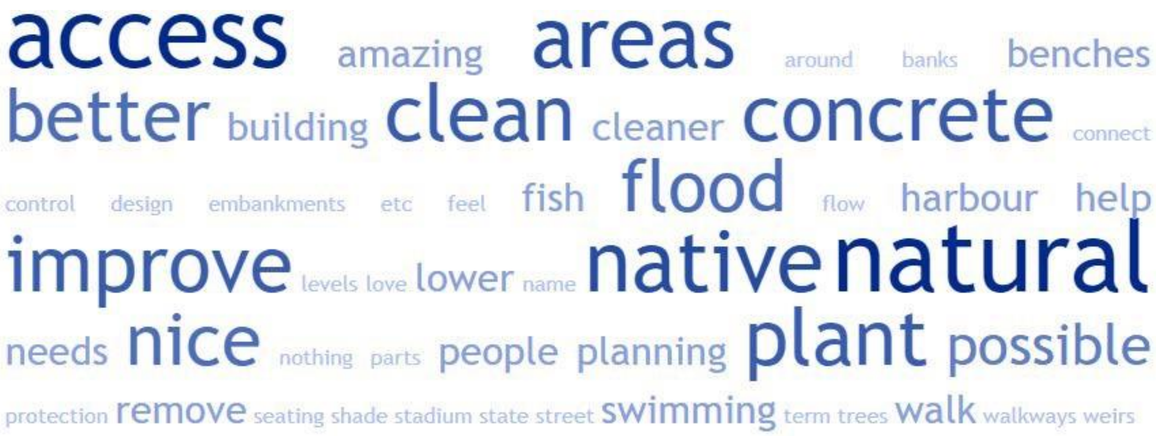
Sometimes it's dirty, sometimes seems a bit too concretey and industrial.
Really ugly flood channels further down - doesn't invite you to walk along it.
it gets treated as the "town drain" a bit and left in a mess but this is improving as better access is provided to the riverbed to allow people to appreciate the river more
the end near Unipol is pretty ugly!
Concrete channels are ugly, rubbish and litter floating in water, difficult to sit near the water in some parts, its inaccessible. I am concerned about the water quality. I don't like the idea of putting plastic ducks etc into water - even with the best of intentions - as there is a risk of pollution.
Its lack of useable recreational stretches of water
It looks like a drainage ditch.
Plain and boring which is not a good look for visitors to the Stadium.
The mess within - the rocks look messy (I know this happens at heavy rain periods - but...)
Big high walls. Can't even see the river if you're a child, let alone go and have fun in it.
Lack of access at some points, ugly section next to harbour, graffiti
I don't like how it has been engineered in deep concrete channels. Plenty of examples in Europe, America and elsewhere can shed light on better ways of guiding rivers through our built realm.
A few cans and rubbish
It’s in a concrete reservoir, doesn’t help the ecology of the river, fish can’t swim upstream etc
Abuse by those who do not respect it as a waterway
Rubbish
Filthy and full of rubbish. Always.
Dirtiness
The ugly bit down by the harbour.
Flooding
Flooding, water contamination, always under construction
Bit dirty
Student pollution
Water quality
Pollution
All the industrial looking concrete surrounding it.
A bit dirty looking
Dirty sometimes
It becomes more polluted near town, becomes industrial looking
It’s had a lot of construction/changes done to it
It’s a bit dirty
Not much really
Not greatest walking paths
Not the best for walking
The high velocity channel between the gardens and George street as it can prove a barrier to fish migration.
The amount of glass littered
The amount of glass and trash that you can see in it is sad because pollution of any kind sucks
Nothing
Overflows
Looks really rocky

Can’t eat fish due to poor quality
Not as nice further down.
Looks a bit unnatural
The view on the lower end by harbour street
Water rats
I’m scared it will flood my flat
It’s cold
Cans around
Dirty
Dirty as
Concrete is a bit bland
Floods and dirty at times
I can’t see fish very often
When it floods and looks dirty.
Overflowing
This last part of the Leith is just plain ugly. Even though birds use it, it's not very welcoming for wildlife and certainly not for humans either.
No access
Concrete jungle
Pollution
Questionable water quality
No acknowledgement of its original name and māori history
Are there any fish or eels running in the river? If not, how can we repopulate/regenerate?
All year round, you used to find students and staff alike sitting on the edge of the Leith, in what used to be a river-like space with the sounds of the flow. Sadly the GIANT concrete fort-like wall (at the corner behind the Richardson and Burns Buildings) blocks any view and now has no seating spaces for those who do not want to be in the big and wind exposed public spaces like the edge of the river by the clock tower or by the next area behind the commerce building. It has destroyed all pedestrian experience of the more restful parts of the river, the more private parts, and is now like walking through a dark alleyway. Something needs to be done about this, it feels unsafe and gloomy.
It’s industrial bottom. Hideous.....and it’s concrete canyon around George St to the gardens. Necessary perhaps but let’s good some good and fitting art work on the walls.
The masses of concrete and lack of aesthetics

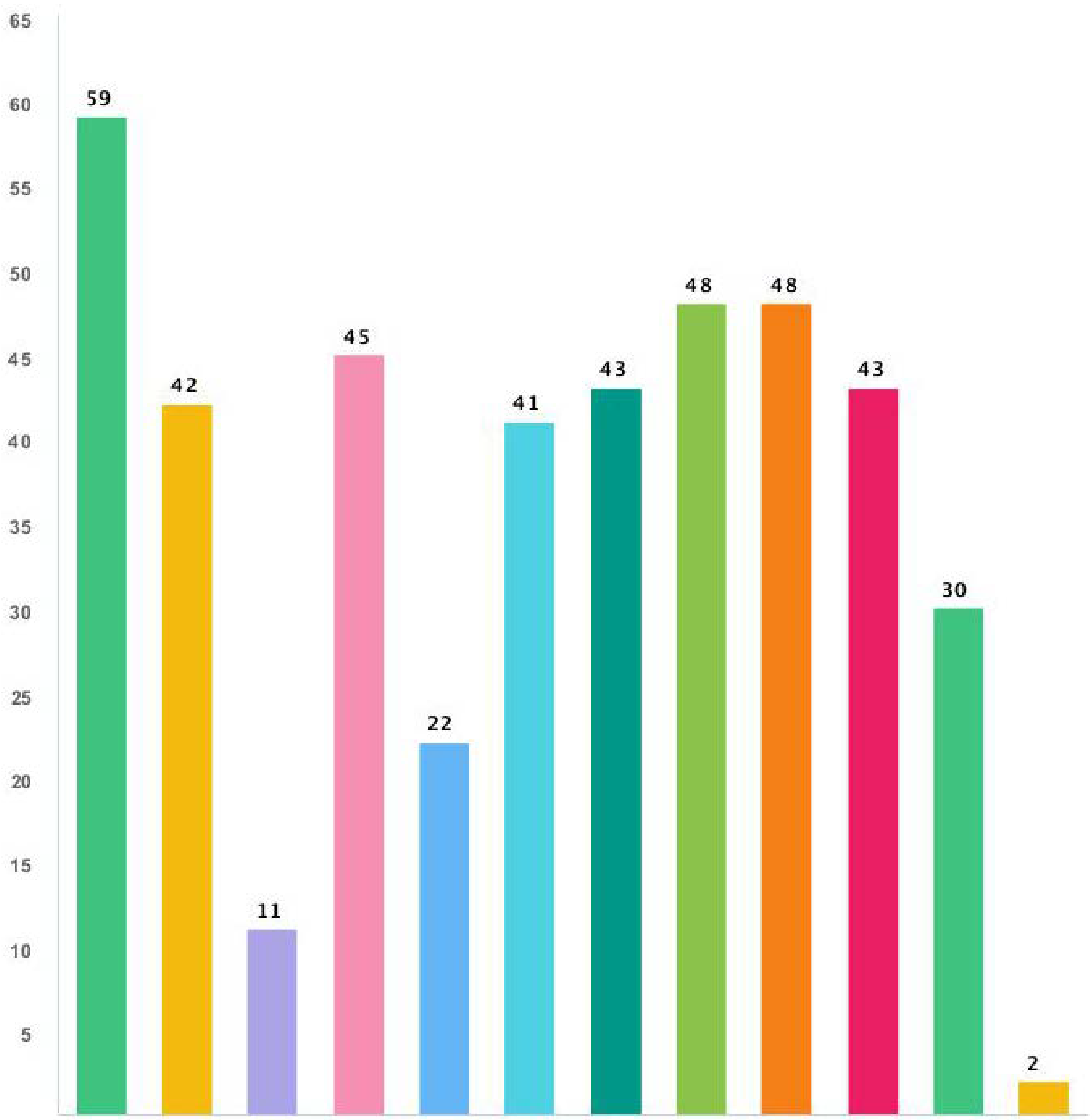
Q5: What would you change about the Leith? Why?
The only section I think needs changed is the end which is what you are hoping to do - I can imagine this section looking great especially good for international sports matches at the stadium and concerts.
Most all of the infrastructure needs significant revitalisation. It could be that it just needs some planned, aesthetically matching (inspired by nature) street art down the banks. Some more urban planning with areas enticing the public down to the water (much like the university part) would be greatly welcomed, though I appreciate the fact that this could be difficult as there isn’t much development in the areas around the Leith. A walkway/cycleway along the water would be fantastic. Also some public relations to increase the presence of the Māori name Owheo (I didn’t even know this name before I saw the video!)
Make more parts of it accessible, place park benches alongside it for more comfortable seating than the new stone steps.
Brighten it up and make it more inviting, it would be awesome if there were places to sit by the water and do some work, or have some lunch.
walkways along the Leith from the harbour to botanic gardens with benches etc for resting spots
Get rid of the greyness
The weirs, as above-they're unsightly and environmentally limiting.
Also, the large, grey cement embankments were relatively inhibiting before, but the height increase of the embankments near the Richardson and ITS buildings (although necessary) are unsightly and inhibit ORC/UoO attempts at drawing a closer connection to the river---I feel less connected, it's dark, it's grey. Even street art along the in and outside of these embankments would be amazing, a University focussed mural, almost a time travel would be amazing. Somehow trying to connect people to the stream near this Richardson/Castle/ITS building area would be great.... let's raise the footpath by... let's say 3m? (that last bit was a joke, you can laugh)
Remove the visible concrete but keep the flood protection aspect. More trees and grass would be cool
In areas where concrete is not necessary for flood protection or other means are possible, try and naturalise the river as much as possible. Bring back in NATIVE fish (brown trout is not a native fish!), plant more native trees to help purify and shade the water (I appreciate this is already the intention). It'd also be awesome if there was an area that was labelled safe for swimming! We have an amazing Eco Sanctuary down the road and if the Leith is naturalised it would help to provide habitats for native animals also.
Less rubbish and more areas to look at it
Improved water quality for swimming and for aquatic life.
Modify sub-strait to assist trout & salmon spawning.
I would plant more plants nearby, while still allowing people to walk alongside. This would make it feel like more of a natural river rather than the concrete industrial feel
Improve the river to a destination and an inviting place to walk along - urban design improvements and the like. Cycleway beside it from uni to the harbour (would make a lot of sense considering the DCC are building a new cycle bridge down by the stadium across the Leith). At the moment it's a pain of winding around different streets with no cycle lanes to get from uni to the stadium / harbour.
much more access... people can't love what they can't reach.
Balance safety and aesthetics - make the river a focal point, and improve safety during high water volume. Lots more native plants to encourage birds and insects.
Remove the rock weirs and design one big weir at its mouth to contain a long recreationally useable stretch of water. Build benches along the bank.

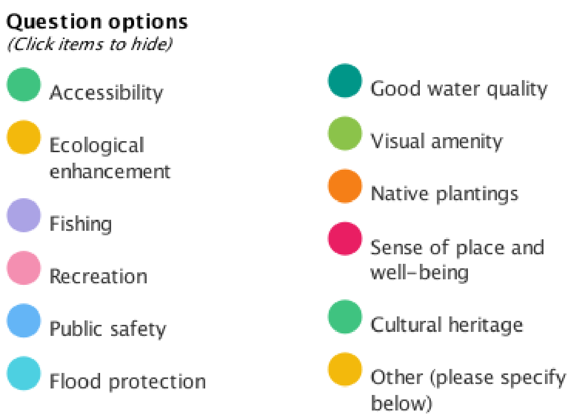
To the extent possible, it would be nice to see it reinstated to something approaching its original state. Obviously there still need to be flood control systems in place, including controlling access to some extent during high water. On the other hand, once the water reached the harbour, the movement of the water slows anyway.
It would also be really nice to incorporate some planning that allows the whitewater to be active and interesting. At the moment, the gradient is moderated by the gradual slope of the lower concrete creek bed and the concrete barriers outside of Commerce. How about planning it in a way that it is an enhanced whitewater experience at higher levels? Boaters are going to run it anyway. Might as well make it fun. It's OK as a wave chain, but it could be so much more on the rare occasions it has real flow.
In lower levels, it would be nice to see either natural open soil, or at least some flow patterns that create a way to better engage with the water, including steps that drop down to the water. More open earth banks with native plantings (both tussock down low and trees higher up) would make it more scenic while also helping to control erosion naturally.
It would also be nice to see an education campaign to teach guests (whether that's short term visitors or long term ones like students) about the importance of maintaining the cleanliness of the stream.
Make it prettier and more useful to the community instead of an eyesore in parts.
Not sure about change. The improvements of recent years have been positive.
Concrete drain-like appearance. We should not try to emulate Europe. This is not a canal, it is a living river with floods, etc which should be given space to do their thing.
I would love to see a better interface all around - with the natural wildlife/environs, but also with our built realm and society.
Please have a look at Ljubljana (Slovenia) and how architect / urban designer Plecnik transformed its river's edge. We could do SO much better here in terms of place-making along waterfronts. Many opportunities with the Leith.
Keep it super clean and improve swimming access
Add in runs for fish to swim upstream, possible native planting’s along riverside to provide shade for aquatic animals and invertebrates
No comment
Cleaner
Clean it up
Clean it up and make more accessible
More pretty spaces. Shaded walkways
Flood protection at lower levels
Make it flood less
Cleaner
Clean up waterway, harsher penalties for water pollution, littering
Water access and seats
Make it cleaner and more scenic
Introduce more invertebrates and fish and flora
Put more water and make it nice lo KI’m nh
Make it look less like a drain
Clean it up
Removal of litter - removes pollution
Better walking and signage
Better walking paths
Nothing
Make it cleaner

Nothing
More rec options
Not to over flow
Less rocks?
Improve its recreational value downstream. Be cool if it was deeper.
Not sure
The view (up date)
Dirty
Chill out when it rains
Nothing
Perhaps clean bottles etc
More seating areas
Clean it
Add some murals
Make it Safe to float down
Deeper river
Upper Leith and lower Leith are not as nice and do not seem to be as focused on.
Better river beds near housing
I would love to see the final stretch if the Leith become more natural and break out of its concrete barriers. What has happened just upstream is beautiful with the native plantings and riverside access. Some benches, a footpath/bike path, perhaps some roosts/islands for bird life to use would be amazing. I don't think it needs to be complicated, just help it return to a more natural state and give people access to it. Nearby nature is so important to mental health, especially good for all the stressed, overworked students in the area!
Reclaim the original name
Restore parts of the river to a more natural state where possible
Find ways to make it accessible for mahinga kai purposes
The new construction has destroyed this area, it is now a void amongst the vibrant university grounds, but is an important pedestrian desire line.
Have more of it connected to park-like areas for public use and continous walk/cycle way along at least one side of it.
The last kilometre or #o from Forth Street to the Marina. It's appallingly ugly..... Dunedin at its post-industrial worst. Let the Art School suggest a visual future. Reshape it for walking, cycling, paddling, kayaking and the like. Put up sign boards telling its Maori story.
Make it more beautiful and easier to access is wharf or similar. Grassy band etc..



Q6: What do you value about Leith?





Other (Please specify)
I'm not interested in fishing personally, but the state of health of all of the wildlife is indicative of the health of the river.
Wildlife value - the humour of little ducklings trying to walk over rocks, swimming upstream etc

SUMMARY OF MAPPING TOOL

This interactive mapping tool allowed transparent and site-specific ideas sharing. There were 29 pins ('ideas') dropped in the interactive map.

These are key messages from the pins:

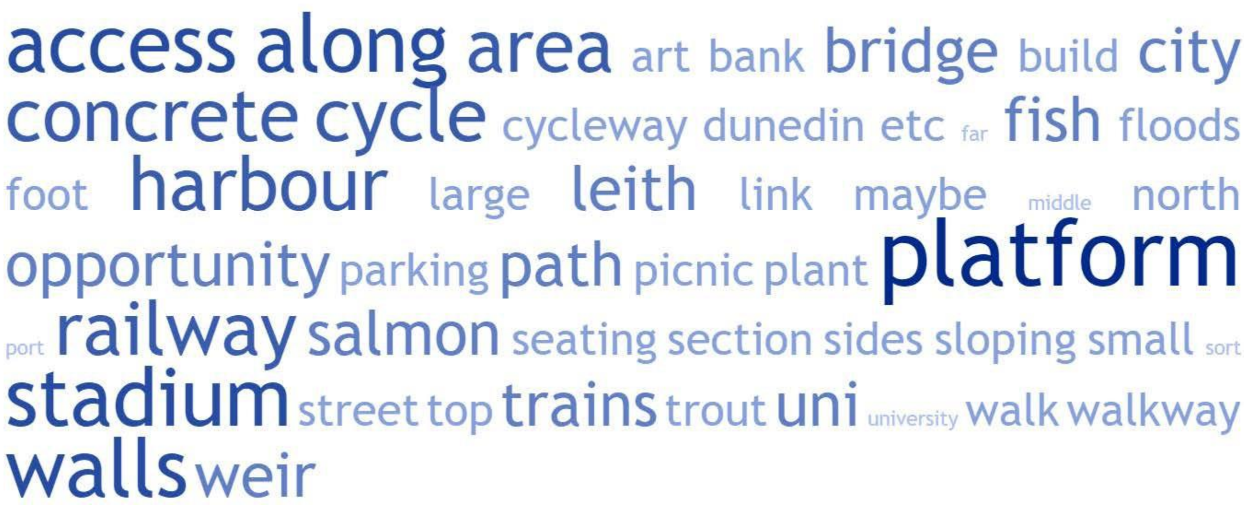
- Accessibility to water
- Street art: murals along concrete walls and creative lights display under bridge
- Train station / platform outside stadium
- Optimise river bed for fish / ecology
- Link with cycleway and exercise machines
- Plant more native plants
- Platform / bridge along middle wall
- Slope banks back
- Walkway to harbour lookout point
- Improve link between University-Stadium-harbour
- Seating and picnic tables

PIN TYPES

MY BIG IDEA **FACILITIES** **IMPROVEMENTS**

We set up these three pin types – My Big Idea, Facilities, and Improvements. We used broad pin types to encourage open thinking and ideas.

WORD CLOUD



#	Address	Pin type	Idea
1.	25 Magnet Street, Dunedin, Otago Region 9016, New Zealand	My big idea	Foot access to the river's edge from Forth Street right to the Harbour. Great fishing along this stretch for chinook salmon and sea run brown trout. No other city in New Zealand has opportunities like this to fish in the city centre.
2.	Ravensbourne Road, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	My big idea	Here is where you need to build a railway platform. For large events at the stadium you could have trains picking people up from north and south of Dunedin, reducing the pressure on parking in the city, and de-clogging SH1. Trains could come from as far away as Invercargill and Christchurch, drop people right outside the stadium, then take them back after the event. Dunedin Railways has a perfectly good train, get them on board with the idea. Would probably be quite a money-spinner, make the trip into a sort of party. But it NEEDS a platform by the stadium. Make it a pretty one, like an old fashioned English station.
3.	89 Union Place, North Dunedin, Dunedin, Otago Region 9016, New Zealand	My big idea	Street Art along the cement embankments from the Staff Club to the Stadium
4.	Ravensbourne Road, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	My big idea	Large salmon and sea trout move up Water of Leith from the harbour from December through to May so I would really like to see angler access for both sides - if not both then at least one. The sub-strait of this section of water is very important as well, it could be designed to assist with trout a salmon spawning. Photo - 10lbs salmon caught in Water of Leith 

5.	Ravensbourne Road, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	My big idea	Up until the 1930s (I think, maybe later even), there was a railway platform here - Pelichet Bay Station. I suggest the ORC investigate reinstating such a platform for trains from the Stadium from here out to Mosgiel via the city and East to Port Chalmers. Such a service would be great for commuters coming from East and West into town and university! No parking required, opening up opportunities for business expansion around the area. Further, any redevelopment of the area should take into account Port Otago's goal to move the majority of heavy freight movements onto the railway, and the noise implications.
6.	112 Anzac Avenue, Dunedin, Dunedin, Otago Region 9016, New Zealand	My big idea	There isn't really a good cycling link from uni to the stadium / harbourside pathway. This would be a good opportunity to put one in.
7.	141 Union Street East, Dunedin, Dunedin, Otago Region 9016, New Zealand	Facilities	paths through campus by Robertson to the polytech! and path down to the river, like in the middle of the university
8.	155 Union Street East, Dunedin, Dunedin, Otago Region 9016, New Zealand	My big idea	easy access by foot and bike to the lower concrete section, built to just above high tide but able to be closed and used as a floodway during floods.
9.	135 Union Street East, Dunedin, Dunedin, Otago Region 9016, New Zealand	Improvements	get rid of the graffiti - it prevents small life forms colonising and softening the concrete. I support street art just not right here. maybe provide room for this sort of thing just a little further away.
10	Minerva Street, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	Facilities	stepping stones over the river at frequent intervals, maybe they could also act as weirs to maintain a small depth of water in the riverbed
11	56 Parry Street West, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	Improvements	trees along both sides of the river planted at the top of the walls to lean over and provide shade for the river. Especially native species like kowhai
12	25 Magnet Street, Otago Region, New Zealand	Improvements	One large weir designed to complement other harbourside developments. Removal of small rock weirs and concrete debris. This would create an uncluttered long stretch of recreational water.

13	25 Magnet Street, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	My big idea	Continue the exercise machines that exist downstream on the cycleway and take them back up as far as the bend in the Leith at the Uni ITS building - making potential exercise circuit that also goes toward the Uni gym
14	61 Clyde Street, North Dunedin, Dunedin, Otago Region 9016, New Zealand	Improvements	Install creative lights display under the bridge mimicking the appearance of a glow worm cave after painting the walls and ceiling black. 
15	53 Forth Street, North Dunedin, Dunedin, Otago Region 9016, New Zealand	Improvements	Commission a new set of murals - each measuring approximately two square metres - along the walls of the river. A good opportunity to showcase different examples of Dunedin art, culture, history, etc. Here's a photo of a similar concept done under a flyover. 

16	19 Riego Street, Dunedin, Dunedin, Otago Region 9016, New Zealand	My big idea	Build a platform or walkway - approximately six metres wide - on top of the middle wall of the Leith. Plant small-sized versions of sustainable "supertrees" in a single row to balance out the river's concreteness. The platform can also serve as a picnic/sitting area. IMAGE INCLUDED: 
17	141 Union Street East, Dunedin, Dunedin, Otago Region 9016, New Zealand	Improvements	Soften the edges of the back by sloping them.
18	254a Fryatt Street, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	Improvements	Inflatable weir that can let water be kept in river. Deflate when in flood to allow excess water to flow out. Place just down stream of rail bridge or part of new dcc cycle crossing bridge.
19	Minerva Street, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	Improvements	Slope Minerva st banks to allow for seating, picnics etc and plantings.
20	149 Union Street East, Dunedin, Dunedin, Otago Region 9016, New Zealand	Facilities	Renovate and reopen stylish foot bridge for Poly/Uni link. Cycleways on top of north bank?
21	254a Fryatt Street, Dunedin, Otago Region 9016, New Zealand	Facilities	Fishing boardwalks on both side to mouth as is a good place to fish with poor access.

22	25 Magnet Street, Dunedin Central, Otago Region, New Zealand	Facilities	Walkway to lookout point with great views of harbour. Perhaps extended platform with seating?
23	25 Magnet Street, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	Improvements	Probably more dcc than orc. Proper parking and turn around area at end of Magnet St. Picnic spaces on hummock by railway line/cycleway.
24	130 Anzac Avenue, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	My big idea	Low level (i.e. covered during floods but accessible 99% of the time) cycle/walk path along the bank at the BASE of the wall right by the water. This is necessary to complete an efficient link from West Harbour cycle path-stadium-university so one doesn't need to faff about going onto and crossing roads and footpaths in order to commute along this very critical route. Would go under Anzac ave. No point having excellent cycle paths if they're all divided up into 100 m sections cut off by roads!
25	130 Anzac Avenue, Dunedin Central, Dunedin, Otago Region 9016, New Zealand	Improvements	Get rid of concrete walls (and graffiti!) and replace it by sloping green sides similar to upstream. Ensure lots of pedestrian access. Add interpretation boards as in walkway from Woodhaugh gardens to Ross Creek area. Add sculptures, seats, etc. Continue right down to mouth so could then walk north and connect with harbour side walk/bike track.

SUMMARY OF STORIES

Respondents were encouraged to share their personal narratives and feedback about issues they think are important. Twelve stories were shared.

- Accessibility with cycleways and pathways
- Māori connection
- Improve pedestrian link between University-Stadium-harbour
- Appreciation for concrete appearance
- Return to natural environment
- Bring the river back to life
- Plant more native plants
- Vertical gardens along walls
- Improve river bed
- Seating, picnic tables and water fountains
- Murals / installations
- Removal of the centre wall from Forth St to Anzac Av

WORD CLOUD

Title	**Story**
A Love Letter from the Leith	On Valentine's Day, 2017 Otago Regional Council released 'A Love Letter from the Leith', a short creative film telling a story from the Water of Leith's point of view. The video can be viewed above and the letter can be read here: Dear people of Dunedin, I am your river. I empty the rainwater from the northern hills, through your backyards and into the sea. I have been here for years. Before your wakas and cars. Before your houses and clock towers. Before you were here. Back then, I spread out over the floodplains, where your city and homes now rest. Only the birds and the fish took from me then. Then some of you came and called me Ōwheo, after your chief who would stand by my side and ponder my flowing waters. We shared the flax from my banks and the fish from my pools. Then more of you came and renamed me the Water of Leith. You made a stone channel for me to follow, and concrete steps to fall down. Your children paddled in my pools and you fished from my banks. You built streets around me and bridges across me. Sometimes I knocked them over when I flooded. Then you built high walls along me and it was difficult for us to be together. Sometimes the clouds send a lot of rain down me to test my walls. Sometimes I flood your

	streets and disrupt your lives. I am sorry I go over the top sometimes. But now you are lowering my walls, replenishing my banks with native plants and encouraging the fish to stay. You are fixing my weak points, so I no longer pose a risk to you. Rather than just a concrete drain, I am a river ready to connect with you again. Come wander along my banks, I am looking forward to seeing you. Love from, your river. – Otago Regional Council
Ko Leith toku awa	I live on Mt Cargill and the waters of Leith feed the cloud forests and bush clads slopes of Kapukataumahaka. In its upper reaches it is a thing of beauty, but apart from its trip through the Uni, the parts in the city are bounded by graffitied concrete walls. I would love to see the riverbanks returned to rock, designed in such a way as to prevent flooding. Mt Cargill is a mountain made of beautiful rocks, and it would be lovely to see some of them used to protect the riverbanks and return the lower reaches to a more natural state. Thank you for the opportunity to comment.
	COMMENT: I like the idea of retaining some of the "brutalist" concrete appearance suggested by another submitter, but your idea of rock walls sounds really nice too. So maybe a bit of both. I like how you name the Leith as your awa, I feel that way too. By the way the ingoa of this awa is Ōwheo... not many people use that name, but the teacher's college named one of their buildings after it
The Beach that never was!	Some time ago a notice in Dundas street informed us that a beach was being constructed. This was looked forward to with mounting anticipation. However, it never eventuated. We really do need somewhere to swim in the Leith. Preferably a boulder free, area with a Sandy approach, this was what we thought was going to happen. So, what did????
	COMMENT: The beach is there, it is at the foot of a long pram and wheelchair ramp at the corner of Dundas St and Montgomery Ave. It only needs children playing down there to make it a beach! Recently the ORC staff kindly (when asked) arranged to have several tonnes of jagged quarry rock removed and replaced with rounded river stones. River sands are naturally building up here.
Brutalist architecture should remain	It seems to me the "drain like" aspects of this space have some merit in their of-the-time style - brutalist concrete, of which little remains in NZ. Practically every bridge in NZ was like this in my youth. Is it possible to retain the looking feel of the concrete works AND enhance the water flow? Perhaps maintaining the main (larger) concrete structures while softening the base flow area? Could the water be channelled in such a way that there was constantly enough to allow kayaking/canoes? Even a minor tourist operation while still supplying flood protection. (Los Angeles managed this when reclaiming the concrete river bed). Given the works upstream does the downstream area still need to be as large? i.e. could one channel be regular flow with the other developed in some other way?
	COMMENT: I agree about keeping the concrete walls while softening the river beds. I also suggest climbing holds on the walls to make a positive advantage from them.
Life in the Leith: the Leith as a living river	I always used to take pleasure in watching the fish feed below the Union street. Ridge whenever work for the University took me in that direction. Now you will have to look hard to see even one or two fish. Why has life in the Leith deteriorated? Is it the toxic run off from our streets or all the concrete that has turned it into an engineer's playground rather than a living river? To my mind the banks can be made as beautiful and restful as you like but the job will still be only half done until the life in the river is brought. Ack to full health.
	COMMENT: Yes, we need cleaner water quality. One way is to provide mini-wetlands at points where stormwater is discharged in to the river, this would filter out contaminants. Maybe the river could be diverted through the Woodhaugh gardens swamp forest, which is suffering from drying out. So, the water would be

	cleaned by the swamp forest and the swamp forest would be watered by the river.
Dunedin's river	Dunedin's river needs good access down to the water level, so people can enjoy and appreciate it. Let's have walking and cycling paths along each side and stepping-stone crossings at regular intervals. These would of course be closed during a flood. I accept the need for strong floodproof walls in the lower part of the river. I don't agree with allowing graffiti on the walls as it removes habitat for lichens and mosses that could grow on the concrete. The flat concrete river beds could have pebbles and rocks glued to them to provide a more natural surface and allow small living things to grow. Alternatively, small weirs and stepped-down lakes formed along the riverbed are better than bleak slimy concrete at low tide. The walls could have climbing holds to encourage people to enjoy the walls in the river's surroundings.
Kayak and recreational vision	This story is about a vision of the OUSA Kayak Racing Club. Kayakers and other recreational users are frequently looking for calm areas of water, when the beautiful Dunedin harbour becomes unruly and difficult. On Dunedin's busy harbour, some find learning water-based sports a road too far. The Leith, lying by the Marina and many different boat clubs, has always been a tantalizing sight. Its access however, is obstructed by a series of rocky weirs. To achieve a usable area of water, construction of one large two-metre-high weir at the mouth of the river would contain a long-uncluttered body of water with removal of the present small weirs. The water would be there through low and high tides. The high weir could be stepped to allow easy access from the harbour side with kayaks and down the other side into the calm water. Access from the bank could be along the top of the weir and down the steps, or from the present slightly widened ramp behind the yacht club. The weir could be designed to complement other envisaged harbour front developments. Occasional benches along the sides would provide pleasant viewing of the Leith and its users throughout the day. Lunch by the river with a view. Users would be many and varied: Recreational safe paddling after school. A lunch time escape instead of a sweaty run. Formal club use to teach and encourage young water users of different disciplines. Guaranteed regular water for training athletes. Easy access for coaches along the river bank. Organised sprint races with spectator viewing. Punting on the Leith! A vision.

Multi purpose park/path	I think a vertical garden on high concrete walls would be great, and the addition of a pathway with benches and some shelter from some planted trees would also be beneficial. A cycling path would be good but would need a wider breadth to accommodate two way cycling traffic, and perhaps the inclusion of small parks along the way which may also include children's swings and see saws, and for everyone else, installations that would allow young and old alike to exercise. Water fountains would be beneficial should the path be really long that runners and cyclists would need to fill up bottles. Lastly, bins for proper disposal of waste perhaps on the other side of the wall to prevent these from getting washed away when the rains come in.
Bring it to life	By narrowing the gully and providing obstacles like boulders would create a deeper flow and create noise of rushing water. Could use the remaining space to create a cycle path or walkway and plant heaps of natives. Could be an awesome nature walk with a lot of planting's. Could have artists create installations along the river.
Comments from University	The Water of Leith / Ōwheo is a highly significant part of the University of Otago campus. The Campus Master Plan identifies the Water of Leith as a counterpoint to the 'Kettle Grid' street layout in the area, and the central landscape feature of the University. The river also plays an important ecological role, including as a corridor between the surrounding hills and the harbour. From initial discussions with staff involved in campus planning, the main themes are: - Retain physical support for University buildings; - Minimise the impact and disruption of any works, especially during the academic year and particularly exams; - Ensure flood safety for both the campus and wider Dunedin; - Improve visual amenity; - Remove or soften the hard concrete walls where possible; - Plantings should be to enhance biodiversity, not just for landscaping; - Retain public access along the top of bank on both sides, and create waterside access on at least one side, including spaces designed for spending time not just as a through route; - There should be a consistent look and approach between new works and the works already completed upstream; - Incorporate public art and urban activation (which could include temporary projects).
Kai Tahu Relationship with the Otago Harbour and the Ōwheo	The Otago Harbour Catchment is a special feature of the Otago region and is highly valued by Kāi Tahu ki Otago. The bays near the mouth of the Otago Harbour provided proximity to the ocean, access on the tide to the head of the harbour and at low tide the abundant shellfish beds were a prized resource. Bays and inlets to the north of Otago Harbour and bays and inlets along the coast of Otago Peninsula and south to Taieri Mouth were popular sites for settlements also. The attributes of shelter, easy access to fishing grounds, and bush-clad hills with an abundance of bird life, building material and edible vegetation complemented the strong kaimoana resource that abounded. The reclamation of this area and the channelization of the Leith has removed its natural character and values. The current project being undertaken by the Otago Regional Council provides an opportunity to restore and enhance some of the natural and cultural values of the Leith (Ōwheo) and to strengthen its connection with the harbour. Kai Tahu see an opportunity through this project to:

	□ Take a holistic view to the management of the Leith and its margins, and its relationship to the Otago Harbour. □ Aim for the most natural state that is achievable within the existing built environment. □ Enhance natural planting. □ Provide access to the Leith and to the Otago Harbour. □ Create and enhance fish passage. □ Minimise the deposit of sediment into the Leith and the Otago Harbour. □ Improve water quality and amenity. Improvements sought by Kai Tahu include: □ Removal of the concrete channel and the reinstatement of a natural form to the greatest extent possible. The highest priority here is the removal of the central concrete island from the Leith. □ Construction of a public park at the head of the Leith adjacent to the harbour. This would provide opportunities to tell the story of the Otago Habour and the Leith through a range of mediums including design elements, sculpture and interpretation. □ Provide opportunities to tell the Maori and European history of the Leith throughout this reach through a range of mediums including design elements, sculpture and interpretation. □ Provision of public pathways (at stream level where possible), similar in nature to the improvements to the Leith above the Clyde Street bridge. □ Creation of public spaces along the Leith including native planting. □ Creation of habitat within the Leith.
Leith for Future Generations	For teenagers and the youth of Dunedin, many of us will continue to be close to the Leith for many years to come, therefore it is important to us that the state of the river is improved. Currently, accessibility is a big issue, in terms of getting down close to the water. An extended public walk / cycle way from the stadium would be a great way to get people of all ages to appreciate the Leith more. Making these paths or the area alongside the Leith more inviting in terms of a more lively appearance would also be worth doing. At the moment, the Leith looks so dirty and bare that it drives people away from seeing it as something of use. Although the water quality does not stop all youth from using the river for recreational activities such as swimming, it can be very off putting for some. It's awesome that Dunedin has a river, and being able to use it without worrying about potential e coli contraction would be ideal. Overall, the Leith is very relevant to the young people of Dunedin, and it is super important that the river is not only turned into something enjoyable for everyone, but also that it is kept enjoyable for everyone. - The Dunedin Youth Council

FOCUS GROUPS SUMMARY

10am Session:
Attendees:

Otago Fish and Game Council	Steve Dixon, Field Officer/Hatchery Manager
Liquigas	Lyndsay Pauling, Dunedin Depot Supervisor

Lyndsay Pauling – Liquigas Ltd

- If the enhancements increase foot traffic to the area outside Liquigas, doesn't want core business impacted by complaints
- Security is a key concern. The fence line provides a layer of security and safety, and its distance is set out by legislation for exclusion zones from the facilities
- Enhancement plantings: supportive of enhanced plantings or support for increased maintenance however, any activities must not compromise fire safety. Avoid hazardous/fire risk plant species
- Can the fence at the point be moved back towards the wharf compound to allow for viewing space at the headland? Maybe – LP doesn't see a reason why not. This land is Port Otago land (see next session notes on this)
- Area of concern noted due to the river bank collapsing along the true right side – LP noted someone from ORC had come to check out the stability at his request
- Suggestion that ORC hold a briefing for businesses (invite) in April when drawn up concepts are presented to the public.

Steve Dixon – Fish & Game Otago

- Support for returning the river to a natural landscape (not manicured), support for establishing better habitats for fish and wildlife, including rocks, boulders, pools, and improved substrate in the river bed
- Improved fishing and angler access along both sides of the river, access is great at the university, similar access down here would be great
- Harbour mouth on true right, the bank is very steep and the rocks are particularly slippery – can the slope be improved?
- Improve the substrate in the channel with a finer gravel to encourage fish spawning
- Support for connected walkways, meandering stream, and for a deeper flow to make it easier for fish passage
- Unrelated to the Amenity Project: the Boulder Trap off Malvern St traps finer gravels and stops them being laid down further downstream. Suggest saving these finer gravels/ sediments when cleaning and depositing them over the other side of the trap/or further downstream

12:30pm Session:
Attendees:

Port Otago	Rebecca McGrouther, Environmental and Consenting Officer

- Main concern is the leachate point at the logging yard: Port Otago are aware of it and are taking steps towards a solution, acknowledge that with the DCC Footbridge going in that this area will need improvement/tidying up
- Another key concern is that whatever improvements occur, that they don't adversely affect Port operations.
- Regarding the headland and shifting the fence for viewing up the harbour, Rebecca will look into the rules and regulations around the potential to open up that space.

2pm Session:
Attendees:

Forsyth Barr Stadium	Kim Barnes, Marketing and Communications Advisor

- Area of concern: garden space between stadium and overbridges on true left: Stadium maintains this space (weeding), although technically it is ORC space? Support for opening and improving this area and connecting it to the pathways.
- Main concern: safety of pedestrians and users of the corridor alongside the stadium and next to the Leith. It would be fabulous to have a shared pathway or laneway along this space, which is likely to address safety concerns and help clear the vehicle accessway.
- Strong support for the connected pathways principle of the working group, and also for the Anzac St Bridge suggestion of improving road safety and placing pathways underneath the bridge.
- Support for any beautification works
- Idea: the potential for an overbridge space connecting Minerva St/Parry St foot traffic into the upper floors of the stadium. Vision of an entertainment space for pre-event, and another entry point for the stadium
- Railway platform idea for improving public transport to the stadium is already being explored.

Love Your Leith

Leith Amenity Project: Community engagement report for round two consultation (feedback on potential concepts for enhancement of the Forth St to Harbour section of the Leith).

August 2018

ROUND 2

Executive Summary

Community feedback was sought and received on three potential concept designs for the lower reaches of the Leith River (from Forth St to Harbour). ORC's online engagement tool, YourSay, was used as the primary platform for consultation. This was supported by a public interactive display in the Otago Polytechnic from 23 July 2018 to 9 August 2018, which was modified and displayed in the Dunedin Public Library from 13 August 2018 to 24 August 2018. Overall, there is general support for the aesthetics and accessibility of the concept designs. Respondents have requested a colonisation area for plants and animals that naturally reside within the Leith, along with an independent cycle path. However, concerns have been expressed about potential flooding damage on the proposed amenities.

Summary of Survey

- An average of 82% who responded to the survey liked each concept design
- The aesthetics of each concept was favourably liked
- Accessibility to the Leith was highly supported
- People like that the designs were consistent with the design established at the University Clocktower building
- There is concern that flooding would damage these amenity concepts if put in place
- A placement area for local birds to situate would be good
- Implement of a cycle path
- Manage vegetation
- There's a desire to improve water quality

Quotes from Feedback

"I am concerned about the impact on wildlife too, as there are a considerable number of bird species that use the river. Paradise ducks, mallards, red-beaked gulls, spoonbills, geese and herons all add to the natural aspect of the area. I agree that the concrete is ugly and needs to come down in the lower part; so this is not a river just for the enjoyment of humans, the wildlife must also be taken into account." – Q12

"The best thing to do for the river's life but the hardest thing would be to have better water quality. It would be expensive to have treatment for the road water rather than directing it into the river. I prefer the idea of keeping the path at a distance from the water so birds can fish in peace." – Q4

"Cycle-wise please have separated pedestrian/cycle sides of this path. With more than just paint if possible. This is a key connection from harbourside, west harbour cycleway up into North Dunedin, Uni, central city etc. I will use it every day as will many commuters and one can go very fast along concrete rams. Please consider the long-term cycle infrastructure asset and plan for the future when it may be a very busy route." - Q8

"Visually it looks great and it does provide angler access to the water's edge." – Q2

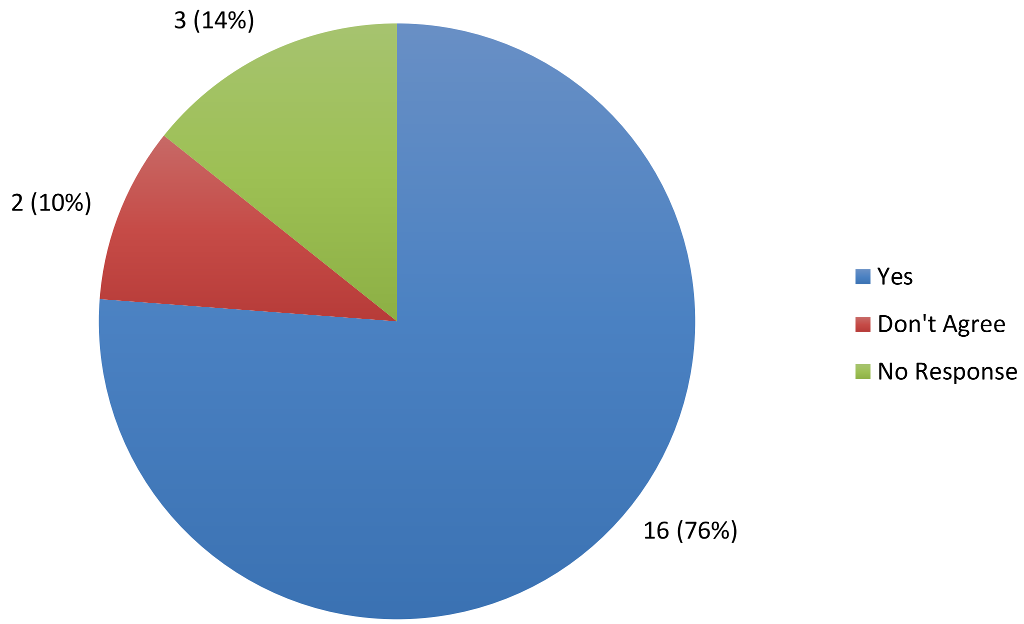
"Beautifying space by Unipol/Stadium excellent idea -- Dunedin playing host to more and more big shows (Ed Sheeran, Kendrick Lamar, Roger Waters, Pink, etc.). It would be nice for visitors to enjoy the full potential of Dunedin rather than being met with a bleak concrete ditch." – Q6

Survey Responses

An online survey was conducted to receive feedback about the three design concepts.

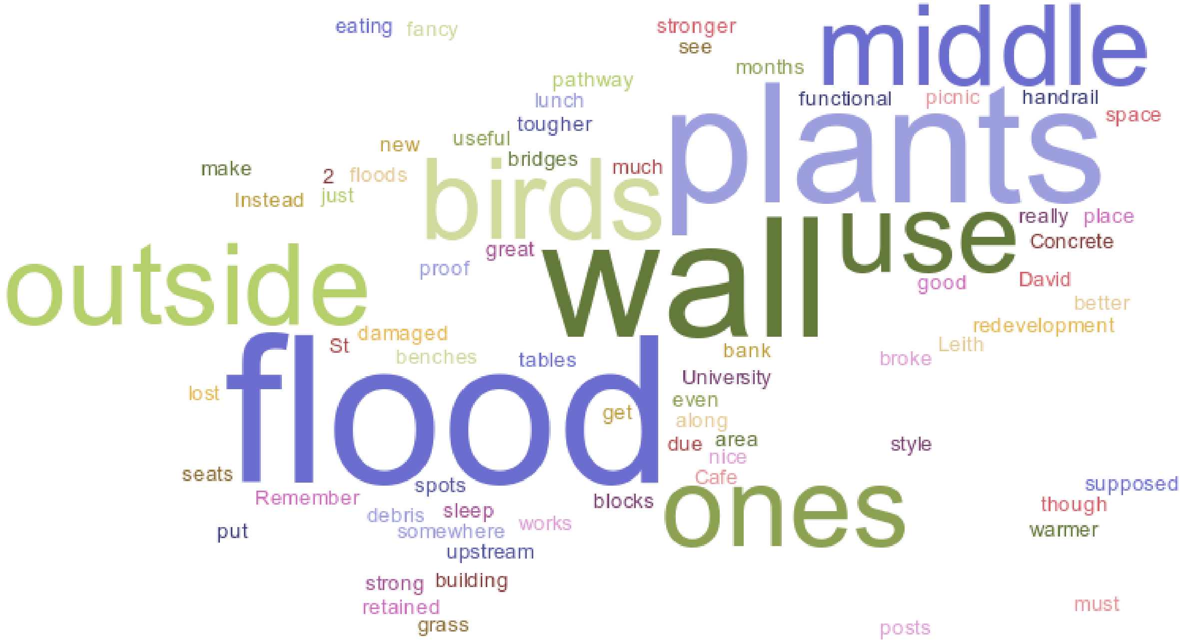
Concept Design 1: Forth St – Anzac Ave

Q1: Do you like this concept? (Forth St - Anzac Av)?



Q2: If you answered yes to this question, what do you love about this 'natural stream' concept for Forth St - Anzac Ave?
Visually it looks great and it does provide angler access to the water's edge.
Go for it, about time something happened - so derelict and depressing at the moment.
By working with mother nature and adding plants and useable spaces.
It looks good and functional and fits into the style of the Leith access at the university and gardens.
It looks a lot more appealing and will be great in summer time.
Doesn't look like absolute garbage. University of Otago routinely rated as one of the most beautiful university campuses in the world. Leith however looks like absolute rubbish and detracts from this, concrete everywhere is like something out of a dystopian horror film.
A lot more natural, less concrete or like a giant drain/canal.
Everything!
Turns the Leith into a tourist attraction and makes it more beautiful.
It looks very nice theoretically.
That it actually makes use of the waterside as a public space instead of just walling it off.
The shared path. At present, biking from uni to the stadium area is annoyingly convoluted and on roads with no cycle lanes.
The paths that you already put under the road bridges work really well. They stop you having to wait to cross the road.
It's OK.

Q3: If you answered don't agree to this question, what would you change about it?
Can we make better use of the space and have some picnic-style tables somewhere along the new re-development? The ones outside the St David Cafe at the university are great. It would be good to have some nice functional spots for eating your lunch over the warmer months. Instead of just some benches and grass bank... We lost 2 of the ones outside the ITS Leith building due to all of these works...
I see birds use the middle wall to sleep. The middle wall could be retained as a place for birds, or posts could be put in, but the wall would be tougher against flood debris. More bridges would be useful. The pathway should not have any fancy seats that will get damaged in floods. Concrete blocks are much stronger. If plants are in the flood area they must be really strong plants. Remember how the flood broke the handrail and plants upstream even though they were supposed to be flood proof.



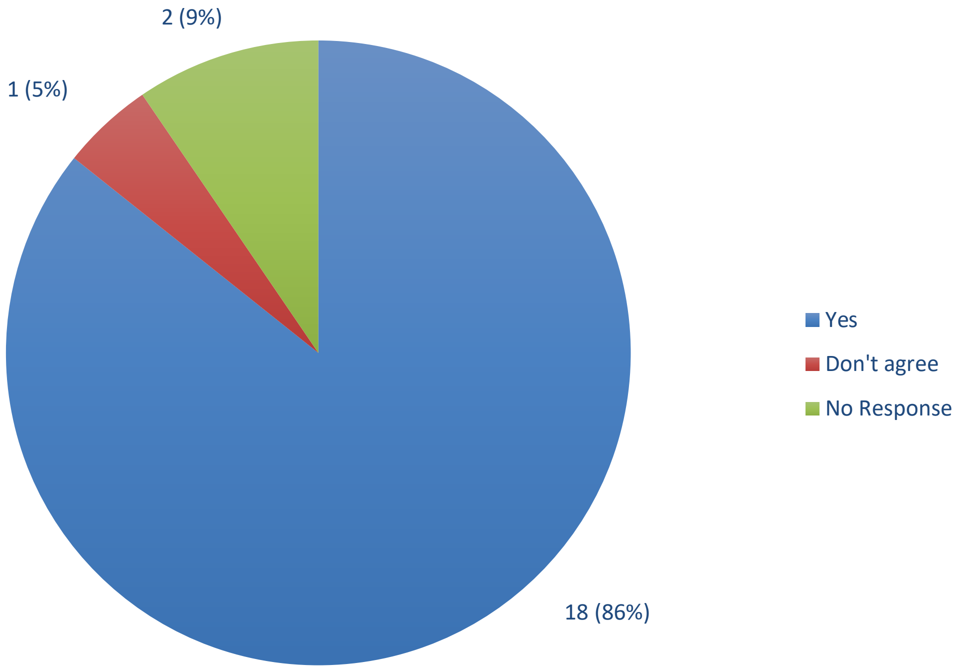
Q4: Any additional comments?
What is not clear is, is the substrate (stream bed) going to stay concrete or is it going to be more Eco-friendly, providing habitat for insects, fish & water fowl?
What is happening along the left bank if you're constraining flow on the right side of the channel? "naturalised" rocky riverbed? Planting? Concrete? Estuary/wetland plants?
Make sure something is still done with the College of education side of the Leith - it's an eyesore!
Decreases stress levels and increases Dunedin's green areas.
You are entirely misguided, go do what I did a week ago, look over the sea side of the Fourth St bridge and see how disgusting the river is! Full of bottles and plastic, clean green my a**e. Stop wasting money beautifying the banks of a filthy creek. Go after and stop the pollution of our rivers, it is an absolute disgrace.
The 'hostile architecture' shown in the bench having anti-homeless designs style arm rests isn't a good look and please don't bring that to Dunedin. Public seat shouldn't be designed to prevent public use. Please do not use benches of the sort shown in these images.
The vegetation that has been planted along the Leith hasn't been maintained - the weed species are increasing in size and with mature plants upstream this management is going to be ongoing along the length of all new plantings - there is a need to identify who is responsible for managing these plants along the length of the Leith.
Perhaps add a drinking fountain or two along the way.
What about flooding? It looks like this would get absolutely destroyed during a flood.
Have you considered the issues when the Leith floods? It becomes a raging torrent and will wipe out all of the work that is to be done. I fail to see that this can be managed effectively. The volume of water becomes too great. But it will be nice for most of the year when the Leith is at normal levels.
The best thing to do for the river's life but the hardest thing would be to have better water quality. It would be expensive to have treatment for the road water rather than directing it into the river. I prefer the idea of keeping the path at a distance from the water so birds can fish in peace.
When the water level is high that path will be unusable, not making it very useful for cycle connections from uni to the harbour / stadium / Emerson's area. I suggest the path be higher above the water line because of this. Additionally, the path does not look very wide. For a shared path, NZTA cycle guidelines require minimum width of 4 metres when a kerb is next to a drop off.

Pūmanawa Wai Feedback on the concepts of Love the Leith (Rosemary Clucas, Vicki, Lenihan, Kuini Scott, Ranui Ryan).
 	
It is great that we are rethinking the Lower Leith. We agree with a natural stream but would like to see more natural elements.
 	
• Concrete is still the feature which dominates. We would like to see less concrete, or that the concrete used is less flat and featureless.
    o Preferable to concrete would be natural materials, such as bluestone, which are not prone to leaching contaminates into the waterways
• The use of straight lines and features of a build environment need softening.
• The native planting in the stylised drawing is a monoplanting with no habitat value.
    o Plantings should provide nectar and refuge and be more than an architectural design element and mimic natural wild growth – be polycultural.
    o Wild waterways are not uniform from source to ocean.
• Agree with removal of the centre wall.
• Instream features will be required to create meander. Bottom features will be required, large rocks and irregularities. The benthic environment must provide refuge and habitat for invertebrate life, that is pools and riffles for fish and

invertebrates and resting areas for shags and gulls.
    - The current proposal does not provide enough natural cover for up-stream migration for spawning species of fish.
- Overhanging features such as material which is embedded in the walls and stick out into the stream are helpful as they provide substrate for insects to emerge from and metamorphosise.
- Structures within the wall – channels – to provide refuge during flood events for fish.
    - These cavities would need to be large enough for eel.
- Constructed rafts or islands for overhanging vegetation (if designs that can manage flood flows can be found).
- Overhanging vegetation along the true left.
- Habitat along the true left which provides for īnanga spawning in suitable vegetation (Carex species) at the stream margin, perhaps interspersed with structures which protect the vegetation.
- Appropriate use of local geomorphic features (rocks and embedded gravels) which could be enhanced with artistry.
- Use of woody debris or engineered alternatives.
- A constructed bottom which is not uniform and which provides dips for ponding and structures.
- Places for stands of native trees
    - Kōwhai stands near the water.
- Consideration of the conditions required for estuarine and migratory species to flourish: a healthy peritidal zone.
    - The proposal considers the aesthetic appeal of the surroundings to humans and recreational use by humans above this zone but makes no concession to ensuring the viability of the animals that live in the waterway.
- Artistic measures which allow for story telling of biodiversity and cultural practices.
- Haul out areas for marine mammals, grassy areas inaccessible from dogs and people.
- Areas of rough surface where lichens, mosses and ferns can grow vertically.
- Water features that make use of rain water off roofs during rain which feed rain gardens and vertical walls.

Concept Design 2: Anzac Ave -State Highway 88

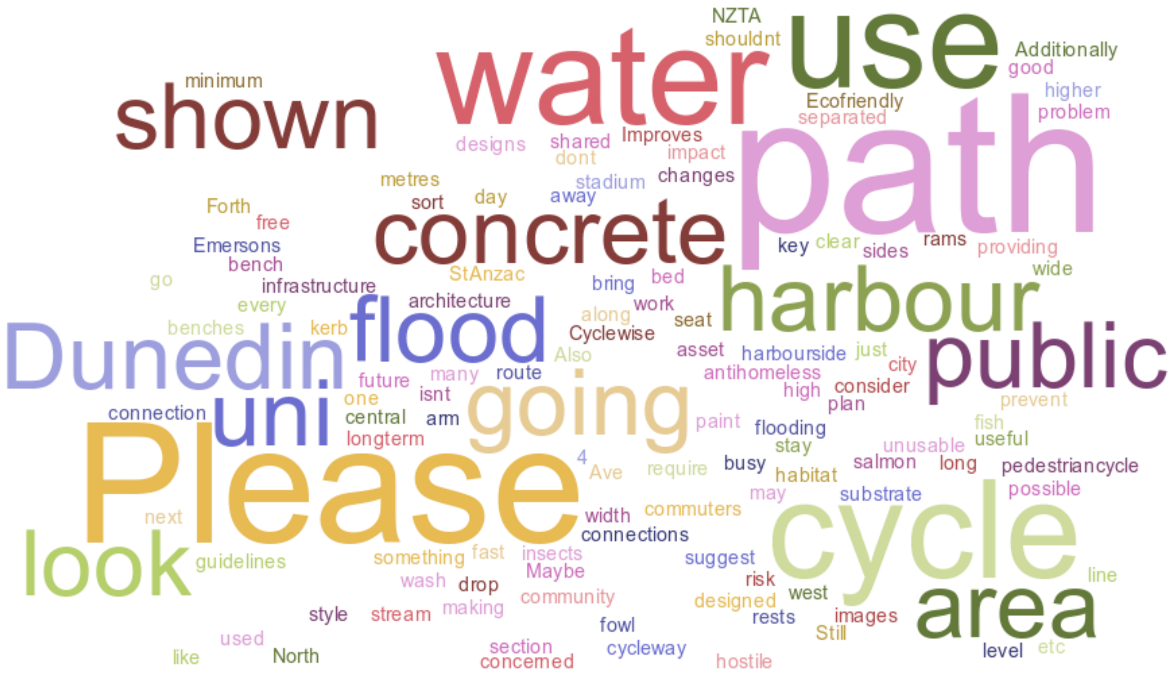
Q5: Do you like this concept? (Anzac Ave - State Highway 88)



Q6: If you answered yes to this question, what do you love about this 'tidal estuary' concept for Anzac Ave - State Highway 88?
Once again visually this looks great and provides great angler access. Not a fan of the sculptures though. I don't think the Leith needs these.
Wonderful to finally have properly connected cycle/walk way under SH88 right from the pedestrian bridge over the Leith to the uni, NEV, central Dunedin. Can now get into the city from St Leonards without crossing the road as a cyclist. Has potential to really grow active commuting for people working in these areas and living along west harbour!
Looks nice to me.
Just as previous anything that does not taper earth mother nature is good
The space between the railing and the Leith on the stadium side has looked awful for years and it is great to see this plan for it. The rest looks good and functional.
Beautifying space by Unipol/Stadium excellent idea -- Dunedin playing host to more and more big shows (Ed Sheeran, Kendrick Lamar, Roger Waters, Pink, etc.), it would be nice for visitors to enjoy the full potential of Dunedin rather than being met with a bleak concrete ditch.
Much more appealing area than previously, can go right to water’s edge. Makes the area around the stadium more likely to be used
Everything.
It looks really nice and brings the Leith more into the centre of attraction.
That it actually makes use of the waterside as a public space instead of just walling it off.
The rest of it is good.

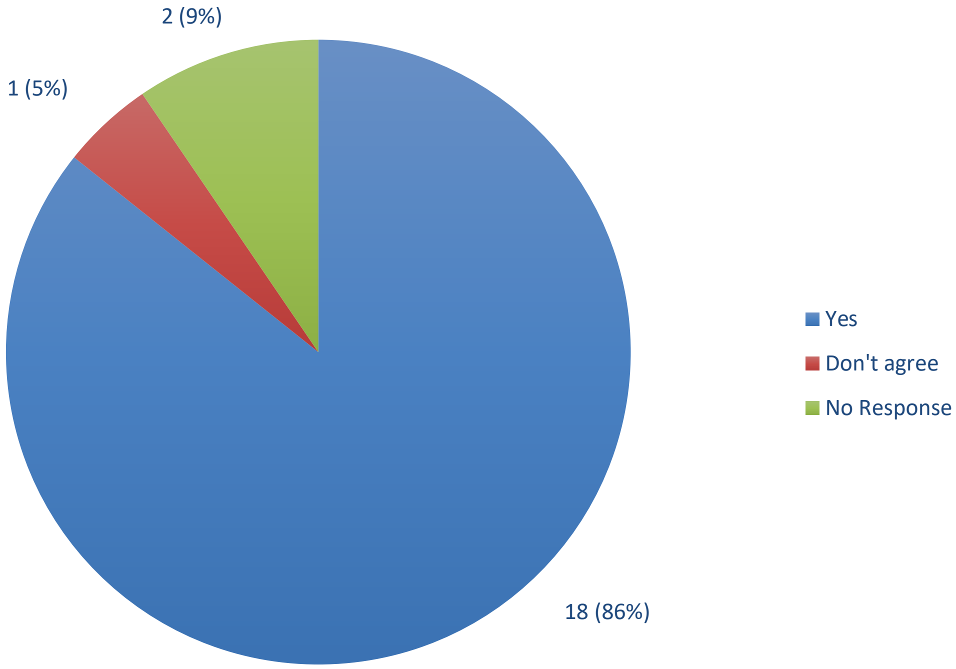
Q7: If you answered don't agree to this question, what would you change about it?
I see birds use the middle wall to sleep. Since you plan for statues on posts, maybe you could make statues with flat tops for birds that are shaped so any water runs away from the statue. A new wall with Maori carvings for the birds might be even more impressive and could have a little drain in the middle for water.

Q8: Any additional comments?
Once again, what is not clear is, is the substrate (stream bed) going to stay concrete or is it going to be more Eco-friendly, providing habitat for insects, fish & water fowl?
Cycle-wise please have separated pedestrian/cycle sides of this path. With more than just paint if possible. This is a key connection from harbourside, west harbour cycleway up into North Dunedin, Uni, central city etc. I will use it every day as will many commuters and one can go very fast along concrete rams. Please consider the long-term cycle infrastructure asset and plan for the future when it may be a very busy route.
Maybe do something like this on the Forth St-Anzac Ave section.
Improves the area as long as it is free and community used.
The 'hostile architecture' shown in the bench having anti-homeless designs style arm rests isn't a good look and please don't bring that to Dunedin. Public seat shouldn't be designed to prevent public use. Please do not use benches of the sort shown in these images.
Flood risk?
Still concerned about flooding. Also, what is the impact of these changes on salmon?
Once again, the flood problem will wash away some of this work.
When the water level is high that path will be unusable, not making it very useful for cycle connections from uni to the harbour / stadium / Emerson's area. I suggest the path be higher above the water line because of this. Additionally, the path does not look very wide. For a shared path, NZTA cycle guidelines require minimum width of 4 metres when a kerb is next to a drop off.

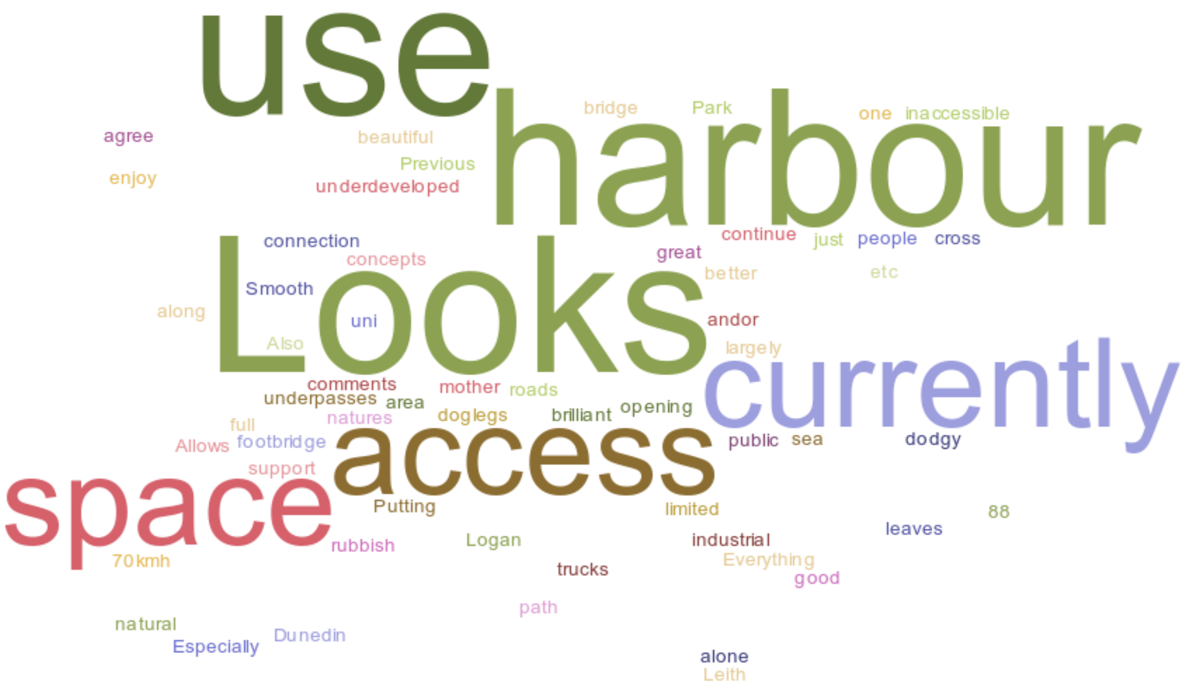

water
use
path
shown
concrete
harbour
Dunedin
flood
public
uni
going
Please
cycle
look
area

Concept Design 3: State Highway 88 - Harbour

Q9: Do you like this concept? (State Highway 88 - Harbour)



Q10: If you answered yes to this question, what do you love about the 'connect to the sea' concept for State Highway 88 - Harbour?
Looks great.
Smooth access along harbour, over Leith, up to uni, Logan Park etc. No more dodgy underpasses or doglegs to cross 70km/h roads full of trucks.
Previous comments continue here. I support all concepts but only agree on the one that leaves mother nature's path alone.
It all looks brilliant. Especially the footbridge and opening up currently inaccessible space to public use. Also, the under SH88 bridge.
Putting space by the harbour to good use. Dunedin has a beautiful natural harbour but has very limited access for people to enjoy it, largely just industrial and/or underdeveloped rubbish.
Allows for connection to the sea, area has no use currently.
Everything!
Looks better.



Q11: If you answered don't agree to this question, what would you change about it?

This would be nice if it was a shared pathway so that walkers and cyclists could go on it.

Q12: Any additional comments?

For anglers this is probably the most important section of the project.
More ideas for this stage of the project:

- There needs to be more angler access points down to the water's edge.
- There should be toilets in or near this section.
- Landscaping the true left of the Leith should also be looked into (even if it's just a few plants and some grass) will look better.
- Are the large rocks below the rail bridge staying or going?

Please plan for increased cycle traffic under SH88, across Leith new bridge, and up into uni, around into town. Stay away from 'shared paths' of ~2 m width. Rather make dedicated cycle part of EVERY path rather than randomly making cyclists share with (meandering, unpredictable) pedestrians on what is a major (and hopefully increasingly efficient) commuting route.

Improves the area as long as it is free and community used. Decreases stress levels and increases Dunedin's green areas.

The area is currently used for fishing frequently so some spot along it might be good to design for that?

Also, the tide level rocks that exist currently might be important to the local birds as there always seems to be paradise ducks or shags on them so it might be worth checking if this plan removes them.

The 'hostile architecture' shown in the bench having anti-homeless designs style arm rests isn't a good look and please don't bring that to Dunedin. Public seat shouldn't be designed to prevent public use. Please do not use benches of the sort shown in these images.

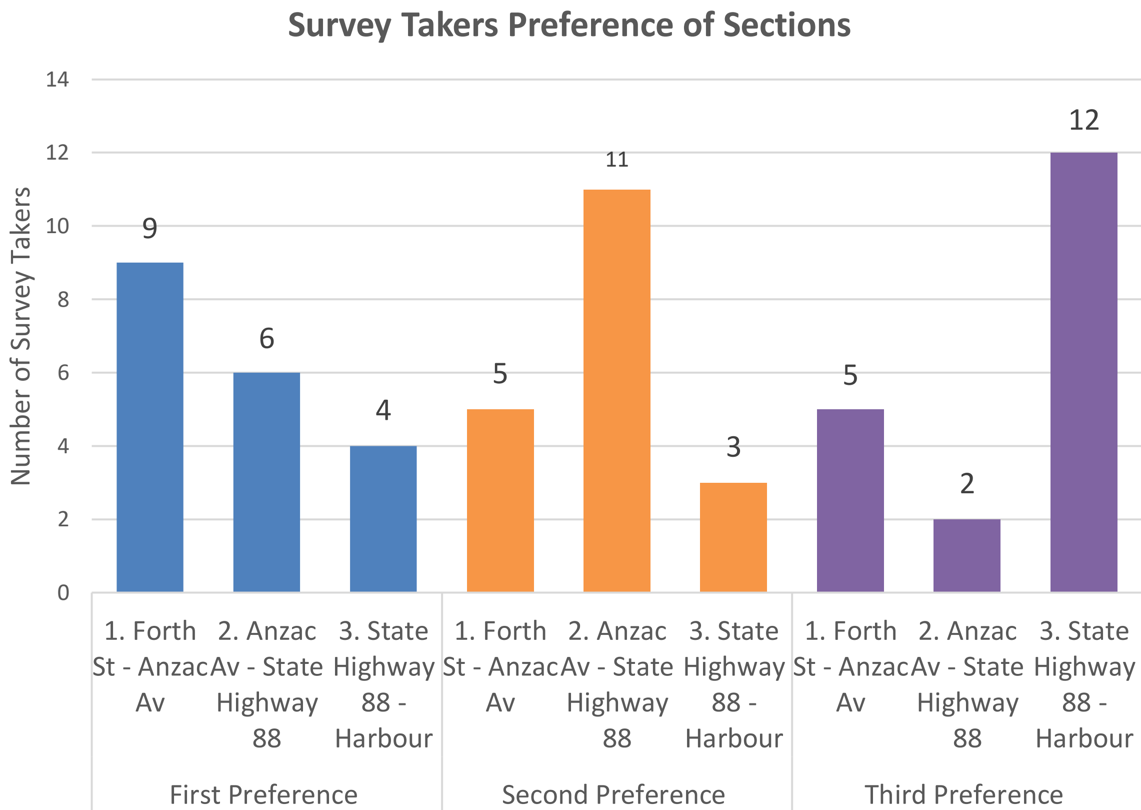
Thank you.

I am concerned about the impact on wildlife too, as there are a considerable number of bird species that use the river. Paradise ducks, mallards, red-beaked gulls, spoonbills, geese and herons all add to the natural aspect of the area. I agree that the concrete is ugly and needs to come down in the lower part, so this is not a river just for the enjoyment of humans, the wildlife must also be taken into account.
When the water level is high that path will be unusable, not making it very useful for cycle connections from uni to the harbour / stadium / Emerson's area. I suggest the path be higher above the water line because of this. Additionally, the path does not look very wide. For a shared path, NZTA cycle guidelines require minimum width of 4 metres when a kerb is next to a drop off.

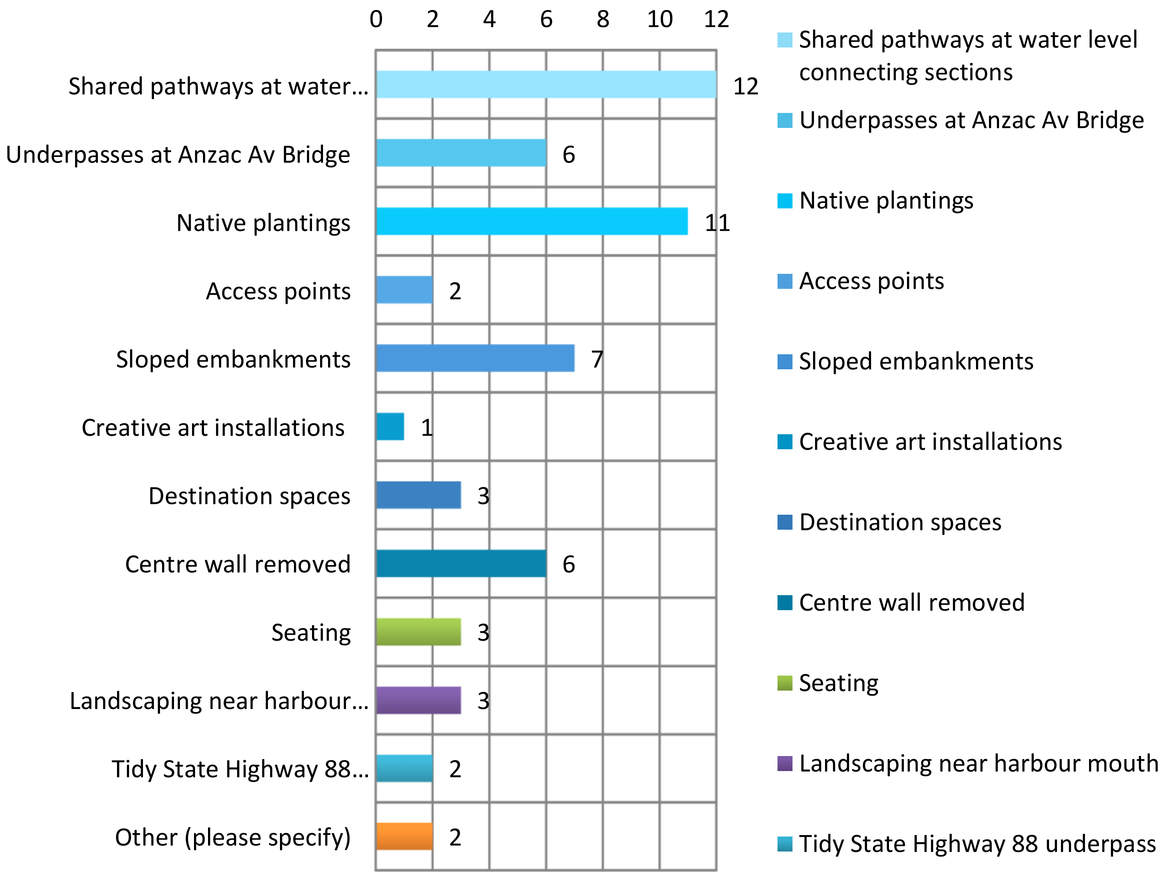
Other Questions

Q13: In what order would you prefer the sections to be constructed?

	Option 1	Option 2	Option 3	Option 4	Option 5
	3. State Highway 88 - Harbour	1. Forth St - Anzac Av	1. Forth St - Anzac Av	2. Anzac Av - State Highway 88	2. Anzac Av - State Highway 88
	2. Anzac Av - State Highway 88	2. Anzac Av - State Highway 88	3. State Highway 88 - Harbour	1. Forth St - Anzac Av	3. State Highway 88 - Harbour
	1. Forth St - Anzac Av	3. State Highway 88 - Harbour	2. Anzac Av - State Highway 88	3. State Highway 88 - Harbour	1. Forth St - Anzac Av
Total Number for Preferred Option	4	7	2	5	1



Q14: Which 3 features would you prefer to see get underway first?



Q15: If you prefer certain features or works to be undertaken first, please share here:
Work with DCC to ensure their Leith bridge and cycleways are carefully worked into the project. The bridge will be finished this year so please work from these already finished access points first.
Just do it!!! it needs to happen. Preferably sooner than later!
Working with the natural paths etc. Would hate to see mire damage because we haven't learned from interfering with mother nature.
Get the bloody creek clean FIRST AND FORMOST!
Highway 88 underpass will help pedestrians and cyclists get to the city from Ravensbourne and the west harbour more easily so it would be good if it got priority.
Whatever will help with flood protection should be a priority.
The pedestrian bridge would be good.

Q16: Any additional comments?
The 'hostile architecture' shown in the bench having anti-homeless designs style arm rests isn't a good look and please don't bring that to Dunedin. Public seat shouldn't be designed to prevent public use. Thank you.

Summary of Newsfeed

The Newsfeed feature enables online viewers to directly comment on the design concepts on the website without needing to do a full survey.

The summary points are listed below:

- Keep a natural stream bed
- Support the colonisation of natural plants and animals
- Agreement of improvement designs

Word Cloud

Newsfeed Responses

Concept Design 1: Forth St – Anzac Ave
I don't understand what the plain grey area shown is meant to indicate but if it is just the existing bare concrete floodway I disagree. I would like to see this become a natural stream bed of shingle or gravel, or a flood plain of grassy vegetation, or paths of course because human access is good too. I support retaining some of the existing concrete walls as shown because they have historic value (in spite of being rather unattractive). I don't support allowing graffiti to remain on these walls so close to the river as it involves industrial chemicals when it is applied (paint) or removed (paint stripper), both of which are harmful to stream life. I would like to see the concrete walls colonised by mosses, lichens and ferns and this could be encouraged by drip irrigating them with stream water gravity fed from upstream. I agree with the natural stony and grassy edge to the stream, as opposed to the straight concrete kerb-like edge used upstream of here, which allows no stream edge habitat to form. Please allow grassy plants to overhang the water to encourage whitebait to lay their eggs.

Concept Design 2: Anzac Ave -State Highway 88
I hope that some form of system is put in place to keep the stream bed covered with water, as at present, but improved from the present pieces of timber.
The idea looks good but I don't understand what the sculptures are about.
There should be a bridge across from the stadium to Parry Street to allow people to walk down there and link up to Anzac ave.
I like the improvements. Please limit a hard, straight edge to the stream to where this is absolutely necessary. The stream edge should be "soft" to allow colonisation by tiny plants and animals. "Soft" includes roughened concrete that can be easily colonised, if a sturdy edge is necessary, or rocks. Overhanging grasses may encourage whitebait by providing egg-laying habitat. Please allow natural processes to occur at the stream edge.
In reply to Mr or Ms N/A who wrote "I hope that some form of system is put in place to keep the stream bed covered with water, as at present, but improved from the present pieces of timber." Patches of sand and mud exposed to air have a lot of ecological value and can attract sea birds. I understand the reason for covering the stream bed at present as it is quite unattractive but I believe some room can be made for allowing a natural tidal habitat.

Concept Design 3: State Highway 88 - Harbour
I agree with the improvements. The rock armouring will provide flood safety but also allow natural processes at the stream edge, such as colonisation of the rocks by tiny plants and animals, and habitat in amongst and behind the rocks for water creatures and reptiles. Allowing and encouraging people to the area will ensure that people see their river and take better care of it rather than treating it as the "town drain" as has happened in the past.
How are we going to stop the rubbish flowing into the moana?

Summary of Love Your Leith Display

Physical Love Your Leith displays were set up at the Otago Polytechnic and Dunedin Public Library to give people an opportunity to place their feedback on the proposed design concepts. Post it notes were used for respondents to have their say directly on the posters. The summary points are listed below:

- Remove centre wall and white pipes
- Keep the street art
- Sculpture concept is supported
- Implementing litter traps
- Support of a cycle path
- Retain albatross foot bridge
- Request lighting
- Concerns of flood safety
- General support of the concept designs

Example of Love Your Leith display in the Otago Polytechnic.

Love Your Leith Display Responses

Otago Polytechnic

Concept Design 1 (Please refer to Page 34 for image)

Concept Design 1: Forth St – Anzac Ave
Keep the street art (x5)
The street art is cool especially the very realistic tomato sauce, please keep it
Gentrification Sux!
Yes, remove the centre wall (x3)
Need 10T water level monitors
Such amazing ideas
Artificial whitebait spawning habitats along above wedge
Remove wall with white pipes
Remove or update wall with white pipes. A hanging plant wall garden would look lit
Make little houses for all the birds to make nests
More natives less grass
Room to cast a fly
Will it handle the floods?
Edible fruit trees
More bridges across
Inner city pā harakeke (flax bush)
Keep the footbridge and the albatross
Please retain, repair, reprint the brilliant “Albatross Foot Bridge”
Love the wheelchair/pushchair access to the water way
Left side is beautiful. Right side a bit of an eyesore (wall with white pipes side)
Remove pipes as no longer used or rigid
Awaiting for a community space is great. Also, if engages involvement of people around nature
What about an aqua observation capsule you can walk into and observe fish etc
Across all three designs I agree with: recycling bins, water fountains (to reduce plastic use), good lighting (rate space for women), love the designs
Create bank habitat for eel refuge in high flow
Fish refuge in banks
Needs instream structural habitat refuge for fish
Creation of instream flow diversity
Walk along right hand side?

Concept Design 2 (Please refer to Page 39 for image)

Concept Design 2: Anzac Ave -State Highway 88
Yes please restore the Leith and public space
Love
Good plan
Great work
Sea-level rise?
Flood proofing?
Lighting?
I disagree
Fly casting space
Great access to restricted area. Also, it looks visually appealing
The sculpture in the stream is a great idea
Looks funky
Recycling bins
Water fountains
Danger for kids and toddlers
Looks like people are drowning
Night light down side
Sculpture and interpretation teaching local heritage and iwi stories would be good
Stepping stones – sites for natural selection (uncoordinated people beware)
Could micro/hydro electricity generation be incorporated into the design (discrete of course)?
Litter traps on all mud traps please
Needs a sculpture that uses water flow in and out to create sound scape
Yes remove this wall too
More consideration to be ecologically specific (to sea shore plants)
Make sure Love Your Leith walkway stays from Ross Creek to Harbour
Information on water quality and amount of rubbish caught in traps
Rowing
Underpasses are a good idea Can we paddle kayak? Waka ama

Concept Design 3 (Please refer to Page 43 for image)

Concept Design 3: State Highway 88 - Harbour
Dog poo bag and bins
Cleaner water
Make the path well lit
Recycling bins
I like tidy and destination places
Bike path (x2)
Cycle Path (health, fitness, activity, wellness, less congestion)
Add a kids' playground similar to Southbank in Brisbane to take the strain off the outdated 'Dinosaur' Park during summer
Cultural interpretation would be useful
Rubbish gatherers
More play spaces: ramps for bikes, random swings, concrete lily pads in stream
I like tidy and destination places
Get real architects and urban designers to investigate not diploma graduates
Not concrete riparian planting for native fish
Agree we need more public art (creative spaces)
Needs good lighting, clean and well maintained (mural installations under a flyover bridge)
Bridge for bicycles (link with DCC footbridge landscaping)
Widen it to allow single rowing skiff (improved landscaping on bank)
Are there buffers (rain, gardens, holding tanks) protecting the waterways from runoff carrying chemicals or loss?
Important we know we are in Aotearoa (bi-cultural visual art)
Rowing Skiffs – single lane

Dunedin City Council

Concept Design 1: Forth St – Anzac Ave
Light it up (x4)
No (x2)
Put proper seats in bus shelters first please
I think you need to think about people and their safety if it floods

Concept Design 2: Anzac Ave -State Highway 88
Love the sculptures
Plant willows
Light it up (x4).
Light up
There are no signs which is a good thing direction is better
Good about access ramp thanks
Would like to see some trains
Get artists from different eco-social backgrounds and with different mediums
No

Concept Design 3: State Highway 88 - Harbour
Use natives
Good connection with the sea
Dunedin will flood either way. I say do it
Flooding people safety guys and gals
Tumeke
Light it up

Appendix 4: ORC Lesser Range Works Amenity Development concepts at Lower Cost

The following images show the Lesser Range of work described in paragraphs [44] to [49].

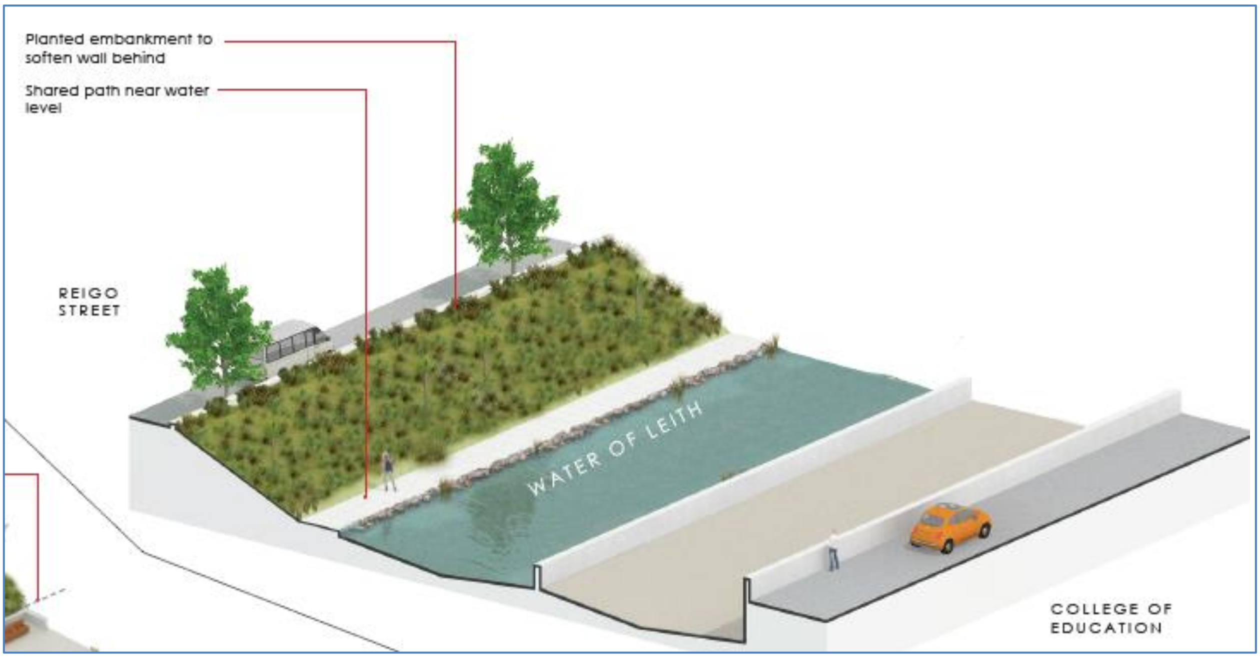
- As an interim step a local civil engineering consultant has identified three regions of lower cost $4.3M package of works likely to provide the most amenity as follows:

4.1 Forth St – Anzac Avenue: Right Bank outside Otago Polytechnic $2.30M

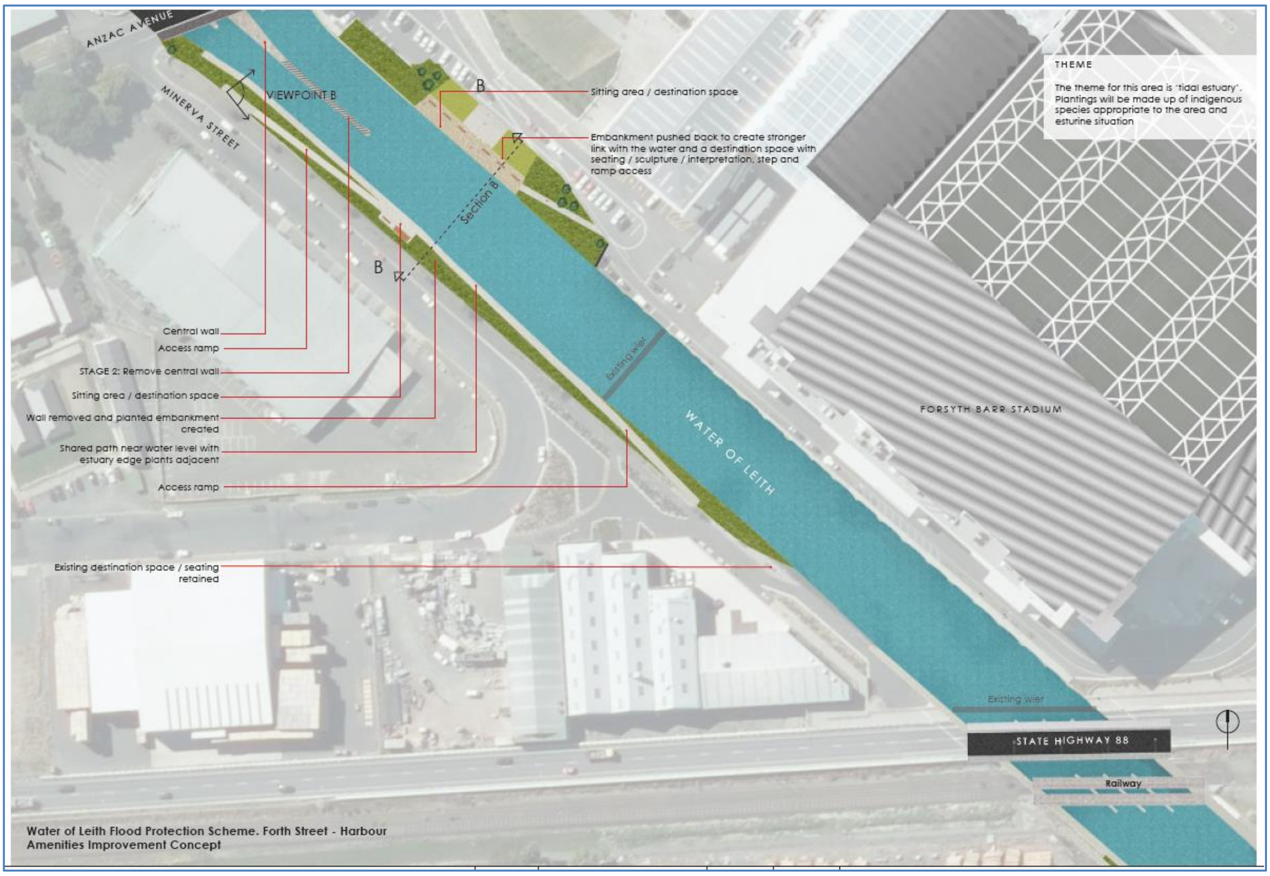
Cost components are:

- Form new embankment, river level walking path, access ramps, soft landscaping, street furniture, and seats $840K,
- Option 1: remove central concrete wall $0.65M,
- Option 2: line right bank concrete bed with bluestone boulders $0.81M

Water of Leith Flood Protection Scheme. Forth Street - Harbour
Amenities Improvement Concept



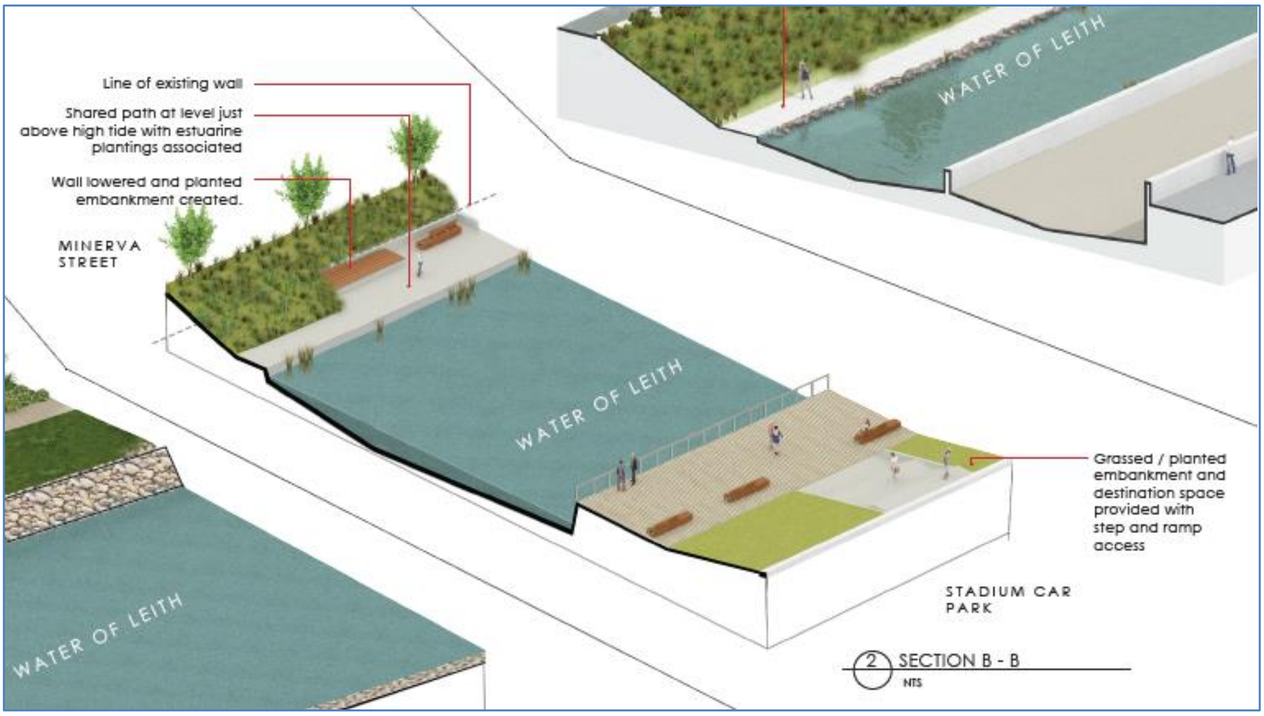
4.2 Anzac Avenue – to State Highway: Terraces & River Level Path $1.67M



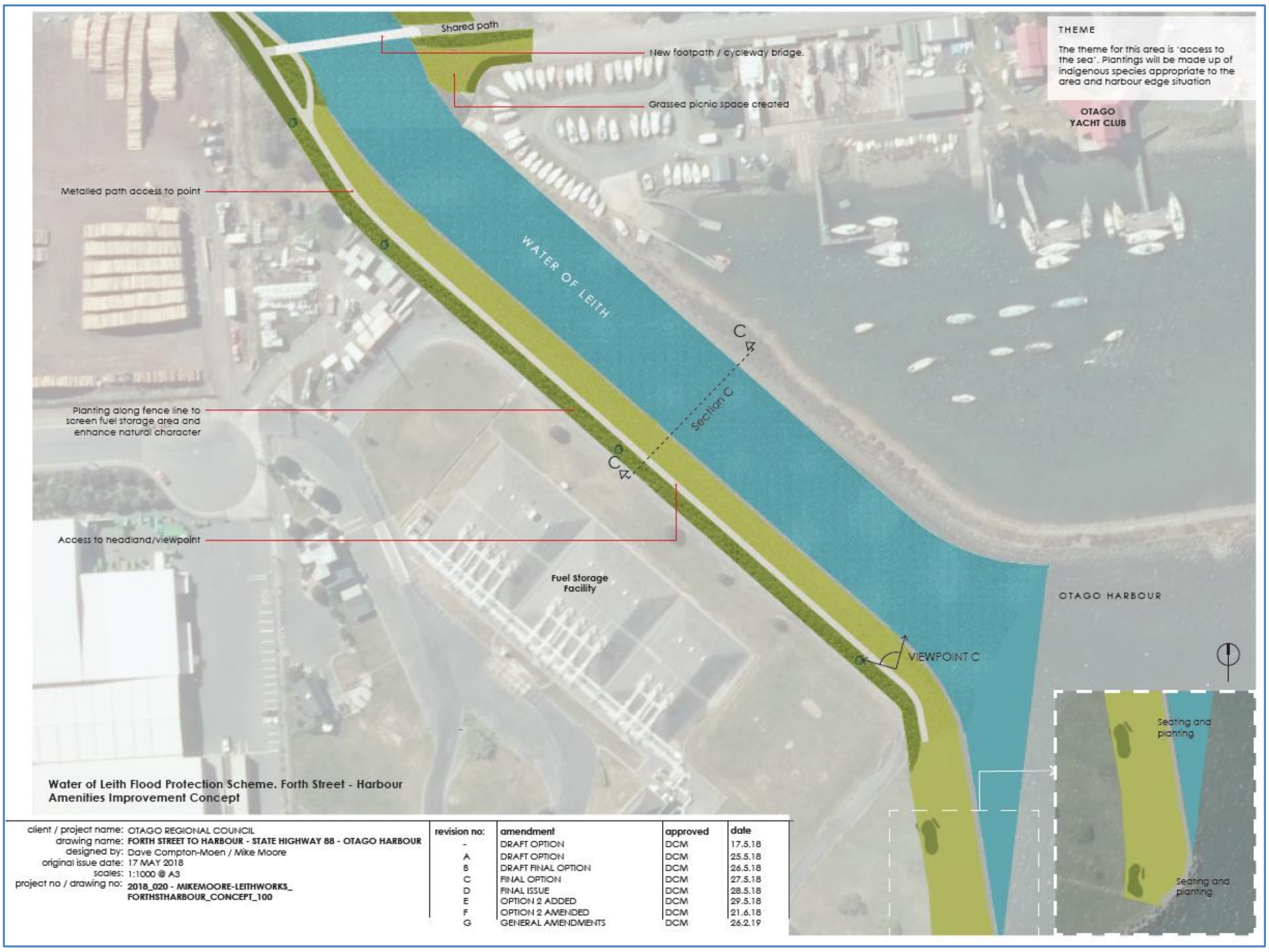
Cost components:

- Left Bank: form new embankment, low retaining wall, river level walking path and access ramps $622K,
- Right Bank: form new sunken terrace slab, low perimeter wall, steps, access ramp, and grass $625K, and
- Remove channel centre dividing wall and repair the concrete bed $0.22M

Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept

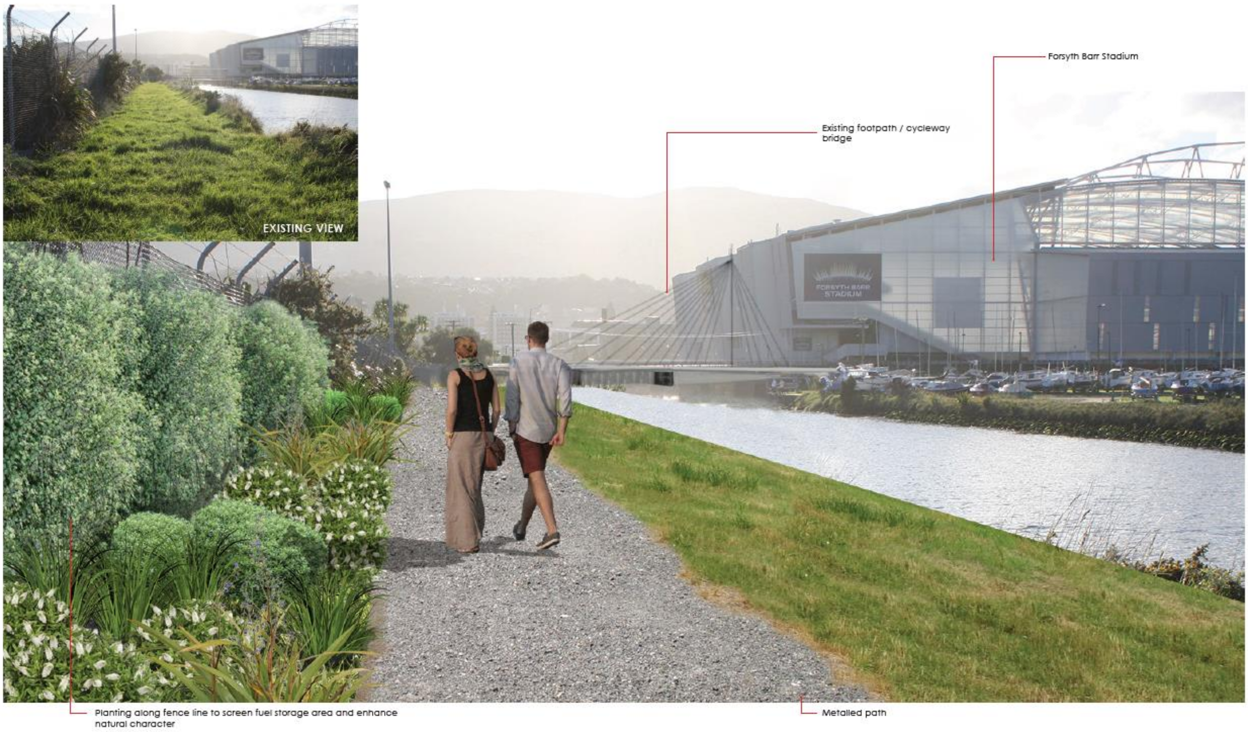


- **4.3 Lower Reach – SH88 to Otago Harbour: New Gravel footpath foot bridge to new picnic spot tables at Mouth of Leith Right Bank point: $0.35M**

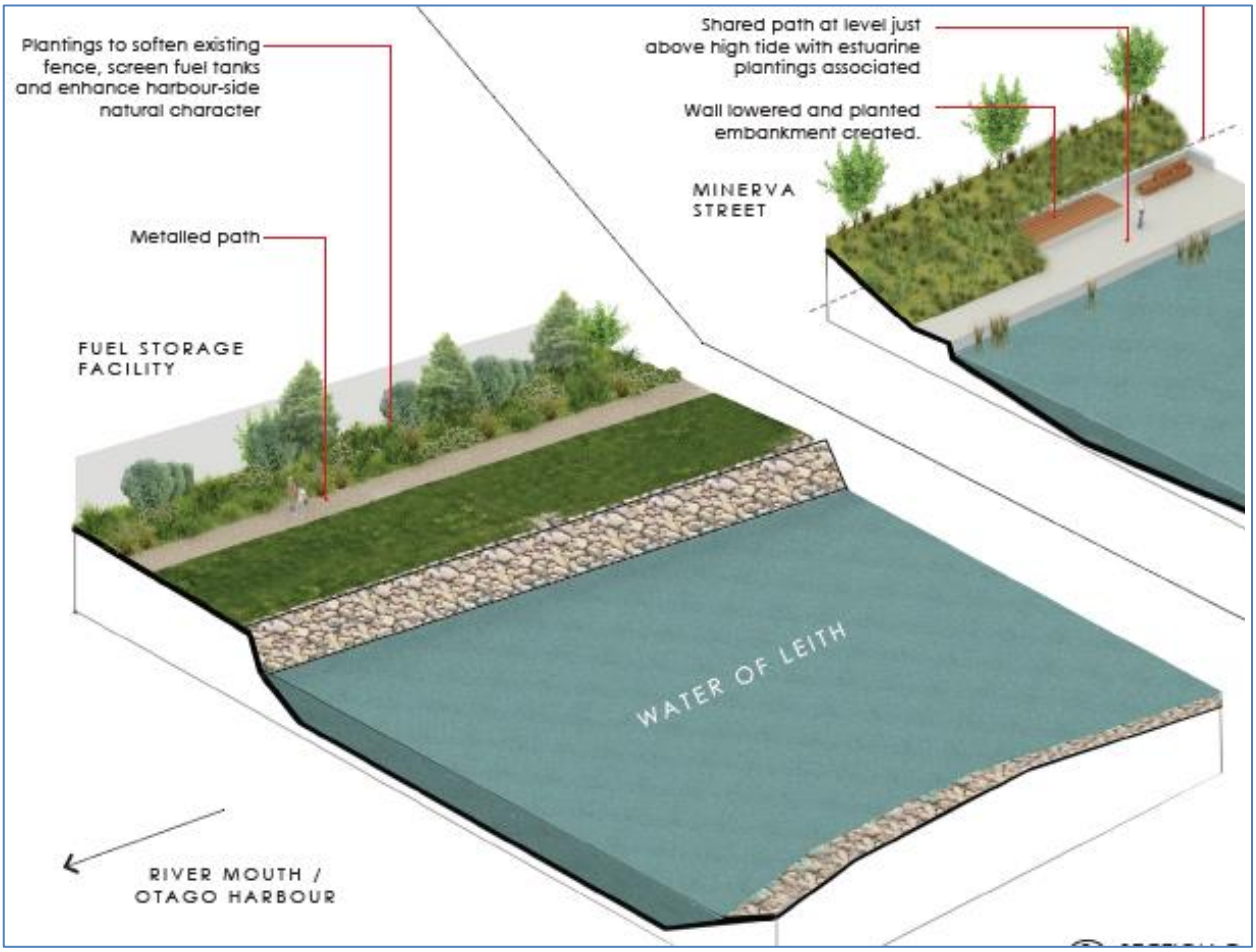


Components:

- 2 m wide gravel path
- Soft planting outside gas holding facility,
- Step access to fishing place
- Picnic table at right bank point with outstanding view of harbour



Water of Leith Flood Protection Scheme. Forth Street - Harbour Amenities Improvement Concept



Stock Effluent Disposal Sites

Options Report – Central Otago

Otago Regional Council

February 2019

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Approved for Release By

Chris Fox
Project Director

Contents

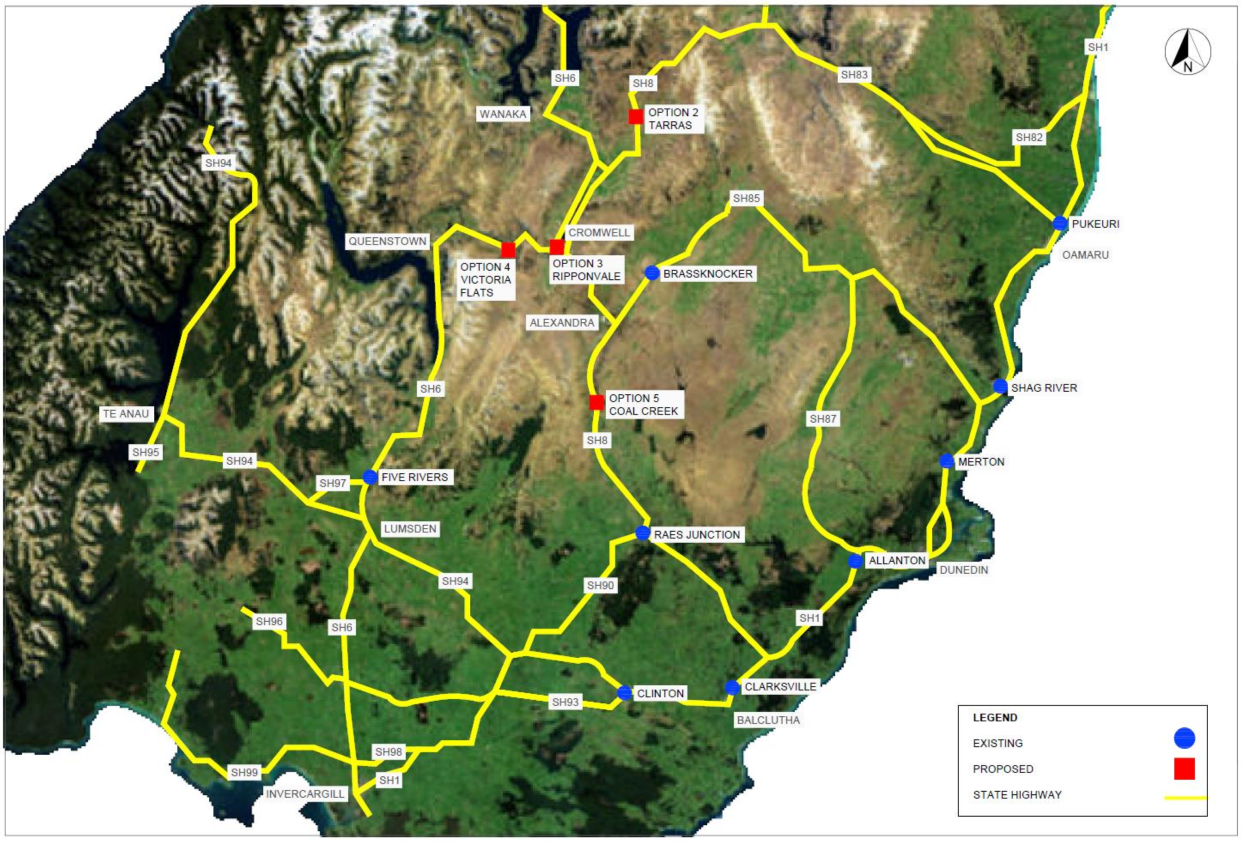
Appendices

Revision Table

Report Status	Date Issued	Revision Details
Draft for Discussion	13 February 2019	
Draft for Discussion V2	19 February 2019	Client feedback
Final	20 February 2019	Client feedback
Final V2	21 February 2019	Correct values in Section 3 table
Final V3	11 March 2019	Update Section 3, expand table content

1 Introduction and Background

The Otago Regional Council (ORC) is the lead organisation establishing Stock Truck Effluent Disposal (STED) facilities along the State Highway network in Otago. To date two facilities have been constructed in Central Otago on State Highway 90 at Raes Junction and on State Highway 85 at Brassknocker Road between Alexandra and Omakau. A map of the existing Otago/Southland STED facilities and the four Central Otago Option sites is below.



This report presents ORC with options for the establishment of further facilities. The report builds on work previously undertaken (November 2018 WSP Opus report, Stock Effluent Disposal Site Options Report – Central Otago), which identified an extensive list of possible sites. A short list of sites is presented below for further consideration. Previous investigations and reports (June 2017 WSP Opus report, Stock Effluent Disposal Site Evaluation – Central Otago) prioritised the key routes where further STED facilities are required to minimise the impact of effluent spillage onto the highway. These key routes are:

- SH6 Kingston – Cromwell (high)
- SH8 Lindis Pass – Cromwell (high)
- SH8 Alexandra – Raes Junction (moderate)

Cromwell is the central location of the two high impact routes.

The constructed site at Brassknocker has addressed the earlier high impact route on SH 85 Kyeburn to Alexandra.

2 Options

The options open to ORC to develop additional STED facilities can range from doing nothing to constructing multiple sites on affected routes. Four individual sites have been identified as providing the greatest benefit in reducing effluent spillage on the road network.

These sites were evaluated using criteria agreed between NZTA, CODC, and ORC and covered the following seven factors:

- Strategic location (scale 1-10)
- Safe Entry/Exit (pass/fail)
- Conflict with future NZTA works (pass/fail)
- Future land use conflict (pass/fail)
- Ease of Access (scale 1-10)
- Environmental/Social/cultural implications (scale 1-10)
- Amenity Criteria (pass/fail)

The evaluation is presented in Appendix B.

The order of sites detailed below is random and should not be taken to be a priority listing.

Location diagrams of the option sites are in Appendix A.

2.1 Option 1 - Do Nothing

This option abandons further development of STED facilities across Central Otago and relies on existing sites adjacent to the area (SH 6 at Five Rivers in Southland, and SH 90 at Raes Junction at the CDC/CODC boundary), along with the new site on SH 85 at Brassknocker, to provide suitable coverage for the area. The reality is that these sites are too sparse and there are not enough sites to prevent ongoing stock effluent spillages along the three key routes noted above.

Effluent spillage would continue to occur along the major tourist routes from the Lindis Pass to Cromwell and on to Frankton (the high impact routes) as well as along SH 8 between Alexandra and Roxburgh. Spillage on these mainly winding and mountainous areas would continue to pose safety risks along the routes, continue to be the cause of ongoing public/visitor complaint, and expend contractor resources and cost to clean up spillages. The major benefit to ORC is the financial saving of not constructing additional facilities.

2.2 Option 2 - SH8 Tarras, Lindis Peaks Straight

2.2.1 Site Location

The proposed location of the STED is on the right-hand side of State Highway 8 approaching Tarras from the Lindis Pass. The site adjoins land owned by Lindis Peak Station. The area is generally flat with a very wide road reserve (60.35m), approximately 40m of which is occupied by Lindis Peaks Farming Ltd via a 'Licence to Occupy' granted by NZTA.

2.2.2 Key Issues

The land is currently occupied and used or farming purposes. Negotiations will be required with NZTA and the occupier to allow the site to be developed.

2.2.3 Estimated Option Total Cost

The rough order of costs to develop a facility at this site is $865,000. This is based on the site being similar to the recently completed Brassknocker STED where adequate flat road reserve is available and traffic volumes are moderate. It has been assumed the facility can be safely constructed with localised highway widening. This will need to be confirmed during the investigation and design process.

2.2.4 Development Programme

Development of this option has not commenced. The programme to develop a facility at this site is 47 weeks, a programme is included in Appendix D. There is a possible funding risk that could extend this period. Funding is outlined in Section 3 below.

2.2.5 ORC Strategic Objectives

This option satisfies ORC's strategic objectives as it will provide a STED facility on the Lindis Pass side of the Tarras township and covers the northern route in and out of Central Otago. It will allow southbound trucks to empty their effluent tanks as they enter the Upper Clutha / Wanaka / Hawea areas and northbound trucks to empty before they reach the more mountainous Lindis Pass region minimising effluent spillage through the pass. This location is also favoured by CODC.

The main disadvantage of this location is the long distance to the next facility, especially for Queenstown bound trucks. Stock truck effluent tanks are likely to overflow before the next facility is reached. It is also a long distance from the Five Rivers facility for north bound trucks.

The site is subjectively assessed as providing a 40-45% reduction in effluent spillage across Central Otago.

2.3 Option 3 – SH6 Cromwell, Ripponvale Straight

2.3.1 Site Location

The proposed location of the STED is on State Highway 6 on the Ripponvale Straight – near Sarita orchard on the right-hand side of the State Highway. The site adjoins land owned by 45 South Cherry Orchards Ltd.

2.3.2 Key Issues

The site is close to commercial operations being orchards and the Highlands Race Track. In recent months a large subdivision has also been proposed for land close to the site.

2.3.3 Estimated Option Total Cost

The rough order of costs to develop a facility at this site is $925,000. This is based on the site being similar to the recently completed Brassknocker STED but enhanced with a right turn bay for west bound traffic. This additional requirement is needed due to higher traffic volumes making it unsafe to just provide a widened highway shoulder as completed for Brassknocker and proposed for Options 2 and 5. NZTA have previously approved funding for two STED facilities, being Brassknocker with this Option previously nominated as the second facility. As noted earlier, funding is outlined in Section 3 below.

2.3.4 Development Programme

Development of this option commenced with designs completed in 2018. The programme to develop a facility at this site is 43 weeks, a programme is included in Appendix D. There is a possible funding risk that could extend this period.

2.3.5 ORC Strategic Objectives

This option satisfies ORC's strategic objectives as it will provide a STED facility central to the two high impact routes and will also capture stock trucks heading towards Queenstown originating from the Alexandra and Wanaka/West Coast directions. It will also allow any stock trucks parked up overnight in Cromwell to empty prior to heading through the Kawarau Gorge.

The main disadvantage is that there is no facility to the north to capture trucks entering Central Otago across the Lindis Pass leaving a risk of effluent spillage on this high impact route for south bound traffic.

The site is subjectively assessed as providing a 35-40% reduction in effluent spillage across Central Otago.

2.4 Option 4 – SH6 Gibbston Victoria Flat

2.4.1 Site Location

The proposed location of the STED is on State Highway 6 at Victoria Flats Road at the Queenstown end of the Kawarau Gorge.

2.4.2 Key Issues

A consent to subdivide the land between the highway and the Kawarau River immediately adjacent to the possible STED site has been approved since the site was proposed. This could result with the site being too close to dwellings. Consultation will be required with the landowner(s). There is also a concern that the road reserve width may not fully accommodate a STED facility and a small amount of land purchase may be required, adding time and cost to the option.

2.4.3 Estimated Option Total Cost

The rough order of costs to develop a facility at this site is $965,000 and includes a right turn bay as detailed for Option 3 above.

2.4.4 Development Programme

Development of this option has not commenced. The programme to develop a facility at this site is 47 weeks, a programme is included in Appendix D. There are possible funding, consultation, and land acquisition risks that could extend this period. Funding is outlined in Section 3 below.

2.4.5 ORC Strategic Objectives

This option satisfies ORC's strategic objectives as it will provide a STED facility to the east of Frankton and will minimise the risk of effluent spillage through the Frankton area for west and Southland bound stock trucks. It will also reduce spillages through the Kawarau Gorge for east (Cromwell) bound traffic.

The main disadvantage is that there is no facility to the north to capture trucks entering the Kawarau Gorge by trucks travelling from the Lindis Pass and Cromwell areas depending on where their days journey started.

The site is subjectively assessed as providing a 30-35% reduction in effluent spillage across Central Otago.

2.5 Option 5 – SH8 Gorge Creek Hill (between Alexandra and Roxburgh)

2.5.1 Site Location

The proposed location of the STED is on the left-hand side of State Highway 8 (heading toward Roxburgh) close to Gorge Creek. The road reserve is 40.23m wide, with approximately 20m of which is occupied by the adjoining land owned by Gorge Creek Station Ltd via a 'Licence to Occupy' granted by NZTA.

2.5.2 Key Issues

The land is currently occupied and used or farming purposes. Negotiations will be required with NZTA and the occupier to allow the site to be developed. It is also likely a moderate amount of earthworks will be required to level the site to create a flat platform for the receptor.

2.5.3 Estimated Option Total Cost

The rough order of costs to develop a facility at this site is $915,000. The ROC is higher at this location than Tarras due to it being more remote and the terrain being more difficult requiring additional earthworks to create the required receptor gradients.

2.5.4 Development Programme

Development of this option has not commenced. The programme to develop a facility at this site is 47 weeks, a programme is included in Appendix D. There is a possible funding risk that could extend this period. Funding is outlined in Section 3 below.

2.5.5 ORC Strategic Objectives

This option satisfies ORC's strategic objectives as it will provide a STED facility that will minimise effluent spillage over the Alexandra to Roxburgh hills and through the two townships. However, as this site is on a moderate priority route, the high priority routes will still be exposed to effluent spillages.

The main disadvantage of this location is that it has little to no impact on the two high impact routes.

The site is subjectively assessed as providing a 15-20% reduction in effluent spillage across Central Otago.

3 STED Facility Funding

The STED Facility at SH85 Brassknocker Road is now completed with an estimated final cost of $840,000. Based on the funding assistance rates of 50% and 100% for the effluent facility and access road respectively the NZTA portion comes to $635,000 and the balance $205,000 from ORC.

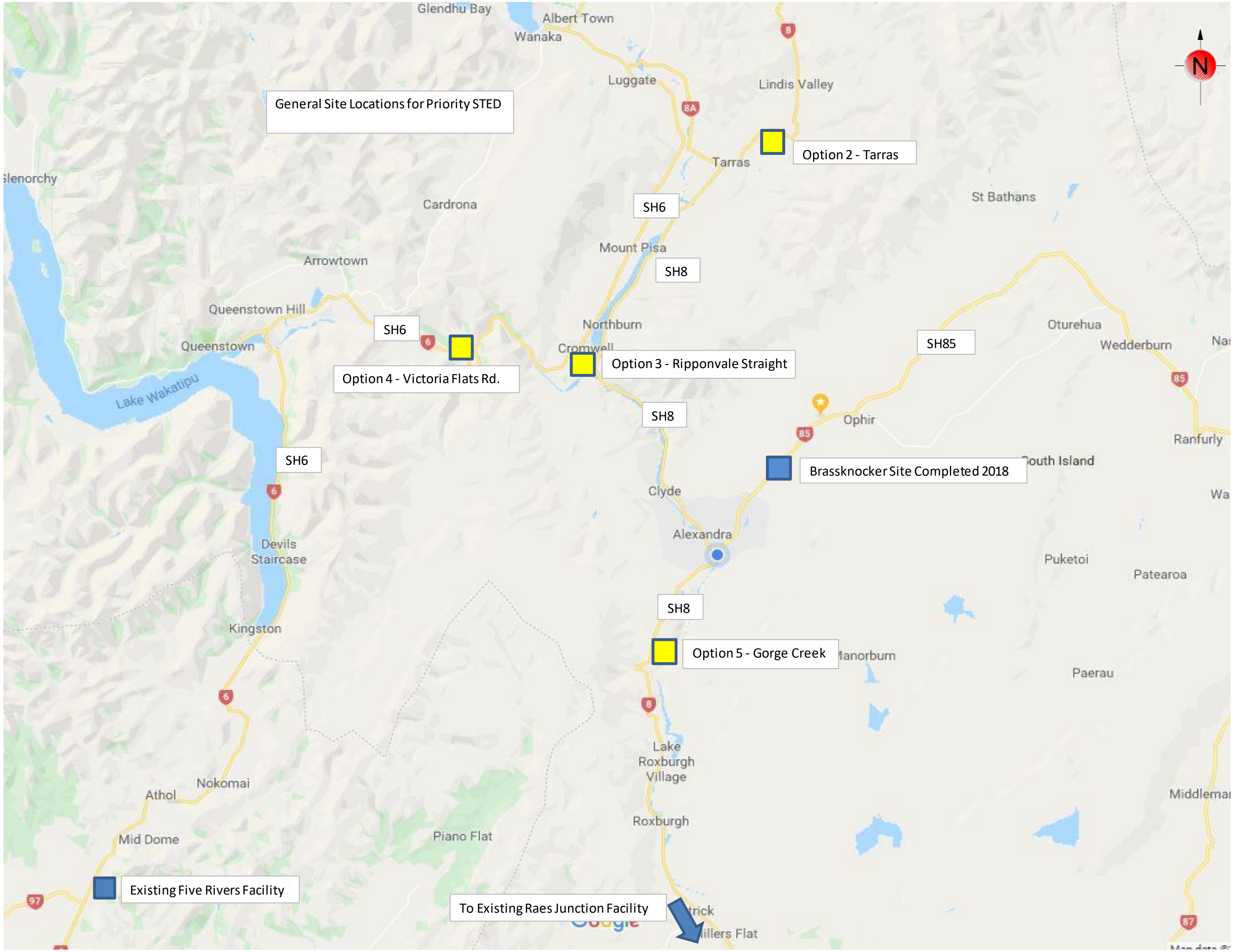
The NZTA approved funding for the STED Project is $940,000 (for two sites, originally nominated as Brassknocker and Ripponvale), leaving a balance of $305,000 for the second site. NZTA would approve the second site changing from Ripponvale to another option. ORC have allocated a budget of $426,000 for its share of the STED Project. The ORC balance for the second site is therefore $221,000. The current total funding available for the second site is therefore $526,000. This is significantly below the second STED rough order of costs of between $865,000 to $965,000. Additional funding is therefore required and is summarised in the table on page 6 below for the different options.

Additional funding can be sought from NZTA through a cost adjustment process to increase the $940,000 currently approved. NZTA have advised that any additional funding would be subject to availability within their current budgets and noted that the project would be competing against multiple projects nationally for this funding. It is therefore recommended that ORC engage with NZTA and commence this process as soon as a decision is made by ORC on the second site.

It is understood that the current approved funding was sought and approved using a rough order of costs prior to the final design of Brassknocker and Ripponvale and based on the cost of the last STED facility developed in Southland by NZTA. The earlier ROC did not recognise the recent construction increases being experienced across the Central Otago area. The industry is buoyant at present and the market is less competitive due to resource shortages. It is common to only receive a single tender and often at a premium price.

Option No	Site	Estimated Project Costs ($)			NZTA Contribution ($) ((a)x50% + (b)x100%)	Balance Approved NZTA Funding ($)	Additional NZTA Funding Required ($)	ORC Contribution ($)	Balance ORC Funding ($)	Additional ORC Funding Required ($)
		STED Receptor Facility	Access Road	Total						
		(a)	(b)	(c)	(d)	(e)	(f) = (d)-(e)	(g) = (c)-(d)	(h)	(i) = (g)-(h)
2	SH8 - Tarras, Lindis Peaks Straight	$380,000	$485,000	$865,000	$675,000	$305,000	$370,000	$190,000	$221,000	-$31,000
3	SH6 – Cromwell, Ripponvale Straight	$360,000	$565,000	$925,000	$745,000	$305,000	$440,000	$180,000	$221,000	-$41,000
4	SH6 – Gibbston Victoria Flats	$380,000	$585,000	$965,000	$775,000	$305,000	$470,000	$190,000	$221,000	-$31,000
5	SH8 – Gorge Creek Hill	$400,000	$515,000	$915,000	$715,000	$305,000	$410,000	$200,000	$221,000	-$21,000

Appendix A – Location Plans



Opus International Consultants Ltd Alexandra Office Tarbert Buildings, 69 Tarbert Street PO 273, Alexandra, 9320 New Zealand Tel: 03 440 2400	**Project:**	Central Otago Stock Effluent options	**Appendix A**
	Project No.:	6-CO057.00	**Site Location Plan - Regional Plan**
	Client:	Otago Regional Council	

Opus International Consultants Ltd
Alexandra Office
Tarbert Buildings, 69 Tarbert Street
PO 273, Alexandra, 9320
New Zealand
Tel: 03 440 2400

Project:	Central Otago Stock Effluent options	**Appendix A**	
Project No.:	6-CO057.00	**Site Location Plan - Tarras Area**	
Client:	Otago Regional Council		

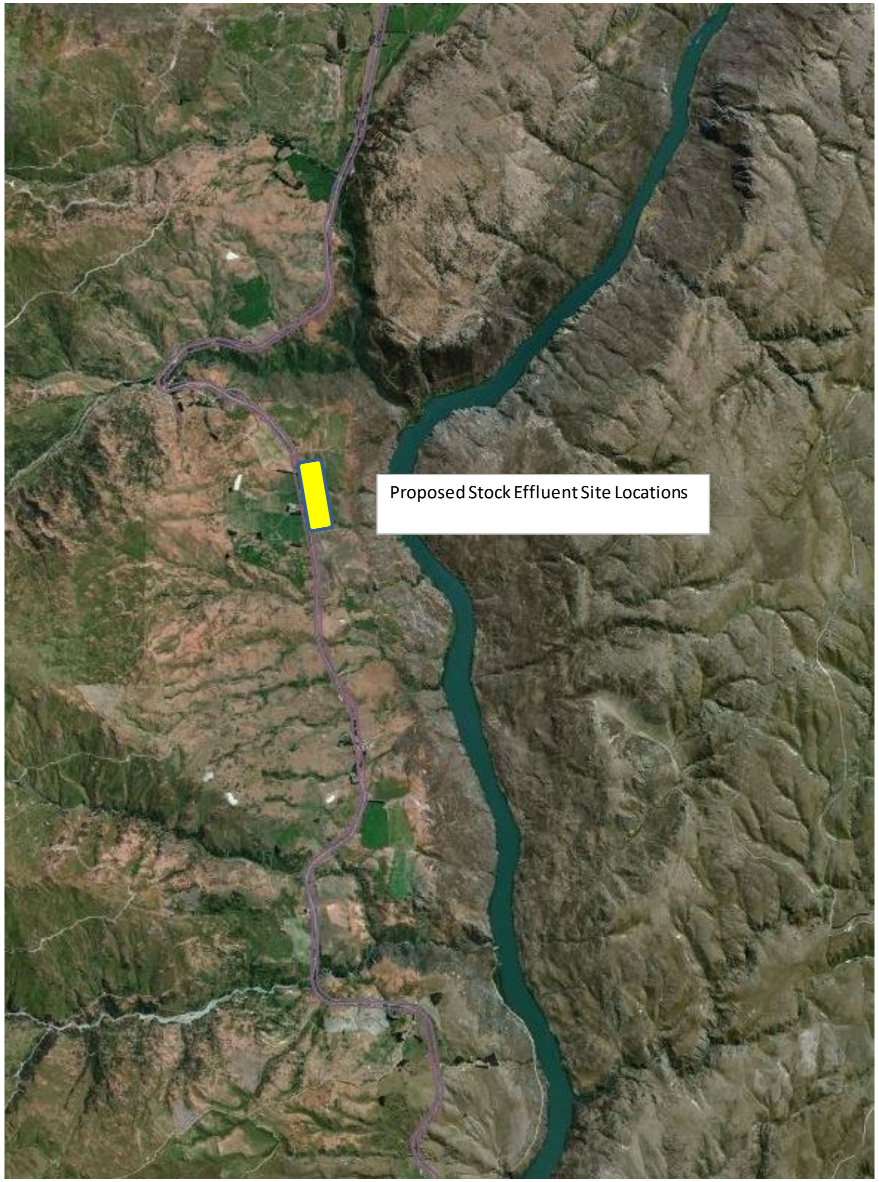
wsp | OPUS	**Opus International Consultants Ltd** Alexandra Office Tarbert Buildings, 69 Tarbert Street PO 273, Alexandra, 9320 New Zealand Tel: 03 440 2400 Fax: 03 440 2401	**Project:** Central Otago Stock Effluent options **Project No.:** 6-CO057.00 **Client:** Otago Regional Council	**Appendix A** **Site Location Plan - Ripponvale Road Area**

Opus International Consultants Ltd
Alexandra Office
Tarbert Buildings, 69 Tarbert Street
PO 73, Alexandra 9340
New Zealand
Tel: 03 440 2400
Fax: 03 440 2401

Project:	Central Otago Stock Effluent options
Project No.:	6-CO057.00
Client:	Otago Regional Council

Appendix A

Site Location Plan - Victoria Area



Opus International Consultants Ltd Alexandra Office Tarbert Buildings, 60 Tarbert Street PO 273, Alexandra, 9320 New Zealand Tel: 03 440 2400	
Project:	Central Otago Stock Effluent options
Project No.:	6-CO057.00
Client:	Otago Regional Council

Appendix A

Site Location Plan - Gorge Creek

Appendix B – Site Selection Evaluation Spreadsheet

Selection Criteria

Route Section	Level of Stock Impact on SH surfacing	Identified Potential development site	1 Strategic Location (scale 1 -10)	2 Safe Entry / Exit (Pass / Fail)	3 Conflict with future NZTA works (Pass / Fail)	4 Future land use conflict (Pass / Fail)	5 Ease of Access (Scale 1- 10)	6 Environmental / Social / cultural Implications (Scale 1-10)	7 Amenity Criteria (Pass / Fail)	**Score** value	**Pass / Fail** 1/2/3/4	**Total** (Score*Pass/fail) value
SH6 Kingston – Cromwell	High	Option 3 - SH6 Cromwell, Ripponvale Straight	10	Pass	Pass	Pass	10	10	Pass	30	4	120
		Option 4 - SH6 Gibbston Victoria Flats	8	Pass	Pass	Fail	8	10	Pass	26	3	78
SH8 Lindis Pass – Cromwell	High	Option 2 - SH8 Tarras, Lindis Peaks Straight	9	Pass	Pass	Pass	10	10	Pass	29	4	116
SH8 Alexandra – Raes Junction	Moderate	Option 5 - SH8 Gorge Creek Flat	8	Pass	Pass	Pass	10	10	Pass	28	4	112

Notes:
1) The selection criteria were developed and agreed between NZTA, CODC, and ORC
2) The toal score is derived by multipling the total of the scaled criteria by the number of pass scores
3) The total mark allows ranking of sites by criteria and is subjective and provides relativity between sites
4) A fail score may or may not be deemed critical, but indicates an issue that will require additional investigation.

Appendix C – Rough Order of Cost Estimates

Cost Estimates

												Cost Breakdown			Total Development Cost
Route Section	**Level of Stock Impact on SH surfacing**	**Identified Priority Development Site**	**Consultation, Resource Management Costs**	**Preliminary Design**	**Detailed Design**	**Tender Process**	**Contract Management**	**MSQA Supervision allowance**	**Establishment & Construction**	**Landscaping**	**ORC Management and Liason Costs**	**Professional Fees**	**Physical Works Costs**	**ORC Costs**	
SH6 Kingston – Cromwell	High	Option 3 - SH6 Cromwell, Ripponvale Straight	$ 15,000.00	Completed	Completed	$ 5,000.00	$ 15,000.00	$ 10,000.00	$ 800,000.00	$ 30,000.00	$ 50,000.00	$ 45,000.00	$ 830,000.00	$ 50,000.00	$ 925,000.00
		Option 4 - SH6 Gibbston Victoria Flats Sites - Road Reserve	$ 15,000.00	$ 10,000.00	$ 40,000.00	$ 5,000.00	$ 15,000.00	$ 10,000.00	$ 800,000.00	$ 20,000.00	$ 50,000.00	$ 95,000.00	$ 820,000.00	$ 50,000.00	$ 965,000.00
SH8 Lindis Pass – Cromwell	High	Option 2 - SH8 Tarras, Lindis Peaks Straight	$ 15,000.00	$ 10,000.00	$ 40,000.00	$ 5,000.00	$ 15,000.00	$ 10,000.00	$ 700,000.00	$ 20,000.00	$ 50,000.00	$ 95,000.00	$ 720,000.00	$ 50,000.00	$ 865,000.00
SH8 Alexandra – Raes Junction	Moderate	Option 5 - SH8 Gorge Creek Flat	$ 15,000.00	$ 10,000.00	$ 40,000.00	$ 5,000.00	$ 15,000.00	$ 10,000.00	$ 750,000.00	$ 20,000.00	$ 50,000.00	$ 95,000.00	$ 770,000.00	$ 50,000.00	$ 915,000.00

Appendix D – STED Facility Development Programme

STED Development Programme - Tarras and Coal Creek Sites

Item	Stage	Scope	Duration	Comments	Week No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
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2	Engagement of Consultant		2 weeks					ORC																																															
3	Site Finalisation																																																						
		ORC consideration	4 weeks								ORC																																												
		Discussion with NZTA	2 weeks								ORC																																												
		Discussion with CODC	2 weeks								ORC																																												
		Funding Application with NZTA	2-4 weeks	Programme Risk							ORC																																												
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		Stakeholder consultation	4 weeks											ORC																																									
		Landowner consultation	4 weeks											ORC																																									
5	Planning Consents																																																							
		Planning Consents	12 weeks									CONSULTANT / ORC																																											
6	Investigations & Design																																																							
		Site Investigations	6 weeks															CONSULTANT																																					
		Survey	2 weeks														CONS.																																						
		Detailed Design	8 weeks																		CONSULTANT																																		
		Cost Estimation	1 week																						CONS.																														
		Prepare tender documentation	1 week																						CONS.																														
7	ORC review																																																							
		ORC review & approval	4 weeks																								ORC																												
8	Tender Process																																																							
		Tender period	3 weeks																											CONTRACTOR																									
		Tender evaluation	1 week																														ORC																						
		ORC approval and Award	1 week																															ORC																					
9*	Construction programme																																																							
		Construction	15 weeks																																							CONTRACTOR													
		MSQA	15 weeks	part time based on CM2																																								CONSULTANT - PART TIME											
		Commissioning	1 week																																																ORC			

STED Development Programme - Ripponvale Straight Site

WEEKS

Item	Stage	Scope	Duration	Comments	Week No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
					Week Beginning	18/03/19	25/03/19	01/04/19	08/04/19	15/04/19	22/04/19	29/04/19	06/05/19	13/05/19	20/05/19	27/05/19	03/06/19	10/06/19	17/06/19	24/06/19	01/07/19	08/07/19	15/07/19	22/07/19	29/07/19	05/08/19	12/08/19	19/08/19	26/08/19	02/09/19	09/09/19	16/09/19	23/09/19	30/09/19	07/10/19	14/10/19	21/10/19	28/10/19	04/11/19	11/11/19	18/11/19	25/11/19	02/12/19	09/12/19	16/12/19	23/12/19	30/12/19	06/01/20	13/01/20	20/01/20	27/01/20	03/02/20	10/02/20	17/02/20	24/02/20
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		Commissioning	1 week																																													ORC							

STED Development Programme - Victoria Flats

																										WEEKS																													
Item	Stage	Scope	Duration	Comments	Week No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
					Week Beginning	18/03/19	25/03/19	01/04/19	08/04/19	15/04/19	22/04/19	29/04/19	06/05/19	13/05/19	20/05/19	27/05/19	03/06/19	10/06/19	17/06/19	24/06/19	01/07/19	08/07/19	15/07/19	22/07/19	29/07/19	05/08/19	12/08/19	19/08/19	26/08/19	02/09/19	09/09/19	16/09/19	23/09/19	30/09/19	07/10/19	14/10/19	21/10/19	28/10/19	04/11/19	11/11/19	18/11/19	25/11/19	02/12/19	09/12/19	16/12/19	23/12/19	30/12/19	06/01/20	13/01/20	20/01/20	27/01/20	03/02/20	10/02/20	17/02/20	24/02/20
1	ORC Decision on Options on 20/3/19		1 Day			x																																																	
2	Engagement of Consultant		2 weeks					ORC																																															
3	Site Finalisation																																																						
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		Discussion with NZTA	2 weeks								ORC																																												
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4	Stakeholder consultation																																																						
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5	Land Acquisition & Planning Consents																																																						
		Land Purchase	12 weeks	Activity to be confirmed - has the protential to delay the project								CONSULTANT / ORC																																											
		Planning Consents	12 weeks									CONSULTANT / ORC																																											
6	Investigations & Design																																																						
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		Detailed Design	8 weeks																		CONSULTANT																																				
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		Prepare tender documentation	1 week																								CONS.																														
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		Commissioning	1 week																																																	ORC			

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Lake Hayes Remediation

Options Overview Report

M. Goldsmith, D. Hanan

GHC Consulting Limited Consultancy Report
March 2019

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REFERENCE

Goldsmith, M. & Hanan, D. 2019. Lake Hayes Remediation, Options Overview Report, *GHC Consulting Limited Consultancy Report* 2019/1.

CONTENTS

LIST OF FIGURES

View across Lake Hayes towards the south

1.0 PRÉCIS

The Otago Regional Council (ORC) is developing a programme to improve water quality in Lake Hayes, with an overall objective of making the lake swimmable at all times. To achieve this objective, ORC has identified two mechanisms; improving the quality of water entering the lake, and addressing the historic accumulation of nutrients in lake sediments. This report addresses the second component, whilst still acknowledging that improvements in land and waterway management in the upstream catchment will be required if meaningful improvements to the water quality of Lake Hayes are to occur.

Human activity has resulted in Lake Hayes becoming enriched in minerals and nutrients over the last 70 years. Of particular concern is an accumulation of phosphorous (P) in lake-bed sediments, which in some years can lead to algal blooms in the lake. An ORC Technical Committee report[1] examined the potential of 3 lake remediation methods previously evaluated by NIWA and other scientific experts. For the purposes of this report, an additional method has also been reviewed (as listed in Table 1-1).

Table 1-1 Technical methods considered for the remediation of Lake Hayes water quality. Methods examined in the 2018 ORC Technical Committee report are marked with an asterisk.

1. Water Augmentation*	Augment the flow of Mill Creek with water from the Arrow River.
2. Destratification*	Artificially mix the lake water column, keeping it well oxygenated and preventing thermal stratification from occurring.
3. Hypolimnetic withdrawal	Nutrient-rich and oxygen depleted water is taken from depth within the lake, and then discharged into Hayes Creek via a cascading bed of gravels and weirs designed to re-oxygenate these waters.
4. Sediment capping*	Transforming dissolved P in the water column into a non-bioavailable form through the addition of chemicals.

This report provides a comprehensive assessment of all 4 methods, using information provided by previous authors, and further investigations to determine how each method could practically be implemented. Further work has also been undertaken to determine the likely costs to construct and operate any equipment required. The risks associated with each method have been clearly identified, along with an assessment of how likely they are to succeed.

Either a single method, or a combination of methods may be selected as the preferred option for improving water quality within Lake Hayes. A summary table is provided in section 9.0 which lists 8 potential implementation options, and identifies the likely costs of each, the key risks involved, and the speed with which it will help the lake recover. This table has been designed to allow for easy comparison and to inform the decision-making process.

This report also considers the costs and benefits of continuing to monitor lake water quality over time. Although this is not a lake restoration method in itself, it is listed as a separate, stand-alone method, so that it can be considered as part of any decision-making process. Monitoring would also form part of any remediation program, and the costs of lake monitoring are therefore included in all 8 implementation options listed in section 9.0.

[1] Mackey, B., 2018. Lake Hayes Restoration, ORC Technical Committee Paper, 1 August 2018. See section 3.0 for a full list of references.

2.0 INTRODUCTION

Lake Hayes is a small lake located about 3 km to the south of Arrowtown, in the Wakatipu Basin (Figure 2-1). The depression within which the lake sits was carved by glacial activity, about 20,000 years ago. The lake is approximately 3 km long and 1 km wide, with a maximum depth of 33 m. The primary inflow is Mill Creek, while the outlet is via Hayes Creek which flows for just 1.5 km before discharging to the Kawarau River. Mill Creek has a mean flow of approximately 0.43 m^3 per second (cubic meter per second), while the lake has a total volume of 55,100,000 m^3.

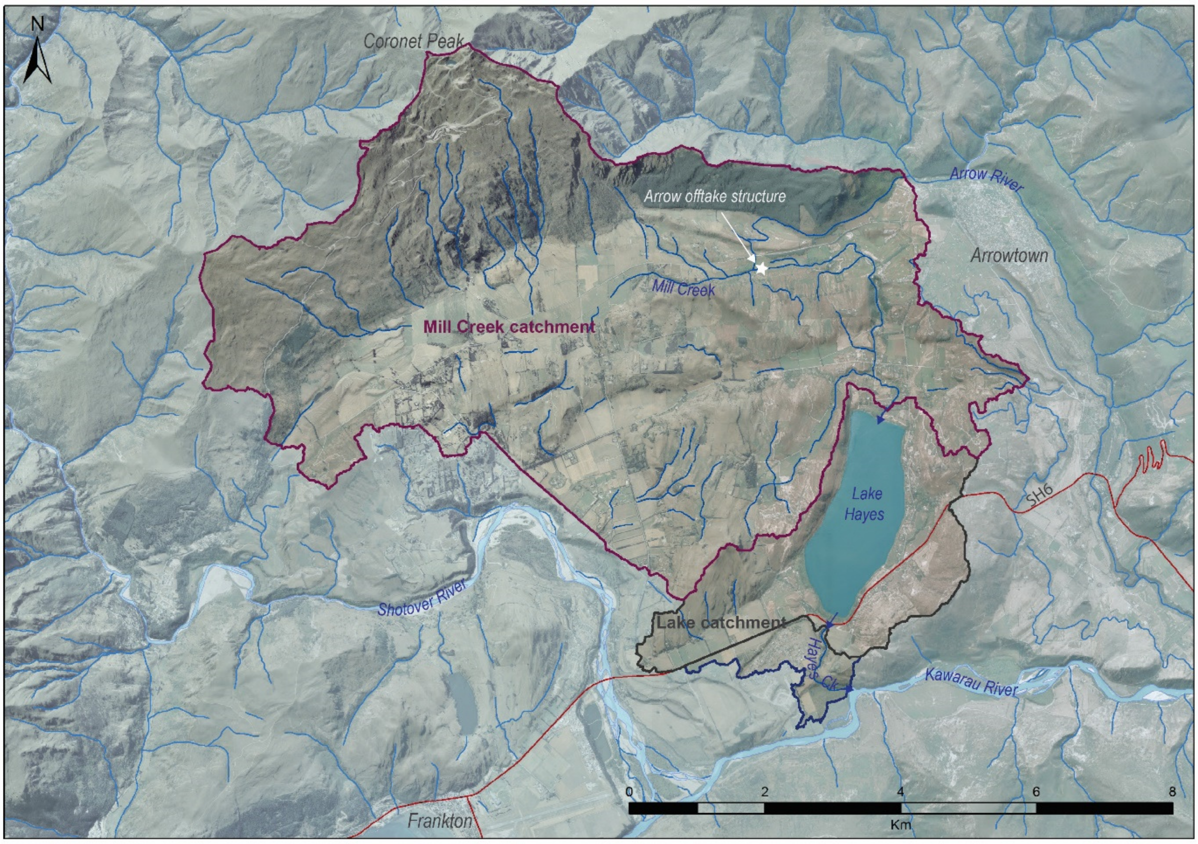


Figure 2-1 Map showing natural extent of the Lake Hayes and Mill Creek catchments. Source: ORC.

2.1 WATER QUALITY PROBLEM

Lake Hayes has become enriched in nutrients over the last 70 years – particularly phosphorous (P). This has occurred primarily as a result of human activity, including historical fertilizer application, industry, septic tank effluent from nearby residences, and removal of wetlands and riparian plantings.

The physical characteristics of the area mean that runoff from the surrounding catchment will drain reasonably quickly to Lake Hayes, and then be ‘stored’ in the lake for a long period (months or even years)[2] before exiting via Hayes Creek. This provides an opportunity for P which enters the lake via surface runoff (generally bound to sediment) to descend to the bottom of the lake, where it can accumulate in lake-bed sediments.

Over summer, Lake Hayes (like most deep lakes) becomes ‘thermally stratified’ – where a warmer surface layer forms, and overlies cooler water on the bottom of the lake. In Lake Hayes,

[2] The theoretical mean residence time for water in Lake Hayes is 3.8 years (Gibbs, 2018a).

the bottom water oxygen-depleted, allowing P to be released from lake-bed sediments into the water column, feeding algal blooms which can affect the colour of the lake, turning it a brown or greenish colour, and cause scums on the surface. Under certain circumstances, types of algae can produce toxins which can cause rashes, nausea and be potentially deadly for dogs if ingested. These processes can have a significant impact for locals and visitors, due to the popularity of this area for recreation and other activities.

2.2 PROJECT DEFINITION

Otago Regional Council (ORC) has been investigating remediation methods to inhibit algal growth in the lake, with an overall objective of making the lake swimmable at all times. A range of potential intervention methods have been identified through previous reports (as listed in section 3.0), produced for ORC and the Friends of Lake Hayes Society.

This report provides an overview of four technical methods that have been identified by specialist lake scientists as suitable for improving water quality in Lake Hayes. Each method has been assessed for its risk potential, costs and likelihood of success. Additional information has been gathered to help with this assessment, including from potential suppliers and contractors with the skills and experience to implement the various technical methods available.

Technical methods which are considered suitable for improving water quality in Lake Hayes are listed in Table 1-1. Together with the 'do minimum' approach (i.e. continue to monitor and evaluate), these are discussed in sections 4.0 to 8.0.[3]

A single method, or a combination of methods, may be put into effect as an 'implementation option'. Section 9.0 lists potential implementation options, and summarises the likely cost, key risks, and the likelihood of success, to allow for easy comparison and to inform any decision-making process.

None of the methods outlined below help to resolve the ongoing issue of nutrients (including P) entering the lake from Mill Creek. A separate program of work is underway by ORC to identify contemporary sources of catchment-derived nutrients, and implement methods which will improve the quality or water entering the lake via Mill Creek.

[3] The objective of each technical method is listed in Appendix 8. Sections 4.0 to 8.0 describe how these will help to reach the overall objective (making the lake swimmable).

Figure 2-2 3D view of Mill Creek (blue line) where it enters Lake Hayes. Source: Google Earth.

3.0 PREVIOUS WORK

The following sections have drawn heavily on information provided by previous authors and other experts. The primary references used to inform this report are listed in Table 3-1. Other material and advice was provided by Andy Bruere, Lakes Operations Manager, Bay of Plenty Regional Council.

Table 3-1 References relating to the water quality of Lake Hayes, used to inform this report

Author and year	Title	Prepared for
Castalia Strategic Advisors, 2018.	Economic Assessment of Lake Hayes Remediation (updated, November 2018)	ORC
Gibbs, M., 2018a. (NIWA)	Lake Hayes Water Quality. Remediation options.	ORC
Gibbs, M., 2018b. (NIWA)	Lake Hayes Water Quality. Expansion on remediation options.	ORC
ORC and QLDC,1995.	Lake Hayes Management Strategy	ORC / QLDC
Schallenberg, M., and Schallenberg, L., 2017.	Lake Hayes Restoration and Monitoring Plan.	Friends of Lake Hayes Society Inc.
Mackey, B., 2018	Lake Hayes Restoration	ORC Technical Committee

3.1 SCIENCE

Declining water quality has made Lake Hayes the subject of many studies over the past few decades. This includes scientific studies, management strategies, and restoration strategies. This report has primarily drawn on the 2017 review by Schallenberg and Schallenberg which provides a summary of the lake's history, the decline in water quality, and potential remediation options. In addition, the technical methods described in this report are drawn from the 2 reports prepared in 2018 by Max Gibbs (NIWA for ORC), which provide a review of the Schallenberg report, and further evaluate remediation options.

3.2 ECONOMIC ASSESSMENT

An economic assessment of the benefit of remediation using three technical methods (augmentation, destratification and sediment capping) was undertaken by economic experts Castalia in 2018 for ORC. The key findings of this report were that:

- *The state of water quality in Lake Hayes in the absence of remediation is uncertain. Therefore, three no-intervention scenarios for the lake ('stable', 'natural recovery', and 'deteriorates') were compared against potential remediation methods.*
- *The three remediation methods investigated are, in general, economically viable, in that the benefits of improved water quality outweigh the costs of remediation.*
- *Recreational activities will see the greatest positive benefits of remediation.*
- *The primary beneficiaries of improvements to water quality are concentrated around the lake and nearby residents.*

4.0 MONITOR AND EVALUATE (NO LAKE INTERVENTION)

4.1 DESCRIPTION

The 2017 Schallenberg report concludes that Lake Hayes may be approaching a recovery tipping point, although it also states that it is still unknown how long it will take for the lake to achieve consistently high water clarity. The Schallenberg report notes that the lake experienced extremely clear waters in 2009/10 and 2016/17 years. Gibbs (2018a) also notes that the release of DRP from the sediment has been slowly decreasing since 2011.

ORC is deploying a permanent water quality monitoring buoy in the lake during the 2018/19 summer, and also expanded its sampling program. The buoy is expected to be operational by April 2019. Additional data from continuous and sample type monitoring will help track physical, chemical and biological changes in the lake over time. In particular, it will help to identify any long-term trends in water quality (noting that it may take some years for these to become apparent).

Monitoring data will be used to inform subsequent decisions about whether (and how) other methods should be implemented, and to potentially optimise any remediation efforts. Monitoring can also be used alongside other methods to determine their effectiveness, and to inform operational decisions, such as timing of critical decisions and operations.

Figure 4-1 Monitoring buoy similar to that to be installed in Lake Hayes by ORC

Monitoring and evaluation could be described as the ‘do minimum’ approach. It has been identified as a separate, stand-alone method so that it can be considered as part of any decision-making process – it should not be discarded simply because there is a perceived need to ‘do something now’. A period of intensified monitoring may help to identify the most effective intervention option, or alternatively confirm whether the lake is recovering naturally, and active intervention is not warranted. Monitoring and evaluation is included in all of the implementation options outlined in section 9.0.

4.2 MONITORING OUTCOMES

As for other methods, taking steps to reduce the amount of P which enters Lakes Hayes will be an important part of improving the overall water quality in this catchment.[4] If this could be achieved, then the total mass of P in the lake will gradually reduce over time, although it is likely that this process will be influenced by a range of environmental factors and food web interactions.[5]

However, it is uncertain how long such a natural recovery process will take, given the current levels of P in the lake. In addition, it may be unrealistic to expect that the supply of phosphorous from the catchment will be significantly reduced any time soon.

The monitor and evaluate approach would help to quantify any 'natural' improvement (or degradation) in the lake. It may help to inform later decisions, but by itself, it will not lead to any direct changes in water quality. As a result, improvements in water quality may take longer than with active intervention, and water quality will continue to fluctuate from year to year.

[4] ORC is currently undertaking work to better understand the main source of nutrients in the Lake Hayes catchment. See https://yoursay.orc.govt.nz/lakehayes/forum_topics/lake-hayes-catchment-a-new-study

[5] For example, Schallenberg (2017) describes a possible mechanism for this, where the *Ceratium* alga helps to transfer P from bottom waters to the surface, which in turn allows P to be flushed out of lake via outflow of water into Hayes Creek.

4.3 COST AND RISK ANALYSIS – MONITOR AND EVALUATE

Cost		Land acquisition		Resource Consent		Comment
Capital[6]	Operational	Issues	Cost	Likely issues	Cost	
• Purchase and install monitoring buoy: $86,000 • Updates to ORC website to display real-time data: $4,000 • Communications / stakeholder relations: $4,000 • Contingency cost: N/A - this method has already been costed and commissioned. **Total: $94,000**	• Maintain and service buoy: $15,000 • Sampling program: $10,000 • Contingency: $5,000 • Publicity and Communications $15,000 **Total: $45,000**	N/A	N/A	Consent for the monitoring buoy was obtained in 2018. Issues to address included: • Noise • Colour • Reflective light • Position • Navigational safety	Cost to obtain consent (including staff time, planning advice, and consent fees): $6,000 **Total: $6,000**	• There is a risk that this approach may not meet the expectation of residents and the wider public that direct action should be taken to improve water quality. • The approach relies primarily on a successful catchment management program. • It does not provide a mechanism for addressing years where DRP levels are high, either due to inflows, or mobilisation of P already in the lake due to lake stratification. • As noted above, it is difficult to determine the likely timeframe to meet the overall objective (swimmable water at all times). • There is some uncertainty about whether the lake is actually recovering naturally, and the speed of that recovery. • The monitoring buoy will be a highly visible structure in the lake. It may be damaged (either by accident or intentionally) or fail to provide a continuous supply of data.

6 In this report, capital costs refer to the initial construction costs

5.0 TECHNICAL METHOD 2 - ARROW WATER AUGMENTATION

5.1 DESCRIPTION

This method involves augmenting the flow of Mill Creek with water from the Arrow Irrigation Company irrigation scheme.[7] Water would be taken from the company's pipeline where it crosses Mill Creek (Figure 2-1, Figure 5-1), about 4.5km upstream from the creek's outlet into Lake Hayes. Water from the Arrow River is low in nutrients compared to water in Mill Creek and Lake Hayes, and therefore 'cleaner'. Monitoring also shows that water in the Arrow is colder than that in Mill Creek.

Council approved funding in the 2018-2028 Long Term Plan to undertake physical works, to preserve the potential to add Arrow water to Mill Creek should this method be selected. Installation of a 130m long pipe and a discharge structure to Mill Creek was completed in January 2019, prior to golf course development by Millbrook Resort. If this work had not been done prior to golf course development, the option to add Arrow water to Mill Creek would have been lost. Some follow-up work would be required to make the offtake operational.[8]

This method has 2 main benefits:

- Clean water being added ('augmented') to Mill Creek, and therefore increasing the volume of water passing through Lake Hayes – i.e. clean water from the Arrow River would displace (flush) a greater volume of nutrient-rich lake water than would occur otherwise.
- If the temperature in Mill Creek as it entered Lake Hayes was sufficiently cool to cause Mill Creek water to plunge to the lowest part of the lake, it could oxygenate the bottom waters.[9] It is expected that the oxygenated water would reduce the likelihood of anoxic conditions[10] and the associated release of P from lake bed sediments. It is thought that the benefit associated with this process would be greater during the spring and summer months.

The overall cost associated with this method is low, compared with other methods.

[7] The scheme takes water from the Arrow River and pipes it across the Wakatipu Basin for irrigation purposes.

[8] There is a 10m section of pipe that has not been connected, which is where the control valves would be located.

[9] The target zone for the cooler Mill Creek water (i.e. deeper waters) is also influenced by lake currents, which are susceptible to wind and changes in the temperature profile of the lake over the year. The greater the temperature difference between Mill Creek and the Lake, the deeper the plunging waters are likely to penetrate.

[10] where water is depleted of dissolved oxygen

Figure 5-1 Arrow Irrigation Company pipeline as it crosses Mill Creek, January 2019. Credit: D Hanan

5.2 LIKELIHOOD OF SUCCESS

An evaluation of previous reports and other literature suggests that this method, if implemented to its fullest extent, would have some positive effects on lake water quality, mainly through additional flushing and the addition of cleaner water to the lake. If applied consistently throughout the year, the additional water in Mill Creek would help to improve the water quality in this waterway (and consequently Lake Hayes).

These potential positive effects need to be balanced against a range of factors which create risk in terms of this method being able to meet the overall objective (as listed in section 5.3). In particular, there is a risk associated with accessing water from the Arrow River over the longer term, particularly during the summer period which is when augmentation is most likely to provide some benefit in terms of improved lake water quality. In summer months there is increased demand from other users of Arrow irrigation water, and flows in the Arrow River are comparatively low.

It is noted that the environmental risk associated with this method is relatively low, as it simply augments an existing natural process.

The risks listed below assume that the augmentation method was chosen as a stand-alone option. It is recognised that augmentation is compatible with a range of other methods, and this is discussed further in section 9.0.

5.3 COST AND RISK ANALYSIS – ARROW WATER AUGMENTATION

Cost		Land acquisition		Resource Consent		Risks, including time to meet the overall objective
Capital	Operational	Issues	Cost	Likely issues	Cost	
• Physical works already completed in Mill Creek: $200,000 • Additional work to connect to pipe and make operational: $50,000 • Staff time: $20,000 to date, $10,000 to come. • Contingency cost: N/A - most of the structure has already been built. **Total: $280,000**	• Annual cost to purchase water: $20,000.[11] • Contingency: $2,000 • Publicity and Communications $3,000 **Total: $25,000**	N/A	N/A	• Cultural / ecological impact of transferring water from the Arrow catchment to the Lake Hayes catchment. • Mitigating physical effects due to increased stream flow.	$15,000 **$15,000**	• Water availability may be limited, particularly in summer when poor lake water quality is more likely to occur, and remediation is therefore more urgently required. • The Irrigation Company's ability to supply water from the Arrow River may be further reduced, as their deemed permit expires in 2021. This could significantly affect the quantity of water available for augmentation. • Potential minimum-flow requirements for the Arrow River. • If less water is available, then the unit cost may increase. • The success of this method is, in part, determined by the temperature difference between water from the Arrow river (in the irrigation pipeline) and water in Mill Creek. • Even if the Arrow water does cool Mill Creek to some extent, it may not be enough to cause the outflow from Mill Creek to plunge towards the bottom of Lake Hayes. • The distances involved, and the potential for warming as the water passes via the pipeline and Mill Creek to Lake Hayes may reduce the impact of this method. This risk is greater during the warmer summer period, when remediation is more likely to be required. Therefore, there is a risk that, on its own: i. this method will not adequately oxygenate the water at the bottom of the lake, and therefore ii. P will continue to be released from lake bed sediments as a result of thermal stratification within the water column. • This process will need to run over many years to be effective. Schallenberg (2017) suggests that flushing will displace approximately 7% of the entire lake volume annually. • Work may be required to improve the capacity of the Hayes Creek outlet, to offset additional inflows to Lake Hayes and avoid excessively high lake levels.

[11] This assumes the full amount (as suggested by the Irrigation Company) was available, at their suggested rate of 0.5 cents per m^3.

6.0 TECHNICAL METHOD 3 - LAKE DESTRATIFICATION

6.1 DESCRIPTION

As noted in section 2.1, over summer Lake Hayes can become thermally stratified – where a layer of warmer surface water overlies cool, anoxic water on the bottom of the lake. This method seeks to artificially mix the lake water column, keeping the lake oxygenated (to levels above 5 g/m^3), which prevents P from changing to the dissolved state. Thermal stratification is still likely, but significantly reduced. The method does not aim to remove phosphorous from the lake. However, it is thought that the creation of currents within the lake, through artificial mixing will help to keep bottom waters well oxygenated, which consequently keeps the phosphorus bound in the lake bed sediments and out of the water column.[12]

There are various mechanisms which can be used to mix the lake water. However, the method investigated here is to create an air curtain through the lake, achieved by blowing compressed air along a perforated pipe which lies across the bed of the deepest part of the lake (Figure 6-1).

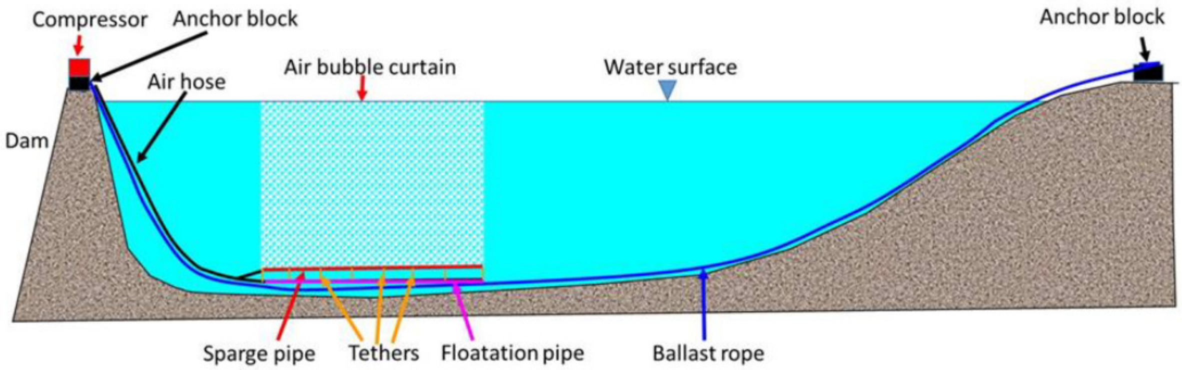


Figure 6-1 Schematic diagram of a bottom-mounted air curtain aerator system, aligned through the deepest part of the lake. From Gibbs (2018a).

Additional investigations have been completed to determine how such a system could be installed in Lake Hayes, given the unique characteristics of the lake and the surrounding area. The main components required for this method are an industrial-scale compressor, a shed designed for noise reduction, and pipes to transport and then deliver the air into the lake. The requirements for this system are explained in Appendix 1, and a step-by-step description of how this option works is provided in Appendix 2. Figure 6-2 shows the main components required for this option, with a suggested location for the compressor (between SH6 and the Wakatipu Rowing Club) identified. A possible alternative is Bendemeer Bay, although there is likely to be noise and visual impacts for neighbouring properties at this location.

[12] Creating artificial currents within the lake helps to minimise thermal stratification (where phosphorous in the lake sediment can change state from solid to dissolved reactive phosphorous (DRP), which in turn stimulates algal blooms).

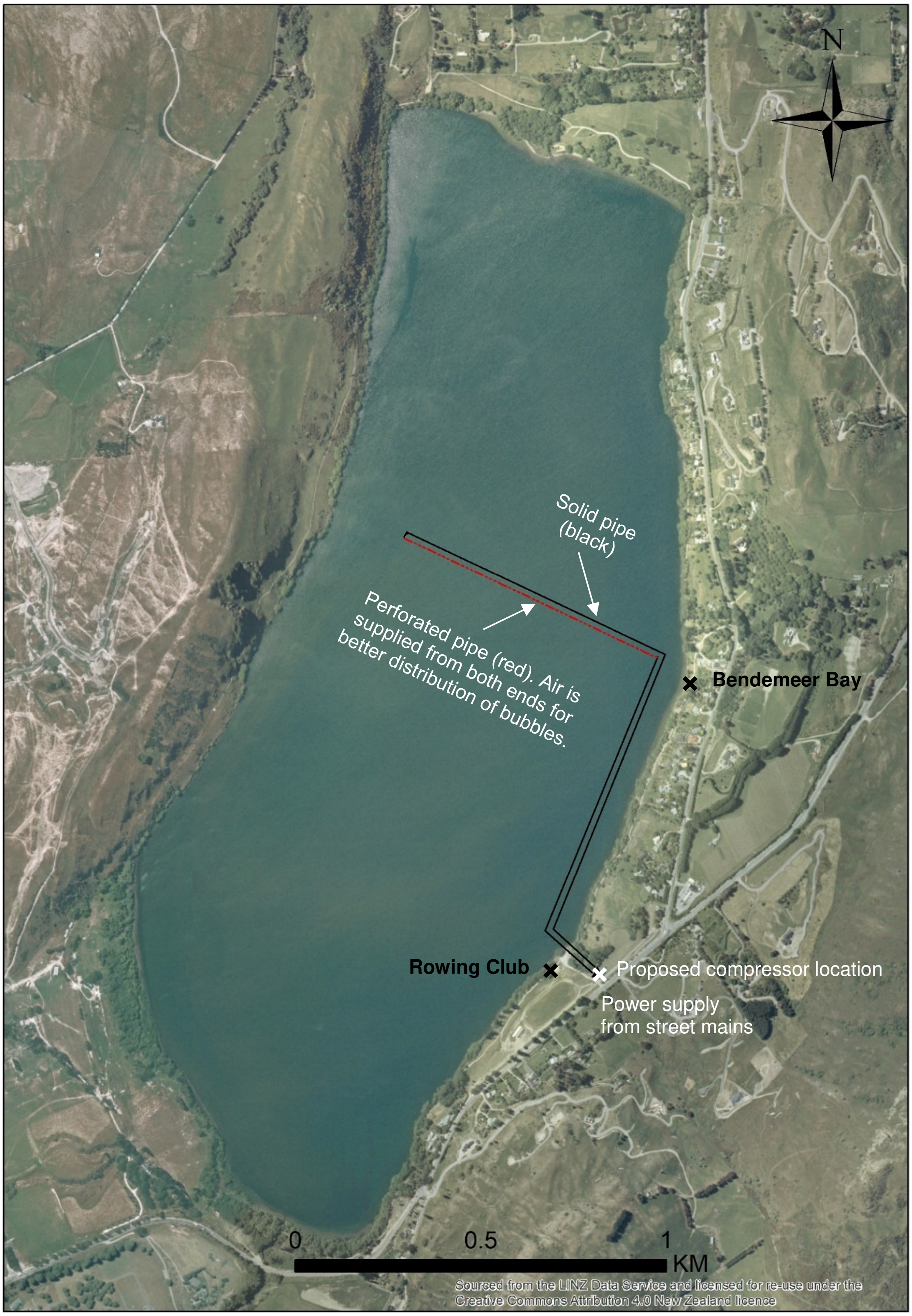


Figure 6-2 Potential positioning of the bubble curtain aeration line[13]

[13] The system shown here has been informed by design requirements specified in Gibbs (2018a) and a quote to meet those requirements, as provided by AshAir. Further investigation may determine that a simpler (and cheaper) system would be sufficient to prevent thermal stratification occurring.

6.2 LIKELIHOOD OF SUCCESS

To be successful, this option would require artificial mixing of the lake to prevent the release of DRP from sediments at the bottom of the lake. Instead, P will remain bound in the lake bed sediments and not be released into the water column.

This option appears to have a reasonably high likelihood of success, and it has been used successfully in several other lakes, including Lake Waikopiro (Hawkes Bay) and several Auckland City Council drinking water reservoirs.[14] If the intention is to eventually remove the air curtain, then a reduction in organic matter and P from the upstream catchment will also be required. The system would be less successful if catchment management was not undertaken simultaneously.

The method could be used in conjunction with other options such as augmentation.

There are several critical risks to bear in mind when considering this option (as explained in section 6.3). Careful monitoring of the lake's water quality, together with precise management of the equipment would be required to ensure ongoing success.

[14] Andy Bruere, Lakes Operations Manager, Bay of Plenty Regional Council and Gibbs (2018a)

6.3 COST AND RISK ANALYSIS - DESTRATIFICATION

Cost		Land acquisition		Resource Consent		Risks, including time to meet the overall objective
Capital	Operational	Issues	Cost	Likely issues	Cost	
• Purchase equipment (compressor, piping): $232,000 • Installation of equipment, including soundproof shed: $204,000.[15] • Project Management: $60,000 • Contingency: $40,000 • Liaison and negotiation with QLDC $15,000 • Design and peer review $25,000 • Arrange procurement $15,000 **Total: $591,000**	• Maintenance & operations: $61,500 p.a. • Publicity and communications $15,000 **Total: $76,500 p.a.**	Equipment needs to be located near the lake, probably on QLDC reserve land A lease agreement between ORC and QLDC would be required, and would need to be publicly notified.	**Total: $20,000**	• Equipment needs to be sited in a sound-proof building 4.8m x 3.6m x 2.4m high. This needs to be in a position that has limited or no visual impact on residents or visitors. The location on the reserve land adjacent to the show grounds is preferred. Bendemeer Bay is not considered suitable due to the proximity of houses. • Compressor operates at 77dBA which is very loud talking (almost shouting). • A resource consent from QLDC would be required for construction on reserve land. • A resource consent from ORC may be required for disturbance of the lake bed.	$60,000 **Total: $60,000[16]**	• Operational timing is critical. If start-up is delayed after thermal stratification is established, the air curtain will bring nutrient-rich bottom water to the surface, stimulating phytoplankton growth, which will deplete oxygen in the lake. This risk can be reduced if the operation of the compressor was linked to real-time data from the monitoring buoy. • The operation of the air curtain system is dependent on an operational compressor and an uninterrupted power supply. • The surface of the lake will be affected by a line of water disturbance above the pipe. • The compressor will be noisy and will require a specifically engineered building and possibly environmental bunds to minimise sound. • Consent and lease agreement costs could be larger than anticipated, especially if there is opposition to the proposed location. • The required duration of operation is largely unknown. Gibbs (2018a) suggests 5 – 10 years. • The system may not promote mixing across the whole lake (and therefore be less effective). • It is unlikely (but possible) that mixing the lake water column (i.e. 'stirring up the

[15] Section 2.2 describes the method used to determine likely costs of purchasing and installing equipment.

[16] This cost includes ORC processing costs (staff time and consultants), preparation of an Assessment of Environmental Effects (AEE) and a hearing (assuming there is no appeal).

						lake') will bring suspended particles from the lower part of the lake to the surface, thereby reducing water clarity. • Over time, this process will reduce the amount of phytoplankton in the lake, making the water column clearer (see Appendix 2). • There could be other unintended ecological consequences.

Other comments:

- The inclusion of a variable speed compressor with a Programme Logic Controller (PLC), linked to the buoy information would allow the 'bubble rate' to be adjusted, depending on the temperature profile and DO readings at various depths in the lake.
- The system will probably need to be operated from spring (probably October) through to autumn (March). The actual time of operation would be determined by the monitoring data.
- It is noted that the air curtain only has a minor effect on oxygenating the lake. The oxygen-depleted waters which rise from the base of the lake are re-oxygenated as they flow across the lake surface.
- The surface temperature is likely to fall, possibly by 1 °C. This may not be noticed by swimmers and other lake users.
- Once the overall objective has been achieved, the shed, compressor and other associated infrastructure may not be required.
- Bubble hole size is important as well as the amount of air delivered through the line. Too little and the plume may not form; too much and the bubbles may disrupt the integrity of the plume, reducing its efficiency.

7.0 TECHNICAL METHOD 4 – HYPOLIMNETIC WITHDRAWAL

7.1 DESCRIPTION

As described by Gibbs (2018a, 2018b), the concept behind this method is relatively simple, and involves nutrient-rich water being drawn up through a pipe, from the anoxic (or hypolimnetic) zone within Lake Hayes. The pipe would cross the lake (beneath the surface), and discharge to Hayes Creek just above the culvert which passes under SH6 (Figure 7-1). This method is the only system that actively removes P from the lake.

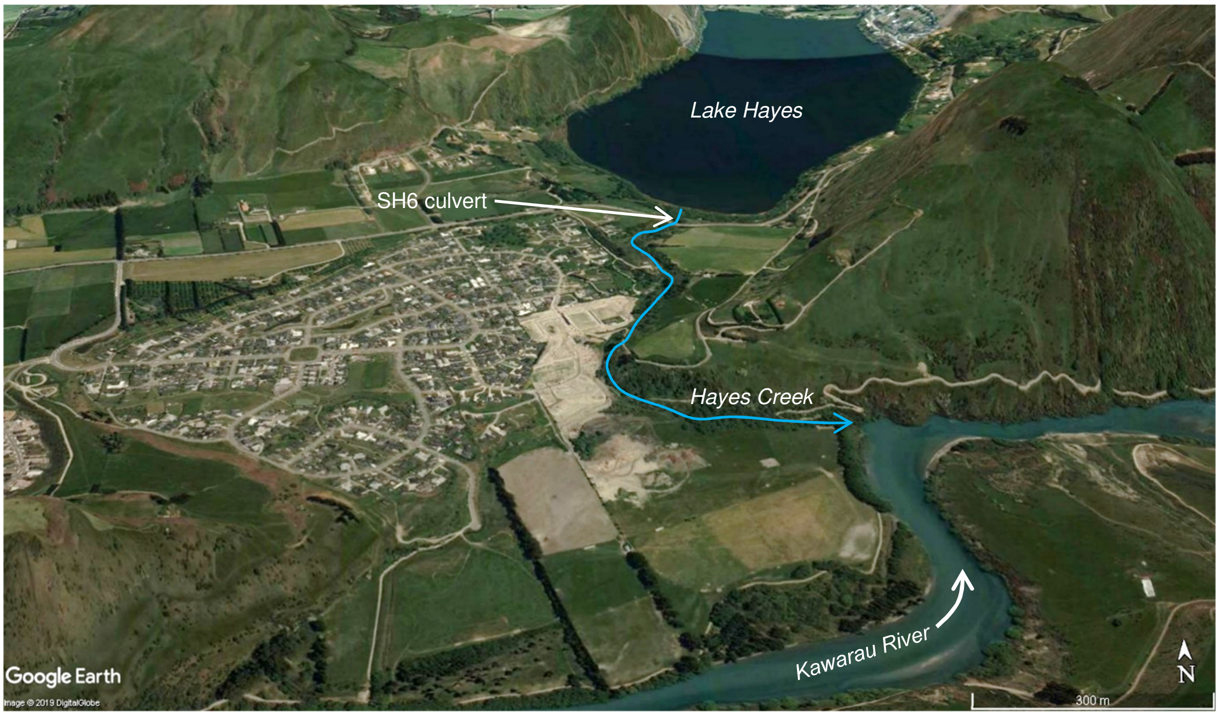


Figure 7-1 3D image showing Lake Hayes, and its outlet (Hayes Creek) which flows into the Kawarau River. Source: Google Earth.

7.2 CONSTRUCTION REQUIREMENTS

This method would require the construction of a weir and associated flanking walls near the start of Hayes Creek. The weir would need to be designed to maintain the lake within its current range. The pipe would pass through the wall, as shown in Figure 7-2.[17] A valve would enable the flow of water from the bottom of the lake to be controlled, or even stopped if required.

An inspection of the outlet area (Figure 7-3) indicates that such a system may be constructible, although further hydraulic and engineering investigations would be required to determine the specific design. The inspection shows that the diameter of the hypolimnetic withdrawal pipe could be as large as 400mm, although a larger pipe would cost more and have a greater visual impact.

It is noted that flow in Hayes Creek can, at times, be restricted by the design and capacity of the SH6 culvert, with an associated impact on lake level. A critical construction requirement

[17] Ensuring that the pipe remains completely submerged is a fundamental part of the design and installation of the withdrawal system.

would be to ensure that this method did not exacerbate any current lake level issues – ideally any structures built as part of this approach would actually help to mitigate these issues.[18]

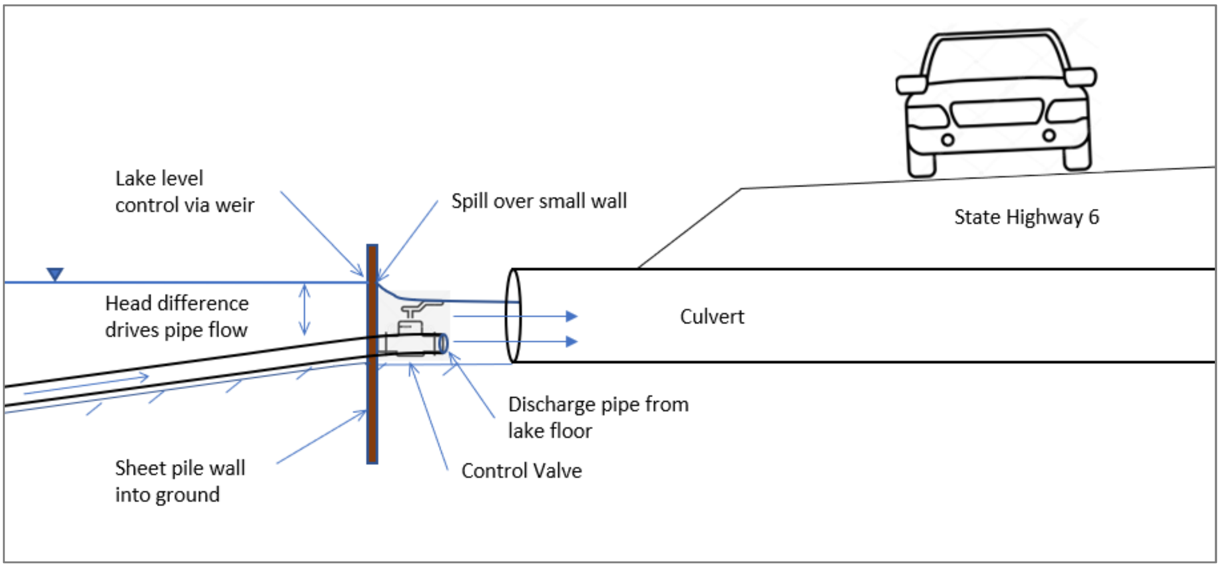


Figure 7-2 Long-section showing discharge point from the hypolimnetic withdrawal pipe, and SH6 culvert.

[18] See https://www.odt.co.nz/regions/queenstown/unsightly-lake-hayes-work-progress

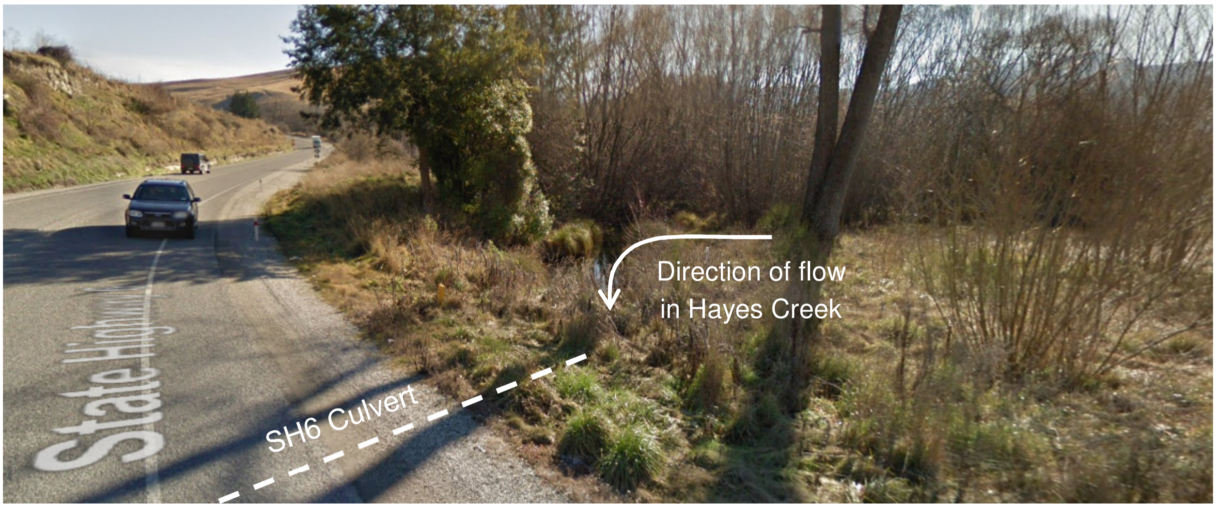


Figure 7-3 **Top: General view of Hayes Creek, upstream of SH6. Bottom: Closer view of the potential location for the weir and flanking walls, just upstream of SH6.**

7.3 TREATMENT REQUIREMENTS

For most of the year the discharge water from this method will be relatively clean, and would therefore have little detrimental effect on the receiving waters of Hayes Creek. However, during the summer period the water which is drawn from the bottom of the lake may have high DRP levels, and may also contain small quantities of hydrogen sulphide. The water discharged into Hayes Creek may therefore need to be treated. Treatment could simply involve allowing the surface and hypolimnetic waters to mix naturally. Alternatively, it may involve aerating the water by cascading it over small dams along the creek (downstream of SH6 - Figure 7-4), and/or agitating across a stone bed or, if necessary, artificially forcing oxygen into the water via a small compressor and aeration hose.

Figure 7-4 View of Hayes Creek, downstream of the SH6 Culvert.

7.4 LIKELIHOOD OF SUCCESS

Gibbs (2018b) states that if it was physically possible to implement, then this technique would have a high probability of successfully improving the long-term water quality in Lake Hayes. A literature review undertaken by Gibbs revealed that this technique has been used successfully in Europe and North America. The risks associated with this method are discussed in section 7.5.

This method could be combined with flow augmentation (section 5.0), as this would provide for additional 'flushing' of the lake with clean water (even when it was not stratified), and lead to a faster recovery of the lake (see also section 9.0). As the system may only require minor energy inputs (e.g. if a compressor was required to deliver oxygen to the water), it offers a lower long-term operating cost solution which can be used throughout the year.

7.5 COST AND RISK ANALYSIS – HYPOLIMNETIC WITHDRAWAL

Cost		Land acquisition		Resource Consent		Risks, including time to meet the overall objective
Capital	**Operational**	**Issues**	**Cost**	**Likely issues**	**Cost**	
Supply and lay a pipe over 1km: $300,000[19] Construct Aeration Beds $19,600 Flanking Wall: $110,000 Investigate design and arrange procurement $80,000 Contingency: $84,000 **Total: $593,600**	Includes visual inspections, stream maintenance and scientific monitoring. $10,000 Publicity and communications $10,000 **Total: $20,000**	• Consent would also be required to place the pipe in the bed of Hayes Creek. • Easements will be required. • Possible opposition from iwi, interest groups or members of the public regarding how the pipe is to be placed and what the effect is likely to be on the Kawarau River.	**Total: Up to $20,000**	• Visual impact of placing the pipe on the bed of Hayes Creek. • Further treatment of the water may be required if the discharge is not satisfactory. • The size of the pipe to effectively remove the P requires further investigation. The cost of this option goes up significantly depending on the size of the pipe required.	$30,000 to $50,000 **Total: Up to $50,000**	• In the short to medium term, the lower levels of the lake will continue to become anoxic, which will cause the release of P. Therefore, algal blooms are still possible. • The success of this method depends on how rapidly it can withdraw P from the system. • P will primarily be withdrawn from the lake during the summer period, when high DRP levels occur. During this period, the water drawn from the lake may be significantly different (in terms of clarity and odour) to the relatively clear-flowing Hayes Creek. • At other times, this method will continue to remove suspended solids from depth, which may reduce the clarity of water in Hayes Creek. • This method may need to be operational for some time before a noticeable difference in lake water quality can be seen. • There would be visual impacts associated with the weir, and the pipe being placed in Hayes Creek. • The hydraulic performance and flow rate of this method will need to be determined.

[19] This assumes a 400mm pipe is used.

8.0 TECHNICAL METHOD 5 – SEDIMENT CAPPING

8.1 BACKGROUND

This method involves transforming DRP in the water column into a non-bioavailable form,[20] through the addition of chemicals (commonly alum). This method was trialled in Lake Hayes in 2010 (Gibbs, 2018a). In that experiment, 'floc' formed rapidly and then settled through the water column over a period of a day. The alum floc adsorbs DRP and aggregates particulate material, including zooplankton and algal cells, as it settles to the lake bed. The addition of alum into the lake is thought to take several days, and occurs as a one-off application, which would need to be repeated between 5 and 20 years, depending on how much P has entered the lake.

8.2 PREVIOUSLY DOCUMENTED APPLICATION METHODS

One method for applying alum is by boat. However, if alum is applied to the surface, the floc that forms absorbs DRP and aggregates particulate materials including zooplankton and algal cells, which then settle to the lake bed. It is estimated that the alum would circulate within the lake for some time before reaching the lake bed. Surface application of alum is more likely to attract zooplankton and beneficial algae to the floc, which is not favourable. In addition, surface application by boat would be slow and cumbersome.

An alternative option is to trickle feed the alum into Mill Creek, via a storage tank and dosing plant. The advantage of this option is that it would limit the dosing of the lake surface. Instead, the cooler waters of Mill Creek tend to plunge to lower levels of the lake rather than disperse over the surface. However, given the geographic setting of lower Mill Creek, this approach also has some major challenges, including the visual impact of locating a dosing plant on the margin of Mill Creek, and transporting alum to the plant on large trucks via the narrow, steep gravel road to the Lake Hayes Reserve.

These application methods are discussed in Gibbs (2018a, 2018b) and Schallenberg (2017).

8.3 DIRECT INJECTION METHOD

Further investigation has identified a potential cost-effective way to apply alum, via a pipeline which would be temporarily laid out at a suitable depth across the lake (Figure 8-1). The target depth is likely to be the top of the hypolimnetic zone, where the alum would be most effective in terms of locking up DRP.

This approach would involve using a pump to transfer alum from a tanker truck out into the lake, and the alum would disperse through holes in the pipe. Three suitable distribution locations for tanker truck and pumps to be set up have been identified; Lake Hayes Reserve, Bendemeer Bay and the Rowing Club. From these central points, the pipe could either be laid out in straight lines, or as shown in Figure 8-2, rotated around a centre pivot in order to increase the coverage area. All equipment would be removed from the lake and reserve areas following each application.

As noted above, issues with the access road to the Lake Hayes Reserve may mean that it is not possible to apply alum from that point. The major application point is more likely to be from Bendemeer Bay, being the deepest part of the lake.

[20] i.e. it is not able to taken up by plants.

An additional benefit of this approach is that the dosing rate can be altered as the DRP level changes over time. Targeted alum dosing would reduce operating costs, and deliver the maximum benefit of the treatment. As above, the dosing would need to be repeated, as fresh sediment inputs from the catchment bury the alum layer in the lake sediments. The actual quantity of alum is determined by the amount of DRP in the water column, and therefore the amount of alum required will vary.

The 2017 Schallenberg report estimates that 856,400 litres of alum would be required per application. This equates to approximately 97 tanker loads, to be delivered to the 3 distribution locations. This would occur over a relatively short period, which may generate public concern.

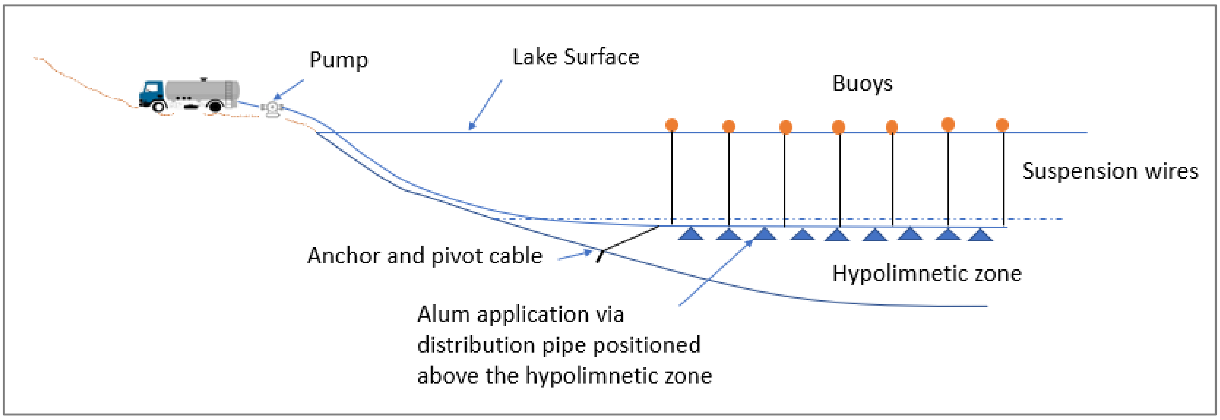


Figure 8-1 Schematic diagram of alum direct injection method

8.4 LIKELIHOOD OF SUCCESS

Previous work undertaken for ORC and the Friends of Lake Hayes (section 3.0) indicates that if it could be practically implemented, alum dosing would have an immediate positive effect on lake water quality, by immobilising P in bed sediments.

The table shown in section 8.5 has been prepared based on the assumption that direct injection at depth was used for delivery of alum. Before this method could be implemented, additional lake current data would need to be collected to optimise the positions of the dispersal pipes.

It is noted that other delivery methods are available (section 8.2), and that these would have a slightly different combination of costs and risks, and may take longer to meet the overall objective.[21]

[21] For example, investigations undertaken for this report suggest that the cost to construct a dosing plant on Mill Creek, and upgrade the access road could be as high as $800,000.

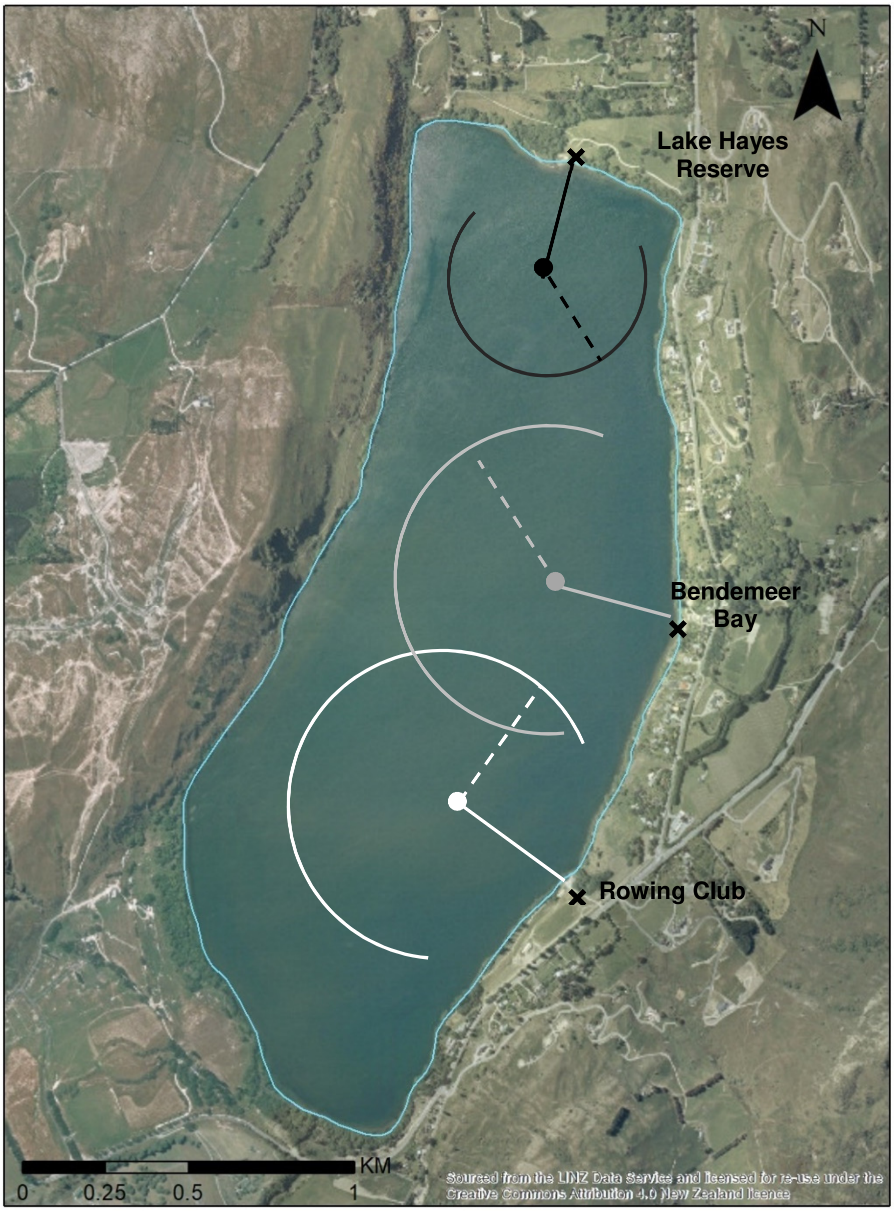


Figure 8-2 Possible layout plan for direct injection of alum from 3 center pivot points (circles), linked to a shore-based tanker and pump system.

8.5 COST AND RISK ANALYSIS – SEDIMENT CAPPING

Cost		Land acquisition	Resource Consent		Risks, including time to meet the overall objective
Capital	**Operational**		**Likely issues**	**Cost**	
Set-up costs for alum delivery (includes pipes, buoys, generator, pump, fittings) $72,000 Investigate design and arrange procurement $40,000 Contingency: $8,000 **Total: $120,000**	Alum: $588,500 per application. Cartage (transport from Invercargill to Lake Hayes in truck and trailer units: $80,000 Staff (supervision & science): $38,500 Publicity and Communications $15,000 **Total: up to $722,000 per application.**[22]	Equipment to be temporarily located near the lake, on reserve land. Minimal, if any cost associated with this. **Total: $10,000 (TBC)**	• Discharge to water consent required. • Opposition from iwi and other interest groups. • Temporary visual impact of alum delivery. • Perceived negative health issues.	$50,000 to $100,000 (depending on appeals) **Total: Up to $100,000**	• Negative public perception - adding a chemical to a waterbody where people swim may be strongly opposed. • The cost of alum may be more than anticipated. The actual amount required is difficult to estimate, and total costs depend on how long dosing takes place and the concentration of the dose. • This method is considered suitable because the overall pH of Lake Hayes is in the correct range. However, if the lake's pH changed significantly, then toxic trivalent Aluminium could be released (low likelihood – high consequence). • Once the alum is applied the benefit is likely to be immediate. • The effect of alum on ecology in the application area is unknown and an unforeseen lake response may be evident (also low likelihood – high consequence). • There is a risk that this method may not be as successful as anticipated. However, the intent of the direct injection method is to reduce this risk by distributing the alum across the lake as widely as possible, and at the most effective depth. • Continued delivery of sediment (P) by Mill Creek would shorten its effective lifespan as alum would be buried – there is therefore also a need for catchment improvement.

[22] This is expected to reduce over time as the lake water quality improves. The longevity of the application is largely unknown. An application may last between 5 and 20 years.

9.0 IMPLEMENTATION OPTIONS

Methods which are considered suitable for improving water quality in Lake Hayes are discussed in sections 4.0 to 8.0. This section describes how one method, or a combination of these methods, may be put into effect as an implementation option.

This overview table has been created to provide a snapshot on relative costs, likelihood of success, key risks and summarise the more detailed tables above. The tables in the previous 5 sections should be referred to for detailed information.

The colour codes used to categorise capital and operating costs are as follows:

	Low-cost	Medium-cost	High-cost
Capital	$0 to $500,000	$500,000 to $750,000	>$750,000
Operational	$0 to $100,000	$100,000 to $200,000	>$200,000

The colour codes used to categorise the likely speed of recovery are as follows:

Fast	Medium/Fast	Medium	Medium/Slow	Slow

As noted elsewhere in this report, ORC has already allocated funds to specific items of work (including the cost of additional monitoring, and preserving the option of adding water from the Arrow River to Mill Creek). These costs are included in Table 9-1 to allow a comparison of the total cost associated with each option.

Although somewhat subjective, a column describing the ‘speed of recovery’ has been included. This is intended to allow a comparison of the speed at which each implementation option would help the lake move towards the overall objective, of making the lake swimmable at all times.

Table 9-1 Implementation options summary

Implementation Option	Capital Cost	Operating Costs	Speed of Recovery	Key risks	Comment
Option 1 • Monitor and Evaluate (No lake intervention)	$100,000	$45,000 p.a.	Slow	• Algal blooms may continue to occur over the short to medium term. • May not meet public expectation that 'something should be done'.	• Monitoring will help to understand chemical and biological processes occurring in the lake, and can be used to support future decisions. • Not a lake restoration method, but would help to determine the success of other options which may be implemented in the future. • Costs for this option are already accounted for in the 2018-28 Long Term Plan. They are included in this table to show the total costs associated with each option.
Option 2 • Augmentation • Monitor and evaluate	$395,000	$70,000 p.a.	Medium/Slow	• Algal blooms may continue to occur over the short to medium term. • Water may not be available, particularly at times when it is needed the most.	• The lake will recover faster than with Option 1, but the rate of recovery remains unknown. • Work to enable an offtake from the irrigation scheme has been completed. • Although augmentation by itself has a low to medium chance of success, when combined with other options it is more likely to help to expedite recovery of the lake.
Option 3 • Destratification • Monitor and evaluate	$771,000	$121,500 p.a.	Medium	• If the air curtain is activated at the wrong time, it may cause algal blooming to become more intense. • Mixing the water column may bring suspended particles from the lower part of the lake to the surface, which may reduce water clarity in the short term.	• There are environmental issues associated with locating and operating the equipment needed for destratification. • The system can be controlled using data from the buoy, to ensure that currents within the lake are established before stratification occurs.
Option 4 • Destratification • Augmentation • Monitor and evaluate	$1,066,000	$146,500 p.a.	Medium/Fast	• The risks listed for Option 3 apply here also. • Water may not be always be available for augmentation.	• The air curtain prevents the lake from stratifying, while augmentation provides additional clean water which will flush P from the lake, helping it to recover faster. • Monitoring provides guidance on how and when to activate the system. • The comments listed for Option 3 also apply here.

Table 9-1 (continued)

Implementation Option	Capital Cost	Operating Costs	Speed of Recovery	Key risks	Comment
• **Option 5:** Sediment Capping • Monitor and evaluate	$330,000	$722,000 per application.[23] Ongoing costs: $45,000 p.a.	Fast	• The treatment process may last a shorter period of time than anticipated. • As the actual amount of Alum required is difficult to estimate, the operational costs may be higher than anticipated.	• There are perception issues associated with discharging chemicals into the lake. If these issues could be overcome, this option has a high likelihood of success. • There would be a need to repeat the dosing process periodically (5-10 years), particularly if the current flow of nutrients into the lake via Mill Creek did not improve. • The direct injection method has not been tested elsewhere. It would require further evaluation to determine how best to implement such a system.
Option 6 • Sediment Capping • Augmentation • Monitor and evaluate	$625,000	$722,000 per application.[20] Ongoing costs: $70,000 p.a.	Fast	• The treatment process may last a shorter period of time than anticipated. • As the actual amount of Alum required is difficult to estimate, the operational costs may be higher than anticipated. • Water may not be always be available for augmentation.	• Comments listed for Option 5 also apply here. • In addition, adding clean, cold, oxygenated water into the lake may mean that dosing is not required as often. Direct injection at depth means there is less risk to beneficial lake algae in the surface waters. • The sediment capping / augmentation components would need to operate sequentially (summer / winter respectively). The purpose of augmentation is to assist in flushing of the lake between doses.
Option 7 • Hypolimnetic withdrawal • Monitor and evaluate	$763,000	$65,000	Medium	• In the short term the lake will continue to become anoxic at depth, with associated release of P. Algal blooms are therefore still possible. • The clarity and smell of water drawn from depth within the lake may have	• The only option that actively targets P for removal from the lake. • Although this system has worked in other places, further hydraulic and engineering investigations would be required to determine the specific design of the system components.

[23] As noted, the length of time between each application is unknown, but is expected to be somewhere between 5 and 20 years. Its success life is largely dependent on the amount of P entering the lake via Mill Creek. Operational costs during non-application years for this option will be significantly lower.

				a negative environmental impact, particularly for Hayes Creek. • Visual impacts of the weir and pipe.	• The success of this option depends on how rapidly P is withdrawn from the system. It may be some time before a noticeable difference in lake water quality can be seen.
Option 8 • Hypolimnetic withdrawal • Augmentation • Monitor and evaluate	$1,058,000	$90,000	Medium/Fast	• The risks listed for Option 7 generally apply here also. • Water may not be always be available for augmentation.	• Comments listed for Option 7 also apply here. • However, improvements in water quality may be observed sooner, due to a greater inflow from Mill Creek (allowing for a greater volume of water to be drawn from the lake, without lowering lake level).

10.0 DISCUSSION

The advantages, disadvantages, cost profile, and the adaptability of the implementation options listed above are discussed in this section, along with an assessment of how easy it would be to suspend or cease operations after initial implementation.

The first two options listed in Table 9-1 are both relatively inexpensive – both in terms of capital costs and operating expenses. In addition, ORC's 2018-28 LTP already accounts for some of these costs – there would be minimal (option 1) or no (option 2) additional cost from what is already specified in the LTP to activate these options. Neither of these two options are likely to result in a rapid improvement of lake water quality, at best a slow rate of recovery might be expected. However, they do provide for a great deal of flexibility – more intensive monitoring will help to inform future decisions, and augmentation can easily be integrated with other methods at a later date, if a decision was made to do so. A key benefit of these options is that they do not 'lock in' a particular approach – they can be suspended, or modified relatively easily. It is noted that little precedence could be found for using augmentation to remediate lake water quality. Gibbs (2018b) did not find any examples of a small inflow of clean water being used to manage the internal P load in a lake.

The third and fourth options listed in Table 9-1 centre on the destratification method. There are higher capital costs (mainly associated with the purchase and installation of the bubbler curtain), while operational expenses would be close to $100,000 p.a. The inclusion of the bubbler curtain would help to increase the rate of recovery, compared with options 1 and 2. However, the lake would require close attention to determine when the various components[24] should be activated, and to what extent. Accurate data from the monitoring buoy is therefore critical for the two options in this group. It is also possible that the bubbler would need to be operated every year, for a decade or more, to avoid the water quality issues described in section 2.1. The two options in this group do not necessarily prevent other methods from being implemented in the future, but it seems unlikely the bubbler curtain could be used in conjunction with other technical methods such as sediment capping or hypolimnetic withdrawal. The use of aeration to avoid lake stratification is a popular restoration technique in Europe and the USA, and several such systems have been installed in the North Island (Gibbs, 2018b).

The use of sediment capping is at the core of the fifth and sixth options listed in Table 9-1. Capital costs associated with this group are not high, but the cost to purchase and transport the alum each time the lake is dosed has been estimated at more than $700,000 (possibly more, as noted above). An advantage of the sediment capping approach is that the alum dosing can be stopped at any time – for example if it was found to have negative side effects, or there were other environmental changes which made it less suitable / desirable. Previous experience shows that the alum dosing approach has a high likelihood of success in the short term, but may need to be continued (albeit on an intermittent basis) for some time. The approach is fairly adaptable – for example, sediment capping could be done once, to 'lock up' existing P in lake bed sediments, and then other methods (e.g. hypolimnetic withdrawal) could be used to maintain high lake water quality into the future. The equipment required to dose the lake could be stored offsite, ready for use if and when it was required. This technique has also been found to work successfully in a range of lake environments, both overseas and in New Zealand (Gibbs, 2018b).

[24] i.e. the bubbler unit / augmentation

The last two implementation options listed in Table 9-1 centre on the withdrawal of water from the hypolimnetic zone. Both options within this group have relatively high start-up costs, mainly associated with the purchase and installation of the withdrawal pipe. However, the operating costs for options 7 and 8 are low, comprising mainly regular inspections by technicians / scientists. Although these costs would likely continue over the long term, inspections could be scheduled with other routine work to keep them to a minimum. This is the only restoration technique considered that would reduce the P load in Lake Hayes. It would be relatively easy to fine-tune the withdrawal process (by altering the discharge flow rate), or to turn off the system completely if necessary. The withdrawal / augmentation option would operate sequentially (summer / rest of year respectively), and the withdrawal system could continue in perpetuity, at minimal cost, if needed. Gibbs (2018b) found that hypolimnetic withdrawal has been used successfully to reduce P levels in many lakes in Europe and the USA.

11.0 SUMMARY

Some robust scientific and economic studies have been undertaken in recent years to identify different approaches which could be used to remediate water quality in Lake Hayes (section 3.0). This comprehensive volume of work has been summarised in this report, in a format that can be easily understood, so that comparisons between these different approaches can be made.

A 'short-list' of 4 technical methods has been identified, and these methods have been assessed, along with the 'do minimum' approach of continuing to monitor and evaluate lake water quality. For each method, the information supplied by previous authors has been supplemented with additional investigative work to determine likely costs and construction methods. An assessment of potential risks has also been undertaken, and the likelihood of success has also been categorised, based on the best information currently available.

It is possible that more than one method may be required to make significant improvements in lake water quality. This report therefore describes how various combinations of methods could be put into effect as 'implementation options' (section 9.0). Again, critical information relating to the risks associated with these options is listed, along with an assessment of the likely speed of recovery.

This report does not make any recommendations on which methods or implementation options should be implemented. Rather, it summarises a wide range of information, which can be used to make future decisions about how to remediate lake water quality. It is noted that there are risks and benefits associated with any approach which may be chosen.

12.0 ACKNOWLEDGEMENTS

GHC Consulting would like to acknowledge the previous work of Castalia Strategic Advisors, Max Gibbs of NIWA, Marc and Lena Schellenberg on behalf of the Friends of Lake Hayes and ORC staff. We are also grateful for the practical guidance from Andy Bruere, Lakes Operations Manager, Bay of Plenty Regional Council and other suppliers whom have dedicated their time to assisting us with this project. A list of references used to inform this report is provided in section 3.

APPENDIX 1. COMPONENTS OF THE LAKE DESTRATIFICATION OPTION

Item	Preferred location	Requirements
Compressor	Lake Hayes Reserve	• A 132-kW variable speed compressor (Largo 132)  • Noise level: 77 dB(A), equivalent to loud talking (almost shouting). • Dimensions: 2800 x 1755 x 1960. • 3-phase, 400v electricity supply. This model compressor was selected based on the specifications set out in Gibbs (2018a), in regards to the amount of air required, hole diameter, and the length of aeration pipe.
Compressor shed	Lake Hayes Reserve	• Dimensions 4800 x 3600 x 2400 • Specifically designed for noise reduction • Ventilated. • Vehicle access. • Building consent (QLDC). • Comply with requirements of the Arrowtown – Lake Hayes Reserve Management Plan, 2013 (QLDC)
Air supply pipe	From compressor shed into the lake, then to Bendemeer Bay	• Air supply pipe extends a total distance of about 900 m. • On land, it would be buried to a depth of 600 mm.
Air curtain	Positioned through the deepest section of the lake	• Air curtain delivered through an airline with 1 – 1.5 mm holes drilled, through the upper side at 20 – 30 cm intervals along its length.

APPENDIX 2. HOW THE LAKE DESTRATIFICATION OPTION WORKS

Below is a simplified description of how the lake destratification option is intended to improve water quality in Lake Hayes. It is noted that the system and lake response is relatively complex and more detailed descriptions are provided in Gibbs (2018a and 2018b).

The ultimate objective of destratification is to oxygenate the full body of lake water. Oxygenated waters encourage a different algae assemblage to become established within the lake. These algae tend to create a positive effect on lake waters, and help them to improve more quickly than would occur naturally.

How it works:

1. The air curtain will cause currents to form, and mixing to occur in the lake, as illustrated in the following diagram.

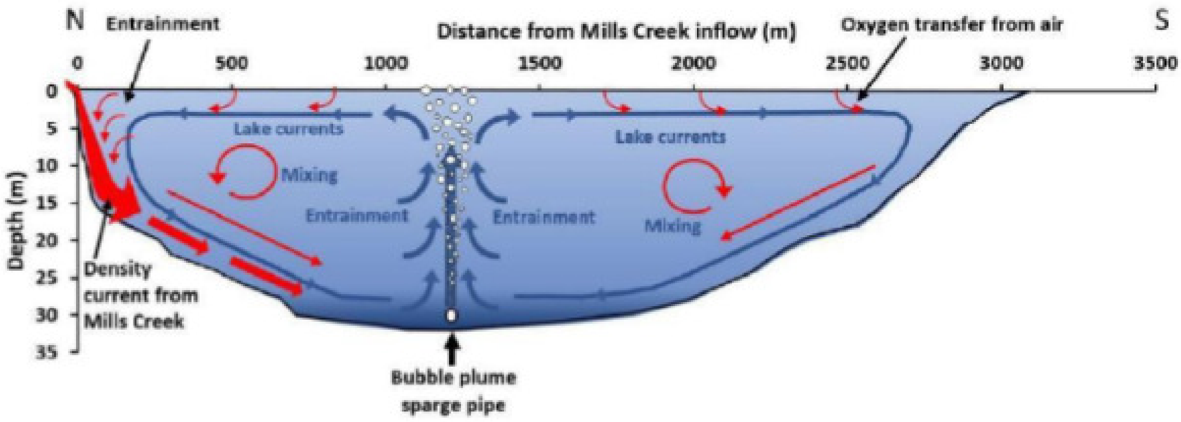


Diagram of the likely flow paths in Lake Hayes with the bubble plume operating. Red paths are oxygenated water, with blue lines expected lake flow paths (From Gibbs, 2018a).

2. These currents will circulate the algae and bacteria within the full depth of the lake. When the algae and bacteria are carried to depth, they die due to insufficient light.
3. When they die, they decompose aerobically, which means they emit CO_2[25], which will reduce the pH of the lake, which will reduce ammonia levels (i.e. nitrogen).
4. Over time, this process will reduce the amount of phytoplankton in the lake. With less suspended particles in the water column, the water column will be clearer, and also more oxygenated (due to a range of processes more fully explained by Gibb 2018a).
5. Light will therefore be able to penetrate deeper into the lake, and the amount of light will reduce gradually, rather than abruptly.
6. A clearer, more oxygenated water column will lead to higher levels of oxygen-producing algae in the lake.
7. As mobile DRP only forms under anoxic conditions, P will not be released from the lake bed, and will remain locked up in those sediments.
8. After a period of 5-10 years (assuming the input of organic matter and P from the upstream catchment is also reduced), the environment within the lake may be sufficiently stable, so that the air curtain system may not be required.

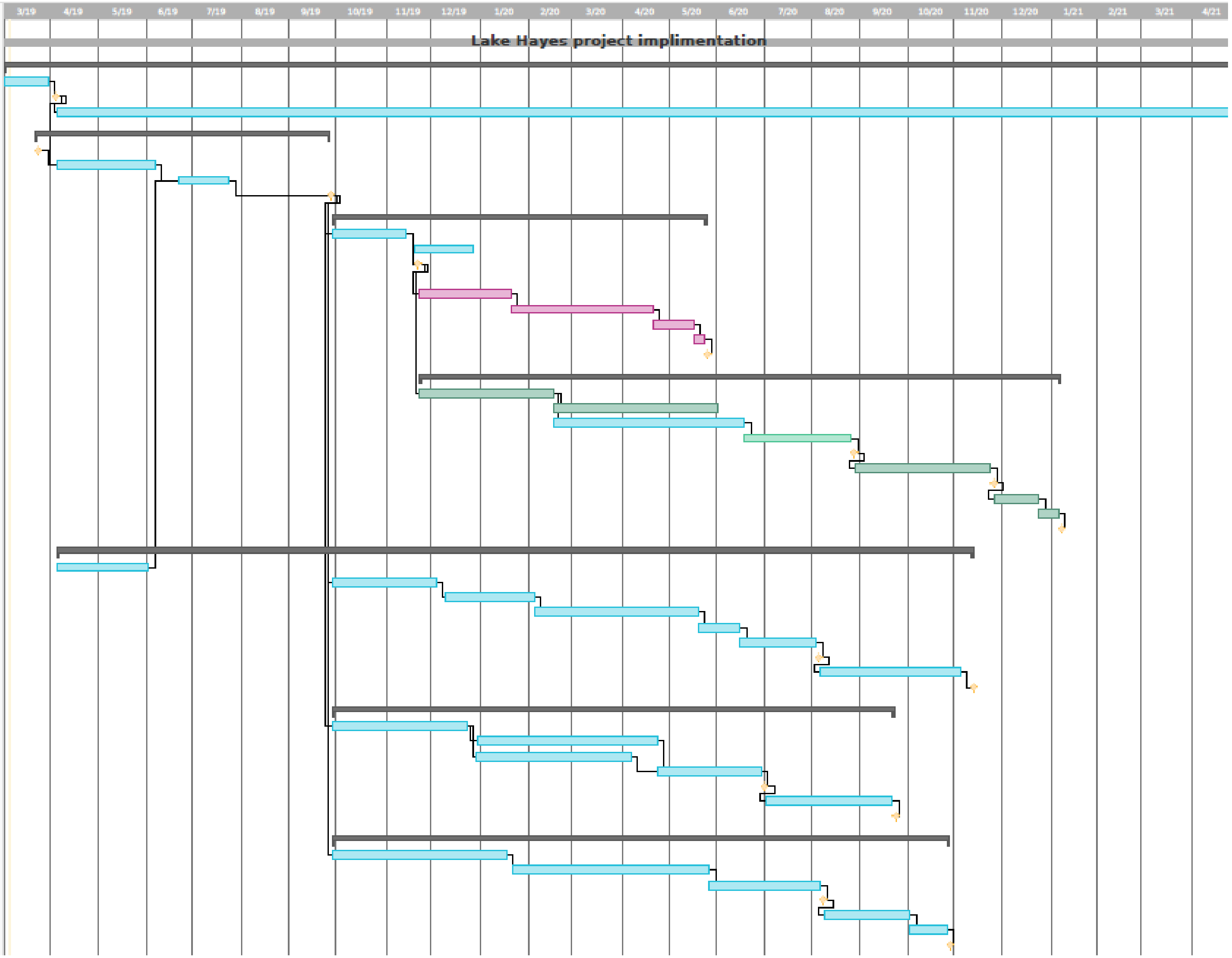
[25] rather than giving off methane, which occurs when they decompose under anaerobic conditions (i.e. without oxygen).

APPENDIX 3. COMPONENTS OF A HYPOLIMNETIC WITHDRAWAL SYSTEM

Item	Preferred location	Requirements
Weir and flanking walls	Located upstream of the Hayes Creek SH6 culvert.	• The weir would have a pipe passing beneath it, designed so that surface waters can still flow naturally over the top.
Pipe to the hypolimnetic zone - preferably the deepest part of the lake (~30m)	Along the lake bed to start of Hayes Creek.	• Pipe travels from the lake bed to the weir, before discharging to Hayes Creek. The pipe may need to be fixed into position using various weights and anchors.
Potential agitated river bed of stones	Downstream from the pipe discharge into Hayes Creek	• To aerate the water so that is re-oxygenated and hydrogen sulphide odour is treated.

APPENDIX 4. PROJECT IMPLEMENTATION TIMELINE

Lake Hayes project implimen...	start	end	0h	0%
No Lake Intervention (Monitoring...	**01/03/19**	**27/04/21**	**0h**	**0%**
Construct monitoring buoy	01/03	28/03	0	0%
Install and commission monitoring ...	02/04	02/04	0	0%
Monitoring operation	04/04	27/04	0	0%
Consulting	**21/03/19**	**25/09/19**	**0h**	**0%**
Council meeting to consider Lake H...	21/03	21/03	0	0%
Public consultation on options	04/04	05/06	0	0%
Evaluate and report to Council on c...	21/06	23/07	0	0%
Council decision (Council meeting ...	25/09	25/09	0	0%
Augmentation	**27/09/19**	**25/05/20**	**0h**	**0%**
Hydrological study	27/09	13/11	0	0%
Execute water take agreement with...	20/11	26/12	0	0%
Can project proceed without negati...	20/11	20/11	0	0%
If Yes .... Proceed to construction	-	-	**0h**	**0%**
Undertake AEE for a discharge to ...	22/11	20/01	0	0%
Prepare and apply for consent	21/01	20/04	0	0%
Construct take off control valve and...	21/04	15/05	0	0%
Augment commissioning	18/05	22/05	0	0%
Task complete	25/05	25/05	0	0%
If No.... Consult findings of hydrol...	**22/11/19**	**06/01/21**	**0h**	**0%**
Assess engineering options for culv...	22/11	17/02	0	0%
Undertake detailed engineering des...	18/02	01/06	0	0%
Prepare and apply for consent	18/02	17/06	0	0%
Advertising tender	18/06	25/08	0	0%
Tender award	26/08	26/08	0	0%
Construction	28/08	23/11	0	0%
Complete culvert	24/11	24/11	0	0%
Complete construct take off valve ...	26/11	23/12	0	0%
Augment commissioning	24/12	05/01	0	0%
Augment complete	06/01	06/01	0	0%
De-stratification	**04/04/19**	**11/11/20**	**0h**	**0%**
In addition to general consultation ...	04/04	31/05	0	0%
Detailed design	27/09	03/12	0	0%
Prepare and apply for resource con...	10/12	04/02	0	0%
Consultation with affected parties	05/02	19/05	0	0%
Prepare tender documents	20/05	15/06	0	0%
Advertise tender and receive propo...	16/06	03/08	0	0%
Award tender	04/08	04/08	0	0%
Construction	06/08	03/11	0	0%
Commissioning	11/11	11/11	0	0%
Hypolymnetic Withdrawal	**27/09/19**	**22/09/20**	**0h**	**0%**
Assess engineering options for Hay...	27/09	23/12	0	0%
Prepare and apply for resource con...	31/12	22/04	0	0%
Undertake detailed engineering des...	30/12	06/04	0	0%
Advertise tender and receive propo...	23/04	29/06	0	0%
Award tender	30/06	30/06	0	0%
Construction	02/07	21/09	0	0%
Construction completed and comiss...	22/09	22/09	0	0%
Sediment capping	**27/09/19**	**27/10/20**	**0h**	**0%**
Undertake lake current study and d...	27/09	16/01	0	0%
Prepare and apply for resource con...	22/01	26/05	0	0%
Advertise tender and receive propo...	27/05	05/08	0	0%
Award tender	06/08	06/08	0	0%
Construct buoy and delivery lines	10/08	01/10	0	0%
Commence supply of Alum into Lake	02/10	26/10	0	0%
Task completed - assess results	27/10	27/10	0	0%



APPENDIX 5. FRESHWATER IMPROVEMENT FUND

The previous National Government in 2016 committed $100 million over 10 years to the Freshwater Improvement Fund, to improve the management of New Zealand's lakes, rivers, streams, groundwater and wetlands. The fund supports projects with a total value of $400,000 or more, that help communities manage fresh water within environmental limits.

At present the fund is now closed for applications, and the Ministry for the Environment (MfE) is currently unable to give any indication when the next Freshwater Improvement Fund round may be. It is noted that in September 2017, a $385,000 grant from the fund was made to improve and maintain the long-term health of the wider Upper clutha area.

If the fund was to re-open for applications, the current application criteria include the following:

- *The project must contribute to improving the management of New Zealand's freshwater bodies.*
- *The project must meet 1 or more of the following:*
  - *achieve demonstrable co-benefits such as:*
  - *improved fresh, estuarine or marine water quality or quantity*
  - *increased biodiversity*
  - *habitat protection*
  - *soil conservation*
  - *improved community outcomes such as to recreational opportunity or mahinga kai*
  - *reduction to current or future impacts of climate change*
  - *reduced pressure on urban or rural infrastructure*
- *increase iwi/hapū, community, local government, or industry capability and capacity in relation to freshwater management*
- *establish or enhance collaborative management of fresh water*
- *increase the application of mātauranga Māori in freshwater management*
- *include an applied research component that contributes to improved understanding of the impacts of freshwater interventions and their outcomes.*
- *The minimum request for funding is $200,000 (excluding GST).*
- *The fund will cover a maximum of 50 per cent of the total project cost.*
- *The project will be funded for a maximum period of up to 5 years after which the project objectives will have been achieved or the project will be self-funding.*
- *The project must achieve benefits that would not otherwise be realised without the fund or are not more appropriately funded through other sources.*
- *The effectiveness of the project and its outcomes will be monitored, evaluated and reported.*
- *An appropriate governance structure in place (or one will be established as part of the project).*
- *The applicant must be a legal entity.*

Similarly, the MfE Freshwater Improvement Fund website currently states that any projects would be assessed against the following criteria:

1. *The extent to which the project addresses the management of freshwater water bodies identified as vulnerable.*
2. *The project demonstrates improvement in the values and benefits derived from the freshwater body.*

3. *The extent to which public benefit is increased.*
4. *The project demonstrates a high likelihood of success based on sound technical information or examples of success achieved through comparable projects undertaken elsewhere.*
5. *The extent to which the project will leverage other funding.*
6. *The project will involve the necessary partner organisations to ensure its success.*
7. *The project will engage personnel with the required skills and experience to successfully deliver the project.*

Previously, applications have been assessed by a panel of experts, which then makes a recommendation to the Minister for the Environment who makes the final funding decision.

APPENDIX 6. DISTRICT PLAN REQUIREMENTS

Any permanent structure to be placed on the margins of Lake Hayes (including reserve areas) would need to comply with the requirements of the Queenstown Lakes District Plan. The area is zoned as *Rural Living Areas* with the *Community Facility* sub-zone overlying it.

The most relevant requirements of the District Plan in this area include the following:

Any building proposed to be located in the zone will be a controlled activity for example:

- *Must avoid mitigate adverse effects on the natural landscape and visual amenity values.*
- *Nature conservation values and the natural character of the environment.*
- *Night time noise levels must be below 40 dB $L_{Aeq\ (15\ min)}$.*
- *Consideration must be made for glare, screening setback distances and colour.*

APPENDIX 7. LAKE HAYES RESERVE MANAGEMENT PLAN REQUIREMENTS

RESERVES ACT:

The Reserves Act 1977 (s17) sets out the purpose of a reserve:

"for the purpose of providing areas for the recreation and sporting activities and the physical welfare and enjoyment of the public and for the protection of the natural environment and beauty of the countryside, with emphasis on the retention of open spaces and on outdoor recreational activities, including recreational tracks in the countryside"

ARROWTOWN – LAKE HAYES RESERVE MANAGEMENT PLAN REQUIREMENTS

Any activity or permanent structure to be placed within the reserve areas adjacent to Lake Hayes would need to comply with the requirements of the Arrowtown – Lake Hayes Reserve Management Plan, 2013 (QLDC). The most relevant requirements include the following:

- *A lease for the occupation of the reserve would be required. This would need to be publicly notified.*
- *Utility services should be placed underground, unless this is impractical due to exceptional circumstances.*
- *Management of the reserves should occur in a manner consistent with the Lake Hayes Management Strategy (1995), to improve the overall ecology and water quality of Lake Hayes.*

Policy 8 (Buildings) of the Arrowtown Lake Hayes - Reserve Management Plan includes the following:

8.1 Proposals for new structures shall consider effects on the park environment, potential increased demand for car parking in or adjacent to the park, and the impact of the additional facilities and requirements on the convenience and wellbeing of other park users. Proposals for new buildings, other than those permitted in this Management Plan, shall be publicly notified in accordance with the Reserves Act 1977.

APPENDIX 8. TECHNICAL METHOD OBJECTIVES

Technical Method	Objective(s)
1. Water Augmentation	• Add clean water to Mill Creek, to increase the volume of water passing through Lake Hayes, and displace a greater volume of nutrient-rich lake water than would occur otherwise. • Reduce the temperature in Mill Creek, so that when it enters Lake Hayes it will plunge to the lower parts of the lake and oxygenate the bottom waters, thereby avoiding the conditions which result in P being released from lake bed sediments.
2. Destratification	• Prevent thermal stratification from occurring, to maintain dissolved oxygen concentrations above 5 g/m^{-3} as a means for preventing the release of dissolved reactive P from the lake sediments.
3. Hypolimnetic withdrawal	• Reduce the availability of dissolved reactive P in the lake by discharging nutrient enriched bottom water from the lake via a pipe to the outlet, rather than discharging cleaner surface water.
4. Sediment capping	• Reduce the amount of P in the lake water column by flocking with alum, causing P to settle to the lake bed, and locking it in the sediment with the resultant active sediment cap.

Lake Hayes Water Quality

Expansion on remediation options

Prepared for Otago Regional Council

October 2018

Prepared by:
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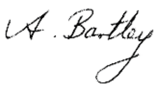
	Formatting checked by:	Alison Bartley
	Approved for release by:	Dr David Roper

Cover photo: Eastern shores of Lake Hayes from the lake. [Photo by Max Gibbs]

Contents

Tables

Figures

1 Introduction

Otago Regional Council (ORC) have asked the National Institute of Water and Atmospheric Research Ltd (NIWA) to produce a short report expanding on the three remediation options presented in an earlier report 'Lake Hayes Water Quality Remediation Options' (Gibbs 2018), written in response to a report by Schallenberg and Schallenberg (2017). The main options to be considered are:

1. Flow augmentation from the Arrow River irrigation scheme.
2. Destratification using bubble plume air curtains.
3. Sediment capping.

Other options covered briefly in the Gibbs (2018) report that could also be considered include:

- Hypolimnetic syphon – Hypolimnetic withdrawal.
- Nanobubble technology.
- Biomanipulation.

ORC would like the report to include:

i. examples of other lakes which have undergone remediation using any of the three options (size, depth, comparability, environmental setting, degree of degradation etc.)

ii. comment on the effectiveness of each remediation example (e.g., % improvement or other)

iii. comment on the likelihood of success of each option in improving Lake Hayes water quality, and

iv. comment on the relevance of case studies. Does effectiveness of remediation options elsewhere transfer to their potential effectiveness in Lake Hayes.

1.1 Overview

To provide the background for how each of the above mitigation / rehabilitation techniques work, it is important to understand the processes associated with eutrophication and the role of humans in accelerating that process.

Definition: Eutrophication is the process by which a body of water becomes enriched in dissolved nutrients (such as phosphates) that stimulate the growth of aquatic plant life, usually resulting in the depletion of dissolved oxygen. (https://www.merriam-webster.com/dictionary/eutrophication).

Eutrophication is a natural process that slowly occurs over time. Nutrients washed off land during rain events are carried to the lake via streams and overland flow. Phosphates are typically bound to iron oxides in the soil and are carried with the sediment rather than as soluble dissolved reactive phosphorus (DRP) in the water. In forested catchments, the amount of sediment washed off the land is about a quarter of that in the runoff from pasture (Eyles & Fahey 2006) but increases by up to six-fold during forest harvesting. The particulate material enters the lake and settles to the bottom, thereby storing the phosphorus (P) in the sediment as a legacy of past activities in the catchment.

As eutrophication intensifies, the dissolved oxygen in the bottom waters of the lake decreases in summer when the lake is thermally stratified and the upper (epilimnion) and lower (hypolimnion) layers a separated by a thermal gradient called a "thermocline". The thermocline is a physical barrier to the transfer of oxygen from the atmosphere into the hypolimnion. When the hypolimnion loses all oxygen and becomes anoxic, the conditions are said to be "reducing" and the ferric (Fe^{3+}) iron oxides binding the P are reduced to soluble ferrous (Fe^{2+}) iron ions and the P is released as DRP into the water column. Typically, the DRP accumulates in the hypolimnion until autumn when the thermocline weakens and breaks down allowing oxygen to oxidise the iron back to ferric oxides, which can once more sequester the DRP and return it to the sediments.

The sequestration process is not instantaneous and during the lag between mixing the oxygen into the lake and the sequestration of the DRP by the iron oxides formed, there is a window of opportunity for phytoplankton use the DRP for growth.

There are four essential requirements for phytoplankton growth: nitrogen (N) as dissolved inorganic N (DIN), P as DRP, carbon (C) as carbon dioxide (CO_2) and light. Remove any one (or more) of these components and phytoplankton growth will be reduced or will stop. Typically, the CO_2 content of water is maintained from the atmosphere and shouldn't be limiting to phytoplankton growth. However, when the dominant phytoplankton species is a cyanobacteria, which are bicarbonate adapted and can remove all the carbonate (CO_3^-) and bicarbonate (HCO_3^-) from the water, other benign phytoplankton species cannot grow.

In most lakes, nutrient nitrogen forms of nitrate (NO_3-N) and / or ammonium (NH_4-N) are in abundance, almost all studies around rehabilitation of lakes and reservoirs reported in the literature focus is reducing P. The amount of N and P in a lake defines how large the phytoplankton grow can be while the balance between N and P proportions in a lake largely determines which phytoplankton species will be present. The balance is described in terms of nutrient limitation, where the nutrient limitation states have been defined with reference to the total N (TN) and total P (TP) concentrations in the water (e.g., Abell et al. 2010) as:

- P-limitation: a mean ratio of TN:TP by mass of >15:1 is indicative of P-limitation.
- N-limitation: a mean ratio of TN:TP by mass of <7:1 is indicative of N-limitation.

Between these two mean ratios, the phytoplankton are likely to be nutrient replete and co-nutrient limitation may occur, i.e., the control of either N or P could reduce phytoplankton growth.

When N-limitation occurs, there is typically an excess of DRP in the water column, which favours the growth of cyanobacteria (Havens et al. 2003).

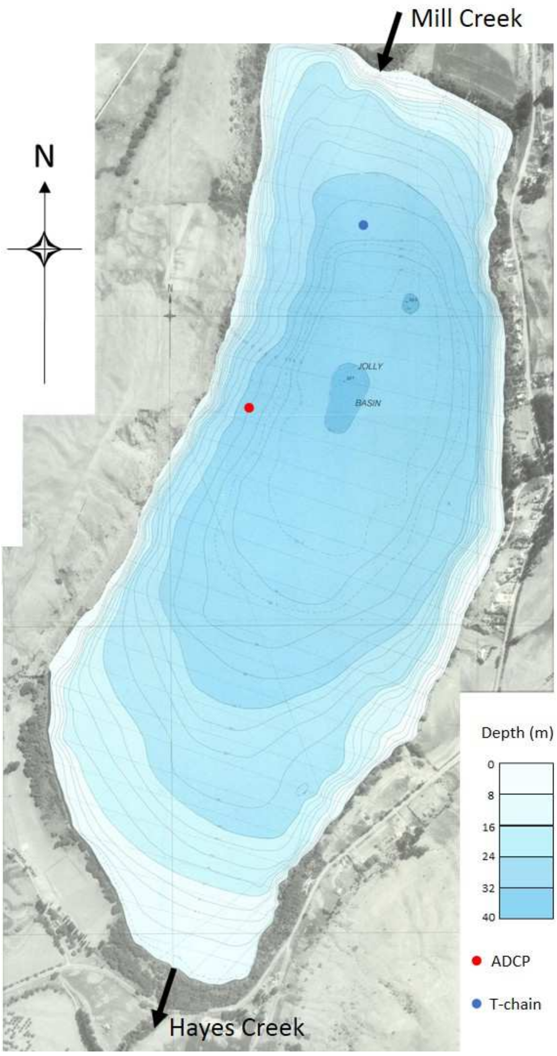
1.2 Lake Hayes

Lake Hayes is one of several sub-alpine temperate lakes in the South Island of New Zealand (Selvarajah 2015) at latitude ~45° S. At this latitude, winter light levels are mostly below those required for phytoplankton growth. Consequently, the lake produces maximum phytoplankton biomass in summer.

The lake has a mean depth of 18 m and a maximum depth of 33 m. Profile data shows that it thermally stratifies at a depth of between 10 m and 15 m and the that hypolimnion can become anoxic through summer. Monitoring data also shows that during the anoxic phase, DRP is released from the sediments and accumulates in the hypolimnion. This can drive a late summer algal bloom

(Gibbs 2018). The dominant phytoplankton species in recent years has been *Ceratium hirundinella*, a motile dinoflagellate which has formed nuisance blooms. Cyanobacteria blooms have also occurred.

Lake Hayes bathymetry and morphological characteristics are shown in Figure 1-1.



Lake Hayes morphological characteristics:

Area	2.76 km^2
Length	3.1 km
Mean depth	18.0 m
Maximum depth	33.0 m
Volume	55.1 x 10^6 m^3
Volume of hypolimnion	28.9 x 10^6 m^3
Catchment land area	44.0 km^2
Surface elevation	315 m
Theoretical mean residence time[1]	3.82 y
Residence time (added inflow)	2.98 y.
Inflow via Mill Creek (mean 1984-97)	0.43 m^3 s^{-1}
Latitude: 44.9824° S,	
Longitude: 168.8099° E	

Figure 1-1: Lake Hayes bathymetry and morphometric data (Figure 1.1 from Gibbs 2018). Red dot indicates position of an acoustic doppler current meter (ADCP) deployment. Blue dot is position of thermistor chain deployment. (Chart redrawn from Hurley 1981).

There are a wide range of restoration techniques described in the literature and discussed in the book "Restoration and Management of Lakes and Reservoirs" (Cooke et al. 2005). A list of these techniques is presented in Table 1-1 with a description of each technique, whether it is a short-term or more permanent fix and how it relates to the expansion of the three remediation techniques in this report. The emerging nanobubble technique is improving as the technology behind the technique is developed further.

[1] Lake volume divided by total annual inflow

Table 1-1: List of lake management and restoration techniques from Cooke et al. (2005). Highlighted cells show relevance of these basic techniques to the techniques being discussed in this report.

Methods	Description	Comment	Relevance
Dilution and flushing.	Addition of low nutrient water and / or high-volume water to dilute P concs, wash out algal cells and reduce residence time.	Long term benefits while operating.	Augmentation water (Lake Stratified).
Hypolimnetic Withdrawal	Release of nutrient rich/oxygen poor water from the hypolimnion through selective release rather than the surface.	This technique provides long term benefits. Low cost. Requires oxygenation of discharge.	Augmentation water (Lake Stratified).
Hypolimnetic aeration / oxygenation	Addition of compressed air, or pure oxygen to hypolimnion during stratified period. Does not mix the lake.	Short term benefits, expensive to run. Includes nanobubble technology.	Not relevant to this study.
Artificial circulation, destratification	Use of mechanical devises or aeration to mix the lake. Bubble plume curtains commonly used.	Short term benefits while running; long term benefits after use for several years.	Destratification.
P removal	Dredging, draw down and scraping.	Shallow lakes.	Not relevant to this study.
P-inactivation using Alum, Phoslock, iron, calcium	Aluminum salts added to water produces a floc which precipitates P and forms an active barrier to P release from the sediment. Similar for Phoslock.	Treatment is likely to have an immediate effect in clearing a bloom. Unless the external sources of P are eliminated, retreatment will be required.	Sediment capping (Natural lake stratification cycle – timed application).
P-inactivation using "Riplox" process	Oxidation of the top 10-20 cm of sediment through discing or injection of nitrate to enhance denitrification and P-binding to iron.	Shallow lake.	Not relevant to this study.
Biomanipulation	Food web management (restructuring fish communities) to control algae.	Treats symptom. May work in Lake Hayes if the planktivorous fish populations are reduced.	Not relevant to this study.

Restoration options for Lake Hayes should focus on reducing the internal P load which is supporting the summer phytoplankton blooms. However, whatever restoration technique is used, the longevity of the restoration treatment will depend on catchment management to reduce the input of more P to the lake.

2 Expanding on the three remediation options

2.1 Flow augmentation from the Arrow River irrigation scheme

Summary from Gibbs 2018: *When the entrainment factor of surface lake water into the density current from Mills Creek is included, there is potential for this option to prevent the bottom water (hypolimnion) becoming anoxic during the stratified period, thereby eliminating the internal phosphorus (P) load which is required by Ceratium for growth. There are issues with this option in that it is 'fragile' and relies on the ambient temperature to cool the Mills Creek water sufficiently to cause the density current to plunge to the hypolimnion. In a warm year this might not happen, and the internal P load could return along with a substantial algal bloom*.

A literature survey found no references where a small inflow of clean water was used to manage the internal P load in a lake. Most references were associated with using the augmentation water to reduce the mean residence time of water in the lake to less than a year. This is so that the carbon load associated with the algal bloom was flushed out of the lake rather than being returned to the sediment where it would replenish the sediment oxygen demand (SOD) causing anoxic conditions the following year.

2.1.1 Flushing.

This is an extension of flow augmentation where a larger volume of water is used to alter the hydraulic regime and dilute the contaminants in the lake with cleaner water. Most lakes where flushing was used were shallow at less than 6 m deep and the flushing flows were in the order of 10+ $m^3 s^{-1}$ and the results indicated a steady recovery of the lake.

For example, flushing with a flow of 19 $m^3 s^{-1}$ low nutrient water, was successfully used in Lake Veluwe, a large (32.5 km^2), shallow (mean depth, 1.55 m; max. depth, 5 m), elongated (18 km) lake in the Netherlands, for control of *Oscillatoria* blooms and internal phosphorus loading (Jagtman et al. 1992; Hosper 1997; Hosper and Meyer 1986). There was an initial lag of 2 years before the effect of flushing became apparent, then the TP concentrations decreased from 0.4-0.6 g m^{-3} to 0.1-0.2 g m^{-3} and DRP accumulation in the water during summer reduced from 0.2-0.3 g m^{-3} to $<$ 0.02 g m^{-3}. The cycle of *Oscillatoria* blooms was broken.

A flushing flow for Lake Hayes would need to be at least 1.8 $m^3 s^{-1}$, a 4-fold increase over the present inflow via Mills Creek, to reduce the mean annual residence time to less than a year. A higher flow during summer stratification would be most beneficial. Putting this into perspective, this would be about half the mean flow in the Arrow River.

2.1.2 Flow diversion

Literature, where flow diversion has been used, is also limited but the potential effects have been modelled (e.g., Hamilton et al. 1995). In that study, modelling predicted that diverting the main inflow to Prospect Reservoir (Sydney), Australia, to a water treatment plant would adversely affect the water quality in the reservoir by removing the main source of dissolved oxygen from the hypolimnion. The model also predicted increased phytoplankton concentrations resulting from anoxic release of P from the sediments. The model predicted that phytoplankton blooms were likely to occur at winter mixing.

In contrast, the diversion of Lake Rotorua water from Lake Rotoiti is an example where this technique has been successfully used to restore the water quality of a lake. In this case, while the diversion of the Lake Rotorua water reduced the input of dissolved oxygen to the hypolimnion of Lake Rotoiti, it also removed the ~18 $m^3 s^{-1}$ inflow of eutrophic water from Lake Rotorua. This inflow represented about 25% of the total inflow to Lake Rotoiti. Subsequently, the water quality in Lake Rotorua has been improved and may now be approaching a quality where the diversion is no longer needed.

2.1.3 Hypolimnetic withdrawal

Hypolimnetic withdrawal is a management technique which has been in use for more than 50 years and is currently being promoted in Europe as an alternative to sediment capping and aeration (Nürnberg 2007). This technique uses the natural hydraulic conditions in the lake to permanently remove P from the lake. In the original report this option was referred to as a “hypolimnetic siphon” (section 3.5.2., Gibbs 2018). To use this option, the lake must thermally stratify in summer and produce and anoxic hypolimnion.

The concept is to draw the outflow water from the bottom of the lake, rather than the surface, during summer when the lake is thermally stratified. When the hypolimnion becomes anoxic, the DRP released from the sediments is removed from the lake rather than discharging low nutrient surface water. Thus, the P is selectively targeted and removed from the lake (Macdonald et al. 2004).

A literature survey indicates that hypolimnetic withdrawal has been used for P reduction in many lakes in Europe and the USA (Wagner 2004; Nürnberg 2007; Dithmer et al. 2016).

Wagner (2004) summarises the results for 17 lakes in the USA with 1 to 10 years of hypolimnetic withdrawal and concluded that they reduced the P content of the lake with reduction in chlorophyll. To use this technique, an outlet structure must be installed to facilitate hypolimnetic withdrawal. This one-time capital cost confers permanent control with minimal operation and maintenance costs. The downstream water quality from hypolimnetic withdrawal must be addressed (Kondolf and Wilcock 1996) and, while costs for treating the discharge by some methods could be substantial, most treatment systems typically consist mainly of aeration by passive means at limited capital and operational cost (Wagner 2004).

Nürnberg (2007) compared water quality variables before and during treatment in about 40 European and 8 North American lakes and concluded that hypolimnetic withdrawal is an efficient restoration technique in stratified lakes. Water quality improvements were apparent as decreased summer average epilimnetic P and chlorophyll concentrations and increased water clarity as measured by Secchi disk, and decreased hypolimnetic P concentration and anoxia. In particular, Nürnberg found that summer average P decreases were significantly correlated with annual water volumes and P masses withdrawn per lake area, indicating the importance of hydrology and timing of the treatment. The lake sizes that were treated ranged from 1.5 ha to over 1450 ha with maximum depths from 5 m to 39 m. See Appendix A for the list.

Comment:
With the exceptions of flushing and dredging, hypolimnetic withdrawal is the only restoration technique that reduces the P load within a lake. It is physically possible to apply this technique to Lake Hayes. If the surface skimmer option described in Gibbs (2018) is also implemented, this technique has a high probability of successfully improving the long-term water quality in Lake Hayes. On-going operating costs are likely to be very low as it is a passive system using gravity to move the water and oxygen in the atmosphere to manage the water quality in the discharge. Flow augmentation from the Arrow River irrigation scheme would accelerate this process.

2.2 Aeration / destratification

Summary from Gibbs (2018): *The use of a bubble plume air curtain across the middle of the lake would generate circulation currents that would prevent the lake from becoming thermally stratified and mix the lake water column, keeping the lake well oxygenated. These conditions would eliminate the internal P load and reduce the proliferation of algal blooms. The mixing regime would not eliminate algal growth in the lake, rather it would change the algal assemblage from harmful cyanobacteria and Ceratium species to more benign species. Eventually these would diminish dramatically, and the lake water quality would improve rapidly.*

A literature survey shows that aeration used for destratification is a popular lake and reservoir management and restoration technique in Europe and USA and is frequently used in water supply reservoirs for potable waters. A range of aeration systems have been developed over the past 80 years and the focus has gradually turned to using bubble plume air curtain aerators to destratify the lake so that natural re-oxygenation processes through exchange with the atmosphere can occur. Although the initial use of this system is reported in the late 1960s and was installed in the San Diego water supply reservoir (e.g., Fast 1968; Lorenzen and Fast 1977). The destratification technique was installed in many lakes by the U.S. Army Corp. A review by Pastorok et al. (1982) includes water quality data for 107 reservoirs managed by the U.S. Army Corps and includes a comprehensive review of aeration/circulation techniques and past experience encompassing literature from January 1972 through December 1980.

Development of bubble plume air curtain aerators has continued with many publications on design and including air flow required (e.g., Wirth 1988; Kortmann 1989; Lewis 1990; Zic and Stefan 1990; Schladow 1992; Schladow 1993; Schladow et al. 1993; Lemckert et al. 1993; Schladow and Fisher 1995; Schladow et al. 1993; Kirke 2000; Mobley et al. 2000; Singleton and Little 2006a; Singleton and Little 2006b) and the technique is included in the "Water Safety Plan Guide: Pre-treatment Processes" (Ministry of Health 2014).

In New Zealand bubble plume air curtain aerators have been used exclusively in the 10 water supply reservoirs for Auckland City and new systems have recently been installed in several lakes (e.g., Lake Turitea – Palmerston North water supply reservoir). A bubble curtain aeration system was installed in Lake Waikopiro – Hawkes Bay as trial run for restoration of the larger adjacent lake, Lake Tutira. Destratification is being considered for the Nelson City water supply reservoir, Lake Maitai (Kelly 2015).

Bubble curtain aeration systems work well when designed for the lake/reservoir and are used to prevent the establishment of thermal stratification. This means that the timing of start-up each year is very important. Started too early is wasting money, starting too late and there is a significant risk of the system becoming a nutrient pump which could stimulate an algal bloom. This latter situation occurred in Lake Waikopiro in 2017 and resulted in a substantial algal bloom developing with an associated fish kill. Because there was oxygen in the near surface waters, it is possible that the phytoplankton in the bloom raised the pH enhancing P release from iron in the sediment, there by sustaining growth, and turning the non-toxic ammonium-N (NH_4-N) into toxic ammonia (NH_3). Because the system was installed after thermal stratification had developed and a phytoplankton bloom had already become established, it would have been better to delay turn on until the following year. Hind sight is 20:20.

Bubble curtain aeration systems work best in deeper lakes greater than 15 m deep but can be made to work in lakes as shallow as 10 m. Lower Nihotupu lake, in the water supply reservoir network for Auckland City, has a maximum depth of 16 m. With correct timing of aeration turn on, this lake remains a good quality potable water supply. However, it is prone to developing cyanobacteria blooms if the aeration system is not working correctly or the timing is wrong.

A summary of the aeration systems used in the 10 water supply reservoirs for Auckland City (Watson 2012) shows the practical application of the aeration system for destratification. Of particular importance is the air flow through these systems (Table 2-1). The data from these water supply reservoirs show that to achieve destratification within 10 days, the size of the compressor is important and should be tailored to the size of the lake.

Table 2-1: Compressor capacity for Auckland's water supply reservoirs. Data from Watson (2012) and the internet. (* bold = Watercare estimate; (#.#) = Lorenzen & Fast 1977 estimate; [#.#] = Schladow 1993 estimate).

Lake	Area (ha)	Air capacity required to destratify lake in 10 days (m^3 min^{-1}) *	Existing system theoretical capacity (m^3 min^{-1})	Existing system destratification time (days)
Waitakere	25.1	**1.2** (2.3) [1.3]	1.2	10
Upper Huia	18.9	**1.2** (1.74) [0.99]	4.98	2
Lower Huia	50.3	**3.6** (4.6) [2.61]	1.6	22
Upper Nihotupu	12.5	**1.5** (1.15) [0.65]	4.98	3
Lower Nihotupu	52.9	**3.3** (4.87) [2.76]	3.96	8
Mangatangi	185	**30.9** (17.02) [9.66]	10.38	30
Wairoa	98	**6.9** (9.02) [5.12]	10.38	7
Hays Creek	18.2	**0.66** (1.67) [0.95]	10.38	1
Cosseys	123	**8.1** (11.32) [6.42]	9.48	9
Mangatawhiri	128.5	**8.4** (11.82) [6.71]	10.38	8

There doesn't appear to be an upper limit to the size of lake that can be treated depending on the purpose of that aeration. For example, deployment of multiple bubble curtain aeration systems in the centre of Lake Erie were being considered to reduce or eliminate the local area of hypoxia (Boegman and Sleep 2012).

The design guideline by Lorenzen and Fast (1977) recommends and air flow of 9.2 m^3 min^{-1} km^{-2} lake area is likely to meet the aeration requirement for most lakes[2]. However, different methods of calculating the air flow requirement can produce different answers. For example, the calculations for a small reservoir near Whangarei suggested that an air flow of 3.7 m^3 min^{-1} was required based on the Lorenzen and Fast (1977) method but, based on the methodologies of Davis (1980) and Schladow (1993), a flow of only 2.1 m^3 min^{-1} should be sufficient.

The "Air capacity required to destratify lake in 10 days" column (Table 2-1) shows the range of required air capacities that can be obtained by different methodologies for the same lake. The Watercare estimate method is unknown but falls between the estimates obtained using the Lorenzen and Fast (1977) method and the Schladow (1993) method. Where there is an overcapacity,

[2] For comparison purposes, the aeration efficiency is based on the air flow required to destratify a lake in 10 days.

the lake is destratified in less than 10 days but where there is under capacity, it takes much longer than 10 days to achieve destratification.

In an oval lake without prominent side embayments, it is possible that the value calculated by the Lorenzen and Fast (1977) method may be an overestimate but, because the Whangarei reservoir has multiple side arms that will reduce the efficiency of the lake circulation currents generated by the bubble plume air curtain, the lower estimates may be insufficient to cause lake-wide destratification. Lake Hayes has an area of 2.76 km^2 and would require an air flow of about 25 $m^3\ min^{-1}$ according to the Lorenzen and Fast (1977) method or about 14 $m^3\ min^{-1}$ according to the Davis (1980) and Schladow (1993) method. Because of the shape of the lake bed, the actual air capacity required should be somewhere between these two estimates.

Pastorok et al. (1982) summarised the results from the 107 U.S. Army Corps managed reservoirs (see Appendix B) commenting that artificial destratification by mechanical pumping or diffuser-air mixing usually elevated dissolved oxygen content of the lake by bringing anoxic bottom water to the lake surface where aeration occurs through contact with the atmosphere. Oxygenation may cause precipitation of phosphate compounds and inhibition of nutrient release from sediments. However, with the expansion of the oxic habitat, invasion of benthic macroinvertebrates into the profundal zone may play a role in maintenance of high phosphorus release rates from oxygenated surficial sediments. They noted that the water quality generally improved after treatment, but under sizing of water pumps or improper timing of destratification relative to occurrence of algal blooms can aggravate existing oxygen deficits.

Visser et al. (2016) gives an overview of several studies where artificial mixing has been used as a treatment to prevent the growth of cyanobacteria in eutrophic lakes and reservoirs (see Appendix B). The results showed that artificial mixing caused an increase in the oxygen content of the water, an increase in the temperature in the deep layers but a decrease in the upper layers. They noted that the standing crop of phytoplankton (i.e., the chlorophyll content per m^2) often increased partly due to an increase in nutrients entrained from the hypolimnion or resuspended from the sediments. This was coupled with a change in composition from cyanobacterial dominance to green algae and diatoms where the imposed mixing was strong enough to keep the cyanobacteria entrained in the turbulent flow and mixing was deep enough to limit light availability through critical depth.

These comments are consistent with other studies where the destratification device has been activated after the lake has become thermally stratified with nutrients accumulating in the hypolimnion and a cyanobacteria bloom has developed in the epilimnion (e.g., Lake Waikopiro).

Note: Aeration and destratification does not reduce the internal P load in the lake (Gächter and Wehrli 1998). By maintaining high oxygen levels to the lake bed, it suppresses the release of DRP from the sediments into the water column so that bioavailable P is not available for phytoplankton growth while the mixing device is running. The resultant reduction in phytoplankton biomass means less organic matter is deposited on the sediment each year. Consequently, the organic carbon load in the sediment reduces through decomposition processes and sediment oxygen demand reduces. Over time, this results in a reduction in the rate of oxygen depletion when the lake stratifies, even when the aeration device is not running. A reduction in the external P load on the lake will accelerate this process. Fine sediment with low P content will to slowly bury the P in the sediment.

Other aeration techniques including hypolimnetic oxygenation and nanobubble technology do not cause destratification, which is the primary function of the bubble plume air curtain mixing system. Without disrupting the thermocline, the benefits of deep mixing and critical depth are not available for reducing cyanobacteria blooms.

Comment:
Destratification using a bubble plume air curtain in Lake Hayes, positioned as described in Gibbs (2018) and activated within the protocols based around the temperature structure and DO content of the water column, has a high probability of success in controlling cyanobacteria blooms. Lake Hayes is deep enough to give a strong circulation current from the aerator plume. It is also deep enough that critical depth can be used to reduce cyanobacteria blooms through light limitation.

2.3 Sediment capping – P-inactivation

Summary from Gibbs (2018): *The range of available sediment capping and P elimination agents has been discussed. It was concluded that the 'best' option would be to treat the lake with alum using a low dose drip feed into the Mills Creek inflow. This approach would deliver the alum to the hypolimnion in the density current without impact on the lake surface waters. Using real-time monitoring data, adaptive management strategies could control the application to when it was required and was being delivered into the hypolimnion for the most efficient and cost-effective management of the internal P load.*

Clarification: This technique is P-inactivation, where the treatment product sequesters biologically available P (i.e., DRP) from the water column (or sediment surface) making it unavailable for phytoplankton growth, rather than sediment capping, which implies covering the sediment with an impervious layer of clay or sand. P-inactivation may result in a very thin layer of P-inactivation agent across the sediment surface and that becomes an active barrier to the diffusion of P from the sediment. This distinction is important because there are a variety of ways that P-inactivation agents can be used to achieve a reduction in the internal P load of a lake.

There are many studies, reports, peer-reviewed papers and books available on the internet describing the use of P-inactivation agents on individual lake studies and, more recently, reviews of that research (Dunst et al. 2016; O'Sullivan 2017). Although there have been a wide range of P-inactivation agents used in the past and a few new ones being developed (Douglas et al. 2016), the two most commonly used P-inactivation agents are alum (aluminum sulphate - $Al_2(SO_4)_3{\cdot}18(H_2O)$) and Phoslock®, a lanthanum modified bentonite clay commonly referred to as LMB.

A study by Blázquez-Pallí (2015) compared the use of alum and Phoslock® to reduce internal P cycling in lakes and found that that alum was able to bind 93-95% of mobile P at the highest dose compared with a maximum of 25-35% of mobile P by Phoslock® at the same dose rate. A comparison between theoretical and real binding ratios also showed that alum was more effective than Phoslock® at removing mobile P from sediments and that it was substantially cheaper at 83 €/kg of P and 1227 €/kg of P inactivated, respectively. Blázquez-Pallí (2015) concluded that, from these results, coupled with potential non-target side effects and treatment longevity gathered from literature, in general terms, alum was a better product for most lakes, but that Phoslock® may be better in shallower systems where there was likely to be frequent wind-induced sediment resuspension.

These findings are consistent with a study by Jensen et al. (2015), who found from six Danish lakes that, if dosed sufficiently relative to the pool of excess P in the lake sediment and water column, alum could block sediment P release and thereby improve water clarity in eutrophic lakes. They also found that, while alum treatment has been used in >200 lakes worldwide, in some 30% of the known cases water clarity did not improve beyond the first year- mostly shallow lakes. They suggest that this was most likely because of under-dosing or continued high external P loading. They concluded that if external P-loading was sufficiently low, lasting improvement of water quality can be obtained if Al is dosed 10:1 or higher relative to the size of the mobile P pool.

The longevity of effectiveness of alum treatment was assessed from 114 lakes treated with aluminum salts to reduce internal P loading (Huser et al. 2016). Factors driving longevity of post-treatment water quality improvements included morphology (lake bed shape) and applied Al dose. They determined that treatment longevity based on declines in epilimnetic total P (TP) concentration averaged 11 years for all lakes (range of 0-45 years). When longevity estimates were used for lakes with improved conditions through the end of measurements, average longevity increased to 15 years. There were significant differences in treatment longevity between deeper, stratified lakes (mean 21 years) and shallow, polymictic lakes (mean 5.7 years) indicating factors related to lake morphology are important for treatment success.

A case study on Süsser See, a hardwater lake in Germany (similar to Lake Hayes), which had been treated with alum annually for 15 years, found that the treatment was clearly recognizable in sediment depth profiles as increases of total phosphorus (Lewandowski et al. 2003). However, while the sorptive capacity of alum in the sediment was still not exhausted, it had little or no effect on the P release from the uppermost fresh sediment layers. This study demonstrates that the P-inactivation material forms a layer which can become a permanent block, stopping P diffusion from the sediment below. This is effectively resetting the lake without an internal P load. However, if the new sediment entering lake has the same P load as before treatment, the P-inactivation layer will become buried below a new sediment layer this continues to release P. The take-home message from this study is that, for long-term restoration of a lake, the external load from the catchment needs to be reduced or the in-lake mitigation measures will be negated.

Few similar studies on the longevity of Phoslock® have been undertaken because this product has only relatively recently been commercially used. A combined field and laboratory scale study of 10 European lakes treated between 2006 and 2013 with LMB (Phoslock®) to control sediment P release was conducted by Dithmer et al. (2016). From their work, DRP release experiments on intact sediment cores indicated conditions of P retention (with the exception of two lakes) by sediments, indicating effective control of sediment P release for between two and nine years after treatment.

Notwithstanding the above, while P-inactivation using alum or aluminium salts has been used in the USA for more than 50 years (Welch et al., Cooke et al. 1993, 2005), and Phoslock® treatment of European lakes are similarly effective for reducing internal P loads that drive phytoplankton proliferation, the use of chemical lake restoration methods is not regarded as a panacea. Implementation of P-inactivation should consist of a targeted management approach as a part of an integrated management plan (Hickey and Gibbs 2009; Zamparas and Zacharias 2014). This point is also made in several papers. Zamparas and Zacharias (2014) found that the longevity of the treatment effectiveness using P-inactivation agents was reduced if not given the necessary importance in managing the external nutrient loads. They concluded that the successful implementation of internal P management measures requires a site-specific study of a range of factors affecting viability of the method used, in connection with an assessment of the potential adverse effects on humans, livestock, biotic and abiotic factors.

Physical factors can influence which product to use in shallow lakes where wind disturbance can resuspend the sediments. Egemose et al. (2010) found that treatments containing Al reduced the P concentration immediately after sediment resuspension, whereas Phoslock® required several days after resuspension to reduce the P concentration. They found that Phoslock® increased the sediment stability threshold by 265% whereas alum had no effect and the floc was 5x easier to disturb than the untreated sediment. Consequently, Phoslock® would be more useful in a shallow lake, even though it is more expensive. In deeper lakes, the alum floc may eventually form a cohesive cover on the sediment surface improving the sediment stability (Gibbs et al. 2011).

Similar findings by others that the alum floc was easily disturbed lead to the development of the "floc and lock" technique where the P and particulate material was removed from the water column using a flocculent and subsequently locked into the sediment surface with Phoslock® (Oosterhout and Lürling 2013; Waajen et al. 2016). While the flocculant used in these studies was a low dose flocculant (iron(III)chloride), alum would also be an appropriate flocculant which would be less hazardous to handle. Furthermore, would not release P when the hypolimnion became anoxic thereby improving the efficiency of this technique.

The problem with using sediment capping / P-inactivation in New Zealand is that only one product is registered for use in New Zealand – alum. There is sufficient evidence of the efficacy at P-inactivation and cyanobacteria management to support an investigation of using Phoslock® under New Zealand conditions in shallow lakes. However, given that Lake Hayes is considered a relatively deep lake, and the large cost difference between using alum or Phoslock®, alum is the preferred option.

The floc and lock technique could be used in New Zealand if the Phoslock® locking component was replaced with Aqual-P$^{(TM)}$, which is an aluminium modified zeolite developed in New Zealand by Scion Research Institute and manufactured by Blue Pacific Minerals in Tokaroa. Testing of that product (Gibbs et al. 2011) showed that Aqual-P$^{(TM)}$ P-binding efficacy was comparable or better than Phoslock® with the added advantage that this product also sequesters the ammonium nitrogen released from the sediment at the same time. As with Phoslock®, Aqual-P$^{(TM)}$ stabilises the sediment but is less expensive than Phoslock®. While Aqual-P$^{(TM)}$ has been successfully used by Bay of Plenty Regional Council to manage water quality and reduce cyanobacteria blooms in Lake Okaro and in Okawa Bay on Lake Rotoiti, there has had little further research and development on this product.

The method of treating a lake for restoration is an important factor to consider. The major success for alum has been the improvement in the water quality of Lake Rotorua from eutrophic, with persistent algal blooms, to mesotrophic, without algal blooms and clear water. This was achieved by using a drip-feed of alum solution into two inflow streams to sequester the natural DRP in those spring waters before it entered the lake. The two streams contributed about 30% of the external P load on the lake. It would have been impractical treat these streams with a granular product that is slow to react such as Phoslock®. The alternative of dosing the whole lake with Phoslock® or Aqual-P$^{(TM)}$ was prohibitively expensive and may not have treated the targeted area of lake bed due to the size of the lake and the internal currents that could move the product around the lake from where it was applied (Gibbs et al. 2016). The application time to cover the 80 km^2 lake was also impractical.

As indicated in the original report (Gibbs 2018), the drip-feed dosing technique could be used in Lake Hayes. The treatment costs would be reduced and efficacy improved if real-time lake data were available to provide an adaptive management feed-back for the treatment dose rate.

Comment:
P-inactivation is a quick and practical method of managing sediment P release and the concomitant growth of cyanobacteria blooms in Lake Hayes. While it can reset the lake to conditions without an internal P load, it is not a panacea. Its advantage over other measures is it will control / manage phytoplankton blooms while catchment nutrient loads are being reduced. The cost of this restoration method depends on the P-inactivation agent used and the method of application. For Lake Hayes, a whole lake treatment would be expensive. The most economical strategy would be to use alum applied as a drip-feed into Mills Creek when the lake was thermally stratified. The water from Mills Creek would be the transport mechanism for dispersing the alum around the lake and into the hypolimnion. There is a high probability for this technique to succeed, but it may take time before the improvements are seen.

An application of alum or Aqual-P directly to the lake immediately prior to thermal stratification would most likely produce immediate improvements in lake water quality, as has been seen in Lake Okaro.

3 Summary - overview

The specific outcomes requested to be included in this report have been summarised at end of the section for each mitigation strategy. There are many examples in the literature of other lakes which have undergone remediation using approaches comparable with the three options being considered in this report. However, none are exactly comparable in terms of size, depth, environmental setting, degree of degradation and the treatment process or how the treatment needs to be applied in Lake Hayes. The overall conclusion is that the three techniques work well in many of the lakes treated and in some they don't work well. In many lakes, the effectiveness or otherwise of each remediation example (e.g., % improvement) was a function of the application rather than the technique used, especially the use of the wrong technique in shallow lakes.

Considering relevant literature case studies, the effectiveness of remediation options used elsewhere indicate their potential effectiveness in Lake Hayes, as does the potential for failure if the lake-specific conditions in Lake Hayes are not carefully considered. Notwithstanding this, there is a high likelihood of success for the appropriate application of each option to improve Lake Hayes water quality. The only questions remaining are by how much and at what cost?

3.1 Flow augmentation

There is no published research on the benefits of small augmentation flows to lakes as a restoration technique, the way the augmentation of Mills Creek is intended for Lake Hayes. However, flow augmentation has the potential to be part of the most cost effective and low-cost restoration technique - hypolimnetic withdrawal. The augmentation water from the Arrow River would maintain a flow through the lake in summer when the natural flow in Mills Creek might otherwise be very low.

In a case study publication, Lehman (2014) discusses what happened in Ford Lake, Michigan, USA, when a drought "turned off" the inflow. Ford Lake is an urban reservoir comparable in size to Lake Hayes (4 km^2). The management strategy used hypolimnetic withdrawal to reduce the internal P load and maintain an oxic environment to near the sediments. When the drought turned off the inflow it allowed the lake to thermally stratify in summer. The resultant hypolimnion became anoxic allowing N and P released from the sediment to accumulate. When the flow returned, the lake mixed and experienced a substantial cyanobacteria bloom.

This lake was being managed using hypolimnetic withdrawal and is one of many hundreds of lakes around the world using this technique. (see section 2.1.3). The implication from the Lehman (2014) study is that, had the inflow not stopped, hypolimnetic withdrawal would have continued to maintain the aerated state of the near bottom water in the lake and thus the lake water quality. The augmentation flow from the Arrow River would achieve the continuous flow for Lake Hayes. This is the only technique which removes P from the lake and, therefore, it has the potential for long-term restoration, provided external P loads from the catchment are reduced.

3.2 Destratification

Destratification as a lake restoration technique has been used since the 1960s and is being updated from air cannon devices, such as those trialled unsuccessfully on Lake Tutira in the 1970s (Teirney 2009), to more efficient bubble curtain aeration systems that have successfully been used in many deep reservoirs around the world, including San Diego reservoir in California installed in the 1960s and the 10 water supply reservoirs for Auckland City installed in the late 1990s. Where this mixing technique has failed, the bubble curtain aeration systems have either been installed in shallow lakes, had under-capacity air supplies or they have been activated after the lake has become thermally stratified and the hypolimnion has accumulated N and P released from the sediment. Under these latter conditions they become nutrient pumps, stimulating phytoplankton blooms.

With correct sized compressors and activation timing, the bubble curtain aeration systems work very well. They would successfully improve the water quality in Lake Hayes in the first year and the improvement would continue with each year of operation. There is a potential for long term recovery where the P driving the internal P load becomes buried under new sediment, providing that sediment from the catchment has a reduced P content (See section 2.2).

The one-off capital cost of a bubble curtain aeration system for destratification is higher than a hypolimnetic withdrawal installation, and depends on the design which, in turn, is a function of the lake size and morphology. Unlike the passive hypolimnetic withdrawal system, there are annual running costs. Both systems will also have some maintenance costs.

3.3 Sediment capping – P-inactivation

In most studies using alum as a P-inactivation agent, the comment is that alum has an immediate effect on water quality, removing cyanobacteria blooms and generally clearing the water column. It effectively resets the lake to a condition without an internal P load.

Alum would be an appropriate P-inactivation agent in Lake Hayes. It would be considerably cheaper to use than the alternatives - Phoslock® and Aqual-P(TM). If applied as a single dose to the lake, it would likely require retreatment every 3 to 5 years until the external P load from the catchment was substantially reduced. Alum could also be applied as a variable inoculation into the Mills Creek inflow (See section 2.3) at a lower annual cost. However, there is often resistance to the use of alum in a natural lake because it is thought of as a “chemical”. The fact that either alum or poly aluminium chloride (PAC) are safely used in almost every drinking water supply in New Zealand as a clarifier seems to have been missed when considering its potential benefit for the restoration of a lake.

P-inactivation is used in thousands of lakes across USA and Europe, especially for recreational lakes. It is not a panacea, but it can be used to provide immediate water quality improvement while catchment management strategies are implemented to reduce the external P loads on the lake, as a long-term restoration strategy.

3.4 Bottom line

Lake restoration is not new and, globally, there have been literally thousands of lakes restored using variations on the three options discussed above. In all cases the restoration strategy has been tailored to the lake and often there is more than one technique applied. The northern hemisphere restoration techniques are often designed as a compromise, accepting a ‘better quality’ degraded water rather than actually restoring the lake to a much higher water quality. In New Zealand, the drive is to be able to see our feet on the bottom when we go swimming so the much higher level of water quality is preferred. Of the three basic restoration techniques, only drip feed alum dosing and hypolimnetic withdrawal can be used together without modifying the natural thermal stratification, which makes these techniques possible. Sediment capping and aeration can be used together provided a fine granular P-inactivation agent is used (e.g., Aqual-P or Phoslock®).

If the lake is to be mixed, the mixing needs to occur before strong thermal stratification develops in spring. Aeration protocols need to be followed to ensure success.

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Appendix A List of lakes where hypolimnetic withdrawal has been used – From Nürnberg (2007)

Table 1.-Location, morphometry and hydrology of lakes with hypolimnetic withdrawal, commenced in year of "start." Ref = references: 1, Nürnberg 1987; 2, Sampl 1992; 3, Thaler and Tait 1995; 4, Rossi and Premazzi 1991; 5, Špela Rekar, Environmental Agency of the Republic of Slovenia, pers. comm. ; 6, Livingstone and Schanz 1994 and Pius Niederhauser, pers. comm.; 7, Hupfer and Scharf 2002; 8, Keto *et al.* 2004; 9, Rönicke *et al.* 1998; Hupfer *et al.* 2000; 10, Zaiss 1984; 11, Jörg Lewandowski, pers. comm. 12, Scharf *et al.* 1992; 13, Ohle 1972 cited in Klapper 1992; 14, Inke Schauser, pers. comm; 15, Steinberg *et al.* 1982; 16, Klein and Chorus 1991; 17, Dunalska 2002, 2003; Dunalska 2007; 18, Olszewski 1961; 19, Petterson pers. comm.; 20, Sosiak and Trew 1996; Sosiak 2002; 21, Macdonald *et al.* 2004; 22, Nürnberg *et al.* 1987; 23, Henry Runke, Barr Engineering Company, pers. comm.; 24, Holt *et al.* 1986; 25, Lathrop *et al.* 2005; 26, KCM 1986.

Lake[a]	Country, State or Province	Loc[b]	Start Year	Observation (after)	A_d ha	Area ha	Volume m^3 10^6	z m	z_{max} m	Mixing State[c]	Morphometic (Osgood) Index m/km	Possibility of meromixis	Water detention time yr	q_s[d] m/yr	Ref
Hecht	Austria	EA	1973	1977	222	26.3	6.43	24.4	56.5	3	47.6	2.49	2.80	8.7	1
Klopeiner	Austria	EA	1975	1992	423	110.6	24.98	22.6	48	3	21.5	1.48	11.50	1.97	1,2
Kraiger	Austria	EA	1974	1978	65	5.1	0.25	4.8	10	2	21.3	0.67	1.00	4.8	1,2
Leonharder	Austria	EA	1980	1992	230	2.3	0.08	3.6	8		23.8	0.65	long	[e]	2
Piburger	Austria	EA	1970	2000	264	13.4	1.84	13.7	24.6	3	37.5	1.29	1.90	7.2	1
Reither	Austria	EA	1976			1.5	0.07	4.5	8.15		36.2	0.74	0.27	16.5	1
Vassacher	Austria	EA	1979	1992	120	4.5		5.1	10.2	2	24.3	0.70		[e]	2
de Paladru	France	EA	1976		4 800	390.0	97.00	25.0	35	1	12.7	0.79	4.00	6.25	1
Kl.Montiggler	Italy	EA	1979	1994	67	5.0	0.52	9.9	14.5	3	44.4	0.97	10.00	0.99	1,3
Varese	Italy	EA	1999		11 150	1,451.9	153.65	10.6	26	1	2.8	0.42	1.91	5.54	4
Bled	Slovenia	EA	1982	2000	754	143.8	25.69	17.9	30.2	2	14.9	0.87	1.50	11.9[c]	1,5
Burgaschi	Switzerland	EA	1977	1982	319	19.2	2.48	12.9	32	3	29.5	1.53	1.37	9.4	1
Lützel	Switzerland	EA	1982	2003	602	12.8	0.53	4.2	5.9	0	11.7	0.31	0.15	27.7	1,6
Mauen 1974	Switzerland	EA	1968	1974	430	51.0	1.99	3.9	6.8	1	5.5	0.25	0.60	6.5	1
Mauen 1987	Switzerland	EA	1968	1987	430	51.0	1.99	3.9	6.8	1	5.5	0.25	0.60	6.5	7
Wiler	Switzerland	EA	1962		26	3.1	0.33	10.0	20.5		56.4	1.54	1.03	9.7[c]	1
Daemman & 10 other lakes	Finland	EU	1973												8
Arend	Germany	EU	1976	1985	2 980	514.0	147.00	28.6	49	2	12.6	1.03	114	0.25	9
Bostal_Dam	Germany	EU	1979	1980	1 260	119.0	7.45	6.3	17	2	5.7	0.51	1.50	4.17	10
Burg	Germany	EU	2000			10.3	0.50	4.5	26	3	13.9	1.45			11
Gemündener Maar	Germany	EU	1983	1989	43	7.5	1.33	17.7	39	3	64.6	2.36	8.00	2.21	1,12
Grebiner	Germany	EU	1968												13
Kluten	Germany	EU	83-85		250	8.8			5.1	0		0.30			14
Medeweger	Germany	EU	89, 91-98		11 300	95.4	10.15	10.6	28.2	2	10.9	0.90	0.62	17.1	14
Meerfelder Maar	Germany	EU	1982	1989	127	24.8	2.27	9.2	18	3	18.5	0.81	4.50	2.04	1,7
Obinger	Germany	EA	1981	1993	1 567	31.2	2.18	7.0	14	2	12.5	0.59	0.27	25.9	15
Scharteisen	Germany	EU				9.5							22.00		14
Schlachten	Germany	EU	1981	1990		42.0	1.97	4.7	9.5	2	7.2	0.37	0.50	9.38	16
Stadtsee Bad Waldsee	Germany	EU	1988		2 000	13.7	6.88	6.3	10.5	2	17.0	0.55	0.20	31.0	14
Tressower See	Germany	EU	1990		1 000	64.0	4.90	7.7	20	2	9.6	0.71	2.26	3.41	14
Kortowskie 1986-89	Poland	EU	1976	86-89	102	89.7	5.29	5.9	17.2	2	6.2	0.56	1.52	3.87	17

Table 1.-Continued

Lake[a]	Country, State or Province	Loc[b]	Start Year	Observation (after)	A_d ha	Area ha	Volume m^3 10^6	z m	z_{max} m	Mixing State[c]	Morphometic (Osgood) Index m/km	Possibility of meromixis	Water detention time yr	q_s[d] m/yr	Ref
Kortowskie 1990-94	Poland	EU	1976	90-94	102	89.7	5.29	5.9	17.2	2	6.2	0.56	1.52	3.87	17
Kortowskie 1956	Poland	EU	1956	1956	102	90.1	5.29	5.9	17.2	2	6.2	0.56	1.52	3.87	1,18
Rudnickie	Poland	EU				160.9			11.9			0.33			17
Brunnsviken	Sweden	EU													19
Trekanten	Sweden	EU													19
Pine	Alberta	NA	1999	2005	15 280	412.0	20.60	5.0	12	2	2.5	0.27	9.00	0.56	20
Chain	BC	NA	1994	1999		44.0	2.68	6.1	9	0	9.2	0.35	1.75	3.49[e]	21
Waramaug	CN	NA	1983	1985	3 700	286.6	24.76	8.6	12.8	2	5.1	0.31	0.83	10.3	1,22
Wononscopomuc, shallow basin	CN	NA	1981	1985	599	24.0	15.50	8.5	15.2	2	17.4	0.69	4.00	2.13	1,22
Crystal	MN	NA	Before 2001			117.0			8.20						23
Hayes	MN	NA	1984												24
Devil's	WI	NA	2002	2005	686	150.5	13.9	9.2	14.3	2	7.5	0.41		1.8[e]	25
Ballinger	WN	NA	1982	1991	1 172	40.5	1.84	4.5	10	1	7.1	0.40	0.26	17.3[e]	26
Average					1 943	121	17.2	9.7	19.1	2	18.1	0.78	6.6	8.3	
Median					430	42	2.6	7.0	14.9	2	12.6	0.65	1.5	5.9	
n	51				32	39	34	35	38	33	35	37	32	32	

[a] For two lakes distinct different observation periods were used (Mauen and Kortowskie)

Several lakes are known to have been treated besides hypolimnetic withdrawal: Reither See was drained and filled with cleaner water in 1972, then an iron chloride treatment was commenced simultaneously with hypolimnetic withdrawal; Kleiner Montiggler See was oxygenated under ice since 1978, in Schlachtensee inflow P was precipitated with iron chloride simultaneously with hypolimnetic withdrawal, and in Chain Lake at least three treatments had been applied before (dredging, flushing, aeration by small windmills).

[b] Location: EA, Europe – alpine; EU, Europe – non-alpine; NA, North America

[c] Mixing State:

0 = oligo- or polymictic, occasionally stratified in the summer
1 = Monomictic, stratified throughout the summer season only
2 = Dimictic, two stratification periods per year, in summer and winter
3 = Meromictic, a certain layer at the deepest depth is stratified all year long

[e] Surface inflow was enhanced

Appendix B List of lakes where aeration mixing has been used – From Pastorok et al. (1982).

TABLE 4. SELECTED LAKES AND MIXING SYSTEMS

Lake/Location	Reference	Shape	Depth (m) Max.	Depth (m) Mean	Depth (m) Air	Volume x 10^{-6} (m^3)	Area (ha)	Aeration Intensity[a] Q_A (m^3/min)	Q_A/V x 10^6	Q_A/A x 10^6	Start Date	Strat.	Dura. (mo)
Cline's Pond Oregon	Malueg et al. 1973	rectangular	4.9	~2.5	4.9	~0.003	0.13	0.028	10.2	21.50	06/30/69	yes	2
Parvin Lake Res. Colorado	Lackey 1972	rectangular	10	4.4	10	0.849	19	2.1	2.5	11.18	11/69	yes	12
Section 4 Lake Michigan	Fast 1971a	circular	19.1	9.8	18.3	0.110	1.1	2.21	20	200	06/16/70	yes	2.8
Boltz Lake Res. Kentucky	Symons et al. 1967, 1970 Robinson et al. 1969	dentritic	18.9	9.4	18.9	3.614	39	 3.17	 0.88	 8.17	08/06/65 06/02/66	yes yes	1.2[b] 1.7[b]
University Lake Res. North Carolina	Weiss and Breedlove 1973	irregular	9.1	3.2	9.1	2.591	80.9	0.40	0.15	0.49	05/19/71 03/27/70		6 ~8
Kezar Lake New Hampshire	N.H.W.S.P.C.C. 1971 Haynes 1973, 1975	subcircular	8.2	2.8	8.2	2.008	73	2.83	1.41	3.88	07/16/68 05/28/69 05/70 05/71	yes yes	2 3.5 3.4 3.4
King George VI Res. United Kingdom	Ridley et al. 1966 Ridley 1970	rectangular	16	14	10- 14	20	142		pump		07/02/65 07/13/66	yes yes	0.2
Indian Brook Res. New York	Riddick 1957	elliptical	8.4	4.1	2.2	0.302	7.3	4.53	15.0	62.06	06/56	yes	6
Prompton Lake Res. Pennsylvania	McCullough 1974	elongate?	10.7	~3.7	10.7	4.193	~112	4.53	1.08	~4.04			
Cox Hollow Res. Wisconsin	Wirth and Dunst 1967 Wirth et al. 1970	lunate	8.8	3.8	8.8	1.480	38.8	2.04- 4.08	1.38- 2.76	5.26- 10.52	07/01/66	yes yes	38.5
Stewart Lake Res. Ohio	Barnes and Griswold 1975 Barnes (pers. comm.)[c]	rectangular	7.5	3.4	7.0	0.090	2.6	0.25	2.83	9.80	07/26/74 07/15/75	yes yes	3[b] 3.5[b]
Wahnbach Res. W. Germany	Bernhardt 1967	elongate	43	19.2	~43	41.618	214	2.01 5.95	0.048 0.143	0.94 2.78	05/26/61 06/13/62 06/11/64	yes	4.5[b] 5 5
Starodworskie Lake Poland	Lossow et al. 1975	elliptical	23		23		7	0.27		3.81	03/14/72	yes	6.2
Queen Elizabeth II Res. United Kingdom	Ridley et al. 1966 Tolland 1977	subcircular	17.5	15.3	17.5	19.6	128		water jet		03/15/65 05/24/66	yes yes	
Lake Roberts Res. New Mexico	R.S. .err Res. Center 1970 McNall 1971	irregular	9.1	~4.4	9.1	1.233	28.3	3.54 2.26	2.87 1.84	12.51 8.00	06/15/69 07/09/69	yes yes	0.2 1.6

(Continued)

(Sheet 1 of 4)

TABLE 4. (continued)

Lake/Location	Reference	Shape	Depth (m) Max.	Mean	Air	Volume x 10-6 (m^3)	Area (ha)	Aeration Intensity[a] Q_A (m^3/min)	Q_A/V x 10^6	Q_A/A x 10^6	Start Date	Strat.	Dura. (mo)
Falmouth Lake Res. Kentucky	Symons et al. 1967, 1970 Robinson et al. 1969	elongate	12.8	6.1	12.8	5.674	91	3.26	0.58	3.58	05/16/66		4[b]
Test Res. II United Kingdom	Knoppert et al. 1970	rectangular	10.7	9.4	10.7	2.405	25.4	2.01	0.84	7.92	04/01/68		5
Ham's Lake Res. Oklahoma	Steichen et al. 1974, 1979 Toetz 1977a, b; 1979b Garton et al. 1978 Wilhm et al. 1979	dentritic	10	2.9	pump 1.2	115	40		Garton pump		07/16/73 06/19/75 06/03/76 04/19/78 05/31/79	yes yes yes yes yes	3.5 3 3 4.8 3
Test Res. I United Kingdom	Knoppert et al. 1970	rectangular	10.7	9.4	10.7	2.097	22.7	2.01	0.96	8.86	06/68		4[b]
Mirror Lake Wisconsin	Smith et al. 1975 Brynildson and Serns 1977	elliptical	13.1	7.6	12.8	0.400	5.3	0.45	1.13	8.55	10/19/72 03/30/73 09/21/73 09/12/74	yes	1 0.8 0.5 1.5
Stewart Hollow Res. Ohio	Irwin et al. 1966	rectangular	7.6	4.6	pump 7.6	0.148	3.2		axial-flow pump		07/20/64 09/01/64	yes yes	0.1 0.04
Cladwell Res. Ohio	Irwin et al. 1966	irregular	6.1	3.0	pump 6.1	0.123	4.0		axial-flow pump		07/29/64	yes	0.07
Pine Res. Ohio	Irwin et al. 1966	lunate	5.2	2.1	pump 5.2	0.121	5.7		axial-flow pump		08/05/64	yes	0.1
Vesuvius Res. Ohio	Irwin et al. 1966	elongate	9.1	3.6	pump 9.1	1.554	42.5		axial-flow pump		09/03/64	yes	0.8[b]
Vaxjosjon Sweden	Bengtsson and Gelin 1975	elliptical	6.5	3.5	6	3.1	87	7.2	2.32	8.28	summer 1969-71 winter 1971		0.2-0.5 0.5
Corbett Lake British Columbia	Halsey 1968 Halsey and Galbraith 1971	elliptical	19.5	7	19.5	1.689	24.2	4.50	2.66	18.52	10/17/62 10/18/63	yes yes	1.5[b] 1.5[b]
Buchanan Lake Ontario	Brown et al. 1971	elliptical	13	4.9	13	0.42	8.9	0.28	0.67	3.17	07/14/71	yes	2.5
Lake Maarsseveen United Kingdom	Knoppert et al. 1970	irregular	29.9	14	19 29.9	8.018	60.7	2.49	0.31	4.10	07/27/67	yes	1.8[b]

(Continued)

(Sheet 2 of 4)

TABLE 4. (continued)

Lake/Location	Reference	Shape	Depth (m) Max.	Depth (m) Mean	Depth (m) Air	Volume x 10-6 (m3)	Area (ha)	Aeration Intensity[a] Q_A (m3/min)	Aeration Intensity[a] Q_A/V x 10⁶	Aeration Intensity[a] Q_A/A x 10⁶	Start Date	Strat.	Dura. (mo)
Arbuckle Lake Res. Oklahoma	Toetz 1977a, b; 1979a, b	dendritic	24.7	9.5	6 2	8930	951		Garton pump		07/17/74 06/02/75 '/01/77 04/01/78	yes yes yes yes	1.5 3.5 2.8 6
Casitas Res. California	Barnett 1975	dendritic	82	26.8	39- 55	308	1100	17.84	0.06	1.62	04/70 to 1975		~7/yr
Hyrum Res. Utah	Drury et al. 1975	elliptical	23	11.9	15.2	23.1	190	2.83	0.17	1.49	06/01/73	yes	12
West Lost Lake Michigan	Hooper et al. 1953	circular	12.8	6.2	pump 11.9	0.089	1.4		pump		29/52	yes	0.4
Waco Res. Texas	Biederman and Fulton 1971		23	10.7	23	128	2942	3.11	0.02	0.10	06/10/67	yes	~48[b]
Lake Catherine Illinois	Kothandaraman et al. 1979	elliptical	11.8	5	8.5	3.034	59.5	0.76	0.25	1.27	05/18/78	yes	5.5
El Capitan Res. California	Fast 1968	elongate	62	9.8 9.4	21.3 28.3	17.99 21.05	183.9 222	6.09 6.09	0.34 0.29	3.31 2.74	06/65 02/66	yes yes	3.7 7
Lake Calhoun Minnesota	Shapiro and Pfannkuch 1973		27.4	10.6	23	18.01	170.4	2.83- 3.54	0.16- 0.20	1.66- 2.08	08/04/72	yes	4
Eufaula Res. Oklahoma	Leach et al. 1970	irregular	27	8.3	27	3454	41480	33.98	0.01	0.08	06/67 07/68	yes yes	0.8 1.1
Pfaffikersee Switzerland	Thomas 1966 Ambuhl 1967	elliptical	35	18	28	56.5	325	6	0.11	1.85	4 or 5 1958-63	yes	4-5
Wahiawa Res. Hawaii	Devick 1972	elongate	26	~8	2.7	~1.7	20	2.4	~1.4	12	09/20/71	yes	2
Trasksjon Sweden	Karlgren and Lindgren 1963	elliptical	4	~3.0	4?	0.365	12.1				03/63	yes	0.07
Allatoona Res. Georgia	USAE 1973 Raynes 1975	dendritic	46	9.4	42.7	453	4800	21.6- 27.7 27.7	0.05- 0.06 0.06	0.45- 0.58 0.58	05/09/68 03/15/69	yes yes	4.5 6.5
Lafayette Res. California	Laverty and Nielsen 1970	lunate	24	9.1	18	5.243	53	1.68	0.32	3.17	04/68	yes	9[b]
Hot Hole Pond New Hampshire	N.H.W.S.P.C.C. 1979	elliptical	13.3	5.7	13.3	0.733	12.9	0.59	0.80	4.57	05/04/76	yes	3.6

(Continued)

(Sheet 3 of 4)

TABLE 4. (continued)

Lake/Location	Reference	Shape	Depth (m) Max.	Depth (m) Mean	Depth (m) Air	Volume x 10^{-6} (m^3)	Area (ha)	Aeration Intensity[a] Q_A (m^3/min)	Q_A/V x 10^6	Q_A/A x 10^6	Start Date	Strat.	Dura. (mo)
Heart Lake, Ontario	Nicholls et al. 1980; Nicholls (pers. comm.)[d]	elliptical	10.4	2.7	10	0.392	14.5	0.23	0.58	1.56	06/25/75	yes	1.2
								0.34	0.88	2.38	07/31/75	no	4.6
								0.34	0.88	2.38	04/07/76	no	4.4
								0.34	0.88	2.38	06/79	yes	3-5
								0.34	0.88	2.38	04/80	no	~3
								0.92	2.34	6.33	07/80	no	3-5
Clear Lake, California	Rusk (pers. comm.)[e]	irregular	15	10.2	14	115.93 OAKS	1217 OAKS	17	6.82	1.40	1976	yes	
Kremenchug Res. Inlet, Poland	Ryabov et al. 1972; Sirenko et al. 1972		3	~2	2.6	0.002	~0.12	4.38	1750	~3500	07/17/70	yes	0.7[b]
Tarago Res., Australia	Bowles et al. 1979	irregular	23	10.5	14	37.6	360	3.00-9.00	0.08-0.24	0.83-2.50	01/21/76	yes	1.1[b]
								3.00-7.50	0.08-0.20	0.83-2.08	10/05/76	yes	2.5[b]

[a] Q_A = rate of air injection (m^3/min), V = volume (m^3), A = area (m^2).

[b] Intermittent operation of aerator or pump.

[c] Personal communication, M.D. Barnes, October, 1980, Ohio State University, Columbus, Ohio.

[d] Personal communication, K.H. Nicholls, October, 1980, Ontario Ministry of the Environment, Ontario, Canada.

[e] Personal communication, W.F. Rusk, October, 1980, University of California, Berkeley, California.

(Sheet 4 of 4)

Appendix C List of lakes where aeration has been used to manage cyanobacteria blooms – From Visser et al. (2016)

Table 1 Summary of characteristics and effects of artificial mixing in different lakes and reservoirs

Lake	Surface area (km²)	Max depth (m)	Mean depth (m)	Mixing device	Continuous or intermittent	Effect on stratification	Effect on cyanos	Other treatments	Cyanobacteria species	Reference
Lake Brooker, USA	0.105	5.2	4.0	Aeration	Continuous	Destratified	–			Cowell et al. (1987)
Fischkaltersee, Germany	0.034	11.2	5.7	Aeration	Continuous		–		*Oscillatoria redekei, O. rubescens*	Steinberg (1983)
Fischkaltersee, Germany	0.034	11.2	5.7	Aeration	Intermittent	Incomplete			*Oscillatoria redekei*	Steinberg and Zimmermann (1988)
Solomon Dam, Australia	0.069	13.4		Aeration	Intermittent (8 h d^{-1})	Incomplete	–		*Cylindrospermopsis, Anabaena*	Hawkins and Griffith (1993)
Nieuwe Meer, The Netherlands	1.30	30	18	Aeration	Continuous Intermittent	Destratified	– +		*Microcystis*	Visser et al. (1996b), Jöhnk et al. (2008)
East Sidney Lake, USA	0.85	15.7	4.9	Aeration	Continuous	Incomplete	0		*Aphanizomenon flos-aquae*	Barbiero et al. (1996)
Chaffey Reservoir, Australia	5.42	28	11.4	Aeration	Continuous	Incomplete	0		*Anabaena*	Sherman et al. (2000)
Lake Dalbang, South Korea	5.29	35.7	15.8	Aeration	Intermittent	Destratified	–		*Anabaena* and *Microcystis*	Heo and Kim (2004)
North Pine Dam, Australia	21.80	35	10	Diffuser	Continuous	Incomplete	–/0		*Cylindrospermopsis, Planktolyngbya, Aphanocapsa*-group	Antenucci et al. (2005), Burford and O'Donohue (2006)
Lake Yogo, Japan	1.70	13.5	7.4	Aeration	Continuous		0/+	Pumping water from Lake Biwa	*Microcystis*	Tsukada et al. (2006)
Sheldon Lake, USA	0.061	<1	<1	Aeration	Intermittent (only daily)	Incomplete	0	Dredging and addition fish stock	*Microcystis spp.*	Oberholster et al. (2006)
Bleiloch reservoir, Germany	9.20	55		Aeration	Continuous	Incomplete	–		*Microcystis*	Becker et al. (2006)
Ford Lake, USA	4.0	11	4.3	Water flow	Intermittent		–	Reduced P loading		Lehman (2014)

General distribution and characteristics of active faults and folds in the Queenstown Lakes and Central Otago districts, Otago

DJA Barrell

GNS Science Consultancy Report 2018/207
March 2019

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Date that GNS Science can use associated data: February 2019

BIBLIOGRAPHIC REFERENCE

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EXECUTIVE SUMMARY

This report presents a general outline of the locations and character of active geological faults and folds in the Queenstown Lakes and Central Otago districts. The work described in this report is based on a desktop review of information from regional-scale geological mapping, and from more detailed published or open-file geological studies relevant to understanding active faults in the two districts. This project involved the compilation of a Geographic Information System (GIS) dataset that gives the locations of active faults and folds delineated in the two districts. The interpretation and geographic positioning of the fault and folds was aided, where available, by topographic information from airborne lidar scans (laser radar), and from satellite, aerial or ground-based photographic archives.

A fault is a fracture within the rock of the Earth's crust, along which movement has occurred. Commonly, strain builds up in the rock of the Earth's crust and is released suddenly by a slip event (rupture) on a fault, causing an earthquake. Folds represent bending or buckling of rock and are usually associated with an underlying fault. A fault or fold is termed 'active' where it has moved in the geologically–recent past, particularly where the movement has been sufficiently large to have emerged at the ground surface, forming offset and breakage of the ground (fault), or buckling or tilting of the ground (fold). Old landforms of uniform character, such as river terraces formed during the last ice age which ended about 18,000 years ago, are well suited for revealing the presence of active faults or folds, because they may be old enough to have experienced several rupture events and display large offsets or buckles. In areas where the land surface is younger than the most recent fault or fold movements, the presence and location of any active faults or folds may be 'concealed' from view beneath the landform. In this way, active faults or folds are most easily recognised where the landforms are old (e.g. ice-age river terraces), but much more difficult to recognise in areas where landforms are young (e.g. river floodplains).

Commonly, an active fault reaches the ground via a zone of splintering, which in some cases may be as much as several kilometres wide. Individual splinters (strands) can be expressed as fault offsets of the ground surface, as ground-surface folds, and commonly as a mixture of both. Although some individual strands have been named separately, the GIS dataset applies an overall specific name to each active fault structure, whose movements at depth have produced an array of ground-surface fault and/or fold strands. Many of the faults have been named previously, and those names are used here unless reasons exist for applying a different name. As described in this report, a total of 48 named active, possibly active or potentially active faults have been delineated at the ground surface in the Queenstown Lakes and Central Otago districts.

The levels of certainty in recognising an active fault and fold, and their clarity of expression at the ground surface, are included in the GIS dataset. The report contains a tabulation of estimated average slip rate and surface-deformation recurrence interval for each fault, in relation to Ministry for the Environment guidelines on planning for development of land on or close to active faults. Also highlighted in the report is increasing recognition that in the Otago region, many of the faults undergo long periods without movement, which makes it difficult to estimate their level of activity. This difficulty is accommodated by the addition of a classification category of 'potentially active', to encompass faults that despite showing no indications of geologically-recent activity, have characteristics that mean the possibility of future activity should not be ruled out.

Potential hazards associated with active faults include: (i) sudden ground-surface offset or buckling at the fault which may result, for example, in the destruction or tilting of buildings in the immediate vicinity; (ii) strong ground shaking from locally-centred large earthquakes, and; (iii) related earthquake-induced effects such as landsliding and liquefaction in areas susceptible to such processes. No large, ground-rupturing, earthquakes have been centred within the Queenstown Lakes or Central Otago districts since European settlement in the mid-1800s. However, the nature of hazards posed by active faults was well demonstrated during the 2010 Darfield and 2016 Kaikōura earthquakes, both of which caused ground-surface rupture and land shift along faults and the effects of severe ground shaking were experienced across wide areas. The landform record shows definitive evidence for prehistoric fault deformation having occurred at various locations in the Queenstown Lakes and Central Otago districts. This highlights that active fault or fold features in the Otago region should be assessed for their hazard potential.

The GIS map of active faults and folds in the Queenstown Lakes and Central Otago districts is derived from regional (~1:250,000) scale geological information, and is of a generalised nature, with details omitted to aid the clarity of presentation. Information in this report and in the companion GIS dataset highlights areas potentially affected by active fault or fold hazards and the information is intended to help the targeting of any future active fault investigations that may be deemed necessary. This report provides the most up-to-date information available on the locations and nature of active faults and folds in the Queenstown Lakes and Central Otago districts. It is intended to create general awareness of the existence of the potential hazards but the level of detail in the GIS dataset is not sufficient by itself for use in site-specific zoning to avoid fault-generated ground deformation hazards.

1.0 INTRODUCTION

1.1 Background

The geologically-active nature of New Zealand reflects our position astride the active boundary between two large slabs (plates) of the Earth's crust (Figure 1.1). The forces involved in plate movement (tectonic forces) are immense and cause the rock of the Earth's crust to buckle (fold) and fracture (fault) in the general vicinity of the boundary between the plates. The plate boundary through the South Island is marked, at the ground surface, by a sideways tear, the Alpine Fault, and in the northern South Island, by a companion set of tears, the Marlborough Fault System. Although these large faults accommodate most of the plate motion, the remainder is distributed over a wider zone across much of the South Island. The Queenstown Lakes and Central Otago districts lie within this wider zone of tectonic deformation.

Movement on the Alpine Fault is predominantly sideways, with the western side of the fault moving northeast, and the eastern side moving southwest as well as a little bit upwards, which has produced the Southern Alps. The technical term for a sideways-moving fault is 'strike-slip', while a fault where the movement is mostly up-down is called 'dip-slip'. In the south-eastern South Island, including the Queenstown Lakes and Central Otago districts, the relatively small proportion of the plate movement not accommodated on the Alpine Fault is distributed on a series of predominantly dip-slip faults, that are the focus of this report.

Although the movement along the plate boundary is continuous over geological time and can be measured by ground and satellite (GPS) surveying, rock of the Earth's crust is remarkably elastic and can accommodate a lot of bending before letting go and breaking suddenly (rupturing) along a fault, causing an earthquake. On large faults, the break may be big, and extend up to the Earth's surface, causing sudden offset and breakage (faulting), and/or buckling and warping (folding), of the ground surface, accompanied by a large earthquake. The 2010 Darfield and 2016 Kaikōura earthquakes provided good examples of the nature and effects of large, ground-surface-rupturing earthquakes on geological faults (e.g. Barrell et al. 2011; Litchfield et al. 2018) (Figure 1.2).

In favourable settings, prehistoric fault offsets and/or fold buckles of the ground may be preserved by way of distinctive landforms, and these landforms allow us to identify the locations of active faults and folds. In New Zealand, an active fault is commonly defined as a fault that has undergone at least one ground-deforming rupture within the last 125,000 years or at least two ground-deforming ruptures within the last 500,000 years. An active fold may be defined as a fold that has deformed ground surfaces or near-surface deposits within the last 500,000 years. Unfortunately, there are few reliable 'clocks' in the natural landscape (i.e., deposits or landforms with a known age) and, for practical purposes, it is common to identify as active any fault or fold that can be shown to have offset or deformed the ground surface, or any unconsolidated near-surface geological deposits (Figures 1.2, 1.3). This approach for identifying active faults or folds is used on most geological maps published in New Zealand and is followed in this report. It is also common to assess the significance of hazards associated with an active fault or fold by estimating how often, on average, it has undergone a ground-deforming rupture or deformation event (recurrence interval). The average recurrence interval is a primary consideration in Ministry for the Environment guidelines for the planning of land-use or development near active faults (Kerr et al. 2003; referred to henceforth as the MfE active fault guidelines).

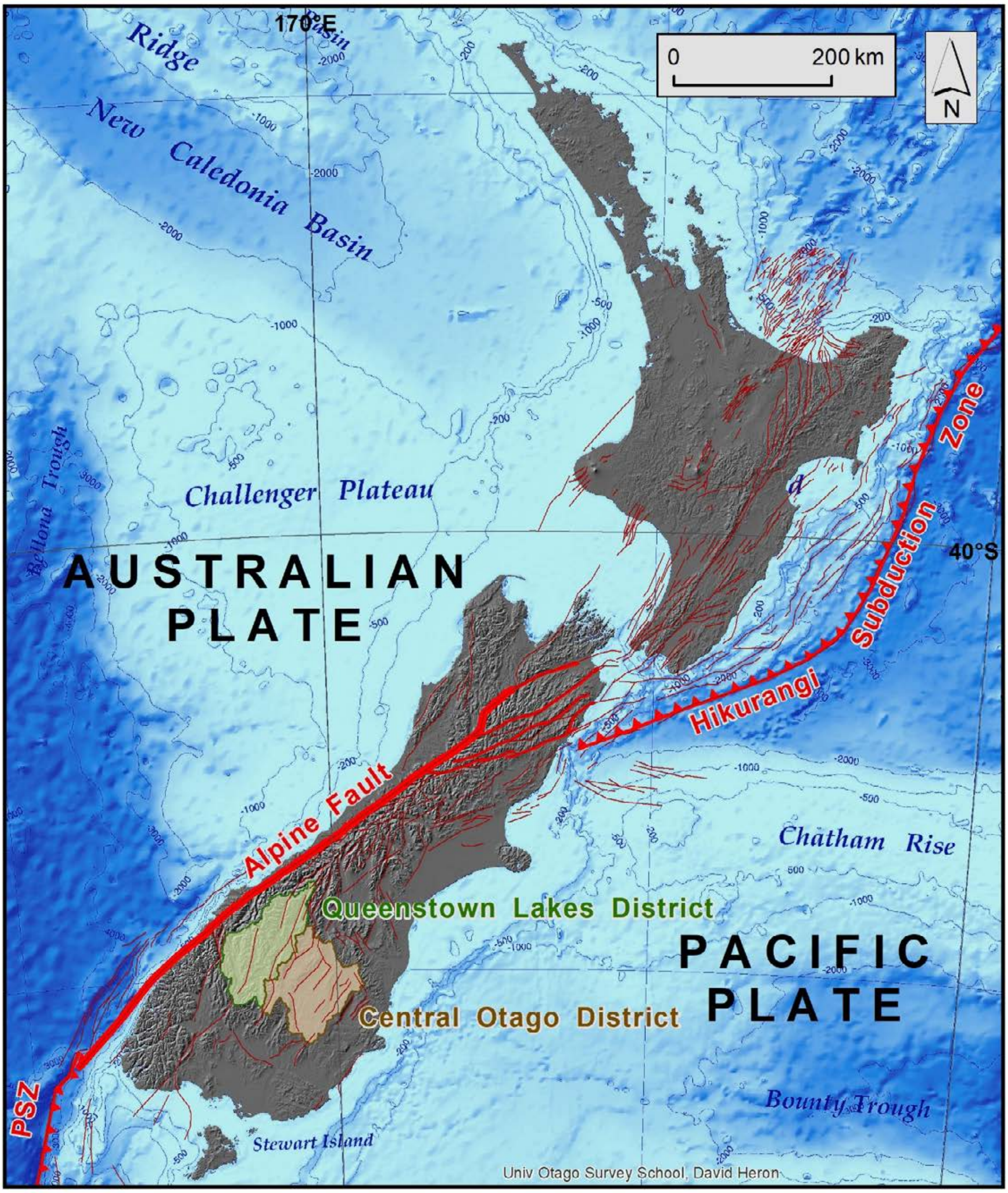

Figure 1.1 The tectonic setting of the Queenstown Lakes and Central Otago districts. The junction between the Australian and Pacific plates of the Earth's crust passes through New Zealand. The Pacific Plate pushes westward against, and under, the Australian Plate at the Hikurangi Subduction Zone, while at the Puysegur Subduction Zone (PSZ), the Australian Plate is being pushed down alongside the southwestern South Island. The Alpine Fault (thick red line) and the Marlborough Fault System (medium thickness red lines) transfer most of the plate motion between the two subduction zones, with the remainder accommodated across a wider zone of deformation marked by other active faults (thin dark red lines; from Litchfield et al. 2014). The offshore image is the New Zealand Continent map (GNS Science) showing shallower water in light blue and deeper water in darker blue. Bathymetric contours are in metres below sea level.

In the south-eastern South Island, including the Otago region, there are indications that many of the faults undergo episodes of several successive ruptures, interspersed with periods without rupture (e.g. Beanland and Berryman 1989; Litchfield and Norris 2000). This part of New Zealand also lies somewhat away from the locus of plate boundary deformation, and rates of strain on the Earth's crust are relatively slow. Recent research has shown that only half of the large historic earthquakes in New Zealand have occurred on faults that would have been recognised as 'active' under today's criteria (Nicol et al. 2016). A recent research study in coastal Otago advocated the consideration, in a seismic hazard context, of faults that have been active within the past few million years (Villamor et al. 2018). Accordingly, the present project has incorporated all faults that show substantial offset of the Otago peneplain, a prominent landscape feature that is the remains of an ancient land surface that was, originally, nearly flat and low-lying (see Section 3.1 for additional information).

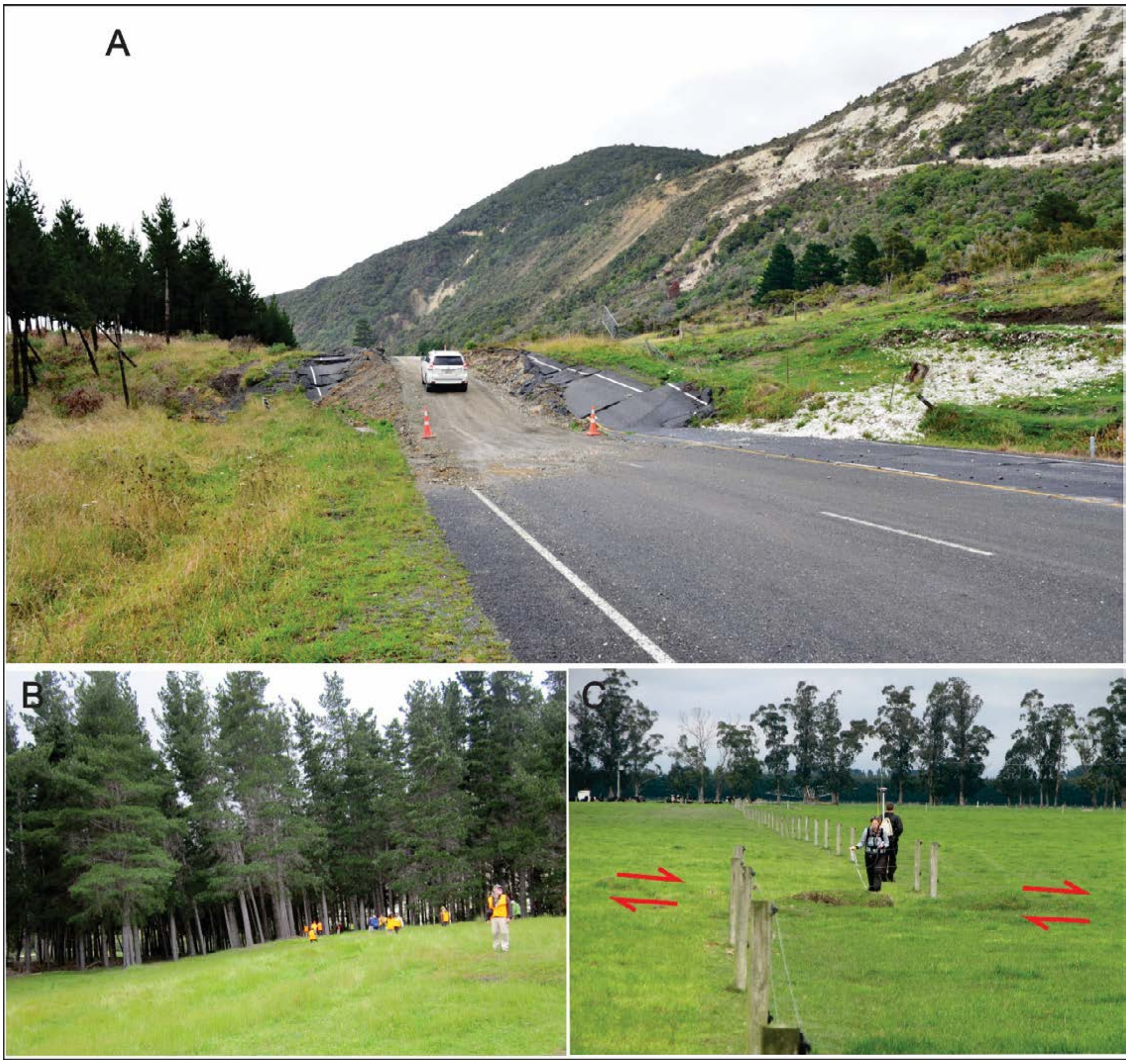

Figure 1.2 Illustrations of recent historical fault rupture deformation of the ground surface in New Zealand. **A**: Offset of State Highway 1 across the Papatea Fault, north of Kaikōura, that occurred during the 2016 Kaikōura Earthquake. The movement included several metres of upthrow as well as several metres of sideways shift to the left. Photo: GNS Science VML ID: 210453; D.B. Townsend. **B**: Monoclinal fold associated with the Papatea Fault rupture during the Kaikōura Earthquake, illustrated well by the tilting of the pine trees. The ground here was flat prior to the earthquake. Photo: GNS Science; D.J.A. Barrell. **C**: A fence offset sideways by ~4.5 m of strike-slip rupture on the Greendale Fault during the 2010 Darfield Earthquake. Photo: GNS Science VML ID: 137457; N. J. Litchfield. Half-arrows either side of the fault indicate the direction of movement, which here involved a shift to the right.

There are many active geological faults and associated folds recognised in the Otago region. As part of ongoing improvements in the recognition and mitigation of natural hazards, Otago Regional Council engaged the Institute of Geological and Nuclear Sciences Limited

(GNS Science) to summarise the state of knowledge regarding active faults in the Queenstown Lakes and Central Otago districts. This report presents that summary and is a companion to a similar report that addresses the Waitaki District (Barrell 2016).

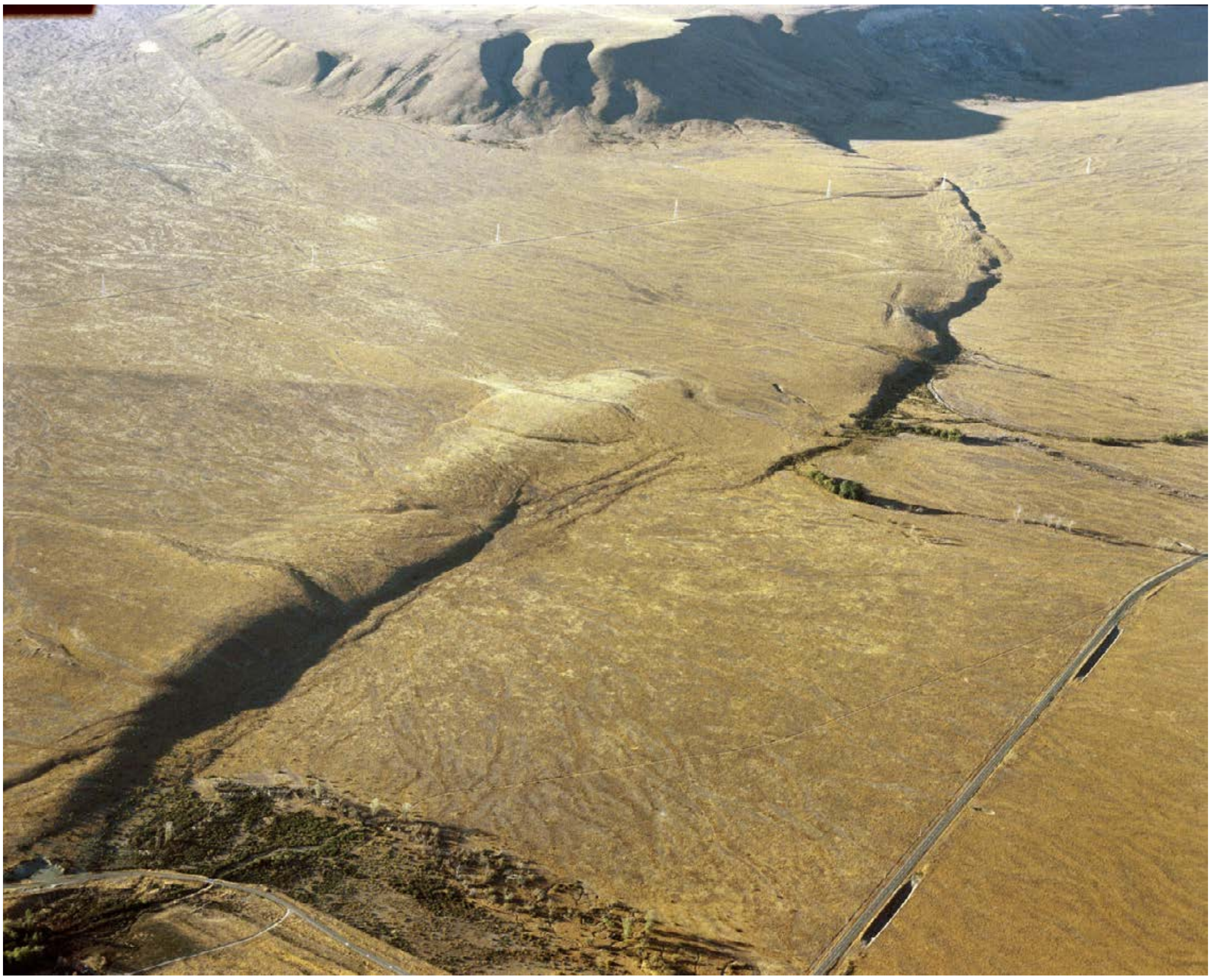

Figure 1.3 A northward oblique aerial view of ground-surface deformation across the Ostler Fault Zone, in the Waitaki District of Canterbury, about 12 km southwest of Twizel.The fault zone runs from lower left to upper right and has offset and buckled a ~22,000-year-old glacial meltwater outwash plain, with well-preserved relict braided channels (Putnam et al. 2013). This location is one of the best expressed examples of fault deformation in New Zealand, because it is entirely across old landforms. This view shows complicated elements of main and subsidiary fault offsets and folds, across a zone that is several hundreds of metres wide. All these elements form part of a single entity, the Ostler Fault Zone. This figure is taken from Barrell (2016), where a more detailed description of the features in this view is provided. Photo: GNS Science, CN576/B and VML ID: 5151. D.L Homer, taken 1995.

1.2 Scope and Purpose

This project comprised an office-based review of existing information, focused on delineating the locations and evaluating the characteristics of known or suspected active faults and folds in the Queenstown Lakes and Central Otago districts. The main product of the project is a Geographic Information System (GIS) map dataset that includes information on the certainty of identification of an active fault or fold feature, and the clarity of its topographic expression at the ground surface. The report includes tabulated information on estimated degree of activity, expressed as average slip rate and earthquake recurrence interval, for each fault (see Section 5). Also indicated are relationships between information in this dataset and the MfE active fault guidelines (Kerr et al. 2003) for fault complexity categories (well defined, distributed, or uncertain) and estimated recurrence interval classes.

The main aim of the work is to provide datasets that highlight locations in the Queenstown Lakes and Central Otago districts where active faulting may be a hazard to look for and be aware of. The information in this report is intended to assist local authorities in delineating the general areas of the Queenstown Lakes and Central Otago districts that are potentially subject to active fault and fold hazards, particularly those hazards related to ground-surface fault rupture and/or folding deformation.

The precision of regional-scale fault mapping is not sufficiently accurate for site-specific use (e.g. at property boundary scales), and specific hazard zonation was outside the scope of the project. The dataset presented here is not intended to be used directly for hazard zoning, but rather to serve as a tool for hazard zoning prioritisation. Thus, a goal of the dataset is to highlight areas where more detailed mapping and site-specific fault avoidance zonation should be considered if substantial building or other infrastructural development is proposed.

2.0 INFORMATION SOURCES

At least four different nationwide datasets in New Zealand provide information on active faults. One is the GNS Science 1:250,000 scale QMAP (Quarter-Million scale map) regional geological map digital database (Heron 2014), which provides, via mapped lines, the general locations and geological characteristics of active faults and folds. Another is the publicly-available New Zealand Active Faults Database (NZAFD; see reference list and also Langridge et al. 2016), which represents the locations of active faults at a nominal scale of 1:250,000, and indicates the general degree of fault activity. In the south-eastern South Island, the NZAFD is based mainly on the QMAP dataset. A third dataset is a national-scale model of active faults (New Zealand Active Fault Model; NZAFM), described by Litchfield et al. (2013, 2014). The NZAFM shows highly generalised locations of active faults, at a nominal scale of about 1:1,000,000. The main purpose of the NZAFM is to quantify the kinematics of near-surface permanent deformation across New Zealand resulting from plate motion. A fourth dataset is the New Zealand National Seismic Hazard Model (NSHM; Stirling et al. 2012), which employs highly generalised locations and characteristics of active faults as earthquake sources for estimating probabilities of levels of earthquake ground-shaking at locations throughout New Zealand. The NSHM linework depicting the locations of active fault earthquake sources is approximately the same as in the NZAFM. A fifth type of active fault dataset comprises information of district or regional-extent held by territorial or regional governmental authorities. An example is Environment Canterbury's 1:250,000-scale active fault datasets, described by Barrell et al. (2015). The active fault dataset described in the present report is of the fifth type.

The five types of active fault datasets have differing purposes, and some are more locationally-accurate at different scales. Most of the datasets have differences in regard to fault locations and extents. The locations of active faults represented geographically in the NZAFM and NSHM are much less detailed and less accurate than in the other datasets.

For the present project, the QMAP dataset was the primary information source, because it encompasses active faults and folds, whereas the NZAFD dataset is confined to active faults. The nationwide QMAP digital dataset (Heron 2014) is derived from a sheet-by-sheet series of published geological maps, represented in the Queenstown Lakes and Central Otago districts by the Wakatipu map (Turnbull 2000; westernmost parts of both districts), Haast map (Rattenbury et al. 2010; headwaters of the Wanaka and Hawea catchments), Murihiku map (Turnbull and Allibone 2003; southernmost part of Central Otago District) and the Waitaki map (Forsyth 2001; eastern part of Central Otago). Appendix 1 presents a brief description of the GIS structure of the active fault and fold dataset that forms a companion to this report. Additions and refinements to the QMAP input dataset are described in Appendix 2 of this report. Some more detailed studies have contributed to the information provided in this report and the companion digital dataset. Where relevant, those studies are discussed in Appendix 2, along with general commentary on aspects of the existing information and explanations of the interpretations adopted in this report for each active fault. The interpretation and geographic positioning of the fault and fold features as aided, where available, by topographic information from airborne lidar scans (laser radar), and by information from satellite, aerial or ground-based photographic archives, including Street View accessible through Google internet services.

Although the work described in this report did not include site investigations or field inspections, the writer has extensive experience of the assessment area, arising from previous geological investigations and inspections over the past 25 years.

3.0 GEOLOGICAL OVERVIEW

3.1 Rocks and Landforms

In the south-eastern South Island, including the Queenstown Lakes and Central Otago districts, the oldest underlying rock (basement rock) consists mainly of hard sedimentary rock ('greywacke') and its metamorphosed equivalent (schist). These ancient rocks, of Permian to Jurassic age (between 300 and 145 million years old) were buried by a blanket of younger sedimentary rocks (cover rocks) including coal measures, quartz sands, mudstones, limestones and gravelly conglomerates, and some volcanic rocks, ranging in age from ~110 million years ago (middle of the Cretaceous Period) to about 2.5 million years ago. Collectively, the basement and cover rocks constitute what may be called 'bedrock'. The cover rocks provide useful reference markers for identifying faults and folds. The well-developed sedimentary layering readily shows offsets due to faulting, while the tilting of these layers may reveal the effects of folding. In much of the hill to mountain terrain of Otago, uplift and erosion has stripped away large areas of the cover rock blanket, exposing the underlying basement rock that forms the main ranges. In many places, remnants of the cover rocks lie preserved on the downthrown, low-lying, sides of major faults. The cover rocks are more widely preserved in eastern Otago.

A valuable reference landform in Otago is the exhumed boundary between the basement and cover rocks (Otago peneplain) that is extensively preserved across Central Otago. Part of a widespread ancient land surface (Waipounamu Erosion Surface; Landis et al. 2008), the Otago peneplain was originally nearly flat and of gentle relief but following the development and propagation of the Australia-Pacific plate boundary through New Zealand about 20 million years ago, the Otago peneplain has been progressively offset and buckled by fault movement and fold growth associated with plate boundary deformation. Across the region, in many cases it is not clear when fault movement began. The best indications come from two faults that strike north-northwest. On the Blue Lake Fault, uplift was underway in the Middle Miocene epoch, sometime between 11 and 19 million years ago (Henne et al. 2011), while uplift and exhumation of the peneplain had occurred on the northeast side of the Waihemo Fault System by ~15 million years ago, shown by the dating of volcanic rocks that rest directly on basement rock (Coombs et al. 2008). General indications are that the northeast-striking faults, such as the Dunstan Fault Zone, developed after the north-northwest striking faults, because at least some of the latter faults have been deformed or offset by movement on the northeast-striking faults. It is suspected that most of the movement of the northeast-striking faults, with formation of the basin and range relief of Central Otago, has occurred in the past few million years, though evidence for this is patchy, and uncertainties remain (Villamor et al. 2018).

The youngest deposits of the districts are unconsolidated sediments whose nature and distributions are primarily a consequence of tectonic uplift and erosion of the mountain ranges and fluctuating climatic conditions during the latter half of the Quaternary Period (from about 1 million years ago to the present day). Uplift and erosion produced voluminous sediment that has been laid down in the basins, valleys and plains on top of the basement or cover rocks. A major feature of the Quaternary Period has been a cycle of large-scale natural shifts in global climate, with periods of generally cool conditions (glaciations, or 'ice ages') separated by periods of warmer climate ('interglaciations'), such as that existing today. Ice-age glaciers that formed in the Southern Alps flowed down the main valleys of western Otago. Lakes Wakatipu, Wanaka and Hawea occupy troughs formed at the downstream ends of those glaciers. The last glaciation ended about 18,000 years ago, after which ice rapidly retreated into the mountains (e.g. Barrell et al. 2013). Wanaka and Hawea townships are built on terminal moraines formed by glaciers.

3.2 Recognition of Active Faults and Folds

The key evidence for recognising active faults or folds is the offset or buckling of landforms or young geological deposits. This is seen most clearly on old river terraces or river plains, where the original channel and bar patterns of the former riverbed are 'fossil' landforms dating from when the river last flowed at that location. Topographic steps or rises that run across such river-formed features could not have been created by the river, and therefore result from subsequent deformation of the ground. If factors such as landsliding can be ruled out, these topographic features may confidently be attributed to fault or fold movements (e.g. Figure 1.2, Figure 1.3 & Figure 3.1).

In this report, and the companion GIS dataset, a distinction is made between the style of active deformation, whether predominantly by fault offset of the ground (fault scarp), or by folding (buckles, tilts or flexures) of the ground. Folds are subdivided into 'one-sided folds', or monoclines, and 'two-sided folds', either up-folds (anticlines) or down-folds (synclines) (Figure 3.1). Monocline is the only class of active fold included in the companion GIS dataset.

Two end-members of fault movement type are shown in Figure 3.1; a dip-slip fault which has up-down movement, and a strike-slip fault which has horizontal (sideways) movement. In practice it is not uncommon for a fault to display a combination of both types of movement; such faults are called 'oblique-slip' and have movement that is partly up-down and partly sideways (see Figure 1.2A). Most dip-slip fault planes are inclined (i.e. are not vertical), and there are two basic types of movement. Where the rock on the upper side of the inclined dip-slip fault shifts upwards along the fault, it is called a reverse fault, and results from compressional forces. Where the rock on the upper side of the inclined dip-slip fault shifts downwards along the fault, it is called a normal fault, and results from tensional forces.

The fault and fold styles illustrated in Figure 3.1 are idealised examples. They do not show the range of variations and complexity that may exist (e.g. see Figure 1.3). To find such simple examples in nature as displayed in Figure 3.1 would be an exception rather than a rule. The steepness of inclination (dip) of the fault may vary considerably (Figure 3.1). Where a fault has a gentle dip (i.e. is closer to horizontal than vertical), each successive movement commonly results in the upthrown side 'bulldozing' outward, over-riding the ground and encroaching over anything in its immediate vicinity. The destroyed building in the upper diagram of the lower panel of Figure 3.1 attempts to convey an impression of a bulldozer effect.

There is rarely an exact distinction between a fault and a monocline at the ground surface. Fault scarps are commonly associated with some buckling of the ground and near-surface layers, particularly on the upthrown side of a reverse fault scarp (Figure 3.1; also see Figure 1.3). In some cases, part of the fault movement may have broken out on a series of smaller subsidiary faults near the main fault. In the case of monoclines or anticlines, subsidiary faults may also occur over buried faults that underlie these folds, resulting in small ground surface offsets. An important message is that on any active fault or fold, there commonly are elements of both faulting and folding close to the ground surface (Figure 3.2). The amount of deformation due to faulting, relative to the amount expressed as folding, may vary over short distances (Figure 1.3).

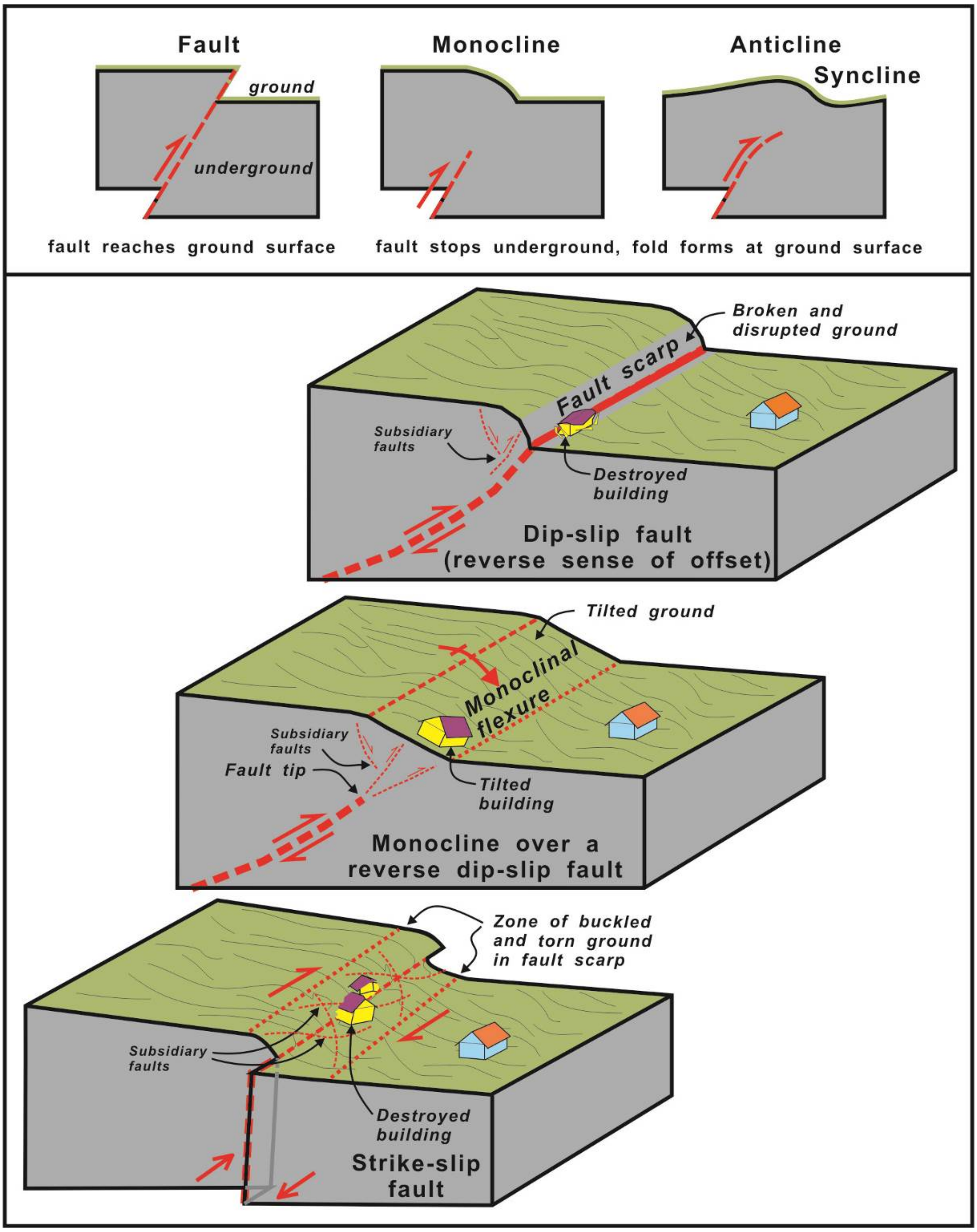

Figure 3.1 Diagrams illustrating styles of active faults and folds. The diagrams show general concepts rather than actual details and are not drawn to an exact scale. Upper panel: Cross-section (vertical slice) diagrams illustrating an active fault, active monocline and active anticline and syncline. Most folds are, as shown here, thought to have formed over faults whose ruptures have not made it all the way to the ground surface. Lower panel: perspective block diagrams showing typical ground-surface expressions of faults and monoclines. The diagrams include hypothetical examples of effects on buildings of a fault rupture or monocline growth event.

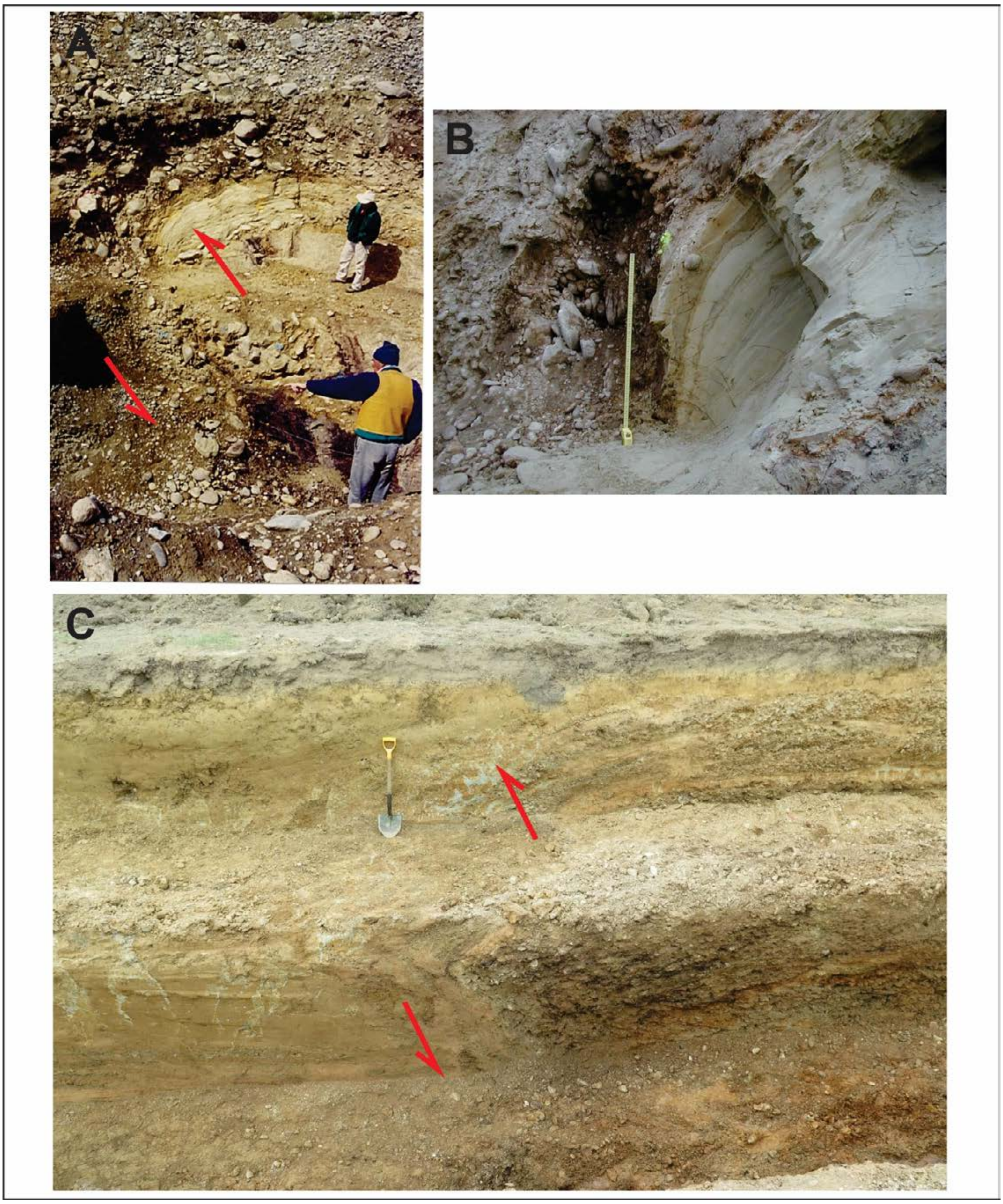

Figure 3.2 Illustrations of faults exposed in investigation trenches. Red half-arrows indicate the relative sense of fault displacement. **A & B**: The Waitangi Fault exposed in 1999 in a trench 700 m downstream of Aviemore Dam, Waitaki District of Canterbury (Barrell et al. 2009). A: the fault runs upper left to lower right and a bed of yellow sand has been pushed up and buckled over against river gravel to the left. B: detail of the fault contact after further excavation and cleaning. The yellow tape measure (extended 1 m) provides scale. Layering in the sand has been dragged down nearly vertical against the fault, while elongate river stones immediately left of the sand bed have been dragged up into vertical alignments. **C**: A view of the wall of a trench excavated across the Titri Fault near Milton in coastal Otago, Clutha District, in 2016. Yellow-brown stream gravel (right of centre) has been thrust up and buckled over against yellow-brown silt (loess) to the left. Detailed examination and mapping of the materials, and dating of the sediments, provides evidence for at least two separate rupture events here, within the past ~38,000 years. The 1-m long shovel illustrates scale. Photos: GNS Science, D.J.A. Barrell.

In practice, where the zone of ground deformation is quite narrow, it is interpreted as a fault, and where it is broad, it is interpreted as a fold (e.g. monocline) (see Figure 3.1). The only way to determine the accuracy of this interpretation is to excavate a trench across the deformed zone to see whether, or to what extents, the near-surface deposits have been offset, or merely folded (Figure 3.2). Sometimes, natural exposures in stream banks provide the necessary information. This highlights a key issue; without detailed work involving examination of what lies within the first few metres beneath the ground surface, we can at best only make informed guesses about the exact locations, form and likely future consequences of fault or fold activity.

It is common to find some surprises as a result of more detailed geological examination of active faults or folds. For example, a broad fault scarp, that might be expected to include a considerable amount of folding may, upon excavation, turn out to have a well-defined fault offset with very little folding. This could occur because after a surface deformation event, natural landscape processes tend to smooth-over the effects. For instance, a steep face of bare broken ground in a fault scarp will settle, subside, and compact due to factors such as rainstorms, frost heave, and soil formation. Over longer periods, wind-blown dust (loess) emanating from river beds tends to accumulate most thickly in hollows and depressions, further smoothing any irregularities produced by fault offset of the ground.

An important message is that while landforms provide important clues as to the general location of active faults or folds, many details of these features which may be relevant to land-use, development and hazard mitigation cannot be obtained without more detailed site-specific investigations (e.g. Figure 3.2).

3.3 Seismicity

The Otago region has experienced very little locally-centred seismicity since European settlement. Most of the earthquakes that have been felt in Otago since European settlement have been centred outside the region, mainly originating in the Fiordland area, close to or on the plate boundary. This pattern is illustrated by the seismicity of the past 30 years (Figure 3.3).

The moment-magnitude 5.8 Matukituki Earthquake on 4th May 2015[1] was the largest earthquake centred within Otago since European settlement. Originating at shallow depth (~9 km) and centred about 30 km northwest of Wanaka, the earthquake was felt strongly in the Wanaka area, but caused only minor damage (Cox et al. 2015). The earthquake was studied using the recorded seismic waveforms and aftershock distributions (Warren-Smith et al. 2017). It was concluded that the rupture occurred on a steeply north-northwest dipping (~70°) fault plane, aligned almost east-west (strike azimuth of 70° east of north). The sector of the fault plane that ruptured lay between 7 and 15 km underground, and was about 5 km long. The movement was strike-slip, with a right-lateral (dextral) sense. The orientation of the subsurface fault that ruptured does not correspond to any identified surface fault, active or inactive. The Matukituki Earthquake highlights four points. The first is that a fault rupture producing an earthquake of close to magnitude 6 is, in this region, well short of being large enough to be able to break up to the ground surface. Second is that the orientation and sense of movement was unexpected, in regard to the much larger known and suspected active faults expressed at the ground surface in Otago. Third, and underscored by the unexpected patterns

[1] Moment magnitude (M_W) is a measure of the total seismic energy released in an earthquake and is usually calculated from low-frequency waveforms recorded on seismographs. It is a better measure of the size of large earthquakes than the Richter, or local, magnitude (M_L), which is based on the largest size of ground motions recorded on seismographs. Richter magnitude is difficult to estimate accurately for strong earthquakes, because the seismographs have difficulty recording the full amplitude of very large ground motions.

of fault movement and deformation observed during the Canterbury earthquake sequence of 2010–2011 and the Kaikōura Earthquake of 2016, is that there is still much to learn about earthquake processes in New Zealand. Finally, the Matukituki Earthquake shows that despite the low historical seismicity, Otago is undoubtedly subject to earthquake activity.

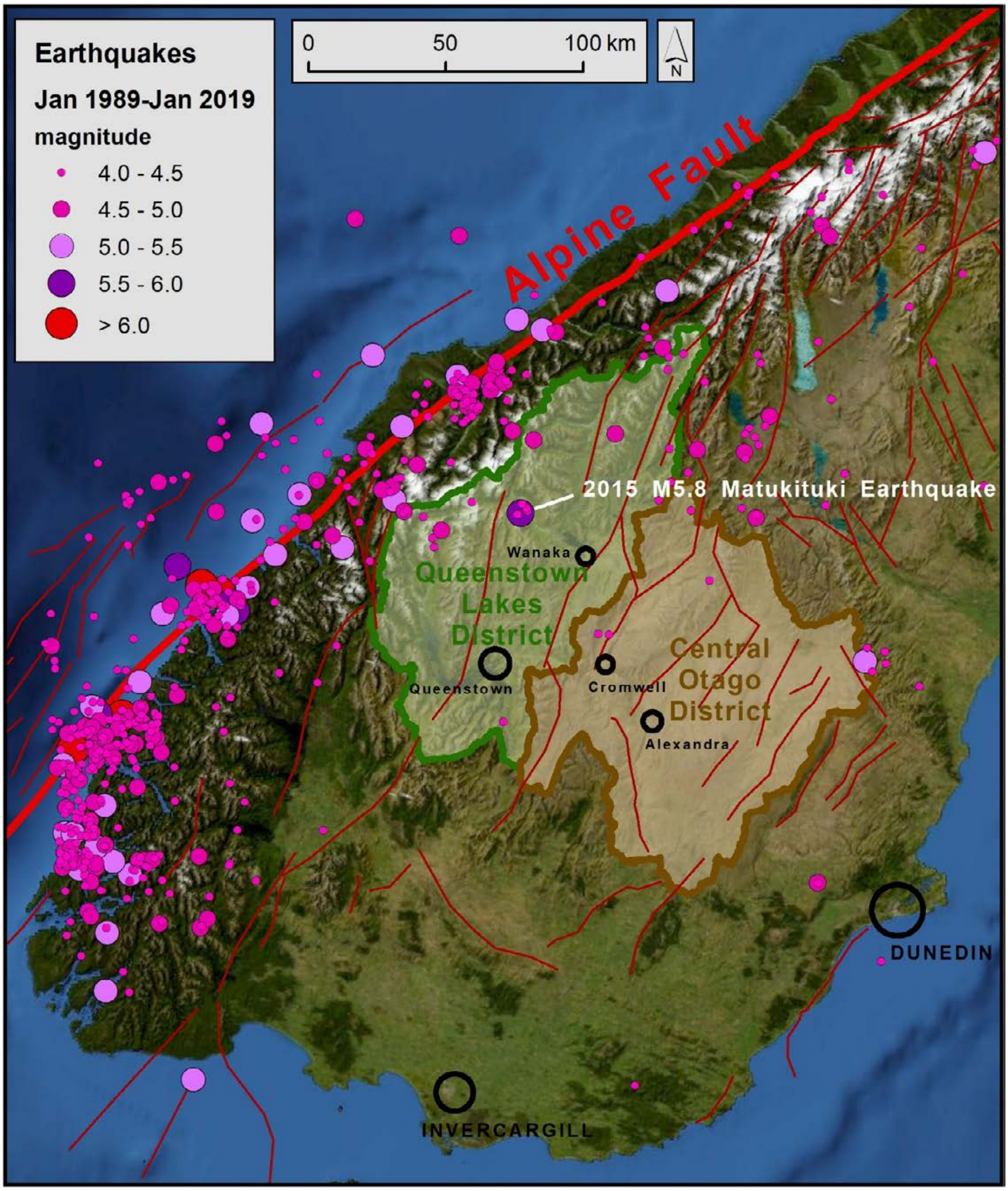

Figure 3.3 Recorded earthquakes in the southern South Island over the past 30 years (1 January 1989–1 January 2019). Earthquake locations are from the GeoNet earthquake catalogue (www.geonet.org.nz). The red lines are active faults as depicted in the New Zealand Active Fault Model (Litchfield et al. 2014). The background image is the NASA 'Blue marble' global base map.

4.0 CLASSIFICATION OF ACTIVE FAULTS AND FOLDS

4.1 Descriptive Classification

The original information on the active faults and folds of the Queenstown Lakes and Central Otago districts was extracted from the QMAP digital dataset (Heron 2014). The QMAP was compiled for presentation at 1:250,000-scale, where 1 cm on a map represents 2.5 km on the ground. For this report, the existing mapping has been re-examined and additions, and some refinements, have been made to the mapping of active faults and folds. These modifications include addition of some previously unmapped features and the reclassification of some existing mapped features. Appendix 2 provides commentary on the mapping and interpretations of the active faults and folds.

Following the approach used in the QMAP digital data structure, faults and folds are separate entities (feature classes) within the GIS dataset. Three data fields (also known as 'attribute' fields) have been added to the active faults and folds feature classes (see Appendix 1 and Table 5.1). The names of these fields are:

- ORC_name (local names for the mapped fault/fold feature; see below)
- Certainty (likelihood that the mapped feature is an active fault/fold; see below)
- Surf_form ('Surface form', indicating how well defined is the surface expression of the mapped feature; see below)

The GIS dataset provides the following information: (i) whether a feature is a fault or a fold; (ii) the level of the certainty with which each feature is recognized as active (definite, likely or possible) or as potentially active, and; (iii) an interpretation of the surface distinctiveness of each feature at the ground surface (well expressed, moderately expressed, not expressed, unknown). Commonly, a single active fault at depth is expressed at the ground surface as a zone of splintering. An individual line of splinters (fault strand) may comprise fault offsets of the ground surface (fault scarps) or ground-surface folds (fold scarps), and commonly a mixture of both. A fault zone may include several lines (traces) of semi-parallel strands and a fault zone can in some cases be several kilometres wide. Some strands have previously been named separately, and this name is retained in the GIS dataset, but the various strands that comprise an active fault are grouped under a common name (ORC_name). This is done to highlight that, collectively, the strands are regarded as part of a single active fault structure, whose movements at depth have produced an array of ground-surface fault and/or fold deformation.

Many of the active faults have been named previously, and those names are used in this dataset unless reasons exist for applying a different name, as explained in Appendix 2. The QMAP dataset only included names for faults or folds where a name had previously been published, and this is the main reason for adding an attribute that assigns a local name to all mapped features (ORC_name). By and large the local name corresponds to any previously used name (in QMAP or the NZAFD). In places where no name has previously been given to an active fault/fold feature, the ORC_name has been taken from a nearby named topographic feature or locality. Where names are newly proposed in this report, and thus regarded as informal, the term fault or fold is in lower case type (e.g. Cluden fault zone). For previously published names, a capital 'F' is used. The basis of all new names is explained in Appendix 2. In this dataset, the name of a fault includes the term 'zone' where it contains individually-named components, comprises distinct, approximately parallel multiple strands, or if the term 'fault zone' has been used extensively in previous work on the fault. In this and subsequent sections of the report, the term 'fault' is used to encompass faults as well as any associated folds, unless in specific reference to a fold feature. Any references to individual fault or fold strands are identified as such, and the term fault, or fault zone, pertains to an overall active fault structure.

The purpose of the Certainty field is to indicate the level of confidence in the interpretation of the deformation features. In the Certainty field, the term 'definite' is applied to those features whose existence can only be explained by active fault deformation. Features designated as 'likely' are most probably due to active fault deformation, but it is not possible to rule out other origins, such as having been formed by erosion. In instances where there is some reason to suspect the presence of an active fault, but there is a lack of direct evidence because, for example, the landforms are unsuitable (e.g. too young) to have preserved any direct indications of young movement, the feature is designated as 'possible'. Another category is added in this project, for faults that could possibly move in the future ('potentially active') even though they have not done so in the recent geological past. Features identified as having a Certainty of 'possible' or 'potentially active' should not be treated as delineated active faults unless further positive information is obtained. They are identified to highlight areas that are worth a closer look for the possible existence of active fault hazards.

Several of the active faults of the Queenstown Lakes and Central Otago districts have been subject to close examination in the field, whereas other faults have been identified primarily using aerial photographs or other imaging such as Google Earth, or in reconnaissance walkover. In all cases, the geometries and locations of active faults as depicted in the QMAP-based datasets are very generalised. At the scale of QMAP, none is located more accurately than plus or minus (±) 100 m, at best, and ± 250 m as a general rule. The Surf_form field provides a preliminary estimate of how well defined the surface expression of a feature is likely to be, were it to be subjected to a detailed, site-specific, examination. Features that are 'well expressed' should be able to be located to better than ± 50 m. Those that are identified as 'moderately expressed' should be able to be located to better than ±100 m. Those labelled as 'not expressed' do not have any known physical expression on the ground, because they lie in areas of landforms that are probably younger than the most recent deformation. Features are labelled as 'unknown' if it is unclear whether or not there may be physical evidence that would aid in locating the position of the fault. The purpose of the Surf_form field is to assist in the planning and targeting of future investigations aimed at a more rigorous characterisation of active fault hazard, should any further work be proposed. For example, features designated as 'well expressed' are likely to be able to be mapped and delineated more quickly, and to greater precision, than features identified as 'moderately expressed'.

4.2 Activity Classification

Two common ways of expressing the degree of activity of an active fault (and any related folding) are average slip rate and average recurrence interval. Either of these parameters provides a way to compare the levels of activity of faults across a wide area (e.g. Queenstown Lakes and Central Otago districts). In this report, an activity estimate is assigned to a fault as a whole. The one activity estimate applies to its component fault strands and any associated monoclinal fold strands. This assumption may not be true in detail, for example if one strand of a fault were to rupture in an earthquake while another strand does not. However, a single activity estimate is regarded here as the appropriate approach to use, because at present there is little if any information on the past rupture behaviour of individual fault strands.

The behaviour of any particular active fault comprises a relatively long period of no movement, during which strain slowly builds up in the subsurface rock, until the fault moves (ruptures) in a sudden slip event, causing an earthquake. For a fault whose largest slip events are sufficient to produce ground-surface rupture (as applies to all mapped active faults in this report), each slip event typically involves sudden movement on the fault of as much as several metres (see Figure 1.2). The amount of fault offset of a geological deposit or a land surface feature, such as a river plain, divided by the estimated age of the deposit or the land surface feature, provides an average slip rate, usually expressed in millimetres per year (mm/yr). This does not mean that the fault moves a certain amount each year but is simply a way of assessing its degree of activity. A fault with a larger (faster) slip rate (say 2 mm/yr) generally experiences a ground-surface rupturing earthquake more frequently than does a fault with a smaller (slower) slip rate (e.g. 0.2 mm/yr).

In most cases throughout Otago, the precise ages of geological deposits and landforms are not known. Instead, geologists usually rely upon provisional age estimates based on regional geological comparisons. By this approach, ages obtained by geological dating of a specific type of landform somewhere in New Zealand are applied to landforms of similar characteristics in another region. For example, geological dating in the upper Waitaki River catchment has shown that the last ice age ended about 18,000 years ago, when the large valley glaciers started to melt away rapidly (Putnam et al. 2013). On that basis, an age of 18,000 years is adopted for glacial landforms in the catchments of lakes Wakatipu, Wanaka and Hawea, in order to estimate the activity of faults that have offset those landforms. With different types of landforms or geological deposits, other criteria such as the degree of weathering, and maturity of soil development, are used to estimate ages for calculating fault activity rates. The approach and reasoning used to estimate the activity of each fault addressed in this report is explained in Appendix 2.

Average recurrence interval is the average length of time that elapses between ground-surface rupturing earthquakes and is a more explicit measure of how frequently surface-rupture earthquakes occur. Recurrence interval is an important quantity because it forms the basis for risk-based evaluation of ground-surface fault rupture hazard in relation to the MfE active fault guidelines that aim to minimise the risks of building across active faults (Kerr et al. 2003). Recurrence intervals range from being as short as a few hundred years for the most active faults in New Zealand (e.g. Alpine Fault), to as much as many tens of thousands of years for other faults. This means that the historically-documented record of earthquakes is too short to be of use for evaluating the average recurrence interval of an active fault. Instead, the geological record of deformation of young deposits and landforms is the main source of evidence for defining a recurrence interval for an active fault.

Recurrence interval is more difficult to quantify than slip rate, because the direct determination of a recurrence interval depends on the ability to establish the ages of at least two, preferably more, past surface-rupture earthquakes on a fault. Determining recurrence intervals, as well as obtaining accurate values for slip rates, requires detailed geological investigations on a fault, with measurement of past offsets, and dating of geologically-young deposits. However, few faults in the Otago region have been investigated in that amount of detail.

Another approach for estimating recurrence interval has been developed from research into historical ground-surface fault ruptures internationally and in New Zealand. That work has identified generally applicable relationships that allow one fault parameter to be calculated from another parameter. For example, the size of a single-event fault rupture displacement can be estimated from the length of the fault. That methodology provides a means for estimating fault activity characteristics for faults where detailed geological investigations have not been carried out and has been applied to such faults in the 2010 version of the NSHM (2010 NSHM; Stirling et al. 2012). The 2010 NSHM methodology calculates, among other things, values for recurrence interval and single-event displacement from estimates of fault length, fault dip (the inclination from horizontal of the fault plane) and slip rate; those estimates are usually determined by an expert panel of geoscientists, drawing on available geological information.

The present project used the 2010 NSHM approach to estimate provisional recurrence interval values for newly defined active and potentially active faults not currently in the 2010 NSHM. This differs from the approach used previously for the Waitaki District (Barrell 2016), which applied a method that assumed a fixed representative value for single-event displacement size and used that along with estimated slip rate to calculate an inferred recurrence interval. An important point is that, except in the case of the few faults that have been investigated in detail and useful results obtained, the slip rate and recurrence interval estimates presented in this report should be regarded as preliminary, until more direct estimates are obtained from site-specific geological investigations of the fault. The estimates in this report are intended primarily to indicate an approximate recurrence interval that may be expected for each fault, allowing the activity of a fault to be placed into general context with the MfE active fault guidelines (Kerr et al. 2003).

This project has made a further addition to the approach used for the Waitaki District (Barrell 2016). Previous compilations only included faults displaying physical evidence for geologically recent activity, thus according with existing definitions of ‘active fault’ (Langridge et al. 2016). However, recent research in coastal Otago (Villamor et al. 2018) has led to a recommendation for including all faults that have experienced substantial movement in the wider geological past, specifically within the past 20 million years since the present plate boundary has been active through the New Zealand region. The inclusion of many more faults in the dataset has little impact on seismic hazard estimation in Otago for faults that have experienced considerable movement in the deeper past, but little if any in geologically more recent times. Those faults are assessed as having very slow slip rates and therefore long recurrence intervals, and thus statistically contribute little to the overall earthquake hazard in the region.

There is considerable uncertainty in the estimated fault activity parameters, but the level of uncertainty is difficult to quantify. This is because there is uncertainty in estimating the size of fault offset of a landform (e.g. estimated from aerial photos), and uncertainty in the age assigned to the landform (e.g. inferred from regional geological comparison – see earlier paragraph). It is not considered meaningful for the present report to try and quantify activity uncertainties, for example by giving a range of estimated values for slip rate or recurrence interval. That would be a desirable goal of future assessments of specific active faults, where detailed geological investigations have been undertaken. However, the present report just gives a single best-estimate value for slip rate, from which a single recurrence interval is calculated using 2010 NSHM methodology. Should anyone wish to apply a level of uncertainty to those values, an uncertainty of ±50% of the stated slip rate or recurrence interval is deemed here to be a useful working representation of the uncertainty.

It is important to appreciate that all of the fault activity estimates in this report, and in preceding datasets, are no more than working best estimates. The main use of those estimates is for enabling comparison of the relative activities of different faults, and providing context for identifying and managing associated hazards, typically via the derived parameter of recurrence interval. A last point to note is that the information on degree of fault activity in this report, notably the extended reviews and discussions in Appendix 2, is more comprehensive than that contained in the NZAFD, as it stood in December 2018, and also builds on and refines information and estimates presented by Van Dissen et al. (2003), Stirling et al. (2012) and

Litchfield et al. (2013, 2014) and references therein. The information in this report also updates the active fault locations as illustrated and discussed by Mackey (2015).

4.3 As-Yet Undetected Active Faults

The Canterbury earthquake sequence of 2010–2011 occurred on a series of previously unknown faults. There are two main reasons why nothing was known about those faults. First, they have a low rate of activity (the average time between surface-rupture earthquakes is many thousands of years), and second, the Canterbury Plains consist of relatively young deposits and landforms, which mask most of the underlying geology, including faults (Hornblow et al. 2014). The 2016 Kaikōura Earthquake involved the rupture of multiple faults, several of which were not previously known to be active faults (Litchfield et al. 2018). Somewhat different circumstances prevail in Otago, where most areas are not buried by young sediments, and many of the faults are clearly expressed in the geology, and topography, especially where hard basement rock has been uplifted to form a range of hills or mountains on one side of the fault. Nevertheless, it is conceivable that there may be other active faults, in areas of relatively young landforms, whose presence is yet to be detected. This means that the active faults of the Queenstown Lakes and Central Otago districts, that have a preserved record of previous ground-surface deformation of young deposits or landforms, should be regarded as a minimum representation of the active faults of these districts.

The active faults and associated folds that are known about can be taken into account in planning, engineering and hazard mitigation or avoidance. Although little can be done to avoid hazards from faults whose presence/location is unknown, modern building and design standards in regard to earthquake shaking do make allowance for minimising adverse effects of a large, nearby, earthquake, even if there is no known active fault nearby. However, there is good confidence that the more active faults of the two districts have been identified and characterised in this report. This is because such faults are likely to have left distinctive landform indicators of their presence. The more active faults present the largest hazard statistically, because they have a greater chance of rupturing again in the geological near-future than faults of lesser activity. However, and unfortunately, that does not necessarily mean that a higher activity fault will be the next one(s) to rupture. This is because there are many more low activity faults than there are high ones.

4.4 Earthquake Magnitudes

For an active fault to be recognisable at the ground surface, it indicates that past ruptures must have been sufficiently large to have broken through to the ground surface. For the types of faults that occur in the eastern South Island, the amount of slip required for a fault to rupture the ground surface will generate a large earthquake, of magnitude somewhere between the high sixes and mid-sevens (e.g. Pettinga et al. 2001). That is reinforced by the example of the 2015 magnitude 5.8 Matukituki Earthquake, which did not cause surface rupture (Section 3.3).

Active folds indicate the presence of underlying active faults whose ruptures have not reached the ground surface. Conceivably, subsurface ruptures sufficient to generate surface folds may produce earthquakes of lesser magnitudes (e.g. in the low to mid sixes). These considerations were borne out in the Darfield Earthquake, where the surface-rupturing Greendale Fault movement had an estimated magnitude of 7.0, while the subsurface Charing Cross and Hororata ruptures had estimated magnitudes of 6.4 and 6.3 respectively and did not cause surface rupture, but did produce subtle, instrumentally-measurable, ground shifts (Beavan et al. 2012). Surface fold growth resulting from non-surface-rupturing faults does not necessarily mean that the earthquakes were not large. For example, a gently-inclined non-surface-rupturing fault may be able to generate an earthquake at least as large as one generated by a steeply-inclined, surface-rupturing fault, such as the Greendale Fault.

Each of the active faults identified in this report should be assumed to be capable of generating earthquakes with magnitudes between the high sixes to mid-sevens, depending on the length of the fault, with longer faults having potential to generate larger earthquakes within this magnitude range. For the 48 active faults discussed in this report, the 2010 NSHM methodology calculates an indicative earthquake magnitude in the range of magnitude 6.8 to magnitude 7.6, with a mean across all 48 active faults of magnitude 7.1.

5.0 DISTRIBUTION AND CHARACTERISTICS OF ACTIVE FAULTS

5.1 Overview

A regional-scale map of the active and potentially active faults delineated in the Queenstown Lakes and Central Otago districts is presented in Figures 5.1 to 5.3, which collectively provide three overlapping panels of the assessment area. Descriptions of the representative characteristics of the categories of active faults and associated active folds used in this report, as well as indicative correlations to the fault complexity classification of the MfE active fault guidelines (Kerr et al. 2003), are presented in Table 5.1. Table 5.2 summarises the main features of each of the delineated active and potentially active faults. The table includes an assessment of the degree of activity of each fault. Appendix 2 provides extended descriptions of the mapping, geological interpretations and activity estimations for each fault.

In many cases, rupture on an active fault may have broken out discontinuously, or in multiple places, on the ground. Some individual faults may converge, or abut one another, and some faults comprise a zone of surface deformation, in which some fault strands have been given individual names. To aid clarity of illustration, each named fault in Figures 5.1–5.3 has been accentuated by a coloured area (‘extent of named area’). In the cases where a fault comprises multiple strands, this helps show which strand belongs to which active fault.

Of the 48 active faults (comprising a total of 55 named fault features in Figures 5.1–5.3) identified in the Queenstown Lakes and Central Otago districts, 21 are classified as comprising ‘definite’ or ‘likely’ components and can be regarded respectively as known or suspected active faults. Of the remaining faults, six are classed as ‘possible’ active faults and another 21 are classified as ‘potentially active’. The classification of ‘possible’ indicates there is reason to think of those faults as having a greater likelihood of future activity than faults classified as ‘potentially active’.

Only nine faults are assessed as having a recurrence interval of less than 10,000 years, namely the Dunstan Fault Zone, Gimmerburn Fault Zone, Highland Fault, Lindis Pass Fault Zone, Livingstone Fault, Motatapu Fault, Nevis Fault Zone, NW Cardrona Fault, and the Timaru Creek Fault. It should be noted that the Highland Fault and Motatapu Fault are regarded as probably rupturing together and collectively only represent one earthquake source. The most active fault delineated in each district is the NW Cardrona Fault in Queenstown Lakes, with an estimated recurrence interval of 5500 years, and the Lindis Pass Fault Zone in the Central Otago, whose estimated recurrence interval is 5600 years. However, the Lindis Pass Fault Zone lies only partly in the Waitaki District. The most active fault contained entirely within Central Otago is the Dunstan Fault Zone, whose estimated recurrence interval is 7000 years.

A point to note is that for most of the faults discussed in this report, there is no information on when the most recent ruptures occurred, and this means that there is little or no information on where the faults are currently sitting within their rupture cycles.

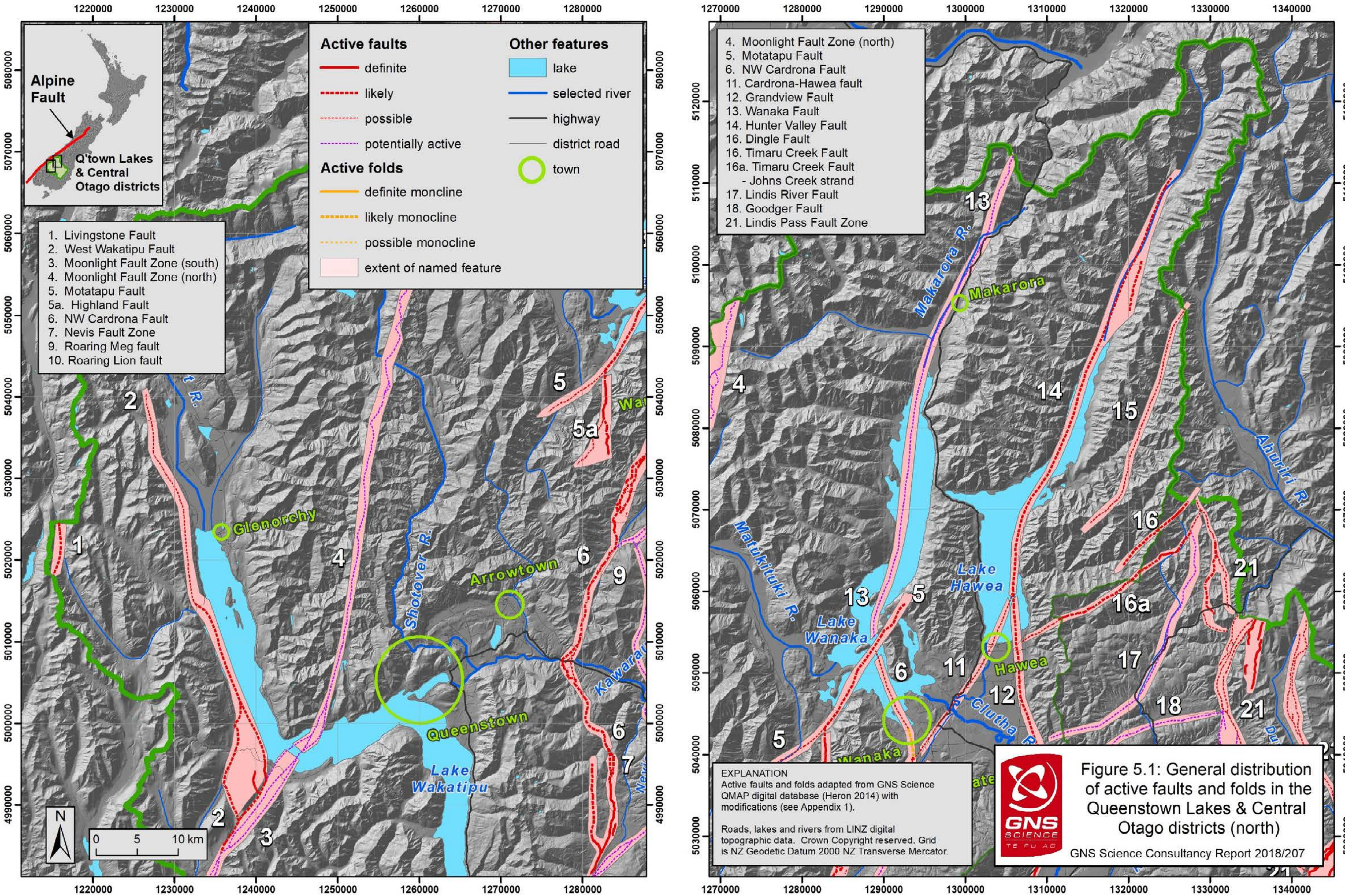

Figure 5.1 General distribution of active faults and folds in the Queenstown Lakes and Central Otago districts (northern panels). The pink areas indicate groupings of fault or fold strands that collectively form part of a single numbered active fault. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation. Each fault that intersects the outer boundary of the combined districts (thick green line) extends into the neighbouring district(s). The location of the overlapping map panels is shown in the inset at top left.

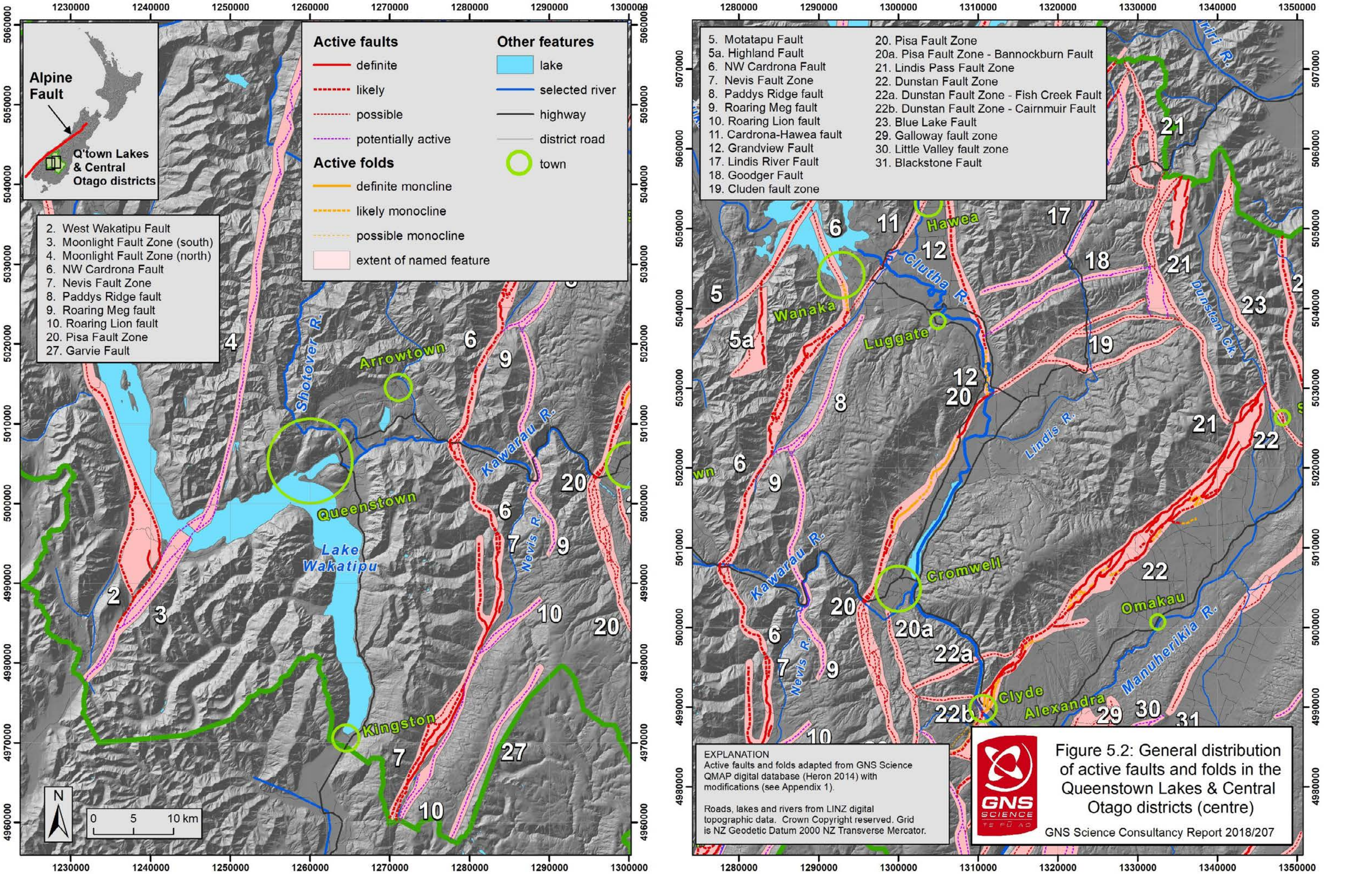

Figure 5.2 General distribution of active faults and folds in the Queenstown Lakes and Central Otago districts (centre panels). The pink areas indicate groupings of fault or fold strands that collectively form part of a single numbered active fault. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation. Each fault that intersects the outer boundary of the combined districts (thick green line) extends into the neighbouring district(s). The location of the overlapping map panels is shown in the inset at top left.

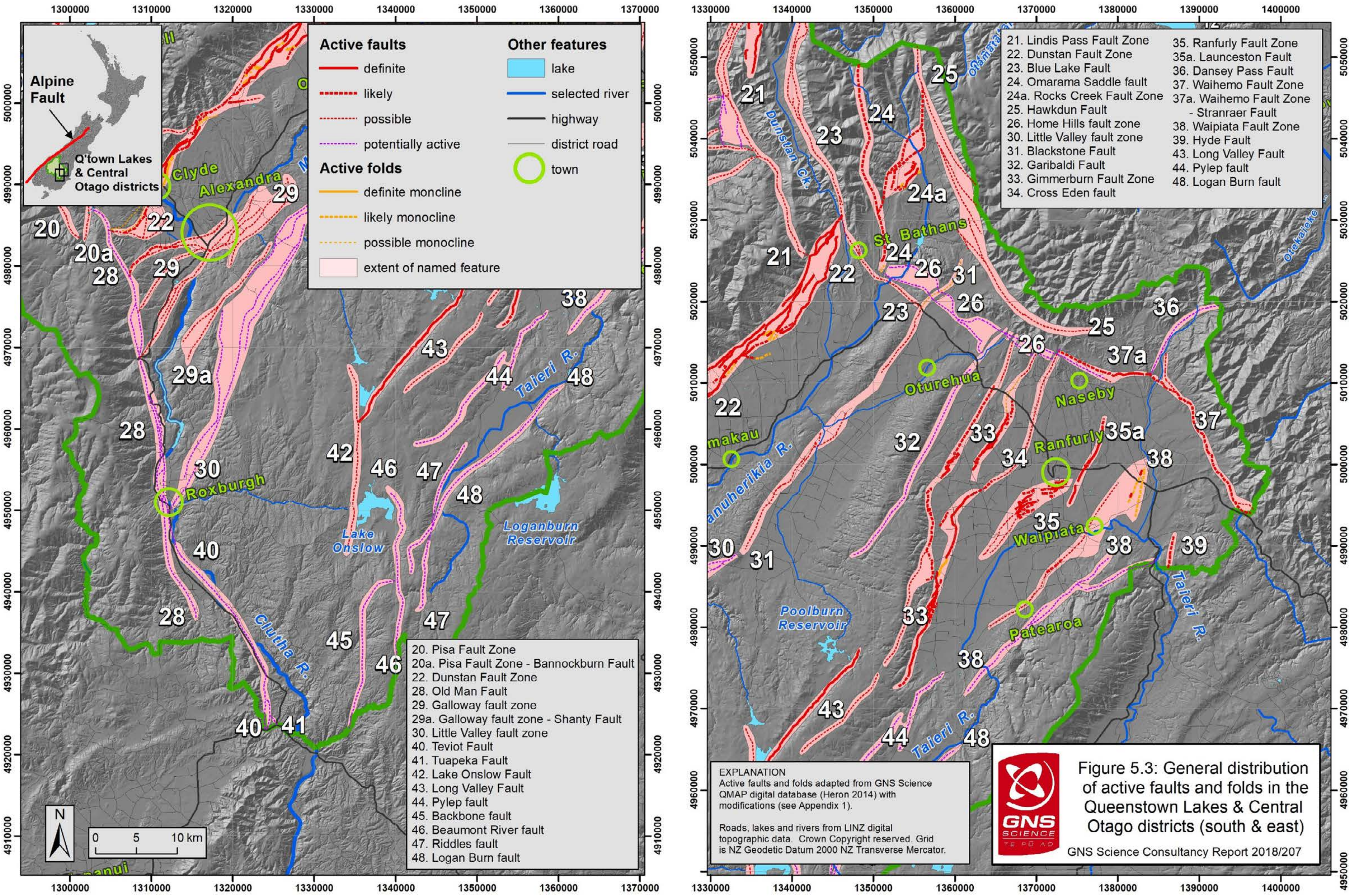

Figure 5.3 General distribution of active faults and folds in the Queenstown Lakes and Central Otago districts (southern and eastern panels). The pink areas indicate groupings of fault or fold strands that collectively form part of a single numbered active fault. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation. Each fault that intersects the outer boundary of the combined districts (thick green line) extends into the neighbouring district(s). The location of the overlapping map panels is shown in the inset at top left.

Table 5.1 Categories and terms used in this report to describe active faults and folds in the Queenstown Lakes and Central Otago districts.

Category	**Characteristics**	**Certainty**	**Surface form**	**Nature of evidence**	**Fault complexity** (based on definitions in Kerr et al. (2003))
Active fault	Deformation predominantly in the form of breakage and offset of the ground surface. This is presumed to occur in sudden events accompanied by a large earthquake. May also include some monoclinal or anticlinal folding	definite	well expressed	Sharp step in ground surface that cannot be attributed to other geological factors (e.g. river erosion or landslide movement)	Well-defined deformation
		definite	moderately expressed	Poorly-defined step(s) in ground surface that cannot be attributed to other geological factors	Well-defined or distributed deformation
		definite	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby definite active fault	Uncertain deformation
		likely	well expressed	Sharp step(s) in the ground surface that cannot readily be attributed to other geological factors	Well-defined deformation
		likely	moderately expressed	Poorly-defined steps in the ground surface that cannot readily be attributed to other geological factors	Uncertain deformation
		likely	not expressed	No surface expression, but lies along trend from nearby likely active fault	Uncertain deformation
		possible	moderately expressed	Coincides with a definite or likely fault in bedrock, along trend from nearby definite or likely active fault; includes steps or topographic features that may possibly relate to fault activity, but other origins are reasonably likely.	Uncertain deformation
		possible	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby likely or possible active fault	Uncertain deformation
		possible	unknown	No known surface expression, but likely that evidence for/against activity may be found on further investigation	Uncertain deformation
		potentially active	moderately expressed	Geological evidence (e.g. visible fault crushed rock) for estimating the specific location of a potentially active fault	No recognised deformation
		potentially active	not expressed	Little or no information from which to estimating the specific location of a potentially active fault	No recognised deformation
Active monocline	Deformation predominantly in the form of tilting, buckling or warping of the ground surface. Growth of the fold is presumed to occur in sudden events accompanied by a large earthquake. May also include some subsidiary fault offsets	definite	well expressed	Broad step or rise in ground surface that cannot be attributed to other geological factors	Distributed deformation
		definite	moderately expressed	Poorly-defined broad step(s) or rise in ground surface that cannot be attributed to other geological factors	Distributed deformation
		definite	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby definite or likely active monocline	Uncertain deformation
		likely	moderately expressed	Broad steps or rises in the ground surface that cannot readily be attributed to other geological factors	Uncertain deformation
		likely	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby likely active monocline	Uncertain deformation
		possible	moderately expressed	Coincides with a definite or likely monocline in bedrock, or a broad rise of uncertain origin, along trend from nearby definite or likely active monocline	Uncertain deformation
		possible	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby likely or possible active monocline	Uncertain deformation
		possible	unknown	No known surface expression, but likely that evidence for/against activity may be found on further investigation	Uncertain deformation

Definite = clear evidence for the existence of an active fault or fold

Likely = good reason to suspect the existence of an active fault or fold

Possible = some reason to suspect the existence of an active fault or fold

Potentially active = a known or suspected fault without identified geologically recent activity, but which could conceivably experience activity in the future

Well expressed = likely to be able to be located to better than +/- 50 m in site-specific investigations

Moderately expressed = likely to be able to be located to better than +/- 100 m in site-specific investigations

Not expressed = able to be located only by large-scale subsurface site-specific investigations

Unknown = probable that evidence for or against an active feature would be found in targeted site-specific investigations

Table 5.2 Summary of evidence and estimated deformation characteristics of active faults and folds recognised in the Queenstown Lakes and Central Otago districts. Refer to text and appendices for further information. In the 'Name' column, a lower case last term (e.g. fault) indicates a newly applied name (this report) while upper case (e.g. Fault) indicates a previously published name. Calculated recurrence interval (RI) values are rounded to the nearest hundred years for values <10,000 years, the nearest thousand years for values <30,000 years, and to the nearest 5000 years for longer RIs.

Name	**Observed characteristics**	**References**	**Deformation estimates**					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Backbone fault (45)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain	This report	Air photo interpretation; geomorphologic interpretation	Potentially active fault	0.05	35,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Beaumont River fault (46)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain	This report	Air photo interpretation; geomorphologic interpretation	Potentially active fault	0.05	50,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Blackstone Fault (31)	Fault in bedrock with offset of peneplain and suspected offset of geologically young landforms	Markley and Norris (1999); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Possible active fault	0.14	22,000	Identified as the Raggedy Fault Zone in NZAFM and NSHM	Class IV (>5,000 to ≤10,000 years
Blue Lake Fault (23)	Fault zone(s) in bedrock, with offset of peneplain	Madin (1988); Henne et al. (2011); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Possible active fault	0.07	40,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Cardrona-Hawea fault (11)	Fault zone(s) in bedrock, with offset of peneplain	Turnbull (2000); this report	Regional geologic mapping; lidar data; geomorphologic interpretation	Possible active fault	0.05	30,000	Formerly the northeastern part of the NW Cardrona Fault. No known evidence for geologically young fault movement	Class VI (>20,000 years)
Cluden fault zone (19)	Fault zone in bedrock, with offset of peneplain; possible deformation of old sediments and landforms	Beanland & Berryman (1989); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Possible active fault	0.10	17,000	Represents in part the Lindis Peak segment of the Pisa Fault Zone	Class V (>10,000 to ≤20,000 years)
Cross Eden fault (34)	Fault zone(s) in bedrock, with indicated offset of peneplain	Bishop (1979); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Possible active fault	0.05	35,000	No known evidence for geologically young fault movement, except at southwest end with suspected slip transfer from Gimmerburn Fault Zone	Class VI (>20,000 years)
Dansey Pass Fault (36)	Fault zone(s) mapped in bedrock, with indicated offset of peneplain	Bishop (1976, 1979); this report	Air photo interpretation; regional geologic mapping	Possible active fault	0.05	40,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Dingle Fault (15)	Fault zone(s) mapped in bedrock, considered to potentially be active.	Turnbull (2000); Litchfield et al. (2013); this report	Geodynamic modelling; air photo interpretation; regional geologic mapping	Potentially active fault	0.05	55,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Dunstan Fault Zone (22)	Fault zone(s) in bedrock, with deformed geologically young sediments and landforms	Beanland et al. (1986); Madin (1988); Litchfield et al. (2013); this report	Air photo interpretation; field inspection & surveying; trenching & dating; lidar data; regional geologic mapping	Definite, likely and possible active fault and fold strands	0.60	7000		Class IV (>5,000 to ≤10,000 years)
Galloway fault zone (29)	Fault zone(s) in bedrock, with suspected deformed geologically young landforms	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping; lidar data; geomorphologic interpretation	Likely and possible active fault strands	0.10	15,000		Class V (>10,000 to ≤20,000 years)
Garibaldi Fault (32)	Fault in bedrock, with offset of peneplain	Forsyth (2001); this report	Air photo interpretation; regional geologic mapping.	Potentially active fault	0.05	45,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Garvie Fault (27)	Fault zone in bedrock, with indicated offset of peneplain	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping.	Potentially active fault	0.05	75,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)

Name	Observed characteristics	References	Deformation estimates					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Gimmerburn Fault Zone (33)	Fault zones in bedrock with deformed geologically young sediments and landforms	Bennett et al. (2005, 2006); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Definite, likely, possible and potentially active fault strands	0.40	7400		Class IV (>5,000 to ≤10,000 years
Goodger Fault (18)	Fault zone in bedrock, with indicated offset of peneplain	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping.	Potentially active fault	0.05	30,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Grandview Fault (12)	Fault in bedrock with deformed geologically young sediments	Beanland & Berryman (1989); Turnbull (2000); Litchfield et al. (2013); this report	Geological drilling investigations; regional geologic mapping	Likely active fault	0.10	22,000		Class VI (>20,000 years)
Hawkdun Fault (25)	Fault zone in bedrock, with offset of peneplain	Bishop (1976); Forsyth (2001); this report	Air photo interpretation; regional geologic mapping;	Possible active fault	0.07	55,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Highland Fault (5a)	Up to 3 m offset of hillslope landforms	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping;	Definite and likely active fault strands	0.32	6500	Interpreted as a strand of the Motatapu Fault or NW Cardrona Fault, and not an independent rupture source. Motatapu Fault slip rate and RI are applied.	Class IV (>5,000 to ≤10,000 years
Home Hills fault zone (26)	Fault zones in bedrock	Bishop (1976, 1979); Forsyth (2001); Henne et al. (2011); this report	Air photo interpretation; regional geologic mapping;	Potentially active fault	null	null	No known evidence for geologically young fault movement. Equates in part to Stranraer Fault and Waihemo Fault System. Included for possibility of transferred secondary slip	Class VI (>20,000 years)
Hunter Valley Fault (14)	Inferred fault zone(s) in bedrock, with indicated offset of geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping;	Likely active fault	0.32	12,000	Also known as the Hunter fault zone (Litchfield et al. 2013)	Class V (>10,000 to ≤20,000 years)
Hyde Fault (39)	Fault in bedrock, with offset of peneplain	Norris and Nicolls (2004); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping;	Likely active fault	0.25	13,000	Slip rate and RI taken directly from 2010 NSHM. The 'likely' classification reflects uncertainty whether the most recent rupture(s) extended into Central Otago	Class V (>10,000 to ≤20,000 years)
Lake Onslow fault (42)	Inferred fault zone(s) in bedrock, with offset of peneplain	This report	Air photo interpretation; geomorphologic interpretation	Potentially active fault	0.05	30,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Launceston Fault (35a)	Inferred fault in bedrock with deformed geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; geomorphologic interpretation	Definite active fault	0.10	17,000	Regarded as a component of the Ranfurly Fault Zone	Class V (>10,000 to ≤20,000 years)
Lindis Pass Fault Zone (21)	Fault zones in bedrock with deformed geologically young sediments or landforms	Litchfield et al. (2013); Barrell (2016); this report	Air photo interpretation; regional geologic mapping;	Definite, likely and possible active fault strands	0.47	5600		Class IV (>5,000 to ≤10,000 years

Name	Observed characteristics	References	Deformation estimates					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Lindis River Fault (17)	Fault in bedrock, with offset of peneplain	This report	Air photo interpretation; regional geologic mapping;	Potentially active fault	0.05	50,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Little Valley fault zone (30)	Fault zone(s) in bedrock, with offset of peneplain	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	60,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Livingstone Fault (1)	Major fault in bedrock, with suspected offset of geologically young landforms	Litchfield et al. (2013); this report	Regional geologic mapping; air photo interpretation	Likely active fault	1.00	6400	Referred to as the Hollyford active fault earthquake source by Stirling et al. (2012)	Class IV (>5,000 to ≤10,000 years
Logan Burn fault (48)	Inferred fault in bedrock, with offset of peneplain	This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	60,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Long Valley Fault (43)	Fault in bedrock, with offset of peneplain and geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; field inspection; geomorphologic interpretation	Definite active fault	0.18	7900		Class IV (>5,000 to ≤10,000 years
Moonlight Fault Zone - north section (4)	Major fault zone(s) in bedrock, with indicated large offset of mid-Cenozoic strata	Turnbull et al. (1975); Turnbull (2000); Litchfield et al. (2013); this report	Regional geologic mapping; air photo interpretation	Potentially active fault	0.05	140,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Moonlight Fault Zone - south section (3)	Major fault zone(s) in bedrock, with indicated large offset of mid-Cenozoic strata	Turnbull et al. (1975); Turnbull (2000); Litchfield et al. (2013); this report	Regional geologic mapping; air photo interpretation	Potentially active fault	0.05	120,000	No known evidence for geologically young fault movement. The lesser RI is because the south section has a shorter length than the north section	Class VI (>20,000 years)
Motatapu Fault (5)	Suspected fault zone in bedrock, with suspected 5 m offset of glacial landforms	Turnbull (2000); this report	Regional geologic mapping; air photo interpretation	Likely and possible active fault strands	0.32	6500		Class IV (>5,000 to ≤10,000 years
Nevis Fault Zone (7)	Fault zone(s) in bedrock, with deformed geologically young sediments and landforms	Beanland & Barrow-Hurlbert (1988); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; field inspection & trenching; geomorphologic interpretation	Definite and likely active fault strands	0.40	9000		Class IV (>5,000 to ≤10,000 years
NW Cardrona Fault (6)	Fault zone(s) in bedrock, with deformed geologically young sediments and landforms	Beanland & Barrow-Hurlbert (1988); Turnbull (2000); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; lidar data; field inspection & surveying; trenching & dating; geomorphologic interpretation	Definite, likely and possible active fault and fold strands	0.38	5500		Class IV (>5,000 to ≤10,000 years)
Old Man Fault (28)	Fault zone(s) with slight deformation of geologically young sediments	Stirling (1990); Hull & Stirling (1992); Litchfield et al. (2013); this report	Regional geologic mapping; air photo interpretation; field inspection	Potentially active fault	0.01	~360,000	Slight offset (<5 m) of 'Lindis Formation' river gravels of assessed age ~330,000 years	Class VI (>20,000 years)
Omarama Saddle fault (24)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain and localised offset geologically young landforms	Barrell (2016); This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Definite and likely active fault strands	0.2	12,000		Class V (>10,000 to ≤20,000 years)

Name	Observed characteristics	References	Deformation estimates					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Paddys Ridge fault (8)	Fault zone(s) in bedrock, with offset of peneplain	Beanland & Barrow-Hurlbert (1988); Turnbull (2000); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	30,000	Also known as SE Cardrona Fault. No known evidence for geologically young fault movement	Class VI (>20,000 years)
Pisa Fault Zone (20)	Fault zone(s) with deformed geologically young sediments and landforms	Beanland & Berryman (1989); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; field investigations & trenching; geomorphologic interpretation	Definite, likely and possible active fault and monocline strands	0.10	30,000	A northeastern extension of the Pisa Fault Zone (Pisa-Lindis Peak branch) is redefined here as the Cluden fault zone	Class VI (>20,000 years)
Pylep fault (44)	Fault zone(s) in bedrock, with offset of Otago peneplain	This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	30,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Ranfurly Fault Zone (35)	Deformed geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; geomorphologic interpretation	Definite, likely and possible active fault strands	0.10	17,000	The Launceston Fault is regarded as a northern continuation of the Ranfurly Fault Zone	Class V (>10,000 to ≤20,000 years)
Riddles fault (47)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain	This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	null	null	No known evidence for geologically young fault movement. Thought to be offset by younger faults. Included for possibility of transferred secondary slip	Class VI (>20,000 years)
Roaring Lion fault (10)	Fault zone(s) in bedrock, with offset of peneplain	Turnbull (2000); this report	Regional geologic mapping; geomorphologic interpretation	Possible active fault	0.05	65,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Roaring Meg fault (9)	Fault zone(s) in bedrock, with offset of peneplain	Beanland & Barrow-Hurlbert (1988); Turnbull (2000); this report	Regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	40,000	Approximates the previously named Gentle Annie Fault. No known evidence for geologically young fault movement	Class VI (>20,000 years)
Rocks Creek Fault Zone (24a)	Fault zone(s) in bedrock, with offset of peneplain and deformed geologically young landforms	Beanland & Fellows (1985); Madin (1988); this report	Air photo interpretation; regional geologic mapping; field inspection & trenching; geomorphologic interpretation	Definite and likely active fault and monocline strands	0.2	12,000	Interpreted to be a splay of the Omarama Saddle fault; slip rate and RI of that fault adopted for Rocks Creek Fault Zone	Class V (>10,000 to ≤20,000 years)
Teviot Fault (40)	Inferred fault zone in bedrock, with indicated offset of peneplain	This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.01	225,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Timaru Creek Fault (16)	Fault zone in bedrock, with deformed geologically young landforms	This report	Air photo interpretation; regional geologic mapping;	Definite, likely and possible active fault strands	0.32	6100	Includes the previously named Timaru Creek Fault and the Johns Creek Fault (16a)	Class IV (>5,000 to ≤10,000 years
Tuapeka Fault (41)	Fault zone in bedrock with suspected offset of geologically young landforms	Turnbull and Allibone (2003); this report	Air photo interpretation; regional geologic mapping;	Likely active fault	null	null	Only the northernmost part lies in Central Otago District, remainder is in Clutha District. Nominal RI Class is applied here, pending future assessment	Class VI (>20,000 years)

Name	Observed characteristics	References	Deformation estimates					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Waihemo Fault Zone (37)	Fault zones in bedrock with suspected offset of geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Likely active fault	0.12	50,000		Class VI (>20,000 years)
Waipiata Fault Zone (38)	Fault zone in bedrock with suspected deformation of geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Definite, likely and possible active fault and monocline strands	0.10	24,000		Class VI (>20,000 years)
Wanaka Fault (13)	Inferred fault zone(s) in bedrock.	Turnbull (2000); Litchfield et al. (2013); this report	Geodynamic modelling; regional geologic mapping	Potentially active fault	0.05	85,000	No known evidence for geologically young fault movement. Referred to as the Makarora Fault by Litchfield et al. (2013)	Class VI (>20,000 years)
West Wakatipu Fault (2)	Fault zone(s) in bedrock, with post-glacial landform offsets at southern end	Turnbull et al. (1975); Turnbull (2000); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Definite, likely and possible active fault strands	0.19	20,000	Post-glacial fault scarps previously attributed to Moonlight Fault reassigned to West Wakatipu Fault	Class V (>10,000 to ≤20,000 years)

5.2 Comparison with Previous Assessments

The present project has delineated 48 active and potentially active faults thought to be capable of generating ground-surface rupturing earthquakes, noting that the total of 55 named fault features in Figures 5.1–5.3 and Table 5.2 includes several regarded as only able to rupture together with other faults. In comparison, the 2010 NSHM identifies a total of 19 active fault earthquake sources partly or entirely within the limits of the combined Queenstown Lakes and Central Otago districts, whereas the NZAFM defined 23 active faults, due to an additional four faults being interpreted as active. The NZAFD, which in this region is based largely on interpreted active fault scarps from the QMAP dataset, mostly shows scattered, disconnected, active fault strands rather than entire active fault structures, as are portrayed in the NZAFM, for example. The present active fault dataset provides a full update of information on active faults in the combined Queenstown Lakes and Central Otago districts. The information on active faults in this report is more comprehensive than the current version (December 2018) of the NZAFD, and the information provided in the report by Mackey (2015) for Queenstown Lakes District, which was based on NZAFD linework.

5.3 Assessment of Fault Activity Estimates

The delineation of many more additional faults in the present project compared to previous assessments raises some issues for fault activity estimation. The estimation of fault slip rates for the 2010 NSHM and the NZAFM took account of the inferred strain from plate convergence across the South Island. In both those datasets, fault characterisation parameters based on geological investigation or landform interpretation evidence were adjusted to achieve a satisfactory accord with predicted plate deformation strain.

This issue was taken into consideration for the new fault dataset presented in this report. For each of the potentially active faults, for which there is no recognised evidence of fault deformation of geologically-young landforms, a nominal slip rate of 0.05 mm/yr has been assigned. The reason for selecting that nominal value is that in the south-eastern South Island, faults with a slip rate of about 0.1 mm/yr generally show some landform indicators of fault deformation, such as uplifted old terraces, or elevated hill terrain, on the upthrown side of line of the fault, for example the Pisa Fault Zone in Central Otago (Beanland and Berryman 1989) and the Titri Fault in coastal Otago (Barrell et al. 2019). A nominal slip rate of 0.05 mm/yr is considered here to be a first-approximation value that is compatible with an absence of preserved landform evidence of geologically-recent fault deformation. A ‘reality-check’ comparison can be made by summing the slip rates of all the faults partly or entirely in the combined districts in the 2010 NSHM, the NZAFM, and the present dataset. While this approach is not a good measure of plate deformation strain relative to the plate boundary, it does give an approximation of internal deformation rate within a three-dimensional block of the Earth’s crust in the combined area of the two districts. In both the 2010 NSHM and the NZAFM, the summed slip rate is ~9.0 mm/yr, whereas the summed slip rate for the 48 faults in the new dataset is 7.7 mm/yr. This indicates that the slip rates applied in the new dataset are broadly in overall accord with those of the 2010 NSHM and NZAFM datasets. If the nominal 0.05 mm/yr slip rate were adjusted upward to 0.07 mm/yr, the summed total slip rate would match that of the 2010 NSHM and NZAFM. It was considered preferable to retain a ‘round-number’ nominal slip rate of 0.05 mm/yr for this dataset, to emphasise its nominal nature, rather than adjust it artificially to allow the summed slip rate of the new dataset to exactly match that of the 2010 NSHM and NZAFM.

The nominal slip rate of 0.05 mm/yr is applied to 18 of the faults delineated in the new dataset. A slip rate was not applied to a further three faults (Home Hills fault zone, Riddles fault and Tuapeka Fault). The first two are interpreted to have been cut off at depth by other active faults and are inferred to not be capable of independent earthquake rupture. They are included in this dataset because of a possibility that they could experience secondary slip transferred from the rupture of adjacent active faults. The Tuapeka Fault lies in the Clutha District, and only its northern tip extends into Central Otago. Although Villamor et al. (2018) assigned the Tuapeka Fault a slip rate of no more than 0.01 mm/yr, it seems desirable to await a fuller assessment of the fault, as part of an anticipated companion active fault assessment for the Clutha District, before confirming a slip rate estimate for the Tuapeka Fault.

Using the 2010 NSHM calculation methodology, all of the faults assigned a nominal 0.05 mm/yr slip rate have a recurrence interval of more than 20,000 years, thus equating to recurrence interval Class VI in the MfE active fault guidelines (Kerr et al. 2003). This class is also applied to the three faults that were not given a slip rate. A total of 18 faults have calculated recurrence intervals between 10,000 and 20,000 years (Class V), and the remaining nine faults have calculated recurrence intervals of between 5,000 and 10,000 years (Class IV).

5.4 Discussion of Fault Activity Close to Population Centres

5.4.1 Queenstown Area

The major change for the Queenstown area arising from the present assessment is that the Moonlight Fault, previously regarded as one of the most active faults in the area, with a recurrence interval of between 6,000 and 7,000 years (Stirling et al. 2012), has had its level of activity greatly downgraded, with its recurrence interval recalculated as more than 100,000 years. Instead, the fault offset landform features previously considered to be associated with the Moonlight Fault are now attributed to the West Wakatipu Fault, for which a recurrence interval of 20,000 years is calculated.

There is no change in activity status for the NW Cardrona Fault which crosses the Kawarau valley at the western end of the Gibbston basin (Figure 5.4). The mapped location of the main, ‘definite’, strand of the fault there has been refined, aided by lidar data. Also, the Nevis Fault Zone was previously mapped as crossing the floor of the Gibbston basin. In the present dataset, the NW Cardrona Fault is extended to ~12 km south of Gibbston. The northern end of the Nevis Fault Zone is now placed at the repositioned southern end of the NW Cardrona Fault.

Overall, the downgrading of activity level of the Moonlight Fault means that the chance of fault rupture and related hazards occurring due to a local-source earthquake is reduced for the Lake Wakatipu area compared to previous estimates. Were rupture to occur on the more active faults in the area (NW Cardrona Fault, Nevis Fault Zone and West Wakatipu Fault, in order of increasing recurrence interval), there would be a large earthquake centred within 30 km or so of Queenstown, which would cause strong ground shaking effects in the Wakatipu area.

5.4.2 Wanaka and Hawea Area

The major change for the Wanaka area is the recognition, due to the availability of detailed topographic information from lidar, that the most recent surface ruptures of the NW Cardrona Fault appear to have extended north from the Cardrona valley, near the foot of the Mt Alpha range, through part of Wanaka township (Figures 5.5, 5.6). Previously, the NW Cardrona Fault was thought to extend northeast to Lake Hawea, passing beneath Albert Town and part of

Lake Hawea township. The interpreted surface deformation through the Wanaka area is in the form of a monoclinal fold, that is most clearly expressed across old lake-beach landforms of an assessed age of no older than 18,000 years. The fold affects a ~100 to ~200 m wide zone of ground that has been up-warped to the west by ~4 or 5 m. The effect has been to impart a gentle easterly tilt to the ground across that zone. This interpretation is currently classed as 'likely', pending more detailed investigation and assessment. Preliminary assessment of lidar data suggests that younger lake-beach landforms show lesser amounts of deformation, indicating that the ~4 to 5 m high warp on older landforms is the result of at least two movement events.

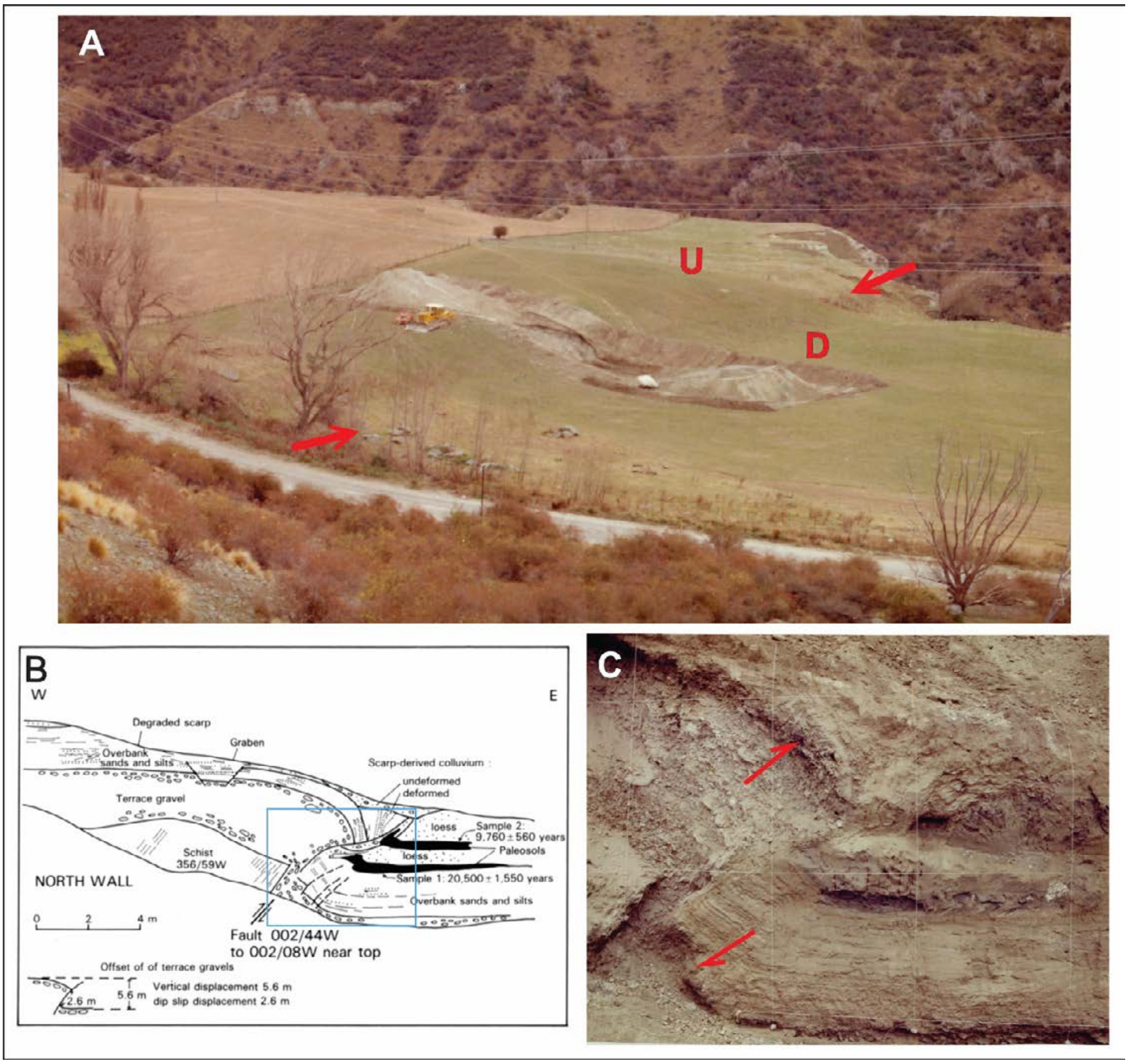

Figure 5.4 Views of a geological investigation trench excavated across the NW Cardrona Fault in the Kawarau valley at Gibbston in 1984. The fault scarp lies about 0.5 km east of the Kawarau Bridge bungy jump carpark, and about 0.6 km west of the Gibbston Valley Winery; the fault scarp is readily visible from the highway. **A**: View north from the slopes of Cowcliff Hill above State Highway 6 (foreground). The fault scarp runs across the river terrace (red arrows highlight the foot of the scarp, with up and down sides lettered). Bulldozer near the left-hand end of the trench illustrates scale. Photo from unpublished report by Beanland and Fellows (1984). **B**: Geological log of the northeastern wall of the trench, from Beanland and Barrow-Hurlbert (1988). Blue box indicates approximate field of view in panel C. Dates for samples 1 and 2 are uncalibrated radiocarbon ages; refer to Appendix 2 for ages recalculated using modern calibration. **C**: View of buckled and offset geological materials in the northeast wall of the trench; refer to panel B for description of materials. Red half-arrows highlight sense of fault movement. Photo from unpublished report by Beanland and Fellows (1984).

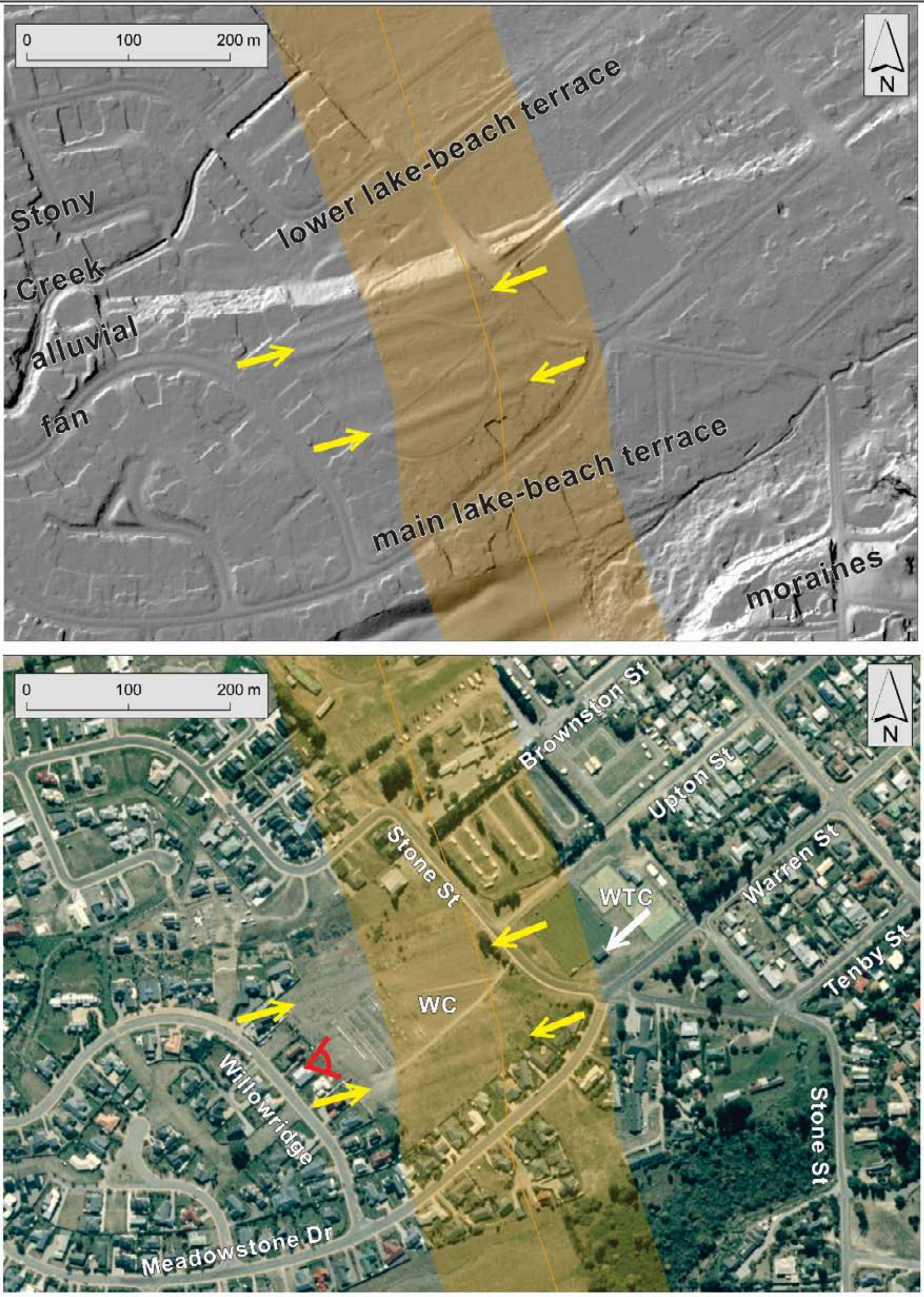

Figure 5.5 Map views highlighting the location of a suspected monocline fold through Wanaka township, close to Wanaka Cemetery (WC). **Upper panel**: A high-resolution topographic relief model generated from lidar, with the main landform features annotated. The thin orange line marks the centreline of the monocline fold, as positioned in the GIS dataset described in this report. The certainty that this feature is an active fold is classified as 'likely'. The orange colour band illustrates, schematically, the approximate width of the tilted ground across the fold. West and east of the colour band, the lake-beach terrace landform is approximately flat, but across the colour band, the ground has a gentle eastward tilt. Yellow arrows highlight two beach ridges, created by wave action at former shorelines of a much larger Lake Wanaka, that are well-resolved in the lidar model. **Lower panel**: Same map area, with a high-resolution aerial photo background (Otago 0.75m Rural Aerial Photos (2004–2011); Terralink and Otago Regional Council). The yellow arrows are in the same position as in the upper panel and illustrate that the beach ridges are evident in aerial photos as well as in the lidar model. The red symbol indicates the vantage point and field of view of the Figure 5.6 photo; the white arrow indicates a building at Wanaka Tennis Club (WTC) that is also arrowed in Figure 5.6).

This new interpretation, while still requiring a more detailed assessment for confirmation, may explain a long-standing geological puzzle. Relatively young landforms have been offset by ruptures of the NW Cardrona Fault in the Cardrona valley, but there is no indication of fault offset of the somewhat older glacial landforms between Albert Town and Lake Hawea. There is undoubtedly a fault in bedrock extending through that area, but in the present dataset that fault is renamed the Cardrona-Hawea fault and is assessed as having a much lesser level of activity (calculated recurrence interval 30,000 years) compared to the NW Cardrona Fault (calculated recurrence interval 5,500 years).

Figure 5.6 A view east across a likely monocline fold at Wanaka Cemetery. Figure 5.5 shows the approximate location of monocline relative to this photo location. Even though the photograph looks across an originally-flat lake-beach landform and was taken at ground level on the up-warped side of the suspected monocline, the roofs of buildings in the distance, on the down-warped side, are at or below the horizonal line of sight. The white arrow denotes the roof of a building at Wanaka Tennis Club, which is also marked in Figure 5.5 along with the photo location. Photo: GNS Science. D.J.A. Barrell.

Another change is the incorporation of the Highland Fault into an active fault context (Figure 5.7). The fault is assessed as being too short to be an independently rupturing active fault structure, and it is suggested to be part of the surface expression of rupture on another fault. The NW Cardrona Fault is one possible associate, but with the detection of 'likely' post-glacial offset on the Motatapu Fault, the interpretation favoured here is that the Motatapu and Highland Fault together form a single active fault. One possibility is that this fault may usually rupture in unison with the NW Cardrona Fault, which potentially is plausible because they have similar estimated recurrence intervals (5,500 years for the NW Cardona Fault and 6500 years for the Motatapu Fault). Alternatively, the combined Motatapu/Highland fault structure may be an independent source of a large, locally-generated earthquake.

An issue arising is that with the likely presence of the Motatapu Fault and NW Cardrona Fault extending beneath Lake Wanaka, a future earthquake rupture that deforms or displaces the lake bed is likely to create a localised tsunami. This is also potentially the case with the Wanaka Fault beneath the northern arm of Lake Wanaka, and the Hunter Valley Fault beneath Lake Hawea, although those two faults are assessed as being of low activity, with relatively long recurrence intervals.

Overall, this re-assessment has not markedly altered the expected chance of fault rupture and related hazards occurring due to a locally sourced earthquake in the Wanaka and Hawea area. However, the locus of potential fault-related ground deformation has been revised, with the NW Cardrona Fault now likely passing beneath part of Wanaka township. The Cardrona-Hawea fault that passes under Albert Town and Lake Hawea township is regarded as having a much lesser average rate of activity than previously assumed.

Figure 5.7 A view east across a geologically-young fault offset of hillslope landforms on the Highland Fault, in the catchment of Fern Bern, about 12 km west of Wanaka township. The fault scarp position is highlighted by red arrows, and the sense of up versus down movement is lettered. The fault scarp is upthrown on the downhill side. Photo: GNS Science, CN 10350/31H and VML ID 5035. D.L. Homer, taken 1987.

5.4.3 Upper Clutha Valley

Overall, there is no change at Luggate or Cromwell in the risks of fault rupture and related hazards occurring due to a local-source earthquake. Aside from changes in interpretation of the associations between the Grandview Fault and Pisa Fault Zone, including the newly-defined Cluden fault zone and the addition of the Bannockburn Fault as a strand of the Pisa Fault Zone, the active faults in the immediate vicinity of the upper Clutha valley (downstream of the Wanaka-Hawea basin), are assessed as low-activity faults, with recurrence intervals of more than 10,000 years. The reinterpretation that the Pisa Fault Zone extends south along the foot of the Carrick Range as a ‘possible’ active fault, and inclusion of the Bannockburn Fault strand in the fault zone, places Bannockburn in the potential frame of fault rupture and related hazards. However, risks are low because of the indicated very long recurrence interval for ground-rupturing earthquakes on the Pisa Fault Zone.

5.4.4 Clyde and Alexandra Areas

Geological investigations over the past 15 years have shown that geologically-recent deformation associated with the Dunstan Fault Zone has extended southwest towards Clyde, rather than diverting west-southwest along the southern margin of the Cairnmuir Mountains, as was thought previously (e.g. Turnbull 2000). A monocline fold has deformed old, high-level, river terraces immediately north of Clyde township (Figure 5.8), but there has been no discernible deformation of the lower river terraces upon which Clyde is situated. Further investigations and assessment would be needed to determine potential ground deformation hazards and risks for Clyde in relation to a future rupture of the Dunstan Fault Zone.

Figure 5.8 Views of a Dunstan Fault Zone monocline fold immediately northeast of Clyde. **Upper panel**: A panorama looking northwest towards a broad topographic step that is a monocline scarp, highlighted by red arrows and up versus down letter annotation. The arrowed drilling rig illustrates scale. The monocline extends north-northeast across high-level terraces of the Clutha River. Clyde township lies on low terraces of the Clutha River, immediately to the left of this view. **Lower panel**: Named the 'Reservoir-3 monocline', the fold scarp was examined in a geological investigation trench, positioned at the point of the left-hand arrow in the upper panel. In this northward view, the trench showed that the Clutha River sediments here are tilted by monocline movement. The sediments have a dip from horizontal of between 4° to 5°, whereas the usual depositional angle of Clutha River sediments is less than 1°. Geological dating showed that the river sediments are at least 200,000 years old, and the overall investigation finding was that the monoclinal warp of the river deposits is between 20 and 25 m high, up to the northwest. Photos: GNS Science, D.J.A. Barrell, taken April 2005 (upper) and February 2006 (lower).

Prominent fault zones in bedrock that pass through the Alexandra area (Turnbull 2000) have been classified as 'possible' active and identified here as the Galloway fault zone. This is based on the detection in lidar of a 'likely' fault scarp at the southern margin of the Blackmans Fault strand of the Galloway fault zone near Earnscleugh Flats, but evidence for geologically-recent elsewhere along the fault zone is inconclusive. The scarcity of surface expression of such movements highlights that, if it is an active fault, it has a long recurrence interval, calculated here as ~15,000 years.

5.4.5 Roxburgh Area

Through the Roxburgh area, the Clutha valley follows the line of the Old Man Fault, and the closely aligned Teviot Fault. Geological evidence indicates that very little movement has occurred in the past 300,000 years or so (Hull and Stirling 1992), and both are classified as having very long recurrence intervals.

5.4.6 Maniototo Area

The Stranraer Fault lies about 2 km northeast of Naseby and has displaced medium to high-level terraces in the Little Kye Burn valley, but not the lower terraces (Figure 5.9). The Stranraer Fault is regarded as a strand of the Waihemo Fault Zone, and a recurrence interval of 60,000 years is calculated, indicating that it is a low activity fault.

Figure 5.9 View of the scarp of the Stranraer Fault (Waihemo Fault Zone) across middle to high-level terraces of the Little Kye Burn valley, about 6 km east of Naseby. The base of the fault scarp is denoted by the red arrows and the dotted red line, while the sense of movement is highlighted by up versus down lettering. As seen here looking northwest from Little Kyeburn Road, 3 km north of the Dansey Pass Road intersection, the scarp appears to be about 10 m high on the middle terrace, and about 15 to 20 m high on the high terrace. The low terrace is probably ~18,000 years old and has not offset by the fault. Photo: GNS Science, D.J.A. Barrell, taken January 2018.

The Ranfurly Fault Zone lies 1 km or so south of Ranfurly township. Scarps from the most recent rupture(s) of the fault zone displace low terraces on the Ewe Burn valley floor, and the closely aligned Launceston Fault to the north has offset hillslope landforms, with upthrow on the downhill side. Collectively, an earthquake rupture having occurred since the end of the last glaciation is indicated, but the fault scarps are not much higher across adjacent, much higher and older, river terrace landforms. This indicates that, despite a geologically recent fault rupture having occurred, the recurrence interval is long, assessed here as being about 17,000 years.

6.0 IMPLICATIONS FOR HAZARDS

Since European settlement in the Queenstown Lakes and Central Otago district, there have been no known ground-surface fault rupture events. The geological record and landforms show clear evidence for many zones of geologically-recent (though pre-dating European settlement) fault and fold deformation of the ground surface. This highlights that it would be prudent to treat the active fault or fold features of the Queenstown Lakes and Central Otago districts as potentially hazardous. Figures 1.2 and 1.3 illustrate examples of the types of ground-surface deformation hazards associated with active faults or active monoclines, noting that at any location, elements of both faulting and folding may be present within a deformation zone. Faults present the most focused form of ground deformation, in regard to direct rupture, while monocline movement involves broader tilting of the ground surface. Monocline growth is likely to occur in a sudden event, associated with rupture of an underlying fault.

The geological estimates presented in this report indicate that none of the faults in the Queenstown Lakes and Central Otago districts has a recurrence interval of less than 5,000 years, only nine have assessed recurrence intervals of less than 10,000 years, and the rest are considered to have recurrence intervals of more than 10,000 years. For many of those inferred low-activity faults, there is uncertainty as to whether they should in fact be considered active, but their potential for future activity cannot be ruled out. Nonetheless, there are several undoubtedly active faults in the Queenstown Lakes and Central Otago districts and every reason for authorities and residents to be prepared for the occurrence of ground-surface rupturing fault movements, and resulting large, locally damaging earthquakes, over future decades to centuries. It is important to appreciate that the mapped delineation of the active faults and folds of the Queenstown Lakes and Central Otago districts presented in this report has been done at a regional scale (1:250,000). The level of precision is not adequate for any site-specific assessment of hazards (e.g. planning for building or other infrastructure developments). In addition, several of the fault/fold features that have been mapped have not yet been proven to be active. For features classed as 'likely', or 'possible', it would be desirable to prove one way or the other whether they are hazardous active faults/folds, before undertaking any hazard planning, zonation or mitigation in respect to these features.

It is reiterated that the information presented in this report, and the accompanying GIS layers, is primarily intended for indicating general areas where there may be an active fault ground-deformation hazard to look for, and where site-specific investigations may be necessary prior to development.

7.0 CONCLUSIONS

1. Regional geological mapping has identified a number of active fault and fold features in the Queenstown Lakes and Central Otago districts. In total, 48 known, suspected, possible or potentially active faults are delineated. The existence of most of these faults was already known, and they have previously been shown on published geological maps, for example, although many were classified as ‘inactive’.
2. A GIS dataset of information on the active faults and folds accompanies this report. For each mapped fault and fold, an attribute of ‘certainty’ indicates the level of confidence in the mapping of the feature, whether ‘definite’, ‘likely’ or ‘possible’. Also included is a classification of ‘surface form’, whether ‘well expressed’, ‘moderately expressed’, ‘not expressed’ or ‘unknown’. The surface form classification provides a provisional estimate of how easy it would be to pinpoint the location of the particular fault or fold feature on the ground.
3. Table 5.2 summarises what exists in the way of geological evidence for the degree of activity of each feature. Average slip rate is a common way to compare the level of activity of a fault or fold. This can also be expressed as an average recurrence interval for deformation events, aided by some assumptions. The recurrence interval estimates provide a linkage to Ministry for the Environment active fault planning guidelines.
4. The information presented here is not sufficiently precise for site-specific hazard assessment. Instead, the information is intended to highlight those areas which, at the current state of knowledge, are potentially affected by active fault or fold hazards. The information may help to target site-specific investigations that may be desirable, or required, prior to development, and allow identification of lifeline vulnerabilities and emergency management response plans.

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APPENDICES

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APPENDIX 1 GIS DATASET

The GIS dataset referred to in this report comprises an ArcGIS file geodatabase, containing three Feature Classes:

- CODC-QLDC_active faults_Feb 2019
- CODC-QLDC_active folds_Feb 2019
- CODC-QLDC_active fault entity_Feb 2019

The original attribute fields for first two feature classes were extracted from the QMAP (Quarter-Million-scale geological mAP) 'seamless' dataset (Heron, 2014), sourced from map data represented in the Queenstown Lakes and Central Otago districts by the Waitaki map (Forsyth 2001), and in the far northwestern part of the Waitaki District by the Aoraki map (Cox & Barrell 2007), Haast map (Rattenbury et al. 2010) and Wakatipu map (Turnbull 2000).

In order to make clear the linkage between the QMAP dataset and the amended dataset prepared as part of this project, several attribute fields of the QMAP dataset are retained, comprising ‘NAME’, ‘ZONE’, ‘DOWN_QUAD’, ‘QMAP_NAME’ and ‘QMAP_NUMB’. In addition, for the folds feature class, the QMAP fields of ‘TYPE’ and ‘FACING’ are retained. New fault or fold features in the dataset can be identified by an absence of data attributes in QMAP_NAME and QMAP_NUMB database fields.

For this project, three new feature classes are added:

- ORC_name (local names for the mapped features)
- Certainty (see report text)
- Surf_form (see report text)

Unless indicated otherwise, all the data have been compiled at a regional scale (1:250,000) and the locations of active faults and folds should be regarded as having a general accuracy of ± 250 m, and at best, ± 100 m. The geographic coordinate system for the data is New Zealand Geodetic Datum 2000.

Interested readers can examine and query the QMAP digital database (Heron, 2014) online at GNS Science, www.gns.cri.nz, search term < QMAP digital data webmap >.

APPENDIX 2 COMMENTARY ON ACTIVE FAULT MAPPING

A2.1 Background Information

The information in this Appendix is largely of a technical nature and written for a technical audience. Its primary purpose is to set out the knowledge basis for the interpretation of faults and folds in this report. Readers of this Appendix may find it of benefit to refer to Google Earth, and topographic maps, such as may be accessed from www.topomap.co.nz.

The source of information on active faults and folds described in this report is from the 1:250,000-scale Geological Map of New Zealand, dubbed ‘QMAP’ because the map is at ‘quarter-million’ scale. Compiled between the mid-1990s and 2010, the maps were published as ~160 km by ~160 km individual sheets in a nationwide cut-up. The Queenstown Lakes and Central Otago districts are encompassed by four published map sheets, with accompanying descriptive booklets, comprising the Wakatipu map (Turnbull 2000), Haast map (Rattenbury et al. 2010; headwaters of the Wanaka and Hawea catchments), Murihiku map (Turnbull and Allibone 2003; southernmost part of Central Otago District) and the Waitaki map (Forsyth 2001; eastern part of Central Otago). Subsequently, all the digital datasets from which these maps were generated were compiled into a nationwide ‘seamless’ dataset, published in digital form on DVD (Heron 2014). The subsets of 1:250,000 scale faults and folds that form the Queenstown Lakes and Central Otago district dataset presented in this report were extracted from the Heron (2014) seamless QMAP dataset.

The classification of active faults and folds in the QMAP dataset, especially in the eastern South Island sheets, is largely evidence-based. Where there is observed evidence for geologically-recent movement, such as offset landforms or offset young deposits, the fault, and closely adjacent sectors of the fault, were attributed as ‘active’, whereas other, more distant, sectors of the same geological fault were attributed as ‘inactive’. While the subdivision of a fault into active and inactive sector is somewhat artificial (a fault is either entirely active or it is not), it provided a way of emphasising evidence of recent activity on a fault in a particular area (attributed as ‘active’) and distinguishing that from faults whose existence is identified on geological criteria, but for which there is no specific evidence for or against recent movement. Thus, in the QMAP dataset, particularly in the eastern South Island, the attribution of a fault as ‘inactive’ means that rather than the fault being definitively ‘inactive’, there is no known evidence demonstrating that it is active. Much of the QMAP delineation of faults classified as ‘active’ in the central to lower South Island has been taken up, with little modification, into the New Zealand Active Faults Database (NZAFD; Langridge et al. 2016).

Subsequently, a more conceptual interpretation of fault activity in the Southern Alps was published by Cox et al. (2012), which identifies a considerable number of what are called ‘potentially active’ faults. A similarly generalised nationwide interpretation of active faults (the New Zealand Active Fault Model – NZAFM), was published by Litchfield et al. (2013, 2014). In the South Island, the information in the NZAFM is largely derived from reviews undertaken by the GNS Science earthquake geology team between 2005 and 2008, as described in Litchfield et al. (2013, 2014) The NZAFM datasets indicate the generalised location (at a scale of the order of 1:1,000,000) of faults that are known or inferred to be active, based on a range of geological considerations. In similar vein, many of the generalised faults depicted by Litchfield et al. (2013, 2014) are incorporated, again in highly generalised form, in the current version, compiled in 2010, of the National Seismic Hazard Model (NSHM; Stirling et al., 2012). The 2010 NSHM dataset focuses on identifying the location of faults that are considered to be potential sources of large earthquakes. The 2010 NSHM dataset is used primarily to generate statistical estimates of the likely maximum intensity of earthquake motions at any specified location in New Zealand, over specified time ranges (e.g. 500 years, 2500 years). For simplicity, any references made henceforth to the Litchfield et al. (2013) detailed report, and the Stirling et al. (2012) paper and associated datasets, are respectively the NZAFM and 2010 NSHM.

The dataset presented in this report is based on the 1:250,000-scale QMAP fault and fold dataset, unless indicated otherwise. In a number of places, refinements have been made to fault locations using lidar data or high-resolution colour aerial imagery, the latter accessed through the Google Earth platform, and through an imagery base map service delivered with the ArcGIS mapping software used for this project. In some cases, archival black and white aerial photography held by the GNS Science Dunedin Research Centre was examined, interpreted geomorphologically by the writer, and used to assist improved locational mapping of fault-related landforms. Commentary on these refinements, and the addition of any newly-identified, or reinterpreted, fault features, is provided in this appendix.

Extensive reference is made to the ‘Otago peneplain’, which is a key geological reference entity for assessing tectonic deformation in the eastern to south-eastern South Island. It is part of the Waipounamu Erosion Surface (Landis et al. 2008), which marks a major unconformity on top of Mesozoic-age rock, and at the base of younger sedimentary cover strata that were deposited on the older rock. In the project area, the peneplain is recognised as the top of schist or greywacke rock, where formerly overlying cover strata have been largely or completely eroded away, but with little erosional modification of the underlying rock (e.g. denudation of less than a few tens of metres).

The methodology of the 2010 NSHM was used for this project to calculate recurrence intervals for faults not previously in the 2010 NSHM, or for faults whose lengths have been revised. The 2010 NSHM methodology calculates, among other things, values for recurrence interval and single-event displacement from estimates of fault length, fault dip (the inclination from horizontal of the fault plane) and slip rate. Those estimates are usually determined by an expert panel of geoscientists, drawing on available geological information. For the present report, they were undertaken by the writer, in order to produce preliminary estimates, as explained for each fault in this appendix. It is expected that a panel approach would be used if new faults identified here are in future taken into the NSHM environments.

In this appendix, faults are discussed in alphabetical order. The adopted slip rate and recurrence interval estimates are compiled in Table 5.2 in the body of the report.

A2.2 Backbone fault (feature 45; Figure 5.3)

The north striking Backbone fault is a newly recognised feature on the western flank of the Lammerlaw Range, with an indicated a vertical separation of the peneplain of between ~100 and 200 m, up to the west. The feature as defined here is not included in the QMAP, NZAFD, NZAFM or 2010 NSHM datasets, but see later paragraph regarding a nearby short active fault feature on QMAP.

The name is taken from Backbone Ridge, in the Little Beaumont Stream catchment. It is an inferred fault, because there are no known recorded geological field observations of fault outcrop and the fault is positioned along the foot of the topographic escarpment. It is assumed to be a west-dipping reverse fault. In this dataset, it is mapped as extending from the Tuapeka Fault, just outside the Central Otago District, north to enclose Teviot Swamp, high on the

Lammerlaw Range. It approaches, but does not cross, the Beaumont River fault escarpment (see below).

The Backbone fault lies close to a short (~1 km long) segment of active fault depicted in QMAP and included in the NZAFD. However, review of archival aerial photos and high-resolution colour aerial imagery indicates that the topographic lineament previously interpreted as a fault scarp is more likely related to slope movement, and the short active fault feature is deleted from this dataset.

Following on that that revised interpretation, there are no discernible offsets of geologically young landform features and the Backbone fault is classified here as a 'potentially active' fault. For the estimation of activity parameters, the Backbone fault is assigned a dip of 60°, length of 24 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~35,000 years is calculated.

A2.3 Beaumont River fault (feature 46; Figure 5.3)

The north striking Beaumont River fault is a newly recognised feature across which there is an indicated vertical separation of the peneplain of between ~100 and 200 m, up to the east. It is an inferred fault, because there are no known recorded geological field observations of fault outcrop. It is not included in the QMAP, NZAFD, NZAFM or 2010 NSHM datasets.

The fault is positioned along the topographic escarpment, using a variety of landform features visible in high-resolution colour aerial photography. These include prominent gaps in rock outcrop, arrays of small landslides, and prominent seepage lines in the slope. Along sections without any other information, the fault is drawn at the foot of the escarpment.

The fault escarpment forms the eastern margin of the Beaumont River catchment, from which the fault name is taken. The fault crosses the crest of the Lammerlaw Range, and for most of its length, approximates the drainage divide between the Clutha and Taieri catchments. The southernmost ~15 km of the fault lies in the Clutha District. It is mapped as extending from the Tuapeka Fault north to the eastern side of Lake Onslow. Beyond there, a broad, slightly asymmetric hanging-wall anticline extends north a further 8 km, before petering out approaching the Long Valley Fault.

There are no discernible offsets of geologically young landform features, and the Beaumont River fault is classified here as 'potentially active', 'not expressed'. For the estimation of activity parameters, the Beaumont River fault is assigned a dip of 60°, length of 36 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~50,000 years is calculated.

A2.4 Blackstone Fault (feature 31; Figures 5.2–5.3)

The Blackstone Fault marks the eastern side of the Raggedy Range to Blackstone Hill ridge, whose axis is an anticlinal fold. It is unclear the extent to which that margin of the ridge is an over-steepened anticline limb (e.g. Markley and Norris 1999), or an emergent fault. Several suspected fault scarps have been depicted along the margin of the range (Forsyth 2001). There is poor coverage from archival aerial photos, and no lidar coverage. In order to highlight the uncertainties on this structure, the QMAP linework is adopted without modification, and all the mapped fault strands are classed as 'possible'.

This fault is identified by the name ‘Raggedy’ in the NZAFM and 2010 NSHM. The name ‘Blackstone Fault’ has been in long-standing geological usage and is applied in both editions of the QMAP dataset (Mutch 1963, Forsyth 2001). That name thus has precedence and is retained in the present dataset. The slip rate of 0.5 mm/yr assigned in the 2010 NSHM is judged too fast to accord with the poor topographic expression of ‘possible’ fault scarps. The rate of 0.14 mm/yr used in the NZAFM is considered more suitable and is adopted here.

A2.5 Blue Lake Fault (feature 23; Figures 5.2–5.3)

The Blue Lake Fault is a major north-northwest striking fault which has produced vertical separation of the peneplain of as much as ~1000 m, largest in the central sector of the fault and diminishing progressively north and south. Henne et al. (2011) present evidence that the Blue Lake Fault was initiated in the mid-Cretaceous as a major normal fault, downthrown to the east. In the Late Cenozoic, movement was reversed, resulting in the uplift of the St Bathans Range. At the Manuherikia River, evidence is presented for minor reverse movement of the fault during the Miocene, and relatively little movement subsequently (Henne et al., 2011). The southern limit of the fault is placed at its intersection with the Blackstone Fault at Pennyweight Hill, where the post early-mid Miocene throw displacement is no more than ~100 m (Beanland and Forsyth 1988), who also reported that the Blue Lake Fault does not cross the Blackstone Fault, whose prominent expression is an anticline.

At the Manuherikia River, three parallel fault strands are indicated, and were referred to as the Blue Lake Fault Zone by Henne et al. (2011). However, the north-eastern strands have previously been referred to as the Stranraer Fault by Madin (1988) and as the Waihemo Fault System by Forsyth (2001). In order to minimise confusion and reduce any connotations of direct association with other faults, these two north-eastern parallel strands are referred to in this dataset as the Home Hills fault zone (see separate section).

Topographic steps along a ~ 7 km long stretch of the Blue Lake Fault on the eastern side of the Dunstan Creek valley, down to the west, interpreted as fault scarps on QMAP, appear on modern imagery to be the result of landslide movement, with headscarps in places offsetting scree aprons upslope, and toe thrusts breaking out within sheared schist of the Blue Lake Fault zone. The landslide interpretation is strongly favoured because elsewhere along the fault, there are no offsets of landforms of comparable age to those that are offset prominently along the ~7 km long sector of the fault. With the new interpretation, there is no compelling evidence for Late Quaternary surface rupture of the Blue Lake Fault.

The Dunstan Fault Zone appears to die out against the Blue Lake Fault and raises the possibility of motion transfer from that fault to the Blue Lake Fault. For that reason, the Blue Lake Fault is identified here as a ‘possible’ active fault. It is classified as ‘not expressed’, except for the 7 km long sector interpreted as having experienced landslide movement, which is classified as ‘moderately expressed’.

In the 2010 NSHM, a slip rate of 0.47 mm/year is applied to the Blue Lake Fault, and a recurrence interval of 6080 years was calculated. This originates from the interpretation that the landform offsets, here attributed to landslide movement, were formed by fault rupture. The stratigraphic evidence for syn-depositional movement of the Blue Lake Fault in the Middle Miocene allows the use of an approach that differs from other faults in the region, for which there is evidence of post-Middle Miocene movement, but no constraint on when, post-Middle Miocene, their movement began. For the Blue Lake Fault, a slip rate is obtained here by dividing the ~1000 m maximum offset of the peneplain, by an assumed initiation at ~15 million years ago. This returns a long-term average vertical slip rate of 0.07 mm/year. In conjunction with an assumed pure dip-slip motion, an adopted fault dip of 70° east and fault length of 41 km, the latter two from the 2010 NSHM, a revised recurrence interval of ~40,000 years is calculated. This estimate acknowledges the possibility that the Blue Lake Fault has been a slow slip rate throughout its history. Alternatively, if the fault has been more active in the past, for example during the Miocene, the slip rate estimated here is likely to be a maximum, and the recurrence interval a minimum, for the recent geological past.

A2.6 Cardrona-Hawea fault (feature 11; Figures 5.1–5.2)

Geological relationships indicate the presence of a substantial northeast-striking fault, upthrown on its north-western side, extending from near the Cardrona/Clutha river confluence towards Lake Hawea. The fault lies somewhere between the basement rock massif of Mt Iron, and steeply-dipping Cenozoic-age sedimentary strata exposed in the banks of the Clutha and Hawea rivers near Albert Town. The fault is further extrapolated northeast between Mt Maude, composed of basement rock standing 1 km above the Wanaka/Hawea basin, and Camp Hill, on whose northwest side is an exposure of gently-dipping Cenozoic strata resting on bedrock.

New information that has led to the NW Cardrona Fault being repositioned northwards near Wanaka, at least in regard to its most recent ruptures, necessitates a status change for the northeast-striking fault that extends northeast between Wanaka and the Hawea area. It is not known whether it was formerly part of the NW Cardona Fault, or is simply a similar, but separate, fault. In this dataset, this fault is renamed the Cardrona-Hawea fault, to avoid any confusion in regard to recent (post-glacial) activity of the NW Cardrona Fault.

Lidar confirms previous visual assessments that the surfaces of glacial outwash plains, assessed as being 18,000 years old, are not deformed across the line of the Cardrona-Hawea fault, indicating that this fault has not experienced surface rupture in at least in the past ~18,000 years. Due to indications of geologically young activity on the faults against which it terminates, it is classified here as a ‘possible’ active fault. It characterised as a 60° northwest dipping fault, with a nominal slip rate of 0.05 mm/year, and length of 23 km, extending from the NW Cardrona Fault in the southwest, northeast beneath Lake Hawea township to a presumed three-way intersection with the Grandview Fault and Hunter River faults (see separate sections). Using 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.7 Cluden fault zone (feature 19; Figure 5.2)

As discussed in the section on the Pisa Fault Zone, what was formerly interpreted as the north-eastern sector of the Pisa Fault is interpreted here as a separate entity. It comprises three northeast-striking strands showing offset of the peneplain, with local remnants of overlying Cenozoic strata. Displacement on each strand is up to the northwest. They are collectively named the Cluden fault zone, after nearby Cluden Stream. The two north-western strands are closely spaced, being no more than 2 km apart. Each has as much as ~100 m vertical separation of the peneplain, while the third strand lies as much as 4 km to the southeast and has as much as ~200 m of vertical separation of the peneplain. Their collective vertical separation of the peneplain is about 300 to 400 m. They appear to terminate to the northeast against the Longslip Fault (Lindis Pass Fault Zone). To achieve sufficient length to have produced the observed peneplain displacement, the Cluden fault zone must extend southwest to near the southern end of the Grandview Fault. This affords a maximum length of ~26 km for the Cluden fault zone.

Previous workers have suggested that to the northeast, the Pisa Fault Zone continues along the foot of the Lindis Peak range (Officers 1984; Halliday 1986; Beanland and Berryman 1989).

The major difference of interpretation here is that the uplift of the Lindis Peak range is attributed to the Goodger Fault on its north-western side, meaning that the south-eastern face of the range is not a range-front fault scarp, as previously interpreted, but rather a dip slope off the uplifted block.

Although the interpretation is not explained, Figure 1 of Halliday (1986) shows a ~600 m wide, ~50 m amplitude monoclinal fold in the post-Lindis lake sediments under the Clutha River channel, about 5 km west of Tarras, on the projected line of the Pisa Fault (now referred to here as the Cluden fault zone), There is a note written on the map that lake sediments there have dips of as much as 9°. The only surface deformation feature interpreted in this immediate area on QMAP comprises a warp on a terrace of correlated ‘Luggate’ age, near Jolly Road. However, the area lies just within lidar coverage. Examination of the lidar suggests that these landforms are probably old alluvial fan remnants built out onto a river terrace. It is possible that the apparent gradient anomaly could be due to overlapping alluvial fan surfaces, and for that reason, the feature is classified as ‘possible’, ‘moderately expressed’ in this dataset.

Farther to the west, where the two north-western strands have merged, aerial imagery indicates that there is a linear, though vague, topographic step, up to the northwest and 10 or 15 m high, running across old, very dissected, alluvial fans surfaces. It is classified here as a ‘moderately expressed’ ‘possible’ fault scarp.

A potentially important topographic feature is evident at Cluden Hill saddle on SH 8, ~7 km east-northeast of Tarras village. To the north are dissected moraine/outwash terraces that stand ~50 m higher than very extensive moraine/outwash terrace remnants to the south. They have been interpreted and mapped as two different sets of glacial landform sets, the older ‘Lowburn’ landform set to the north, and the younger ‘Lindis’ landform set to the south. This change is on the projection of the main strand of the fault, and it is tentatively suggested that at this location, these terraces were originally a single landform set that has subsequently been deformed by fault movement. This tentative interpretation is highlighted by classifying the fault near Cluden Saddle as ‘moderately expressed’.

Overall, the three strands of the Cluden fault zone are inferred to merge towards the west into a single strand. Apart from the ‘moderately expressed’ features discussed above, other parts of the fault zone are classified as ‘possible’, and ‘not expressed’.

For consistency with previous work, the Cluden fault zone is characterised with similar parameterisation as applied to the Pisa and Grandview faults in the 2010 NSHM, with a net slip rate of 0.1 mm/year. Inferring a fault plane dipping 60° west-northwest and a fault length of 26 km returns a recurrence interval of ~17,000 years.

A2.8 Cross Eden fault (feature 34; Figure 5.3)

The Ranfurly geological map (Bishop 1979) showed a short northeast-southwest striking un-named fault concealed under the valley floor of Ewe Burn East Branch. Geological relationship either side of the stream valley imply that the fault has at least several hundred metres upthrow to the east. To the east, schist outcropping at Quartz Reef Hill is overlain by the Cenozoic cover rock strata dipping gently to the southeast through the Naseby area, whereas Late Cenozoic Maniototo Conglomerate lies on the western side of the valley. As mapped (Bishop 1979), and incorporated directly into QMAP (Forsyth 2001), the fault has been shown as only ~2.5 km long. It is likely that this was done because it was unclear where to draw its southern continuation. Strikes of southeast, south, or southwest are equally possible. In order to give the fault a plausible length to account for the geological relationships, I have extrapolated it to the southwest, along the eastern margin of a belt of steep and locally folded Cenozoic strata, whose bedding traces are in places visible in aerial imagery. Although these dipping strata have not previously been reported, and no structural attitudes measured, the aerial photographic evidence is judged sufficient basis for the faulting interpretation made here, of a 60° eastward dipping reverse fault, of 25 km length. The fault name is taken from Cross Eden Creek, which flows southwest for ~4 km along the line of the fault, an unusual drainage direction for this sector of the Maniototo Plain.

There are no indications of geologically-young offsets on the fault, except at its southwestern end where these is a 'well expressed' 'likely' scarp. The interpretation is made here that it is probably represents slip transferred from a strand of the Gimmerburn Fault Zone, which does deform geologically-young landforms.

A2.9 Dansey Pass Fault (feature 36; Figure 5.3)

Mapped in bedrock by Bishop (1976), the Dansey Pass Fault is thought to be associated with Cretaceous normal movement that led to deposition of the Kyeburn Formation (Bishop and Laird 1976), with substantial reversal of movement in the Late Cenozoic, there are no known offsets of geologically-young landforms, and it is classified as 'potentially active'.

The Stranraer Fault was also involved in the Cretaceous normal faulting regime, and there is a geologically-recent on that fault (see Figure 5.9 in the body of the report). The question arises as to whether the Stranraer Fault movement also involved the Dansey Pass Fault. However, there are scarps on the adjacent Waihemo Fault Zone to the east, similar in form to that of the Stranraer Fault, and on balance, an association is made in this dataset between the Stranraer Fault and Waihemo Fault Zone.

A length of 28 km and nominal slip rate of 0.05 mm/yr are applied to the Dansey Pass Fault, and a recurrence interval of ~40,000 years is calculated.

A2.10 Dingle Fault (feature 15; Figure 5.1)

This northeast-striking fault is mapped in bedrock (Turnbull 2000; Rattenbury et al. 2010), based on a difference in basement rock type either side of the fault (schistose greywacke to the northwest, semischist to the southeast). It has been identified as a 'potentially active' fault by Cox et al. (2012) and Litchfield et al. (2013, 2014). The peneplain is not preserved in this area, and it is not known whether or not there has been any Late Cenozoic deformation. Its inclusion in this dataset, and that of Barrell (2016), is on account of its inclusion in the NZAFM. It is not included in the 2010 NSHM.

There have been inconsistencies in the naming of this fault, and this is discussed in the report by Barrell (2016). The position of the Dingle Fault in this dataset is taken from the QMAP digital dataset (Heron 2014) and differs slightly from the more generalised depictions of its location given by Cox et al. (2012) and Litchfield et al. (2013, 2014).

As there is no evidence for any landform offsets along the Dingle Fault, it is classified here as 'potentially active', with a surface form attribute of 'not expressed'. The northern ~11 km of the mapped fault lies in the Waitaki District (Barrell 2016). Using 2010 NSHM methodology, with a nominal length of 40 km, a dip of 60° southeast and nominal slip rate of 0.05 mm/year, a recurrence interval of ~55,000 years is calculated.

A2.11 Dunstan Fault Zone (feature 22; Figures 5.2–5.3)

The northeast-striking Dunstan Fault Zone is the most thoroughly investigated active fault in Otago, due to its proximity to the Clyde Dam. Investigations in the early 1980s were reported by Officers (1983), with a summary published by Beanland et al. (1986). Further work, involving trenching of fault scarps and dating of past movements was carried out in the mid-2000s (GNS Science, unpublished data 2007), as part of an earthquake hazard reassessment for the Contact Energy, owner and operator of the Clyde Power Station.

Lidar information has become available along the Dunstan Fault Zone since the above studies and has been used to adjust the fault strand locations in the QMAP dataset to more accurate positions. Only new findings or significant changes to previous mapping are outlined below, from northeast to southwest.

About ~8 km northeast of Lauder village, lidar information indicates a previously unreported fault scarp, about ~1.2 km long, immediately north of Lauder Creek farm homestead. This east-trending scarp offsets a flight of stream terraces by between 2 and 4 m, upthrown to the south. It can be traced using lidar profiling farther east as a broad monocline for at least 2 km, with an amplitude of uplift of ~1 m to the south. Notably, this scarp lies southeast (basinward) of the main scarps of the Dunstan Fault Zone and is upthrown the other way. Without having more context for it, it is included here within the Dunstan Fault Zone, identified as the ‘Lauder strand’. It is classified a ‘likely’ feature, until such time as any future field investigations are carried out.

A similar feature occurs at Devonshire Road, ~8 km northwest of Omakau, where a northeast-trending fault scarp crosses a broad stream plain, known as the Devonshire Fan, and has ~1 to 2 m upthrow to the southeast. It is classified as ‘likely’ because there is a small possibility that it may have been cut by stream action. To the northeast, it intersects the Dunstan Fault Zone scarps immediately north of Wallington Road. To the southeast, the fault scarp meets the terraced valley of Chatto Creek, and the current limit of lidar coverage, and cannot be traced further in that direction. It is classified in this dataset as the Dunstan Fault Zone - Wallington strand.

A third similar feature has been identified using lidar information at Moutere Disputed Spur Road, ~12 km west of Omakau. A ~1.7 km long, east-trending topographic step, up to the south, crosses high-level stream terraces on the northern side of the Young Hill Creek valley. The step is as much as several metres high and is judged a ‘definite’ fault scarp because the topographic profile along the base of the topographic step is horizontal. Therefore, the step cannot have been formed by stream action, because that would have required a downstream gradient for water flow. To the west, the scarp meets the line of the Dunstan Fault Zone. To the east the terrain is more irregular and gullied, and the feature is difficult to trace. It is extrapolated for 2 km beyond the ‘definite’ scarp along the margin of higher ground to the south, to the edge of lidar coverage, and stopped there. It is identified in this dataset as the Dunstan Fault Zone - Disputed Spur strand.

Lidar profiling does not support the existence of the ‘Kilmarnock’ trace on the western side of the Campbell Creek valley, ~14 km northeast of Clyde, or the ‘Brassknocker - 2’ trace on the coalesced alluvial fan of Young Hill Creek and Dry Creek, ~11 km northeast of Clyde, as depicted on maps in Officers (1983) and included on QMAP. Both traces are drawn as arcuate steps across broad alluvial fan landforms and described as ‘subtle’ steps up the northwest. They approximately follow the topographic contour on each fan. Because there is no step revealed by lidar information, each is interpreted to mark an upstream increase in gradient on each fan that, viewed from down-fan positions, may have looked like a step running across each fan. Here, they are both interpreted to be related to stream depositional processes and both have been removed from this active fault dataset.

Lidar information reveals that the Waikerikeri - 2 trace of Officers (1983) breaks into two separate fault scarps immediately to the northeast of an early 1980s trench investigation site in Waikerikeri valley, ~5 km northeast of Clyde. The north-western scarp (classified in this dataset as Waikerikeri-2a) continues northeast parallel to the Waikerikeri-1 fault scarp, and between 150 and 200 m southeast of it, as mapped by Officers (1983).

The south-eastern scarp (identified here as Waikerikeri - 2b) has not previously been reported. It diverges east-northeast from the Waikerikeri - 2 fault scarp, crosses the Waikerikeri Creek valley. Lidar indicates that along the Waikerikeri - 2b fault, there are low scarps (0.5 to 1 m high) across the floors of incised minor tributary valleys draining to Waikerikeri Creek, and a scarp of similar height is indicated across part of the Waikerikeri Creek valley floor. Due to the smallness of the valley-floor scarps, it has been classified as 'likely', until such time as future field investigation is undertaken. As there is no indication of valley floor displacement along either the Waikerikeri-1 or Waikerikeri-2a faults, it appears that the most recent fault surface rupture in the Waikerikeri area was along the Waikerikeri - 2b fault.

To the northeast, the Waikerikeri - 2b strand is inferred to links to a prominent, also unreported, fault scarp on the Waikerikeri fan, ~6 km northeast of Clyde. Farther northeast, that scarp links with the Kelliher-3 and Kelliher-2 fault scarps identified by Officers (1983).

The Waikerikeri-3 fault trace of Officers (1983), and included in the QMAP dataset, was disproved as a tectonic feature by a 2004 trenching investigation (GNS Science, unpublished data, 2007), and is not included in this dataset.

Southwest of Waikerikeri towards Clyde, investigations during the mid-2000s (GNS Science, unpublished data 2007) have shown that the most recent Dunstan Fault Zone deformation has been concentrated on a monoclinal fold, identified in this dataset as the Reservoir-3 monocline. Movement has warped the prominent and extensive river terrace beside Clyde on the north-eastern side of the Clutha River valley, up to the northwest by ~20 m. This terrace has also been warped by two monoclines, both up to the southeast, lying ~0.4 km (Reservoir-2 monocline, ~2 m high) and ~1 km (Reservoir - 1, ~7 m high) noth-west of the Reservoir-3 monocline. Those smaller monoclines are interpreted to link northwards to the Waikerikeri-1 fault scarp. At Clyde, there is no discernible deformation the lower level terraces of the Clutha River, on which most of Clyde township lies, on the line of those monoclines. This indicates that no monoclinal growth events have occurred since those lower terraces were formed. The Reservoir-3 monocline is extrapolated beneath Clyde as 'not expressed' to an inferred meeting with the Earnscleugh Fault.

There is a structural change in the Dunstan Fault Zone at the Clutha River (Figure A2.1). To the northeast, the Reservoir-3 monocline has produced what the available evidence indicates to be a gentle warp of the peneplain surface (GNS Science unpublished data 2007; see Figure 5.8 in the body of the report). Southwest of the river, the Cenozoic strata are dragged into a near-vertical configuration along what has variously been referred to as the Clyde Fault or Earnscleugh Fault (the latter is applied in the QMAP dataset and is used here). Along the Clutha River at the Clyde Dam is the well-documented, north-northwest striking River Channel Fault, which has a steep dip to the east. Near Dairy Creek, immediately upstream of the dam, is a wide zone of steeply southeast dipping sheared and faulted schist, identified in the QMAP dataset as the 'Cairnmuir Fault – Dairy Creek segment'. A long-standing difficulty in interpreting the southern end of the Dunstan Fault Zone has been resolving the question of the east-striking Cairnmuir Fault, which has produced a 100–200 m offset, up to the north, of the peneplain, and locally dragged the peneplain contact into a vertical bend (Officers 1983). By presumption, it is a north-dipping reverse fault, but what has been referred to as the Cairnmuir Fault Zone, exposed in SH 8 batter near Dairy Creek, dips southeast. Mid-2000s trench investigation of the Cairnmuir Fault at Cairnmuir Flats (GNS Science, unpublished data 2007) found north-dipping fault zones, that could accord with the expectation that the Cairnmuir Fault dips in that direction, but also found no evidence for geological recent surface offsets. For the purpose of this dataset, the steeply east-dipping River Channel Fault, and steeply southeast dipping fault zone in Dairy Creek are presumed to have originally been some sort of a transfer zone between the Earnscleugh Fault, and 'Earnscleugh Structure' monocline, to the southwest, and the Dunstan Fault Zone farther northeast. There is no evidence of recent activity on this inferred transfer system, and notably the fault zone at Dairy Creek has reportedly (McSaveney et al., 1992) not offset the river gravels (inferred to be of 'Lindis' age; see Grandview Fault section) forming the terrace that is warped by the Reservoir monoclines. In this dataset, the Earnscleugh Fault is identified as 'likely' active, because of proximity to undoubted geologically recent movement associated with the Reservoir-3 monocline. The River Channel Fault and 'Dairy Creek segment' are classified here as 'possible' active faults.

The Fish Creek Fault and Cairnmuir Fault components of the Dunstan Fault Zone (features 22a and 22b respectively in Figures 5.1–5.3) are considered likely to be abandoned strands of the currently active fault zone and are classified here as 'possible'.

Farther southwest, towards the intersection of the Dunstan Fault Zone with the Old Man Fault, there is an array of steps attributed to faulting of the peneplain, north of Omeo Creek, near a hillock called Sugar Loaf on topographic maps. The main steps are identified as 'potentially active' faults, and in two cases as monoclines, and all included in the Dunstan Fault Zone. The significance and activity of those fault strands is unknown.

Fault characterisation parameters assigned to the Dunstan Fault in the 2010 NSHM (Stirling et al. (2012), including fault dip of 60° and slip rate of 0.63 mm/yr, differ from those adopted as 'best' values in the NZAFM, comprising dip of 45° and slip rate of 0.9 mm/yr. The NZAFM net slip rate range (between 0.25 and 1.5 mm/yr) and dip range (between 35 and 60°) accord with field-based estimates (GNS Science, unpublished data 2007). However, the field data indicate a long-term average recurrence interval of ~7000 years, which matches the value of 6960 years calculated for the 2010 NSHM (Stirling et al. 2012).

To overcome these discrepancies, Dunstan Fault Zone activity parameters were recalculated for this project, using the 2010 NSHM methodology, aligned with existing field data. The maximum possible length of the Dunstan Fault Zone is ~63 km, that being the distance between the Old Man Fault to the southwest, and the Blue Lake Fault in the northeast, neither of which is crossed by the Dunstan Fault Zone. Using preferred estimates of fault length of 60 km, dip of 45° and slip rate of 0.6 mm/yr, a recurrence interval of 6964 years is calculated, along with a net single-event displacement of 4.2 m, both of which are compatible with field data. Accordingly, slip rate of 0.6 mm/yr and recurrence interval of ~7000 years are adopted in this report.

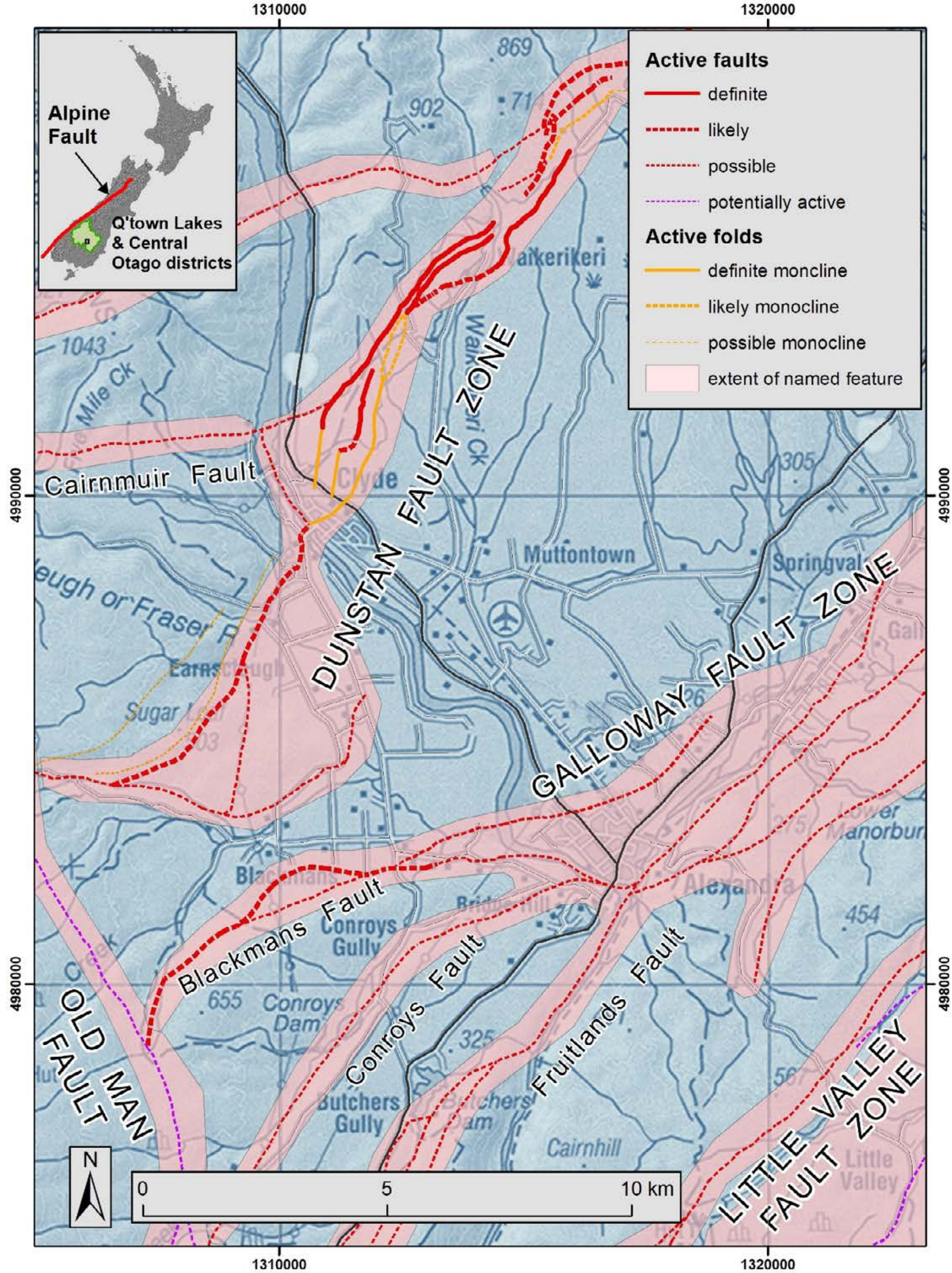

Figure A2.1 Map showing the interpretation and classification of active faults in the Clyde to Alexandra area. The location of the map panel is shown by the black rectangle in the inset at top left.

A2.12 Galloway fault zone (feature 29; Figures 5.2–5.3)

An array of northeast-striking faults, upthrown to the southeast, forms the southwestern margin of the Manuherikia basin, near Alexandra (Figure A2.1). Most are well defined geologically, because the Otago peneplain is extensively preserved on the upthrown side of each fault block, and in places Cenozoic cover strata are preserved on top of the peneplain on the downthrown side. Vertical separation across each fault is between a few tens of metres to as much as 150 m or so. Many of the faults have been named individually, as documented in the QMAP dataset, and the names include the Fruitlands Fault, Conroys Fault, Blackmans Fault and Galloway Fault. The individual faults are no more than 3 km apart and are interpreted here to be splays of a single fault zone at depth. Collectively, the faults are referred to here as the 'Galloway fault zone'. No offset of geologically young landforms or deposits has previously been reported for any of the components of the Galloway fault zone, and these faults are not currently included in the NZAFD, NZAFM or 2010 NSHM.

There is lidar coverage for some parts of the fault zone. The positions of faults as depicted by QMAP have in places been adjusted for this dataset, to accord better with information from lidar, and in areas outside lidar coverage, from high-resolution imagery (aerial and Street View). The only known exposure of any of these faults is on the Conroys Fault, exposed in a cutting on Conroys Road ~1.1 km south of the Chapman Road intersection, where schist rock is thrust over Cenozoic (Manuherikia Group) quartzose sediments on a fault plane dipping southeast at a moderate angle (~40°). On this basis, all components of the Galloway fault zone are regarded as reverse faults. Most of the faults are well defined in the landscape due to the peneplain offset, as illustrated for example in the ~150 m high escarpment of the Fruitlands Fault southeast of the Butchers Dam reservoir, and its north-eastern continuation on which the Alexandra Clock is sited. Despite the prominent peneplain offsets across the Galloway fault zone, there not many places where Quaternary-age sediments straddle the faults, and this hinders the assessment of whether or not there have been any geologically recent surface ruptures.

Close examination of lidar information revealed a topographic step across alluvial fans about 6 km west of the Alexandra town centre, close to the QMAP-defined line of the Blackmans Fault. The step is ~1 to 2 m high, up to the southeast, and is most sharply defined ~0.7 km southwest of the Blackman Road/McIntosh Road intersection. The position of the step midway up an alluvial fan, and alignment across the fan, rather than down the fan as would be expected for a stream-cut feature, suggests that it may be fault-related. Along trend to the southwest and northeast, there are similar, though broader, steps across alluvial fan surfaces. Collectively, these steps are interpreted as marking a 'likely' active fault, either 'well expressed' or 'moderately expressed' depending on the sharpness of the lidar-defined step.

Farther east along strike there is no discernible scarp across the broad floor of Conroys Creek where it emerges onto the main Clutha valley-floor river terrace. About 1 km father east, Earnscleugh Road traverses an old river channel of the Clutha/Fraser river system, cut through rocky terrain and standing a few metres higher than the main Clutha valley-floor river terrace A topographic step runs across an alluvial fan, ~60 m south of Earnscleugh Road and ~0.9 km east of the Conroys Road/Earnscleugh Road intersection. This step is up to the southeast and between 1 and 2 m high. It is however parallel to the grain of schist outcrop in the channel, and also the direction of former river flow down the old channel. Proceeding east, Earnscleugh Road straddles a broad (~60 m wide) topographic step, about 2 m high, on the channel floor. Both these features are classified as 'possible', 'moderately expressed', fault scarps. The potential for origins other than faulting is considered too great to warrant a classification of 'likely', even though the topographic steps are broadly along strike from the 'likely' fault scarps described above.

Records from bridge construction across the Clutha River at Alexandra indicate the possible presence of faults under the river channel. The following account is from Moore (1978), in relation to the original bridge just upstream of the Manuherikia River confluence: "The bridge, opened on June 2 1882, is a tribute to the skill and craftmanship of our pioneers. The 552-foot structure is founded on two magnificent piers, the larger situated on the Alexandra side of the Molyneaux (*Clutha River*). This pier was the most difficult to build as it required a solid concrete foundation. The schistose rock onto which it was to be founded proved to be but a crust, beneath which lay two feet of soft blue clay, followed by a conglomerate of decomposed rock, quartz, and slate. It was decided to excavate into this and lay a three-foot concrete foundation."

One possible interpretation is that the pier penetrated schist rock with an underlying fault zone, although there may be other possibilities (e.g. old riverbank slump debris). The excavation for the southern pier of the new bridge encountered a crushed zone within schist rock (McKellar 1954). The zone dips 30–40° north, and although suggested by McKellar to represent the base of a schist slump, he also noted that it was parallel to a suspected fault zone a few hundred metres to the northeast (Galloway Fault of the present dataset). However, the northerly dip of the crushed zone is opposite to that of the Conroys Fault, which projects northeast close to the location of the bridge. It is conceivable that the crushed zone could be a conjugate fault associated with the Conroys Fault zone.

None of the information from the Clutha bridge excavations allows any firm interpretation of faulting. For the purpose of the present dataset, a provisional interpretation is made that the Blackmans Fault and Conroys Fault merge under the Clutha River channel and pass northeast under the Clutha bridge at Alexandra, to meet the Fruitlands Fault and Galloway Fault close to the Clutha/Manuherikia river confluence. Specifically, the merged Blackmans/Conroys fault is positioned under the north pier of the old bridge (which is still preserved), and between the two piers of the new bridge. This working interpretation is considered the best accommodation of the available geological information and is consistent with the overall topographic relief across the fault array. To the southwest, the vertical separations of the Blackmans (~50 m), Conroys (~60 m) and Fruitlands (~150 m maximum) faults is about the same as the elevation change southeast of Alexandra township, between schist rock outcrop (close to peneplain surface) in the lowest reaches of the Manuherikia River, and the crest of the range-front, as traversed by Little Valley Road. All are classified as 'possible'.

To the northeast, near Galloway, there is a broad northeast trending topographic step, ~1–2 m, high along a Manuherikia valley floor terrace, and in places alluvial fans. Although broadly parallel to the river flow, the step is commonly ~60 to ~80 m wide, and thus has features more in common with a tectonic feature (e.g. a monocline), rather than a river-eroded terrace edge. It is classified here as a 'possible', 'moderately expressed' fault scarp. At its northeast end, the topographic step does not extend across the combined fan/plain of Dip Creek and the Manuherikia River, so those landforms are presumably younger than the last surface rupture, if it is indeed a fault. It is named the Galloway 2 fault, to distinguish it from the QMAP-named Galloway Fault, another parallel strand of the Galloway fault zone, ~0.5 km to the southeast.

An age of late last glaciation (~18,000 years) is assigned here to the landforms offset by ~1–2 m by the 'possible' fault scarps. Although there appears to be no fault-related offset of the main Clutha valley floor terrace that is correlated in QMAP with the 'Albert Town' glacial advance (Turnbull 1987, 2000), other evidence indicates this correlation, and implied age, is incorrect (Barrell 2011, and GNS Science unpublished data 2007). Instead, it is considered more likely that the so-called ‘Albert Town’ terrace in the Clyde to Alexandra area is post-glacial and was formed during incision of the Clutha River into the ‘Hawea’ and ‘Mt Iron’ glacial and outwash deposits in the upper Clutha valley. An age of ~10,000 years is considered more likely. On this tentative basis, the most recent ‘possible’ surface rupture(s) on the Galloway fault zone that may have produced a ~1–2 m high scarp, occurred between ~10,000 and ~18,000 years ago. This implies a low slip rate, and relatively long recurrence interval, for the Galloway fault zone. If instead, the suspected fault scarps have a non-tectonic origin, then the estimates are a maximum for its slip rate and minimum for its recurrence interval.

For the purposes of estimating activity parameters for the Galloway fault zone, a length of 22 km is assigned, from a presumed meeting with the Old Man Fault in the southwest, along the Blackmans Fault, through the area of merged faults at Alexandra and to just beyond the mapped north-eastern end of the Galloway 2 fault. Taking the ‘possible’ 1.5 m vertical component of offset of alluvial fans across the Blackmans Fault and assuming an age of 18,000 years for the alluvial fan landforms, in conjunction with an inferred representative fault dip of 60° southeast, implies a slip rate of ~0.1 mm/year. From the length and slip rate estimates, a recurrence interval of ~15,000 years is calculated for the Galloway fault zone using 2010 NSHM methodology.

Between 3 and 5 km southeast of the main strands of the Galloway fault zone is a semi-parallel fault, across which the peneplain is upthrown to the northwest by several tens of metres. The fault extends northeast from near Lake Roxburgh for ~18 km to the Manor Burn valley. It is assumed to be a northwest-dipping reverse fault, and by implication is assumed to be a ‘back-fault’ splay off the Galloway fault zone. It is identified in the dataset as ‘Galloway fault zone – Shanty fault’ (feature 29a of Figures 5.1–5.3), the latter part of the name being taken from Shanty Creek, along whose valley the southwestern part of the fault runs. It is interpreted here that this strand of the Galloway fault zone is not an independently rupturing active fault, but rather is part of the surface expression of the Galloway fault zone.

A2.13 Garibaldi Fault (feature 32; Figure 5.3)

This fault lies on the south-eastern side of North Rough Ridge and shows peneplain offset of as much as several hundred metres. It shows no known offset of geologically-young landforms. Its name has been in long-standing geological usage and is applied in both editions of the QMAP dataset (Mutch 1963, Forsyth 2001). It is assigned a length of 32 km and nominal slip rate of 0.05 mm/yr, from which a recurrence interval of ~45,000 years is calculated**.**

A2.14 Garvie Fault (feature 27; Figure 5.2)

The northeast-striking Garvie Fault separates the eastern high ridge of the Garvie Mountains from the Dome Burn valley. The fault position is adopted from the QMAP dataset without modification. Only the northern half of the Garvie Fault lies in the Otago region; the southern half is in the Southland region. The Garvie Fault has produced a ~300 to 400 m vertical separation of the peneplain, up to the southeast. There is no evidence for geologically young landform displacement across the fault. It is classified in this dataset as ‘potentially active’. It is proposed here as a potential earthquake fault source, with nominal length of 55 km, a dip of 60° southeast and nominal slip rate of 0.05 mm/year. Using 2010 NSHM methodology, a recurrence interval of ~38,000 years is calculated.

A2.15 Gimmerburn Fault Zone (feature 33; Figure 5.3)

The north to northeast striking Gimmerburn Fault Zone is notable for having great complexity of surface faulting expression, comprising numerous relatively short fault scarps. It is included in the 2010 NSHM and the NZAFM. For ease of reference in the GIS dataset, the fault zone is divided into three general sectors, referred to here as strands.

The 'Gimmerburn Fault Zone – Rough Ridge strand' runs along the southeast side of the Rough Ridge and Little Rough Ridge rangefronts. The rangefronts are up to the northwest, with overall vertical separation of the peneplain of the order of 600 m, diminishing north adjacent to Little Rough Ridge. This strand is assumed to be the surface expression of a northwest-dipping reverse fault. In places, there are closely-spaced en-echelon, left stepping fault scarps, most with upthrow to the northwest. To the south of Brasseys Creek, the fault along the foot of Rough Ridge shows no indication of young scarps. It is classified as 'potentially active' because young scarps are present along the foot of a parallel, unnamed ridge, ~2 to 3 km farther southeast, aligned with a presumption that the most recent activity has emerged on that part of the fault.

The 'Gimmerburn Fault Zone – Sharkey strand' (named after nearby Sharkey Road) diverges northeast from the Rough Ridge strand near Dingo Creek and extends for ~12 km to where it is interpreted to abut the Cross-Eden fault. Stepped ~2.5 km north of there is the start of the 'Gimmerburn Fault Zone – Eweburn strand', which continues northeast for as much as ~20 km towards the valley of Ewe Burn West Branch. Between the Sharkey and Eweburn strands is a belt of deformed Cenozoic strata. This has not previously been reported, but is evident from strike ridges of steeply dipping, and in places tightly folded Cenozoic strata. A similar belt of Cenozoic strata lies between the Eweburn strand and the Cross-Eden fault.

Research on dating the exposure of the peneplain on the upthrown side of the Gimmerburn Fault Zone has been reported, most recently, by Bennett (2005, 2006), building on earlier work analysing drainage pattern development (references therein). There are many assumptions and interpretive challenges in that work, and the results do not as yet place robust constraints on Gimmerburn Fault Zone activity. The fault zone is however an important and complex structure and, in the writer's opinion, is deserving of ongoing research effort.

The 2010 NSHM and NZAFM assign slip rates of 0.5 mm/yr and 0.35 mm/yr respectively to the Gimmerburn Fault Zone. The writer has seen a well-defined fault scarp on the Sharkey strand, just north of the Puketoi Highfield Road and Gibson Road intersection, ~14 km west-southwest of Ranfurly. This appears to be the only specific field estimate of an offset yet reported. It is used here in conjunction with the fault dip of 45° used in the 2010 NSHM and NZAFM, and assumed dip-slip motion, to obtain a net slip value of 0.39 mm/yr. This in turn applied to an adopted fault length of 42 km returns a recurrence interval value of ~7400 years.

A2.16 Goodger Fault (feature 18; Figures 5.1–5.2)

The east-northeast-striking Goodger Fault is mapped and named in the QMAP dataset. It extends for ~22 km between the Grandview Fault in the west and the Longslip Fault to the east. The fault is not included in NZAFM or 2010 NSHM datasets. It is upthrown by between ~300 and 400 m to the southeast, as demonstrated by local preservation of Cenozoic strata in the fault angle, and peneplain remnants. The Lindis Peak range lies on the upthrown side of the Goodger Fault (see sections on the Pisa Fault Zone and Cluden Fault Zone for further discussion). The Lindis River has cut a narrow gorge across the uplifted block, and SH 8 follows the gorge. There is no known evidence for geologically young landform displacement across the fault. The fault position is adopted from the QMAP dataset without modification.

In this dataset the Goodger Fault is classified as 'potentially active', with a length of 22 km, a dip of 60° southeast and nominal slip rate of 0.05 mm/year. Using 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.17 Grandview Fault (feature 12; Figures 5.1–5.2)

This north-striking structure is mapped along the east side of the Wanaka-Hawea basin. The geological basis for its recognition is the presence of Cenozoic strata in the basin, compared to the prominent range-margin along the eastern side of the basin formed in basement rock. Geological investigations for possible dam sites on the Clutha River between 6 and 12 km downstream of Luggate, including mapping and drilling, indicate the presence of a north-south trending monoclinal fold in old glacial lake silt below the valley floor. It has an indicated vertical amplitude of as much as ~80 m and is down-warped to the west (Officers 1984; Halliday 1986; Beanland and Berryman 1989). It is interpreted to reflect deformation due to movement of the Grandview Fault. In the southernmost 6 km, where defined by geological investigation, it is mapped as a concealed monocline. Farther north, it is shown as a concealed fault as per the QMAP dataset (Turnbull 2000; Heron 2014). In that area, there are no data on the position of the fault, other than that it must lie at or west of the foot of the Grandview range.

The age of the lake silt is uncertain, and this makes it difficult to calculate deformation rates. Previous workers all agree with an assumption that the silt was deposited in a glacier trough following ice recession from the "Lindis" advance moraines, which form a prominent belt of terraces southeast of Tarras and down-valley towards Cromwell. Previous age estimates for the lake silt range from 35 to 70 ka (Officers 1984), 90 to 120 ka (Beanland and Berryman 1989) and ~450 ka (McSaveney et al. 1992; Turnbull 2000), based on inferred correlation to global ice ages cycles. Barrell (2011) suggested a correlation to the Nemona Glaciation, with an age of approximately 330,000 years.

No change is proposed here to the parameterisation of the Grandview active fault earthquake source as done in the 2010 NSHM, which applies a net slip rate of 0.1 mm/year to a fault plane dipping 60° east, a fault length of 32 km, and calculates a recurrence interval of ~22,000 years.

A2.18 Hawkdun Fault (feature 25; Figure 5.3)

This major north-northwest-striking fault has uplifted the Hawkdun Range, with as much as ~1 km vertical separation of the peneplain, up to the northeast (Bishop 1976). There are no identified geologically young offsets of landform features, and the fault has long been regarded as inactive and is not included in the 2010 NSHM or NZAFM. Because it is abutted by the Omarama Saddle fault and Rocks Creek Fault Zone, it is suggested here that ruptures on those faults could result in secondary slip on the Hawkdun Fault and it is classified in this dataset as a 'possible' active fault. The Hawkdun Fault has a similar strike and amount of Late Cenozoic offset to that of the Blue Lake Fault. Furthermore, uplift and erosion due to initiation of movement on the Hawkdun, Blue Lake and Waihemo faults is thought to have contributed sediment to Middle and Late Miocene depocentres in Central Otago (Youngson et al. 1998). Using the same approach as applied to the Blue Lake Fault, dividing the ~1000 m maximum offset of the peneplain, by an assumed initiation at ~15 million years ago returns a long-term average vertical slip rate of 0.07 mm/year. Assuming pure dip-slip movement and resolving the vertical rate onto an assumed fault-plane dip of 70° together with a fault length of 57 km, a recurrence interval of ~55,000 years is calculated for the Hawkdun Fault using 2010 NSHM methodology.

A2.19 Highland Fault (feature 5a of Figures 5.1–5.2)

Shown as an active fault in the QMAP dataset, and subsequently included in the NZAFD, the Highland Fault is identified primarily from a series of sharply defined north-south trending fault scarps across hillsides in the Fern Burn catchment on the western side of the Mt Cardrona to Mt Alpha range (see Figure 5.7 in the body of the report). Most of the scarps are up to the west. In QMAP the fault is extrapolated southwest of the prominent scarps to the west side of Middle Peak. That sector of the mapped fault is identified as a 'possible' active fault, but in this dataset, the most recent activity is extrapolated southward through a series of prominent fault scarps east of Middle Peak, into the Back Creek catchment. 'Likely' connectors are drawn between the 'definite' fault scarps in this area. Elsewhere in the Fern Burn catchment, connectors between 'definite', 'well expressed' scarps are classified as 'definite', 'not expressed'. The sharpness of the scarps indicates the most recent rupture(s) occurred sometime after the last glaciation ended ~18,000 years ago.

As the fault is relatively short (~12 km), it is tentatively interpreted as some sort of a splay off the Motatapu Fault, rather than a fault that ruptures on its own. It is provisionally assigned the same slip rate and recurrence interval (~6,500 years) as the Motatapu Fault, noting that these are maximum values for the Highland Fault, because it may not necessarily always rupture in unison with the Motatapu Fault.

A2.20 Home Hills fault zone (feature 26; Figure 5.3)

Between two and three parallel, east-southeast striking, fault strands extend from the St Bathans area towards the Naseby area. They have variously been referred to as the Blue Lake Fault Zone (Henne et al. 2011), Stranraer Fault (Madin 1988) and Waihemo Fault System (Forsyth 2001). In this dataset, these fault strands are referred to as the Home Hills fault zone, to minimise confusion with those other named faults. Exposures along the Manuherikia River show that the Home Hills fault strands are associated with east-northeast dipping fault deformation zones, across which basement rock of lesser metamorphic grade lies north of each fault (Henne et al. 2011). This indicates that they were initiated as normal faults in the Cretaceous, downthrown to the east-northeast. All now have basement rock upthrown to the east-northeast against Miocene-age cover strata, demonstrating Late Cenozoic reversal of throw.

Late Cenozoic offset of the peneplain is about 300 m across the fault zone, comprising about 50 m offset on the southwestern strand and as much as ~250 m on the north-eastern strand. All of the anticlines associated with the northeast-striking reverse faults extend across the Home Hills fault zone. These anticlines include the Raggedy Range – Blackstone Hill – Home Hills ridge on the upthrown side of the Blackstone Fault, the North Rough Ridge – Seagull Hill – Idaburn Hills ridge on the upthrown side of the Garibaldi Fault, and the Woodney Hill ridge associated with the Gimmerburn Fault Zone. This indicates that those faults have propagated northeast across the Home Hills fault zone, presumably cutting it off at depth.

Although Bishop (1979) and Forsyth (2001) mapped the southwestern strand of the fault zone as crossing the crest of Seagull Hill, the fault strand is repositioned in this dataset to curve around the southern margin of the hill, in better accord with the location of the peneplain offset.

There is no indication of any displaced landforms across the Home Hills fault zone, although the fault zone does have topographic prominence, due to basement rock, topped by the peneplain surface, having been upthrown northeast across the fault zone. The interpretation made here that the Home Hills fault zone was, like the Blue Lake Fault, active in the mid-Miocene, and more recent tectonic deformation has focused on the northeast-striking faults. Secondary slippage on the Home Hills fault zone during rupture of the northeast-striking faults is a possibility.

The Home Hills fault zone is not recognised here as an independently rupturing active fault, because it appears to have been dislocated by northeast-striking faults, presumably in the latter part of the Late Cenozoic Era. However, it is classified here as ‘potentially active’, to acknowledge the possible issue of secondary slip. Because such an occurrence would relate to the activity of the various primary fault ruptures, it not meaningful to try and place specific estimates of slip rate or recurrence interval on the Home Hills fault zone. However, to place it into context with the other faults assessed in this report, a nominal recurrence interval of greater than 20,000 years is assigned.

A2.21 Hunter Valley Fault (feature 14; Figure 5.1)

This north-northeast striking structure comes from the QMAP dataset, where it was named the Hunter Valley Fault, and classified as an active fault. This fault was suggested as ‘potentially active’ by Cox et al. (2012) and incorporated into the NZAFM under the name ‘Hunter’ fault zone, but no slip rate parameter was assigned in the NZAFM. It is not currently in the 2010 NSHM, but that sector on the Wakatipu QMAP sheet is included in the NZAFD.

The QMAP name Hunter Valley Fault is preferred here over the name Hunter that is used in the NZAFM, because the former has precedence and also confusion is minimized in relation to the Hunters Fault in South Canterbury (Barrell 2016). For most of its length, the Hunter Valley Fault is concealed under the water of Lake Hawea or the floodplain of the Hunter River. It is inferred to be the structure that separates differing grades of schist rock either side of the Hawea/Hunter valley, comprising semischist to the west and schistose greywacke to the east. Thus, it is likely that the fault originated during the Cretaceous Period.

On the eastern side of the Hunter valley, a semi-continuous topographic step tracks along the glacially-sculpted valley side for ~6.5 km. The step is down to the east, by several metres. It is inferred to be a scarp associated with past surface rupture of the Hunter Valley Fault, because it seems too long and too continuous to attribute to gravitational slope movement. It is classified as ‘well expressed’ and a certainty of ‘likely’ to acknowledge a possibility that it may conceivably be a result of gravitational slope movement on as pre-existing weakness in the rock, rather that fault rupture. The fault depicted under the valley floor in the QMAP dataset is also classified as ’likely’, for consistency with the ‘likely’ classification applied to the surface scarp. The Hunter Valley Fault is characterised in this report as a ‘likely’ active reverse fault dipping 60° to the west-northwest and extending 55 km north-northeast from an assumed ‘triple junction’ with the Grandview Fault and the Cardrona–Hawea fault. For estimating slip rate, the ‘likely’ fault scarp on the valley side is inferred to be 5 m high, and affecting a glacial landform assumed to be 18,000 years old. Taking account of the adopted fault dip and assuming pure dip slip motion, a net slip rate of 0.32 mm/year is obtained, and a recurrence interval of ~12,000 years is calculated using 2010 NSHM methodology.

A2.22 Hyde Fault (feature 39; Figure 5.3)

The northeast-striking Hyde Fault is a prominent geological feature of the Middlemarch and Strath Taieri areas, in the Dunedin City district, but only the northernmost 5 km of the fault is mapped as extending into the Central Otago District. The Hyde Fault is interpreted as a major northwest-dipping reverse fault that has elevated the Rock and Pillar Range. Deformation of geologically-young landforms is evident on the line of the fault in the Middlemarch area, but it is not yet clear whether such movements have extended as far as the Central Otago District. Accordingly, the fault there is classified as 'likely', 'not expressed'. It is expected that the Hyde Fault will be discussed more fully in an anticipated future report on the active faults of the Dunedin City district.

The Hyde Fault is included in both the 2010 NSHM and NZAFM, which assigned a fault dip of 45° and slip rates of 0.25 and 0.71 mm/yr respectively. A more sophisticated analysis by Villamor et al. (2018) considered a range of possible slip rates between ~0.7 and 0.02 mm/yr, which returned recurrence intervals in the range of ~6,000 years to ~200,000 years. The slip rate in the NZAFM takes account of geological dating by the optically stimulated luminescence method in proximity to the Hyde Fault (Norris and Nicolls 2004) that I suspect is incompatibly young in relation to the character of deformed landforms across the fault. For the present dataset the 2010 NSHM values of slip rate and recurrence interval (12,800 years, rounded up here to ~13,000 years) are used, pending further research.

A2.23 Lake Onslow fault (feature 42; Figure 5.3)

The north striking Lake Onslow fault is a newly recognised feature on the eastern flank of the Lake Onslow and upper Manor Burn basins, with an indicated a vertical separation of the peneplain of as much as ~100 m, up to the west. The feature as defined here is not included in the QMAP, NZAFD, NZAFM or 2010 NSHM datasets.

It is an inferred fault, because there are no known recorded geological field observations of fault outcrop and the fault is positioned along the foot of the topographic escarpment. It is assumed to be a west-dipping reverse fault. There are no discernible offsets of geologically young landform features and the Lake Onslow fault is classified here as a 'potentially active' fault. For the estimation of activity parameters, the Lake Onslow fault is assigned a dip of 60°, length of 22 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.24 Launceston Fault (feature 35a; Figure 5.3)

Named in the QMAP fault dataset after Launceston farm in the Hog Burn valley, the fault is identified from a discontinuous array of fault scarps, up to the west, across stream terrace and hillslope terrain. The scarps begin ~4 km southeast of Ranfurly township and extend north-northeast for at least ~10 km. One example is a broad scarp that is crossed by SH 85, 0.7 km east of the Bypass Road intersection. The scarp is between 5 and 10 m high on very old down-land terrain, but no more than 1 or 2 m high on inset valley floors to the northeast and southwest. This indicates that the fault has experienced repeated Quaternary movements. This fault has notably straight and sharply expressed 'definite' scarps. In particular, near Launceston homestead, the fault has a sharp, straight, uphill-facing scarp that appears to extend across gully floors. This indicates that the fault has moved probably within the last few thousand years, and certainly more recently than the last ice age. The straightness of the fault scarp across terrain indicates a near-vertical dip.

In order to place the fault in a hazard perspective, an indicative average slip rate of 0.1 mm/yr is inferred, based on a scarp height of ~10 m relative to an assumed age of ~100,000 years for the down-lands. The freshness of the Launceston Fault scarps is comparable to those of the Ranfurly Fault Zone, suggesting that the most recent surface rupture of the Launceston Fault may possibly have also involved the Ranfurly Fault Zone. Because their relatively short individual overall lengths, the Launceston Fault and Ranfurly Fault Zone are inferred to represent a single active fault feature, and following the NZAFM and 2010 NSHM, referred to here as the Ranfurly Fault Zone.

A2.25 Lindis Pass Fault Zone (feature 21; Figures 5.1–5.3)

This broad zone of overall north-striking faults extends from the Waitaki District into the Central Otago District. It is discussed in detail in the Waitaki District active faults report (Barrell 2016), and people should refer to that report for in-depth information. In summary, geologically recent activity is seen on parts of two named fault strands, the Longslip Fault and Dalrachney Fault. Towards the southwest in the Central Otago District, the most recent fault scarps step progressively to the southeast off the mapped line of the Longslip Fault, into the Dunstan Creek catchment. The Longslip Fault is a major fault in bedrock and continues south-southeast to the Dunstan Fault. Although the most recent ruptures have stepped off the Longslip Fault, the Longslip Fault is marked by a prominent topographic escarpment, although quite dissected by erosion, up to the northeast. Although the peneplain remnants are patchily preserved, there is estimated to be vertical separation of several hundred metres on the peneplain across the Longslip Fault. The Longslip Fault escarpment appears to have been folded across the Dunstan anticline, suggesting that most of the Late Cenozoic deformation on the Longslip Fault occurred before that of the Dunstan Fault. Nevertheless, because of proximity to the Dunstan Fault, and because the Cluden Fault Zone and Goodger Fault appear to end against the Longslip Fault, the fault overall is identified as a ‘possible’ active fault. This acknowledges that ruptures on those adjacent faults could potentially extend at least partly onto the Longslip Fault. There are several small fault-bounded blocks in the intersection zone between the Longslip Fault and the Cluden Fault Zone. The block-boundary faults are denoted as ‘potentially active’ in view of there being some, but small, possibility of secondary slip being transferred from the main faults.

Another strand of the Lindis Pass Fault Zone is evident north of Lindis Pass, here-named the Pavilion fault, after Pavilion Peak, one of the highest points on its upthrown side. A north-northwest striking fault in bedrock displays a several-hundred-metre vertical separation of the peneplain, up to the east-northeast. There are scattered remnants of ‘likely’ fault scarps along the line of the fault, and ‘likely’ connectors are drawn between scarps. The bedrock fault, where no scarps are evident, is classified as ‘possible’. With an indicated fault length of only 16 km, it is interpreted to be a strand within the wider Lindis Pass Fault Zone rather than an independent active fault.

The current parameterisation of the Lindis Pass Fault Zone in the NZAFM and 2010 NSHM appears to be appropriate for encompassing the most recent movements of the fault zone that have extended into the Central Otago District. The 2010 NSHM assigns a slip rate of 0.47 mm/year, a dip of 75°, a length of 38 km and calculates a recurrence interval of ~5600 years.

A2.26 Lindis River Fault (feature 17; Figures 5.1–5.2)

The east- to northeast-striking Lindis River Fault is called the ‘Lindis Fault’ in the QMAP dataset, but the name Lindis River is applied here, to minimise the potential for confusion with another nearby fault system, the Lindis Pass Fault Zone. The fault is downthrown to the northwest, with Cenozoic strata preserved locally at the foot of the fault angle, and patchy remnants of the peneplain either side of the fault. The Lindis River has cut a narrow gorge across the uplifted block, and SH 8 follows the gorge. The fault is not included in NZAFM or 2010 NSHM datasets.

The QMAP dataset shows the north-eastern half of the fault as downthrown to the southeast, but it is considered here that a case can be made for an alternative view, based on interpreted peneplain offset, and that the Late Cenozoic downthrow is the northwest for the full length of the fault.

The peneplain shows as much as 300 m vertical separation, up to the southeast, across the fault and there is no known evidence for geologically young landform displacement across the fault. The fault position is adopted from the QMAP dataset without modification, which shows the fault as extending from close to the Grandview Fault, northeast to an intersection with the Johns Creek Fault in the northeast.

In this dataset the Lindis River Fault is classified as ‘potentially active’. In order to estimate recurrence interval using 2010 NSHM methodology, fault length of 35 km and dip of 60° southeast are adopted. Applying a nominal slip rate of 0.05 mm/year, a recurrence interval of ~50,000 years is calculated.

A2.27 Little Valley fault zone (feature 30; Figures 5.2–5.3)

This comprises an array of north-northeast striking array of faults, upthrown to the southeast. The array includes individually-named faults identified in the QMAP dataset as ‘Crawford Hills’, ‘Little Valley’ and ‘East Roxburgh’. The individual faults are no more than 3 km apart and are interpreted here to be splays of a single fault zone at depth. Collectively, the faults are referred to here as the ‘Little Valley fault zone’, named after the most prominent strand.

All the faults are defined by offset of Otago peneplain, which is extensively preserved on the upthrown side of each fault block, and in places Cenozoic cover strata are preserved on top of the peneplain on the downthrown side. Vertical separation across each fault is between a few tens of metres to as much as 300 m or so. Aggregate vertical separation of the peneplain across the fault zone is typically about 300 m.

The mapping is adopted from QMAP with some minor positional refinements based on high-resolution colour aerial imagery. One northerly-striking strand has been added in the Knobby Range area, based on indicated offset of the peneplain. No offset of geologically young landforms or deposits has previously been reported for any of the components of the Little Valley fault zone, and these faults are not currently included in the NZAFD, NZAFM or 2010 NSHM.

Because other similarly orientated faults in the surrounding regions show evidence of geologically recent activity, the Little Valley fault zone is classified in this dataset as ‘potentially active’, ‘not expressed’. For the purpose of estimating activity characteristics, a length of 42 km and nominal slip rate of 0.05 mm/year are assigned. Using 2010 NSHM methodology, a recurrence interval of ~60,000 years is calculated.

A2.28 Livingstone Fault (feature 1; Figure 5.1)

The approximately north-striking Livingstone Fault crosses the western edge of the Queenstown Lakes District, and a ~6.5 km length of the fault lies in the district. It is a geologically major fault which originated during the Mesozoic Era, and separates basement rocks of the Dun Mountain-Maitai Terrane to the west from rocks of the Caples Terrane to the east (Mortimer et al. 2014). There is evidence in places for geologically young reactivation of sectors of the fault. Its northern sector, including that portion in the Queenstown Lakes District, is classed as an active fault earthquake source in the 2010 NSHM and referred to as the Hollyford Fault. This same fault is identified in the NZAFM as the Livingstone-Key Summit Fault Zone. In the 2010 NSHM, the fault source is assigned a net slip rate of 1 mm/year and a recurrence interval of ~6400 years is calculated.

The fault is classified here as 'likely' active, because it is possible that the topographic steps (identified in this dataset as 'moderately expressed') that are suspected to be an expression of fault rupture could have other origins, such as stream erosion, or slope movement. The Greenstone Track and Caples Track both cross the mapped line of the Livingstone Fault beside Lake McKellar, just inside the limits of Fiordland National Park.

A2.29 Logan Burn fault (feature 48; Figure 5.3)

A northeast-striking fault, upthrown to the southeast, has long been mapped along the foot of the steep edge of the Rock and Pillar Range, on the southeast margin of the Serpentine basin in the upper Taieri catchment (Mutch 1963; Forsyth 2001). It is expressed as vertical separation of the peneplain of as much as ~350 m, up to the southeast. It is presumably a southeast-dipping reverse fault. A name has not previously been applied to the fault on those published geological maps.

Although originally drawn as being continuous with other similar faults farther northeast (Mutch 1963), there was later recognition of a lack of continuity of peneplain deformation between the two structural areas, as illustrated in the mapping by Forsyth (2001). That later depiction showed a ~22 km long inactive, un-named, fault adjacent to Serpentine Flat, separated by ~7 km from other un-named faults of similar character farther northeast.

The digital version of the NZAFD shows the inactive fault from QMAP as an active fault and applies a name 'Logan Burn Fault'. The origin of that interpretation, and the naming, appears not to have been documented. The NZAFM and 2010 NSHM approximate this fault, and other similar faults farther north, including the QMAP-named Waipiata Fault, as a single, ~65 km long, feature referred to as the Waipiata fault zone (NZAFM) or active fault earthquake source (2010 NSHM). The interpretation in the NZAFM and 2010 NSHM more closely approximates the earlier Mutch (1963) depiction of a contiguous fault, than the later QMAP interpretation of separated faults (Forsyth 2001).

Overall, the geological evidence favours the existence of separate faults rather than a continuous structure. The step is taken here of including the QMAP-defined fault in this dataset, under the name Logan Burn fault, taken from a large stream that crosses the fault escarpment, and recognising the NZAFD's existing use of that name. The fault escarpment can be traced farther southwest than shown by QMAP and, as mentioned in the Riddles fault section, appears to cross the Riddles fault and die out south-westward approaching the Beaumont River fault.

There are no discernible offsets of geologically young landform features anywhere along the Logan Burn fault, and it is classified here as 'potentially active'. For the estimation of activity parameters, the Logan Burn fault is assigned a dip of 60°, length of 42 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~60,000 years is calculated. By this interpretation, the Logan Burn fault becomes separate from the Waipiata fault zone depicted in the NZAFM and 2010 NSHM, and the need for revision of the latter is discussed in a separate section.

A2.30 Long Valley Fault (feature 43; Figure 5.3)

This northeast striking fault forms a prominent escarpment, upthrown to the southeast, in the upper catchment of Pool Burn. The fault is included in the NZAFD, 2010 NSHM and NZAFM. The fault escarpment has a clearly expressed length of ~21 km, and vertical separation of as much as 200 to 300 m of the peneplain across the fault. There are geologically young offsets of alluvial fans along the foot of the escarpment, with heights of as much as 8 m (GNS Science, unpublished data 2000). It is classified here as a 'definite' active fault.

There is currently no good context for assessing the age of the offset fans. A slip rate of 0.5 mm/year was assigned in the 2010 NSHM and NZAFM. However, if the rate were that large, a different morphology would be expected, with a flight of offset fans along the foot of the range-front. Rather, it seems more likely that the fans are older than previously thought. In order to refine the seismic hazard assessment, it is suggested that an age of ~50,000 years is a more realistic estimate for the offset fan surfaces. A scarp height of 8 m on a landform of that age indicates a vertical slip rate of 0.16 mm/year. Resolved on a 60° dipping fault, a net slip rate of 0.18 mm/year is obtained and a recurrence interval of ~7900 years is calculated using 2010 NSHM methodology.

Between 2 and 4 km southeast of the Long Valley Fault is a ~13 km long fault that offsets the peneplain by as much as ~80 m, up to the southeast. Because of its relatively short length, proximity to the Long Valley Fault and having the same sense of throw, it is interpreted here to be a break-out from the Long Valley Fault at depth. It is identified in this dataset as the 'Long Valley Fault - southeast strand'. It is regarded here as part of the surface expression of the Long Valley Fault, rather than an independently rupturing fault. A lack of indication in high-resolution aerial imagery of any geologically young landform offsets along this strand suggests that it has not experienced the most recent surface ruptures of the main strand of the Long Valley Fault. It is classified here as a 'possible' active fault.

A2.31 Moonlight Fault Zone (features 3 and 4; Figures 5.1–5.2)

Detailed studies of this major northeast-striking fault zone have been documented by Turnbull et al. (1975) and Norris et al. (1978). Its wider tectonic significance was discussed by Kamp (1986). Existing interpretations place it as part of an Eocene to Oligocene continental rift system, whose opening allowed incursion of the sea from the Tuatapere area (Southland) north into what is now part of the Shotover River catchment (all of this 30 million years ago, long before the modern topography developed). Distinctive marine sedimentary rocks, including sandstones, mudstones and limestones, known in the Queenstown area as the Bobs Cove Beds, were deposited in the rift. Development of the present plate boundary, and the Alpine Fault, in the earliest Miocene (~22 million years ago) led to closure of the rift and eventually produced the present mountains. These considerations are important because they have bearing on how the recent activity of the fault zone has been interpreted.

Two geologically recent fault scarps near the Mount Nicholas homestead, on glacially-sculpted bedrock and post-glacial lake beaches, are upthrown to the east and have been attributed to movement on the Moonlight Fault (Turnbull et al. 1975; Turnbull 2000). However, both are aligned north-south, rather than on the north-easterly strike of the Moonlight Fault Zone. Also in that area, the only preserved remnants of the Bobs Cove Beds are associated with a north-striking fault, the Home Creek Fault (Turnbull et al., 1975), which is upthrown to the east.

The 1975 interpretation was that Late Cenozoic movement of the Moonlight Fault ‘scissored’ across Lake Wakatipu, with the northwest side upthrown north of the lake, and the southeast side upthrown to the south of the lake. Kinematically, this is challenging if the Late Cenozoic motion is correctly interpreted as reversal of mid-Cenozoic normal faults of a rift zone, because the fault would need opposing dip directions either side of the lake.

The two scarps near Mount Nicholas are the only demonstrated Late Quaternary offsets in proximity to the Moonlight Fault Zone in the Queenstown Lakes District. About 70 km southwest of Lake Wakatipu, in the Southland Region, there is a prominent fault scarp at the northern foot of the Takitimu Mountains close to the mapped line of the Moonlight Fault at Elmwood. This north-northeast trending scarp is upthrown to the west-northwest on an alluvial fan inferred to be ~250,000 years old (Turnbull 2000). From examination of aerial photos, I estimate the height of the scarp to be as much as 15 m. A notable point is that the westerly sense of upthrow is opposite to the easterly sense of upthrow expected for the Moonlight Fault Zone southwest of Lake Wakatipu (Turnbull et al. 1975; Norris et al. 1978). Another important observation is that 45 km to the southwest of Lake Wakatipu, the Moonlight Fault Zone is mapped as ‘concealed’ beneath glacial moraine and outwash deposits inferred to be ~250,000 years old (Turnbull 2000). This indicates the fault in that area has not experienced discernible surface rupture since at least that time. Furthermore, on the line of the fault zone across the Lake Wakatipu trough, there is no discernible offset of post-glacial lake beaches or glacial-age landforms. Farther northeast along the line of the fault zone, which is mostly in rugged mountainous topography, there are no discernible fault-related offset on landform surfaces, notably including the glacially-smoothed valley sides of the Matukituki River west of Lake Wanaka. In that area there are some topographic steps on or close to the line of the fault, but all are down to the northwest, in opposition to the expected sense of throw on the fault and can satisfactorily be attributed to gravitational slope movement.

On balance, it seems more likely that the fault scarp at Elmwood is associated with a fault other than the Moonlight Fault. Otherwise there ought to be more indication of landform offsets elsewhere along the Moonlight Fault Zone. A more likely association for the Elmwood fault scarp is the arrays of northerly-striking contractional Late Cenozoic faults that mark the eastern margin of the Te Anau-Waiau tectonic basin (Turnbull 2000; Turnbull and Allibone 2003).

The following working interpretation for the Moonlight Fault Zone is adopted in this report. The Moonlight Fault northeast of Lake Wakatipu has been reactivated as a reverse fault in the Late Cenozoic, with slivers of Bobs Cove Beds caught up along the fault. Throw diminishes to the southwest approaching Lake Wakatipu, and the most extensive remnants of the Bobs Cove Beds are alongside the eastern shore of Lake Wakatipu, close to the inferred southwestern end of the reverse fault. The more extensive preservation of these strata here may indicate that the amount of Late Cenozoic contraction is much less than farther northeast. Southwest of Lake Wakatipu, the relatively high elevation of the Eyre Mountains southeast of the fault zone may simply reflect the original structural relief of rift-related normal movement on the fault zone, for at least ~50 km southwest to the Mararoa River valley, and one possibility is that sector of the fault has not reactivated in the Late Cenozoic. Alternatively, it may have resulted from the reversal of a former, southeast-dipping, rift-related, normal fault, although on a different fault strand to that associated with Late Cenozoic movement on the northeastern sector of the Moonlight Fault Zone. The Late Quaternary scarps, and the Home Creek Fault of Turnbull et al. (1975) are interpreted here as being associated with a separate north striking, Late Cenozoic fault zone, upthrown to the east (see section on West Wakatipu Fault).

In the 2010 NSHM and NZAFM, the Moonlight Fault Zone is interpreted as having a vertical dip and is divided into two sections, named Moonlight North and Moonlight South, separated at the Von River/Oreti River drainage divide, ~20 km southwest of Lake Wakatipu (outside the Otago Region). Both sections were assigned a slip rate of 1 mm/year in the 2010 NSHM, with respective fault lengths of 88 and 100 km applied to the north and south sections, from which respective recurrence intervals of ~6100 and ~7000 years were calculated. The basis for estimating the slip rate was not stated in the NZAFM documentation, other than the value having been assigned by an expert panel. As far as I am aware, the only previous suggestion of a slip rate of that order comes from a tentative estimation of an uplift rate for the Takitimu Mountains, contained in a report by Carter and Norris (2005). They highlighted an altitudinal sequence of fluvial or glacial terraces, and gently sloping benches, of inferred glacial erosion origin, on bedrock forming the lower hillslopes of the Te Anau basin margin. Assuming that the height differences reflect progressive uplift over time, they used the heights to infer ages for the landforms, based on 'counting-back' correlation to Quaternary glacial cycles. They then used the height differences and inferred ages to calculate a long-term uplift rate. They concluded that the Takitimu Mountains, on the eastern side of the basin and on the presumed upthrown side of the Moonlight Fault Zone, have been rising at ~1 mm/year over the past 750,000 years or so. They also concluded that the Fiordland mountains, on the upthrown side of the faulted western margin of the basin, have also been rising at the same rate. This analysis implies that the basin is not being uplifted, or if so at a lesser rate. Arguable deficiencies with the analysis include: (1) there is no direct dating of the landforms; (2) if the bedrock benches really are glacial erosion features, their height cannot be meaningfully compared to fluvial terraces, because depending on ice-mass thicknesses in the valley, benches could be scoured by ice some distance above the bedrock floor of the basin, and; (3) there are other ways to create an altitudinal flight of glacial/fluvial landforms, such as by progressive erosional deepening of the valley, or by regional uplift unrelated to the faulted margins of the basin. In sum, the inferred 1 mm/year uplift rate, which could be taken to approximate a slip rate on the southern section of the Moonlight Fault Zone, is of questionable merit and should be set aside, especially when other landform evidence points towards a much lesser degree of fault activity.

A slip rate of 1 mm/year implies that an offset of the order of 20 m would be expected on landforms dating from the retreat of ice-age glaciers (~18,000 years ago), but there is no discernible offset of landforms of that age across the Moonlight Fault Zone in either the Lake Wakatipu valley or the Matukituki valley. For the purpose of this report and associated dataset, a nominal slip rate of 0.05 mm/year is assigned to each section of the Moonlight Fault Zone. The north section is interpreted here as extending northeast from Lake Wakatipu to the northern extent of the fault zone as shown in QMAP, at about the northern boundary of the Otago region, some 30 km farther northeast than depicted in the 2010 NSHM and NZAFM. This gives the revised Moonlight North active fault earthquake source a length of 100 km which, using 2010 NSHM methodology in conjunction with a slip rate of 0.05 mm/year, yields a recurrence interval of ~140,000 years. The Moonlight South fault source is repositioned as extending southwest from Lake Wakatipu for ~85 km to the Waiau River in the Manapouri area. Recalculation of its recurrence interval using the revised fault length and slip rate estimate returns a value of ~120,000 years.

A reality check on these estimates is provided here by assuming hypothetically that the offset alluvial fan at Elmwood, mentioned earlier, is related to surface rupture of the Moonlight Fault. The ~15 m offset of the inferred ~250,000-year-old fan surface returns an average slip rate of 0.06 mm/year, and would imply a recurrence interval of the order of 100,000 years. The absence of offset of landforms at Lake Wakatipu formed following the retreat of ice ~18,000 years ago, on the line of the Moonlight Fault, provides another check, by implying a maximum recurrence interval of more than 18,000 years. Together with the absence of indicated offset of ~250,000-year-old landforms across the Moonlight Fault Zone ~45 km southwest of Lake Wakatipu mentioned earlier, these checks illustrate that the nominal 0.05 mm/year slip rate adopted here is a reasonable value for estimating the activity of the Moonlight Fault Zone, based on overall weight of evidence.

The various strands of the Moonlight Fault are classified here as 'potentially active', except for a ~10 km long sector of the fault, classed as 'likely', that extends from the easternmost 'definite' scarp of the West Wakatipu Fault southwest to ~4 km beyond where the Home Creek Fault meets the Moonlight Fault. The reasoning is that rupture on the West Wakatipu Fault extending so close to the Moonlight Fault Zone may trigger localised slip on the Moonlight Fault Zone.

A2.32 Motatapu Fault (feature 5; Figures 5.1–5.2)

This northeast-striking fault was included and named in the QMAP dataset. QMAP shows this fault as ~20 km long, extending along the north-western foot of the Mt Cardrona - Mt Alpha range to abut the Wanaka Fault. High-resolution aerial imagery reveals a very well expressed, northeast trending, topographic step, up to the southeast, on ice-smoothed rock terrain on the eastern end of Roys Peninsula, and a similar step across comparable terrain north of Stevensons Arm. The step is estimated to be ~5 m high and is clearly due to ground movement. However, in this setting, it is difficult to rule out the possibility of stress-release relaxation of the rock mass following ice retreat from the Wanaka basin. For that reason, the steps are classified as 'likely' rather than 'definite' fault scarps.

The preliminary interpretation made here is that the Motatapu Fault is a 'likely' active reverse fault. Assuming a dip to the southeast of 60° and pure reverse motion, the inferred 5 m vertical scarp on landforms of an estimated age of 18,000 years indicates a net slip rate of 0.32 mm/year. Using 2010 NSHM methodology with a nominal fault length of 30 km, a recurrence interval of ~6,500 years is calculated.

A2.33 Nevis Fault Zone (feature 7; Figures 5.1–5.2)

This major northeast-striking fault runs along the north-western side of the Nevis valley, and forms the southwestern part of a major geological structure, named the Nevis-Cardrona Fault System by Beanland and Barrow-Hurlbert (1988). A notable feature of this fault system is that to its northwest, the terrain is generally mountainous, whereas to the southeast, the terrain comprises well-defined ranges and basins across which the Otago peneplain, in places still buried by Cenozoic sedimentary strata, is extensively preserved (Turnbull 2000). The other main component of the Nevis-Cardrona Fault System, the NW Cardrona Fault, is described in a separate section.

The Nevis Fault Zone has been responsible for uplift, on its north-western side, of the Hector Mountains, and their northernmost component, the Remarkables, relative to the Nevis valley. Although usually just called the Nevis Fault, it does include some individually-named components, such as the Schoolhouse Fault, and the word 'Zone' has been added here, for clarity. The southwestern part of the fault zone extends into the Southland region.

The mapping in this dataset here is taken directly from QMAP, without refinement. The reasons for this are three-fold. There is no lidar coverage, and there is a general lack of high-resolution aerial imagery for most of the length of the fault zone, even within Google Earth. This means that the QMAP work, compiled on a 1:50,000 scale topographic map base, cannot be improved upon without new fieldwork. Third, the area is remote and largely unpopulated, and there is currently no impetus there for detailed fault mapping.

Offset of geologically young landforms across the Nevis Fault Zone has been documented at selected sites in the Nevis valley by Beanland and Barrow-Hurlbert (1988), including some geological investigation trenches that confirmed a fault origin for several suspected fault scarps, but it was not possible to date any deformation events. Generally speaking, alluvial fan landforms assessed as having formed near the end of the last glaciation (~18,000 years ago) show fault deformation of the order of 2 m, whereas equivalent-age landforms along the NW Cardrona Fault typically have fault deformation of about 5 m. Progressive deformation of a flight of terrace surfaces at Drummond Creek, on the southwestern part of the fault zone ~35 km southwest of the Kawarau valley, indicate at least 4 surface rupture events on the Nevis Fault Zone in the past 18,000 years, but each with uplift of less than 0.5 m (Beanland and Barrow-Hurlbert 1988). This however may not be the only active strand of the fault at that location.

Fault scarps associated with the Nevis Fault Zone are classified here as ‘definite’, with differentiation of ‘well- expressed’ or ‘moderately expressed’ as appropriate based on what can be gleaned of their prominence in Google Earth, with ‘not expressed’ connections between them. Sectors at either end of the Nevis Fault Zone lacking any known preservation of deformed geologically young landforms are designated ‘likely’. This included the ‘Western Boundary Fault’ of Beanland and Barrow-Hurlbert (1988) mapped along the base of the range-front.

In the 2010 NSHM, the Nevis Fault Zone is modelled as a single rupture segment, extending for 69 km from the Kawarau River southwest to the Mataura River, with a net slip rate of 0.4 mm/year and a fault plane inferred to dip northwest at 45°. Calculated single-event displacement is about 5 m, and recurrence interval of ~12,000 years. This appears incompatible with the indication of at least 4 ruptures in the past ~18,000 years, and single-event displacements more of the order of 1 m. Those data suggest that the fault likely has rupture segmentation, with at least two separate segments. This warrants an expert panel review beyond the scope of this project. For present purposes, the only amendment made is to reduce the fault length, to accommodate the southern end of the NW Cardrona Fault having been shifted to Doolans Saddle. The new length for the Nevis Fault Zone is 52 km, from which a revised recurrence interval of 9000 years is calculated using 2010 NSHM methodology, and is used for the purposes of the present assessment.

A2.34 NW Cardrona Fault (feature 6, Figures 5.1–5.2)

This major northeast-striking fault runs along the north-western side of the Cardrona valley. The NW Cardrona Fault forms the north-eastern part of a major geological structure, named the Nevis-Cardrona Fault System by Beanland and Barrow-Hurlbert (1988). A notable feature of this fault system is that to its northwest, the terrain is generally mountainous, whereas to the southeast, the terrain comprises well-defined ranges and basins across which the Otago peneplain, in places still buried by Cenozoic sedimentary strata, is extensively preserved (Turnbull 2000). The other main component of the Nevis-Cardrona Fault System, the Nevis Fault Zone, is described in a separate section.

The NW Cardrona Fault has been responsible for uplift, on its north-western side, of the Mt Cardrona to Mt Alpha range, relative to the Cardrona valley. To the southwest, the fault is extrapolated through the Crown Range saddle to the southwestern side of the Kawarau valley. To the northeast of Wanaka, the NW Cardrona Fault has been previously extrapolated to the Lake Hawea area. As explained later in this section, a different name (Cardrona-Hawea fault) has been applied here to the sector of the fault northeast from Wanaka township area, and it is described in a separate section.

Offset of geologically young landforms across the NW Cardrona Fault has been documented in the Kawarau valley floor and in various places along the north-western side of the Cardrona valley (Beanland and Barrow-Hurlbert 1988) as far northeast as Branch Burn, about 15 km southwest of Wanaka township. No fault offset of geologically young landforms has previously been identified farther northeast towards Wanaka township. Features of the mapping, interpretation and classification of the NW Cardrona Fault are discussed below, starting in the southwest area and working northeast.

A2.34.1 Gibbston Area

A north-trending fault scarp runs across a river terrace on the Kawarau valley floor near Gibbston (Beanland and Barrow-Hurlbert 1988). The scarp (referred to here as the Kawarau valley scarp) is about 5 m high, up to the west, and is clearly visible running at a right angle to the trend of the valley, on the river-side of SH 6 about 0.5 km east of the Kawarau Bridge bungy jump carpark. It is illustrated in Figure 5.4 in the body of the report.

In 1984, a geological investigation trench was excavated across the Kawarau valley scarp, described in detail by Beanland and Barrow-Hurlbert (1988) and on which the following summary is based (see Figure 5.4 in the body of the report). The trench revealed a reverse-sense offset, involving schist bedrock overlain by ~4 m of river sediments, thrust eastwards over river and windblown silt sediments. The fault dip at the base of the trench is 44° west but flattens upwards through the sediment sequence. Geological relationships in the trench exposure indicate that the offset of the terrace deposits accrued from at least 3 surface rupture events, with an average uplift of 1.1 m per event. Taking into account the fault dip, this indicates an average net (i.e. dip-slip) single-event displacement of ~2 m (to the nearest metre). Deposit stratigraphy in conjunction with radiocarbon dating of offset buried soils indicates that at least one rupture occurred before 20,500 ± 1150 radiocarbon years BP, at least two events occurred after that date, and that the most recent event was younger than 9760 ± 560 radiocarbon years BP (Beanland and Barrow-Hurlbert 1988). Using the SHCal curve in the 'Calib' radiocarbon calibration programme, publicly available online at www. http://calib.org/calib/, these ages convert to calibrated calendar-year ages of 24,300 ± 3300 years BP and 11,200 ± 1500 years BP (rounded to the nearest century). This means that the fault, at this location, has experienced at least two surface ruptures during the past ~21,000 years (taking the younger bound of the older age), which together with an aggregate ~4 m dip-slip for two events, indicates a maximum dip-slip rate of ~0.2 mm/year at this site.

The Kawarau valley scarp is classified here as 'definite', 'well expressed'. In the QMAP dataset, this scarp was drawn as a short entity, not connected to the main mapped line of the Nevis-Cardrona Fault System, which was positioned ~0.5 km farther down-valley. In the QMAP dataset, the NW Cardrona Fault is interpreted as stopping on the northern margin of the Kawarau valley. Southwest from there, the main line of faulting was identified as the Nevis Fault, approximating the way the two faults were originally depicted by Beanland and Barrow-Hurlburt (1988). However, there is considerable geological continuity of the fault system either side of the Kawarau valley. On the eastern, downthrown, side of the fault, for ~10 km to the north and ~15 km to the south of the Kawarau valley, remnants of the Otago Peneplain dip west towards the fault at between 10° and 15°, with isolated slivers of Cenozoic strata preserved adjacent to the fault plane. The Kawarau valley scarp is of similar height to other geologically young scarps of the NW Cardrona Fault in the Cardrona valley (described in the following sub-sections). In contrast, the Nevis Fault only shows offset of notably older landforms, while landforms produced near the end of the last glaciation appear to show no deformation. In addition, the Nevis Fault in the Nevis valley shows structural complexity, commonly with two of more parallel strands, whereas the NW Cardrona Fault is typically a more discrete geological structure. In this dataset, the NW Cardrona Fault is extended as an entity to just south to Doolans Saddle, about 15 km south of the Kawarau River. South from there, the zone of more complex, multi-strand faulting is assigned here to the Nevis Fault Zone.

In the interpretation adopted for this dataset, the Kawarau valley scarp is regarded as lying on the main line of the NW Cardrona Fault, and a 'likely', 'not expressed' connector line has been drawn from the scarp to the main mapped lines of the fault to the north, across extensive landslide terrain on the northern side of the valley, to the saddle on the Crown Range Road, which is interpreted to mark a remnant of the Otago Peneplain on the immediate eastern (downthrown) side of the fault.

A long-standing puzzle concerns the location of a southern continuation of fault-related deformation expressed on the Kawarau valley scarp. In the area south of the Kawarau valley, there are flights of old alluvial fan terraces, the higher levels of which are undoubtedly older than the river terrace that is offset in the Kawarau valley. The considerable size of the single-event displacements (~2 m) identified in the investigation of the Kawarau valley scarp makes it very unlikely that the surface rupture deformation stopped at the south side of the Kawarau valley. Rather, the surface rupture deformation almost certainly continued for some distance farther in a general southerly direction. Lidar coverage now extends through part of that area, and profiling of the lidar, along with examination of archival air photos, reveals a broad step, several metres high and up to the west, sidling across a minor alluvial fan surface about 1 km south-southeast of the Kawarau valley scarp. Beyond there, ~2 km south-southeast of the Kawarau valley scarp, an ~2 m high broad step sidles across an inset low-level terrace of Toms Creek. On the presumption that surface rupture of the NW Cardrona Fault must have crossed this area, these two features are classified as 'likely', 'moderately expressed'. Intervening terrain comprises eroded valley-side or hill terrain, across which 'likely', 'not expressed' connector lines are drawn. A connector line is extrapolated around the northern foot of Camp Hill, to join a sector of the fault that is well established by geological relationships, by way of a sliver of Cenozoic strata preserved along the downthrown side of the fault for ~3 km from the floor of Camp Creek southeast to Coal Pit Saddle. The terrain from here through to the edge of the broad Nevis valley is mountainous, with extensive landslide terrain, and no geologically young surface fault-deformation has been identified. This sector of the fault is identified as 'likely', 'not expressed'.

While these interpretations of the NW Cardrona Fault south of the Kawarau valley are tentative, they are considered to provide the best accommodation of available geological information, notably the relatively discrete fault geometry extending south from the Cardrona valley to just beyond Doolans Saddle, the similarly of geologically young scarp heights in the Cardrona valley and Kawarau valley, and the likelihood that recent surface fault ruptures has extended south of the Kawarau valley.

A2.34.2 Cardrona Valley Southern Sector

For about 10 km north-northeast from the Crown Range Road saddle to Blackmans Creek, the NW Cardrona Fault is positioned at the western edge of a series of topographic benches along the foot of the Crown Range. These benches are interpreted to be remnants of the Otago Peneplain, a relationship confirmed by the presence of Cenozoic strata preserved on a bench at Coal Creek. The eastern face of the Crown Range is largely landslide terrain, and the location of the fault is largely obscured, or masked by recent gravitational mass movement. Geologically recent fault offsets have been identified across valley-floor alluvial-fan terraces in two locations, Maori Gully and Blackmans Creek.

The Maori Gully fault scarp lies about 6.5 km north of the Crown Range Road summit. It is described by Beanland and Barrow-Hurlbert (1988) as a ~4 m high topographic step, up to the west. The presence of fault offset was confirmed by geological investigation trench across the scarp, which exposed a northwest-dipping reverse fault, but the number of displacements could not be determined (Beanland and Barrow-Hurlbert 1988). The scarp is classified as 'definite', 'Immediately to the northeast, there is a topographic step, up to the west, across landslide terrain, that Beanland and Barrow-Hurlbert (1988) interpreted as a fault offset. However, it is possible that it is a gravitational scarp within the landslide that just happens to align with the adjacent fault scarp. It is classified as 'likely', 'moderately expressed'.

The Blackmans Creek fault scarp is about 10 km north-northeast of the Crown Range Road summit, and about 3.5 km southwest of the Cardrona Hotel. The feature was described by Beanland and Barrow-Hurlbert (1988) as a fault scarp, about 7 m high and up to the northwest, across an alluvial fan. This feature lies close to the Cardrona River, and the question arises as to whether the step, and the lower terrace at its base, are products of river erosion rather than fault movement. If that were the case, the ground on the lower side of the step would be a Cardrona river terrace, rather than a Blackmans Creek alluvial fan, and the terrace would slope down the Cardrona valley at the same gradient as the river. However, lidar shows that the ground on both sides of the topographic step slopes towards the Cardrona valley axis, showing that the feature is a faulted alluvial fan. The lower side of the step can be seen in Street View from Cardrona Valley Road; and the entire tread of the fan is visible from the road. Were it a river terrace, only the road-ward edge of the terrace would be visible, and not its full extent. This provides further illustration that the feature is a faulted alluvial fan surface.

It has been proposed that at this site there is ~10 m right-lateral offset of a stream-cut channel-edge feature on the Blackmans Creek fan surface (Beanland 1984; Beanland and Barrow-Hurlbert 1988). Close examination of lidar information for the purpose of this report shows that the fault scarp here has a plan-view width of 15 to 20 m, while the channel edge feature is 7 to 8 m wide in plan view. A slight change in trend of the channel edge in the area where the fault scarp now is could satisfactorily account for the positions of the channel-edge feature either side of the fault scarp. While it is possible that there has been lateral offset of the amount suggested, the uncertainties mean that the interpretation should be regarded as tentative without additional field evidence. Instead, the view provisionally preferred here is that the channel patterns on the fan can be accounted for adequately without lateral displacement, and a working interpretation is adopted that there is no confirmed discernible component of lateral offset.

About 0.5 km southwest of Blackmans Creek, a step about 1 m high on a low-level fan terrace was interpreted as a fault scarp by Beanland and Barrow-Hurlbert (1988). It is not well resolved in the lidar, and is classified here as 'likely', 'moderately expressed'. The height of this relatively small scarp, assuming it is a fault scarp and not of some other origin, provides a maximum constraint on the vertical component of a single-event displacement at this location.

For about 300 m southwest of Blackmans Creek, there is a marked rise from the valley floor up onto higher fan surface remnants. The interpretation is made here that this step approximates the position of a former fault scarp, now somewhat eroded by the Cardrona River. For that reason, this section of the fault is classified as 'likely', 'moderately expressed'.

From Blackmans Creek north for about 4 km to the Cardrona village area, there is no sign of fault deformation on the slopes and terraces on the northern side of the valley, and it is assumed that the fault is concealed beneath the young river flood-plain landforms of the Cardrona valley, or possibly by landslide debris on the lower flanks of the valley west of the river. This, and all other parts of the fault in this section of the Cardrona valley not mentioned above are classified as 'likely', 'not expressed'. While there is no doubt that the active NW Cardrona Fault runs through this section of the valley, uncertainty about the fault's location may in places be as much as several hundred metres. The designation of 'likely' is thought the best way to highlight that uncertainty.

A2.34.3 Cardrona Valley Northern Sector

Immediately north from Cardrona village, the general line of the fault curves northward and a conspicuous scarp, up to the west, crosses old fans in the Pringles Creek area. As revealed by lidar, the scarp is as much as 20 m high on the oldest landforms and the smallest scarp, in the incised Pringles Creek valley floor, is about 2 m high. That provides a maximum value for the vertical amount of single-event surface rupture displacement on the fault strand at this location. This fault scarp approaches the foot of the range at Boundary Creek. Northeast from there, discontinuous topographic steps, up to the northwest, are present along the foot range in the Macdonalds Creek catchment, about 5 km north-northeast of Cardrona village. These are interpreted to be fault scarps and are classified as 'likely', 'moderately expressed'. The lower slopes of the range have been extensively affected by landslide movement, and this is probably why there is little landform evidence for recent fault offset. A line classified as 'likely', 'not expressed' is interpolated along the foot of the range between the 'moderately expressed' features.

For a distance of about 8.5 km between Boundary Creek and the south side of the Spotts Creek catchment, discontinuous northeast-trending fault scarps, up to the southeast by as much as several metres, lie parallel to, but about 0.5 km southeast of, the range-front fault. In this dataset, they are assumed to be the expression of a single active fault strand, named in this dataset as the 'NW Cardrona Fault – backfault'. In 1984, a geological investigation trench was excavated across a ~4 m high 'definite', north-trending, scarp on a terrace of Macdonalds Creek (Beanland 1984; Beanland and Barrow-Hurlbert 1988; 'Branch Creek Road trace'). The trench exposure showed a steeply southeast-dipping fault plane within similarly orientated Cenozoic strata bedrock, overlain by relatively thin alluvial sediments. The stratigraphic relationships were interpreted to indicate a net overall reverse offset of ~5 m, up to the east, on the fault plane, probably accrued in three rupture events. This implies an average slip of ~1.7 m per event. An image accessible in Google Earth, dated 22 December 2012, shows the stream channelling on the faulted terrace surface in fine detail, and there is no discernible lateral component of offset of the channel features. The terrace deposits could not be dated but are inferred to be about 18,000 years old (Beanland and Barrow-Hurlbert 1988). The well-expressed channel morphology on the terrace makes it unlikely that the terrace surface could be much older than that, because if it were it would likely carry a cover of windblown loess that was widely deposited during the last glaciation. The estimate of 18,000 years is considered here to be a working estimate for the age of the terrace surface. Assuming that an aggregate 5 m of net slip has occurred at the Macdonalds Creek trench site since 18,000 years ago, implies a net dip-slip rate of 0.3 mm/year (to the nearest decimetre) at this location.

The NW Cardrona Fault – backfault has similarity in form and setting with backfaults (referred to structurally as 'antithetic faults') associated with some other Central Otago fault systems such as the Dunstan Fault Zone and the Pisa Fault Zone (Beanland et al. 1986; Beanland and Berryman 1989). However, in the Cardrona valley there is no evidence for an underlying 'synthetic' fault breaking out farther east, as would be necessary to support the antithetic fault interpretation. Instead, Beanland and Barrow-Hurlbert (1988) hypothesized that the fault referred to here as the NW Cardrona Fault – backfault may be a bedding-plane slip fault associated with deformation in the steeply dipping Cenozoic strata underlying this part of the Cardrona valley.

An alternative possibility is suggested by geological relationships at the northern end of the NW Cardrona Fault – backfault, on the south side of the Spotts Creek catchment. There, the easterly-upthrown backfault disappears at about the same place where a westerly-upthrown southeastern strand of the NW Cardrona Fault at Spotts Creek (mentioned below) appears. The interpretation proposed here is that the NW Cardrona Fault – backfault represents a type of 'pop-up' developed over a section where the south-eastern strand of the NW Cardrona Fault has not broken out to the ground surface but instead terminates underground. By this reasoning the backfault's position would approximate the location of the blind, subsurface, tip of the south-eastern strand of the NW Cardrona Fault. If correct, this interpretation implies that surface rupture of the backfault is directly linked to large ruptures of the NW Cardrona Fault. In that case, the paleoseismic information from the Macdonalds Creek trench will provide an approximation of the timing and size of near-surface rupture events of the south-eastern strand of the NW Cardrona Fault. Overall, because there is interpreted to be another strand of the NW Cardrona Fault at the foot of the range, the slip rate estimated at the Macdonalds Creek trench site will be a minimum for the NW Cardrona Fault structure as a whole, because it does not account for any as-yet undocumented slip on the range-foot strand of the fault, or any folding and distributed minor faulting not clearly evident at the ground surface.

In the Spotts Creek valley, about 13 km northeast of Cardrona village, a topographic step, several metres high and up to the west, sidles across alluvial fan terraces, evident in high-resolution aerial imagery (it is outside of lidar coverage). Identical stream channel patterns can be seen either side of the step, and it is classified here as a 'definite', 'well expressed' fault scarp. It has not previously been identified. Northeast from Spotts Creek, a 'likely', 'not expressed' fault is extrapolated for a further 4 km along the foot of the range, through extensive landslide terrain (Figure A2.2).

Starting from the south side of the Spotts Creek catchment, lidar reveals another line of fault scarps, up to the northwest, diverging northeast from the foot of the range. The scarps are evident on fan terraces and some hillslopes and are classified as 'likely', 'moderately expressed', with 'not expressed' connectors in between. A ~2 m high scarp crosses the main terrace on the northern side of Spotts Creek, about 1 km upstream from the Cardrona Valley Road bridge. A fault-origin of this scarp is more certain, but the landform here is complicated by small alluvial fans built out across the terrace from the valley side, and a classification of 'likely' is preferred here, pending future field investigation. On the same line, 1.5 km northeast of Spotts Creek, a fault scarp classed as 'definite' crosses the floor of an un-named gully. Lidar shows it to be ~3 m high, up to the northwest.

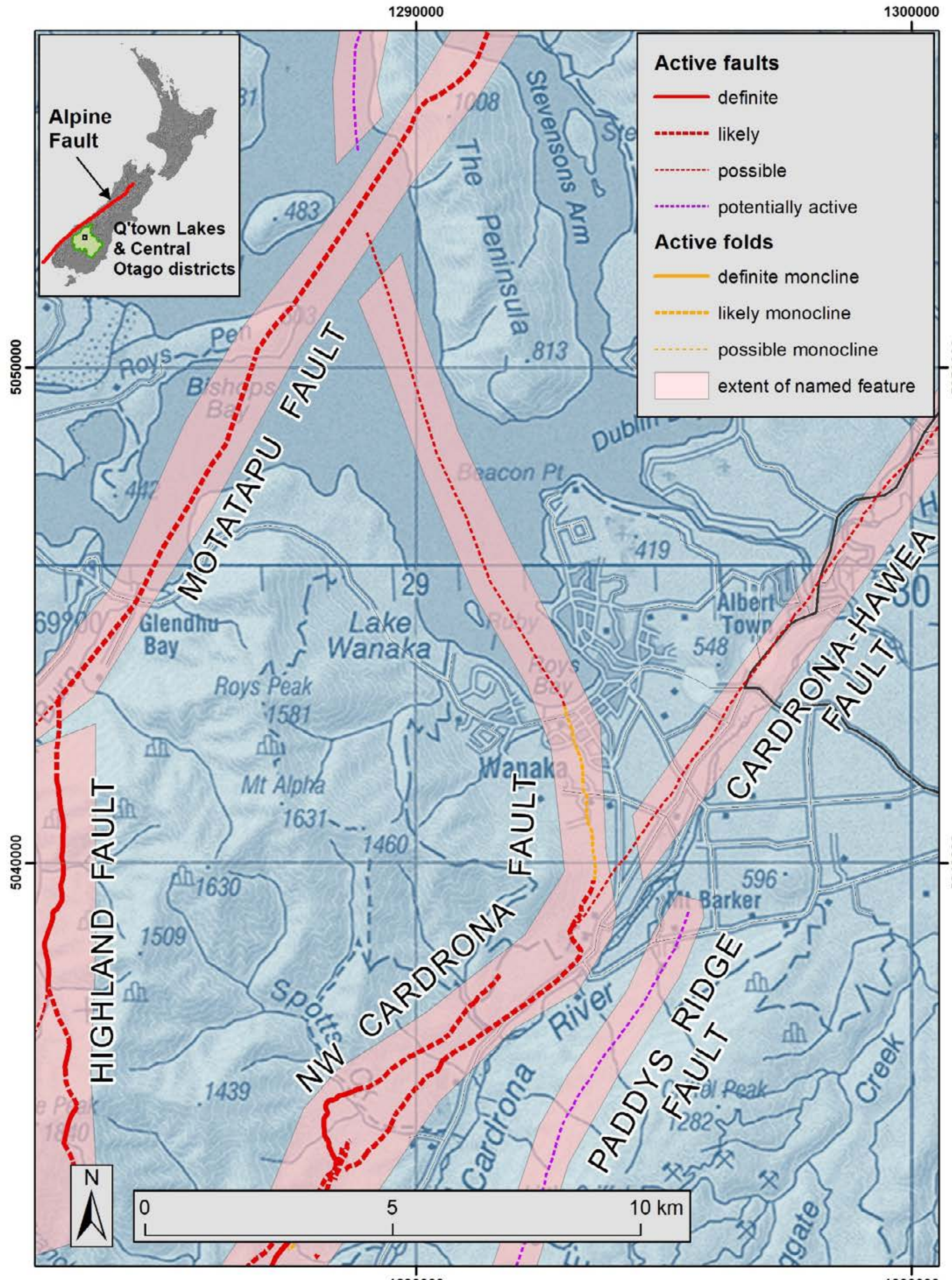

Figure A2.2 Map showing the interpretation and classification of active faults in the Wanaka area. The location of the map panel is shown by the black rectangle in the inset at top left.

Near where the Cardrona valley emerges into the Wanaka basin, an extensive terrace on the north-western side of valley stands about 100 m above the valley floor, west of the Hillend farm buildings. On the terrace, lidar reveals very well preserved glacial moraine and meltwater river plain landforms, formed at a time when ice filled the Wanaka basin during the 'Luggate' glacial advance, and meltwater spilled into the lower Cardrona valley. These landforms are likely to be at least 60,000 years old. There is no indication of fault deformation features crossing the terrace landforms. For that reason, the range-front (north-western) strand of the NW Cardrona Fault is stopped at the western side of this terrace. The south-eastern fault strand, described in the previous paragraph, is inferred to trend northeast beneath the young floor of the Cardrona valley, on the south-eastern side of the high terrace, before remerging across alluvial fan landforms at the foot of the range, northwest of the Hillend farm buildings, as described in the next subsection.

A2.34.4 Wanaka Area

Although previous work had not identified any fault offsets of landforms associated with the NW Cardrona Fault near Wanaka, lidar information and high-resolution aerial imagery has led to the recognition of suspected fault-related landforms in that area (Figure A2.2). Lidar information reveals a suspected fault scarp at the foot of the range on Hillend farm northwest of on the Cardrona Valley Road, about 5 km south-southwest of the Wanaka town centre. The feature is a northeast-trending topographic step, up to the northwest and 4 to 5 m high, running across alluvial fan landforms at the foot of the hillslope. An aspect suggestive of a fault origin for the step is that, in one place, the step peters out, and another step, partly overlapping, commences a few metres downslope and increases in height towards the northeast. However, because the step is very close to the Cardrona valley floor and its associated river terraces, it may be conceivable that the step is a river-cut feature, at the foot of which a sloping apron of material such as wind-blown river sand has accumulated, creating the appearance of an alluvial fan landform either side of the step. That possibility is acknowledged by classifying the step as ‘likely’, rather than ‘definite’. The step is identified as ‘well expressed’ due to its prominent form. Towards the north-northwest, the suspected fault scarp crosses alluvial fan terrain of more complicated geometry, and a classification of ‘moderately expressed’ is applied there.

About 600 m northwest of the intersection between Cardrona Valley Road and Riverbank Road, the discrete step becomes a broad rise that extends towards Wanaka township on a north to north-northwest trend. The rise is about 5 m high, between about 100 and 120 m wide and is interpreted to be a monoclinal fold developed over the top of the suspected fault. The line denoting the monocline position is placed along the centreline of the interpreted warped ground. The landform crossed by this sector of the suspected monocline is a composite array of alluvial fans which have built out eastward from small hillslope catchments on Mt Alpha. The fan complex, at its toe, has been cut by a glacial meltwater channel that emanates from the Wanaka terminal moraine belt, and the fan surface is somewhat dissected by gullies that drain into the meltwater channel. The fan complex is of composite age, with older parts formed during the last ice age when a glacier still occupied the Lake Wanaka basin, while the gullies are probably still actively evolving, through supply of floodwater and possibly sediment from the hillslope catchments.

On the outskirts of Wanaka near Studholme Road, about 2 km south-southwest of the town centre, lidar shows that the suspected monocline crosses the meltwater channel floor. The height of the broad topographic rise is about the same as to the south, 4 to 5 m, but over a distance of about 200 m, the rise broadens northward from about 120 m wide on the south side of the channel floor to about 180 m wide on the north side. This probably indicates an increasing depth of poorly consolidated subsurface sediments associated with the Wanaka glacial trough.

Within the southern sector of Wanaka township, the main landform feature is a belt of moraine and associated meltwater channels and terraces, formed at the terminus of the ice-age glacier that formerly occupied the Lake Wanaka basin. The moraine marks the rim of the Lake Wanaka glacial trough, and is probably about 18,000 years old, because that is the age of similar, lake-impounding, moraine belts at lakes Ohau and Pukaki in South Canterbury that have investigated using geological dating methods (Barrell et al. 2013; Putnam et al. 2013). Inside the Wanaka moraine belt is a flight of beach terraces, produced after the glacier retreated and the lake formed in the glacier trough. The lake initially stood about 20 m above its present level but progressively dropped as the Clutha River eroded more deeply into the lake outlet. The other main landscape element is a complex of alluvial fans in the southwest part of town that have built out from Mt Alpha, partially burying the moraine belt and beach terraces in that area.

The suspected monocline cannot be tracked across the moraine belt, because the highly irregular topography does not provide a uniform reference surface for its recognition, unlike the alluvial fans and meltwater channel farther south, which have uniform gradients, thereby allowing identification of anomalies in their gradients. North (lakeward) of the moraine belt, lidar reveals a well-defined gradient anomaly on the high beach terrace (see Figures 5.5–5.6 in the body of the report). The anomaly comprises a north trending, broad rise about 4 to 5 m high across a ~200 m wide zone. The beach terrace was originally flat, formed by wave action at the shoreline of Lake Wanaka when it was higher. The height change must reflect movement of the land after the lake dropped. The key diagnostic of this height change being due to land movement is that there are old beach ridges at right angles to the slope, such as can be seen trending east-northeast through Wanaka cemetery, about 1.3 km southwest of the town centre. The ground must have been tilted to account for their present arrangement.

A probable reason why this likely monocline on the Wanaka beach terrace has previously escaped notice is that this part of the township is long-established, and urban development has obstructed clear lines of sight across the full width of the rise. Also, by chance, there are no straight roads crossing the rise, which would have provided good lines of sight. With its presence revealed by lidar, it is now possible to see it on the ground, if looking in the right place. For example, it is evident looking east along Meadowstone Drive from the Willowridge intersection. A viewer there is standing beside houses, but the view in the distance overlooks the rooves of houses, even though they are on the same, originally flat, beach terrace.

Although detailed analysis has not been done for this report, lidar indicates that on the next lower beach terrace, on which most of the Wanaka Lakeview Holiday Park is situated, the rise is of similar width, but only about 2 m high. Closer to the lakeshore, the lidar suggests that the rise is present, but only about 1 m high. These are just preliminary interpretations, but they suggest that the rise, where 4 to 5 m high, has been produced in at least three growth events, while lower, younger, beach terraces have experienced fewer events. The ages of the beach terrace flight are as yet unknown, other than being younger than the 18,000-year-old glacial moraine belt. However, another possibility is that the deformation is rapidly dying out northward across the flight of beach terraces.

Although the topographic features described above between the mouth of the Cardrona valley and Lake Wanaka are considered very likely due to fault rupture of the ground surface, or in the case of the monocline, buckling of the ground above a subsurface fault rupture, they are classified here as ‘likely’ rather than ‘definite’. This allows for an outside chance that the steps or rises could have originated from river or stream-related processes, or in the case of the Wanaka beach terraces, differential ground subsidence due to melting of a large block of buried glacier ice. Proving through geological investigation trenching that one of the steps is a fault scarp may provide sufficient basis for elevating the status of all these features to ‘definite’.

The section of the suspected monocline across the Wanaka moraine belt is classified as ’not expressed’, because there is no basis on present information to confirm its location. The designation does not imply that the moraine area has not been affected by suspected monocline deformation.

North of the current lake shoreline, the inferred continuation of the deformation is marked as a ‘likely’ fault, ‘not expressed’ beneath Lake Wanaka. The position is that of the southern part of the inferred ‘Wanaka Fault’ in the QMAP dataset. Due to the changed interpretation of the NW Cardrona Fault in the Wanaka area, the southern sector of the previously mapped Wanaka Fault is included in this dataset as part of the NW Cardrona Fault. It is inferred to end as it approaches the Motatapu Fault. The previously mapped Wanaka Fault north of the Motatapu Fault is retained in this dataset as a potentially active fault under the name ‘Wanaka Fault’ (see separate section).

A2.34.5 Reassessment of NW Cardrona Fault Activity Characteristics

In summary, the suspected fault and fold features extending on a northerly trend from the Cardrona valley through to the Wanaka township area are attributed to post-glacial rupture(s) of the NW Cardrona Fault having transferred north towards the Lake Wanaka basin, rather than continuing northeast towards Lake Hawea as had previously been interpreted in the QMAP, 2010 NSHM and NZAFM datasets.

The recognition of ‘likely’ post-glacial scarps associated with the Motatapu Fault may indicate that post-glacial deformation on the NW Cardrona Fault has not extended north of the line of that fault.

In the 2010 NSHM, the NW Cardrona Fault is modelled as comprising two rupture segments, with the boundary between the northern and southern segments placed at Back Creek, about 14 km southwest of Wanaka, with respective lengths of 34 km and 28 km. A net slip rate of 0.38 mm/year was assigned to both segments in the 2010 NSHM, on a fault plane inferred to dip northwest at 60°. Calculated single-event displacements are about 2 m, noting that this is the displacement on the dipping fault plane, and would resolve as a vertical throw of a little less than 2 m. Calculated recurrence intervals are a little more than 5000 years, with specific values of ~6200 and 5100 years for the northern and southern segments respectively.

The 2010 NSHM assessment is aligned with field observations, including average dip-slip single-event displacements of about 2 m from Kawarau valley and Macdonalds Creek trench investigations, and smallest scarp heights at several locations of between 1 and 2 m, which represent maxima for single-event vertical displacement. Larger single-event scarps (e.g. 3 to 4 m) would be expected if the entire ~60 km length of the fault ruptured in a single earthquake. This provides ongoing justification for characterising the NW Cardrona Fault as comprising two rupture segments.

The recognition that post-glacial ruptures have passed northward to Wanaka, rather than continuing towards Hawea, has implications for the length of the northern segment of the fault. The interpretation suggested here is that the revised NW Cardrona Fault northern segment does not cross the Motatapu Fault, and presumably dies out approaching it. For the re-estimation of fault activity parameters, the northern end is placed 5 km southeast of the Motatapu Fault, passing under Wanaka and along the Cardrona valley to a southern end at Cardrona village, where the Paddys Ridge (aka SE Cardrona) and Roaring Meg (aka Gentle Annie) faults converge. The revised length is 30 km. That in turn affects the recurrence interval, recalculated using 2010 NSHM methodology, which is reduced to ~5500 years. The revised position of the NW Cardrona Fault southern segment extends from Cardrona village in the north, across the Kawarau valley to Doolans Saddle in the south, as discussed earlier. This provides a fault length of 30 km and thus has a ~5500-year recurrence interval, the same as obtained for the northern segment. It is not known when the most recent rupture of the northern segment occurred. For the southern segment, radiocarbon dating at the Kawarau valley scarp indicates that the most recent rupture there is younger than 11,200 ± 1500 years ago.

A2.35 Old Man Fault (feature 28; Figure 5.3)

The north-northwest-striking Old Man Fault is a major structure that has uplifted the Old Man Range, with the uplift equating to as much as ~1000 m vertical separation of the Otago peneplain, up to the west (Stirling 1990). The Old Man Fault is included in the NZAFD, NZAFM and the 2010 NSHM. However, there is no known evidence for geologically young landform displacement across the fault. It is interpreted that no surface rupture has occurred on the Old Man Fault since deposition of the 'Lindis' age outwash gravel (Hull and Stirling 1992), the age of which adopted here is ~330,000 years (see Grandview Fault section). However, more recent work has identified an exposure showing a ~5 m offset of those gravels (GNS Science, unpublished data 2000).

The mapped linework in the present dataset is adopted from QMAP without modification, and fault activity parameters are adopted from the 2010 NSHM, which include an assigned length of 52 km and a slip rate of 0.01 mm/year. The resulting calculated recurrence interval in 2010 NSHM is ~360,000 years. Notably, at that recurrence interval, it would have taken ~100 million years to uplift the Old Man Range. However, other geological considerations indicate that the range's uplift has probably occurred in no more than the past 15 million years or so. This indicates that the Old Man Fault has been become less active in the recent geological past. On account of the extremely long recurrence interval currently indicated, the Old Man Fault is classified in this dataset as 'potentially active'.

A2.36 Omarama Saddle fault (feature 24; Figures 5.2–5.3)

This approximately north-striking fault was included in the QMAP dataset with a classification of inactive (Forsyth 2001), but evidence for geologically recent activity was described by Barrell (2016), for that sector of the fault in the Waitaki District, north of Omarama Saddle. This fault is not in the NZAFD, NZAFM or 2010 NSHM.

For this project, mapping of the Omarama Saddle fault is extended into the Central Otago District based on inferred dislocation of as much as several hundred metres, up to the east, of inferred remnants of the Otago peneplain. Peneplain reconstruction in this area is difficult. The topographic evidence comprises narrow broad-crested ridgelines in basement rock, with intervening wide, deeply eroded, valleys. The ridges show elevation accordance, and are inferred to be peneplain remnants, but an absence of Cenozoic strata preserved on the ridges means that the inference is tentative. The Omarama Saddle fault is positioned along a change in the gradient of the inferred peneplain remnants. To the east of Omarama Saddle, the strike of the tilted peneplain is northeast and the dip is ~6° southeast. To the west, the reconstructed peneplain surface strikes north and has a dip between ~5 and ~8° to the east.

At Omarama Saddle, the indicated peneplain offset of ~400 m, up to the east, and decreases southwards due to convergence of the peneplain gradient trends. About 6 km from Omarama Saddle the indicated offset is no more than ~100 m, and that offset is maintained southwards to the western margin of the Manuherikia basin. Because it depends on a tentative reconstruction of the peneplain, defined from widely separated elevation-accordant ridges, this represents a modelled offset, rather than something that is obvious in the landscape. A crushed zone shown in QMAP on the lower flanks of the St Bathans Range about 8 km north-northeast of St Bathans village, is inferred to mark the Omarama Saddle fault. Across ridges and spurs north from the crushed zone towards Omarama Saddle, a persistent though only partly continuous topographic anomaly is visible in Google Earth imagery, at about the location of the peneplain-inferred fault. It appears to be a several-metre-high step, up to the east. It is classified as a ‘likely’, ‘moderately expressed’, fault scarp. Its recognition is regarded as tentative, pending a future ground inspection.

South from the crushed zone, the Omarama Saddle fault is extrapolated along the Isolated Spur Fault recognised by Madin (1988). This latter fault was not included in QMAP, but has a throw of ~100 m, up to the east, defined by offset of cover rock strata, and to the south ends at or close to the Stranraer Fault, according to Madin (1988). Note that this latter fault is referred to in this report as the Home Hills fault zone. The area close to the Home Hills fault zone just lies within the lidar coverage of the Manuherikia valley, and two en-echelon, broad, northeast-trending topographic steps, about 1 to 2 m high and down to the northwest, about 0.7 km east of the Loop Road/Hawkdun Runs Road intersection, are mapped as ‘likely’ monoclines associated with the Isolated Spur Fault. About 1 km to the north, at the southern end of Isolated Spur and just outside of lidar coverage, colour aerial imagery shows a ‘definite’ fault scarp, trending northeast and up to the southeast, offsetting a hillslope and the floors of gullies draining down the slope. This scarp is inferred to be on the Isolated Spur Fault section of the Omarama Saddle fault.

The tentative nature of the recognition of the Omarama Saddle fault for much of its length, based on modelled reconstruction of peneplain contours, suggests that ‘possible’ would be a preferred certainty to apply to this fault. There is however a need to define a plausible surface-rupturing fault to account for the ‘definite’ fault scarps at either end of the structure (Twinburn in the Waitaki District – see below; and Isolated Spur). Therefore, ‘likely’ is the default certainty adopted here for the fault. It should nonetheless be regarded as a provisional categorisation pending any investigatory field work that may be done in the future.

Using aerial photos, Barrell (2016) identified a landform offset of ~5 m on a river terrace of assumed age 18,000 years near Twinburn farm in the Waitaki District. A subsequent drive-by inspection by the writer indicated that the scarp height is closer to ~3 m. This scarp is up to the northwest, in opposing sense to the peneplain offset, and indicates some complexity of movement on the Omarama Saddle fault. For the purposes of this assessment, the vertical slip rate proposed by Barrell (2016) of 0.3 mm/year is revised to ~0.2 mm/year based on the revised scarp height. Adopting a length of ~32 km, extending from the Hawkdun Fault in the north to the Home Hills fault zone in the south, and assuming a dip of 60° to the east and pure dip-slip reverse motion, the recurrence interval is calculated to be ~12,000 years, using 2010 NSHM methodology.

A2.37 Paddys Ridge fault (feature 8; Figure 5.2)

This northeast-striking fault is mapped along the north-western flank of the Pisa Range, adjacent to the Cardrona valley. It has previously been referred to as the SE Cardrona Fault (e.g. Beanland and Barrow-Hurlbert 1988; Turnbull 2000; McDonnell and Craw 2003). There is a potential for confusing that name with the NW Cardrona Fault, and so a new name is applied here to the SE Cardrona Fault. The new name is taken from Paddys Ridge, shown on the 1:50,000-scale topographic map, which is traversed by the access road from the Cardrona valley to the Waiorau Snow Farm ski area. The mapped position of the fault is taken directly from QMAP, and it is not included in the NZAFM or the 2010 NSHM. The fault is identified on the basis of slivers of Cenozoic strata caught up along the fault, and the need to account for basement rock of the Pisa Range standing high about Cenozoic strata in the Cardrona valley. Upthrow is to the southeast and it is inferred that it is a southeast-dipping reverse fault. There has been substantial Late Cenozoic displacement, since the middle Miocene, but there is no evidence for or against Late Quaternary displacement. Beanland and Barrow-Hurlbert (1988) drew a ‘possible’ fault trace on an alluvial fan ~1 km northwest of the projected line of the Paddys Creek fault but noted that it “does not continue across adjacent fan surfaces, and its origin is doubtful”. I agree with that assessment and consider it more likely to be a landform of erosional origin. Although this possible fault feature is included in the QMAP and NZAFD fault datasets, it is not included in the present active fault dataset.

The Paddys Ridge fault is identified here as a potentially active fault. A length of 22 km is assigned along with an assumed dip of 60° and nominal slip rate of 0.05 mm/year. Using 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.38 Pisa Fault Zone (feature 21; Figures 5.2–5.3)

Movement on the northeast-striking Pisa Fault has been responsible for the uplift of the Pisa Range to the northwest. The Pisa Range is in part a fault block, but with a substantial component of anticlinal folding, seen in the attitude of foliation in the schist on the upthrown side of the fault, and in deformation of the Otago peneplain. To the southwest of the Kawarau River valley, the Carrick Range is a continuation of the Pisa Range uplifted/upfolded block. The Bannockburn to Cromwell basin comprises a prominent synclinal fold, that is paired with the Pisa Range anticline, and the Dunstan Mountains anticline to the southeast. The term ‘Pisa Fault Zone’ is used in this report to encompass the Pisa Fault as well as the Carrick and Bannockburn faults.

Previous workers have suggested that to the northeast, the Pisa Fault Zone continues along the foot (east side) of the Lindis Peak range / west side of the Tarras basin (Officers 1984; Halliday 1986; Beanland and Berryman 1989). I consider there are three difficulties with this interpretation. First, the amplitude of the Pisa Range anticline diminishes north-eastward, and swings northward to plunge into the Wanaka – Hawea basin (i.e. west of the Lindis Peak range). This implies that the range-bounding fault is petering out in that direction. Second, the Lindis Peak range is primarily associated with uplift by a fault (Goodger Fault) on its north-western side. If the Pisa Fault Zone did continue as a prominent feature on the southeast side of the range, the two faults would intersect at shallow depth. Third, at the north end of the Tarras basin there are three faults (Cluden Fault Zone), with up-to-the-northwest displacement of the peneplain. Their collective vertical separation of the peneplain is about 300 to 400 m, and they appear to terminate to the northeast against the Longslip Fault (Lindis Pass Fault Zone). In order to be sufficiently long to have produced the observed displacement, the Cluden Fault Zone must extend southwest to near the southern end of the Grandview Fault.

The interpretation adopted here is the Pisa Fault Zone as a ground-surface feature extends northeast to the Grandview Fault (which is upthrown to the east) but does not cross the Grandview Fault. What has previously been regarded as the northern part of the Pisa Fault Zone is renamed the Cluden fault zone (see separate section).

From Low Burn northeast to about 2 km beyond Lochar Burn, the Pisa Fault has a prominent expression on medium to high terraces. Investigations have shown it is predominantly a monocline rather than a fault break-out (Officers 1984), and in the dataset accompanying this report the feature is generalised as a single monocline, positioned at about the mid-point of the fold. The monocline has associated with a broad zone of surface buckling, locally some discrete back-faults just northwest of the monocline crest, and a broader zone of backtilt extending farther to the west. The most up-to-date information source is the Beanland and Berryman (1989) paper. For the present data set, the line denoting the monocline should be regarded as representing the centre of a 400-m wide deformation zone.

The prevailing assessment is that there has been no surface deformation associated with the Pisa Fault since the river terraces and alluvial fans of the “Albert Town” landform set were formed (Beanland and Berryman 1989). However, the age of these landforms is not well established. They were assessed as having formed in the early part of the last glaciation (~65,000 years go) on QMAP, although Barrell (2011) suggested they may be younger, dating from the latter part of the glaciation. The matter remains unresolved at present.

To the south, the Carrick Fault forms the structural continuation of the Pisa Fault, and comprises a zone of faults along the foot of the Carrick Range. There is no direct evidence for Quaternary-age offset, and the strands of the Carrick Fault are identified as ‘possible’ active faults.

The Bannockburn Fault is well defined near the Bannockburn inlet, where schist is faulted up to the west, with an asymmetric syncline in Manuherikia Group strata, locally overturned, to the east (feature 20a). Farther south, peneplain contours provide a basis, along with patchy remnants of Manuherikia Group Cenozoic strata, for correlating a series of mapped faults in bedrock with the Bannockburn Fault, through to the Fraser Dam area. There is a ~100 to 200 m vertical offset of the peneplain across the fault. The Bannockburn Fault is considered here to be a splay of the Carrick Fault, and is classified as possibly active. The Carrick Fault can be similarly traced to about the same southern extent. Beyond there, both meet the Old Man Fault. By the interpretation presented in this dataset, the Fish Creek Fault and Cairnmuir fault (features 22a, 22b) end south-westwards against the Bannockburn Fault.

Although the north-eastern extent of the Pisa Fault Zone has been reduced in the reinterpretation presented here, it is approximately balanced by the extension southwest along the Carrick and Bannockburn faults. No changes are suggested for the characterisation of the Pisa Fault Zone in the 2010 NSHM, which uses a length of 47 km, dip of 60° to the northwest, and slip rate of 0.1 mm/year. The calculated recurrence interval is ~31,000 years, generalised here as ~30,000 years.

A2.39 Pylep fault (feature 44; Figure 5.3)

The previously-unnamed Pylep fault comprises two northeast striking, partly overlapping, fault strands, well expressed on the peneplain surface, by upthrow of about 50 m to the southeast. In high-resolution aerial imagery, there are in places structural lineaments in rock outcrop and subcrop, presumably marking the fault crushed zone. The two strands are ~12 km (northern) and ~16 km (southern) long, and they overlap by about 3 km, separated by less than 2 km in the strike-normal direction. Both were included in the QMAP dataset, and also on the 1st generation 1:250,000-scale geological map (Mutch 1963). The name is taken from Pylep Creek on the upthrown side of the southern fault strand. Linework positions have been refined in the present dataset, because high-resolution colour aerial imagery allows for much more accurate mapping than was possible by QMAP methods. The features defined here are not included in the NZAFD, NZAFM or 2010 NSHM datasets.

There are no discernible offsets of geologically young landform features, and the Pylep fault is classified here as ‘potentially active’. The two overlapping strands are regarded as the surface expression of a single fault at depth. For the estimation of activity parameters, the Pylep fault is assigned a dip of 60°, length of 23 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.40 Ranfurly Fault Zone (feature 35; Figure 5.3)

The Ranfurly Fault Zone comprises a remarkable array of en-echelon faults that is as much as 2 km across, aligned east-northeast – west-southwest across the Maniototo Plain. Most are up on the southeast side, but there are several with an opposing throw. Overall, the array has the appearance of a dilatational fault system. On the lower river terraces near Ranfurly, there are at least 5 scarps across the zone, each typically with no more than ~1 m offset. The scarps offset all but the lowest, freshest river plains, and it is also notable that the scarps are not much higher (no more than two or so metres) on high terraces or downland terrain, judged likely to be more than 100,000 years old. Overall identified map length of the 'definite' or 'likely' components of the fault zone is 9 km, extending southwest of the southern end of the Launceston Fault. Farther southwest for ~6 km are ill-defined topographic steps on high-level terraces that as classified as 'possible', 'moderately expressed', with 'not expressed' connector lines.

It is unclear from the reconnaissance-level desktop study that forms the basis of this report whether some fault strands affect a particular river terrace, but others do not. If this were shown to be the case, it might indicate different components of the array moved during different surface rupture events. A detailed mapping study of fault scarps and other landforms in the vicinity of the Ranfurly Fault Zone would be needed to address this question.

For the purpose of placing the fault zone in a hazard perspective, an indicative average slip rate of 0.1 mm/yr is inferred, by summing the heights of ~5 scarps across the zone (~10 m) relative to an assumed age of ~100,000 years for the higher terraces and downlands.

The Launceston Fault and Ranfurly Fault Zone each have a relatively short length, and their scarps have a similar freshness. They are inferred to represent a single active fault structure, collectively assessed as being 24 km long. This is markedly more than the 15 km length assigned in the 2010 NSHM (Stirling et al., 2012). Using the extended length, a revised recurrence interval of ~17,000 years is re-calculated using 2010 NSHM methodology. This substantially longer than the value of ~2,200 years in the 2010 NSHM. The longer value is more compatible with the overall landform expression of the Ranfurly Fault Zone.

A2.41 Riddles fault (feature 47; Figure 5.3)

The Riddles fault extends from the uppermost reaches of the Taieri River, north-northeast for ~21 km, and has produced ~100 m of vertical separation of the peneplain, up to the west. The fault forms part of the western margin of the Serpentine Flat basin. It is included in the QMAP dataset and is assumed here to be a west-dipping reverse fault. It is not named in the QMAP dataset, and the name assigned here is from Riddles Creek, which crosses the northern part of the fault escarpment. There are no discernible offsets of geologically young landform features.

The southern ~10 km of the Riddles fault is parallel to, and about 4 km east of, the Beaumont River fault. As the Beaumont River fault and Riddles fault are assumed to have opposing dips, they are interpreted as intersecting at moderate depth. The Beaumont River fault is longer and is therefore assumed to the larger structure. The interpretation is made here that the Riddles fault is an earlier-formed structure and has subsequently been cut off at depth by the Beaumont River fault. In addition, the escarpment of the Logan Burn fault crosses and appears to offset the Riddles fault escarpment, before rapidly petering out about 2 km east of the mapped position of the Beaumont River fault. This lends weight to the idea that the Beaumont River fault and Logan Burn fault have developed interactively, and both are younger than the Riddles fault.

For the current assessment, the Riddles fault is not regarded as an active, independently rupturing fault. It is conceivable however that it could experience secondary slip associated with rupture of the Logan Burn fault or the Beaumont River fault, and therefore in this dataset the Riddles fault is classed as ‘potentially active’, ‘not expressed’. No slip rate or specific recurrence interval are assigned to the Riddles fault in this report, other than identifying it as having a recurrence interval class of VI (greater than 20,000 years), compatible with both the Logan Burn and Beaumont River faults.

A2.42 Roaring Lion fault (feature 10; Figures 5.1–5.2)

This northeast-striking fault is mapped along the north-western foot of the Garvie Mountains at the south-eastern margin of Nevis valley. The mapped position of the fault is taken directly from QMAP, and it is not included in the NZAFM or the 2010 NSHM. It has not previously been named, and the applied here is from Roaring Lion Creek which drains from the Garvie Mountains across the fault escarpment. The fault is identified from schist basement rock faulted up to the southeast relative to Cenozoic strata, with an indicated vertical separation of the peneplain across the fault of as much as 600 m. It is inferred that it is a southeast-dipping reverse fault. There has been substantial Late Cenozoic displacement, but there is no evidence for or against Late Quaternary displacement.

This fault is identified as ‘potentially active’. A length of 46 km is assigned along with an assumed dip of 60° and nominal slip rate of 0.05 mm/year. Using 2010 NSHM methodology, a recurrence interval of ~65,000 years is calculated.

A2.43 Roaring Meg fault (feature 9; Figures 5.1–5.2)

The identification of this north-striking fault is based on the presence of peneplain remnants overlain by patches of Cenozoic strata in the headwaters of Roaring Meg and Gentle Annie Creek, sitting ~500 m below the elevation of schist rock forming the Mt Allan – Queensbury Hill ridge to the west. Unpublished mapping undertaken for Kawarau River proposed hydroelectric development in the 1980s shows numerous approximately north-striking fault zones crossing the Kawarau River east of the Gibbston basin. Beanland and Barrow-Hurlbert (1988) associated the peneplain displacement with the Gentle Annie Fault zone, which comprises a several-hundred-metre wide zone of steeply southeast-dipping shears in schist in the Kawarau River valley floor. This implies a normal sense of displacement to account for the Late Cenozoic geological relationships in the Roaring Meg/Gentle Annie catchments, and is difficult to reconcile with the indicated reverse nature of other peneplain-offsetting faults in the wider region. However, there are also bedrock faults dipping to the northwest, which could represent reverse faults more likely associated with the peneplain offset. The interpretation adopted in this dataset is that the fault(s) associated with the peneplain offset, referred to here as the Roaring Meg fault to avoid confusion with the southeast-dipping Gentle Annie Fault, extends south down Gentle Annie Creek, along the Kawarau River channel at the foot of Mt Difficulty, and then south up Slapjack Creek, and through Slapjack Saddle in the Carrick Range. South of Slapjack Saddle, the peneplain stands about 200 m higher than on adjacent parts of the Carrick Range. The fault is assumed to peter out south of there, as the peneplain dislocation diminishes in that direction. Doubtless other interpretations could be made, but this is considered to be the one that currently provides a satisfactory explanation of the indicated peneplain offset both north and south of the Kawarau River valley. By this interpretation, the Gentle Annie Fault zone described by Beanland and Barrow-Hurlbert (1988) has been truncated at depth by the Roaring Meg fault.

The Roaring Meg fault is regarded as part of the Nevis-Cardrona Fault System, following the reasoning of Beanland and Barrow-Hurlbert (1988) for including the Gentle Annie Fault in that system. It is approximately parallel to, and 5 to 6 km southeast of, the southern segment of the NW Cardrona Fault. As there is no indication of any offset of geologically young landforms, it is classified as ‘potentially active’, ‘not expressed’, on the presumption that the NW Cardona Fault has been accommodating strain in this general area in the recent geological past.

The Roaring Meg fault is characterised here as having an assumed dip of 60, a nominal slip rate of 0.05 mm/year and length of 28 km. Using NSHM methodology, a recurrence interval of ~40,000 years is calculated.

A2.44 Rocks Creek Fault Zone (feature 24a; Figure 5.3)

This encompasses an array of generally northeasterly-striking faults, downthrown to the southeast, along the western margin of the upper Manuherikia basin, as shown in QMAP and classified there as ‘inactive’. This fault zone is not in the NZAFM or 2010 NSHM, although the Vulcan Fault and Tunnel Hill Fault components (see below) are included in the NZAFD.

The QMAP delineation is based largely on the interpretation of lignite exploration drillhole data by Bishop (1981), who applied the names ‘St Bathans’ to northeast-striking fault strands, and ‘Manuherikia’ to more easterly-striking fault strands. Each set of fault strands has displaced the peneplain by 100 m or so. Nowhere has a fault exposure been reported but they are assumed here to be northwest-dipping reverse faults. Between 1 and 2 km southeast of those faults are fault-deformed landform surfaces that were investigated by Beanland and Fellows (1985). They defined the ‘Vulcan Fault’ that deforms fans and river terraces on the west side of the Manuherikia River, and about 2 km to the southwest, the ‘Tunnel Hill Fault’ that affects middle-level fan terraces of Rocks Creek. A fault displacement origin for the Vulcan feature was confirmed by trenching of a scarp across the floor of a small un-named stream, about 1 km west-southwest of the Hawkdun Runs Road bridge over the Manuherikia River. The trench exposure showed gravels deformed by a reverse fault, dipping northwest at 40°. Using airphotos, I have expanded upon the mapping of Beanland and Fellows (1985) by differentiating front and back faults, or monoclines where the deformation zones are broad. Collective vertical deformation is as much as 20 m on river or fan landforms of assumed age ~130 000 years, as interpreted on QMAP. No deformation is evident on low-lying, probably Holocene age, terraces, apart from the Vulcan Fault excavation site. However, in absence of dating, the age estimates are tentative and of high uncertainty. Surface deformation of the Vulcan Fault and Tunnel Hill Fault can be traced for only about 3.5 km along strike.

Collectively, all these fault features are referred to here as the Rocks Creek Fault Zone, adopting a name used by Madin (1988). The Rocks Creek Fault Zone is classified as ‘likely’, apart from ‘definite’ sectors of the Vulcan and Tunnel Hill fault strands. The fault zone has a maximum strike length of only 16.5 km, between the Hawkdun Fault in the northeast and Omarama Saddle fault in the southwest. Due to its shortness, the Rocks Creek Fault Zone is not interpreted here as an independently rupturing active fault, but instead inferred to be a diffuse ‘back-fault’ break-out from the Omarama Saddle fault. The slip rate (0.2 mm/year) and recurrence interval (12,000 years) for the Omarama Saddle fault are adopted as maxima for the Rocks Creek Fault Zone. A cross-check exists via the estimated ~20 m vertical deformation on a landform of assumed age 130,000 years mentioned above, which implies a slip rate of ~0.15 mm/year. While the age estimate is of highly uncertain validity and should not be relied upon, the derived slip rate is compatible with the line of reasoning of an association between the Rocks Creek Fault Zone and the Omarama Saddle fault.

A2.45 Teviot Fault (feature 40; Figure 5.3)

The north-northwest striking Teviot Fault is approximately parallel to, and stepped as much as 4 km southeast from, the Old Man Fault. There is as much as ~300 m vertical separation of the peneplain across the Teviot Fault, up to the west, and no known evidence for geologically young landform displacement. The Teviot Fault is classified in this dataset as ‘potentially active’. It is presumed to have a southern limit where it meets the projected positions of the Blue Mountain Fault and the Tuapeka Fault.

The Old Man Fault lies at the foot of the Old Man Range, which diminishes progressively in height south of Roxburgh, and peters out southwest of Ettrick. The Teviot Fault has uplifted an un-named range of low hills north of Raes Junction, and that range diminishes in height and peters out approaching Ettrick. Two possibilities are that the Teviot Fault is either a separate segment of the Old Man Fault, or is an individual fault, albeit similar to the Old Man Fault. The latter interpretation is provisionally adopted for this dataset. On account of the similarity between the two faults, the Teviot Fault is assigned the same slip rate as the Old Man Fault (0.01 mm/year) and a length of 32 km is adopted. Using 2010 NSHM methodology, a recurrence interval of ~225,000 years is calculated for the Teviot Fault.

A2.46 Timaru Creek Fault (feature 16; Figure 5.1)

This northeast-striking feature is known from a ‘definite’, ‘well expressed’ northeast-trending fault scarp that offsets a valley-floor alluvial plain, up to the southeast by several metres, in the Lindis River headwaters. The offset fluvial landform surface is judged to be no older than the end of the Last Glaciation (18,000 years) and may possibly be a little younger than that. The fault is shown on the geological map of Turnbull (2000), and its name comes from the QMAP digital dataset. It is included in the NZAFD, with linework adopted from QMAP, but not included in the NZAFM or the 2010 NSHM.

Northeast of the ‘definite’ scarp, the fault is classified as ‘likely’, ‘not expressed’, up to a saddle at the Central Otago/Waitaki district boundary, where it adjoins a similarly classified fault strand in the Waitaki District (Barrell 2016). For ~0.7 km southwest from the ‘definite’ fault scarp across the Lindis valley floor, a topographic anomaly extends along the slopes of a tributary valley, and is classified as a ‘definite’, ‘moderately expressed’ fault. In the QMAP dataset, the fault is extrapolated a further 8 km across mountainous terrain. There is no indication of any surface displacement features along that sector of the fault, and it is classified here as ‘likely, ‘not expressed’.

About 2 to 3 km southeast of the Timaru Creek Fault, another northeast-striking fault is mapped, named the Johns Creek Fault in the QMAP dataset. On that structure is a ‘definite’, ‘well expressed’ east-northeast-trending fault scarp that offsets hillslopes, and an alluvial fan, on the northern side of the Lindis River valley, up to the southeast. The alluvial fan offset is several metres, of similar size to that seen on the Timaru Creek Fault, and these two scarps are effectively en-echelon.

The total mapped length of the Timaru Creek Fault shown in QMAP, and collated into the NZAFD, is ~13 km. Only the central, ~6 km long, sector of the strand named Johns Creek Fault in QMAP, and included in the NZAFD, was identified as active in those datasets (feature 16a). Eastern and western parts of the Johns Creek Fault structure were classed as inactive. Individually, these lengths are too short to be independent, surface rupturing faults, and the interpretation is made here that the Timaru Creek Fault and Johns Creek Fault are connected at depth, and two parts of a single active fault referred to here as the Timaru Creek Fault, and that name is applied to all surface components of it, with the Johns Creek component identified in this dataset as the 'Johns Creek strand' of the Timaru Creek Fault. The composite mapped length of the Timaru Creek Fault and Johns Creek strand is ~28 km.

To the west of the 'definite' scarp, the Johns Creek strand is classified as 'likely', 'moderately expressed', across two prominent notched spurs, with two further sectors similarly classified farther west, one a topographic step across landslide terrain north of Little Breast Hill, and one along a hillslope in the northeastern headwaters of Breast Creek, to the west of Little Breast Hill. A classification of 'likely', 'not expressed' is applied to other parts of the fault strand, except that the westernmost sector is classed as 'possible', 'not expressed', on the presumption that surface rupture may peter out approaching the Grandview Fault.

The positions of the surface fault scarps ('well expressed' or 'moderately expressed') have been adjusted from their QMAP locations to confirm closely with the position of surface offsets which are clearly visible in aerial imagery.

For calculating slip rate, the 'definite' scarps are assumed to be about 5 m high and has offset fluvial landforms with an assumed age of 18,000 years. Whether this was a single event or multiple events is unknown. The composite Timaru Creek Fault is characterised here as a reverse fault dipping 60° to the southeast and extending for 28 km northeast from about the location of the Grandview Fault. Using 2010 NSHM methodology and taking account of the adopted fault dip and assuming pure dip slip motion, a net slip rate of 0.32 mm/year is obtained and a recurrence interval of ~6100 years is calculated.

A2.47 Tuapeka Fault (feature 41; Figure 5.3)

The northwest striking Tuapeka Fault is a prominent geological feature of the Lawrence to Waitahuna areas, in the Clutha District, but only the northernmost 1.5 km of the fault extends into the Central Otago District. The Tuapeka Fault is a southwest-dipping normal fault of Cretaceous age (Els et al. 2003), but on the projected line of the fault near Beaumont (Clutha District) there is a several-metre-high, suspected fault scarp crossing medium to high level terraces of the Clutha River. The scarp is upthrown to the southwest, indicating reversal of its original Cretaceous sense of movement.

A 4-km-long sector of the fault is shown as 'active' on QMAP (Turnbull and Allibone 2003) and that sector is included in the NZAFD. It is not included in either the NZAFM or 2010 NSHM.

The north-western-most end of the fault that passes into the Central Otago District is classed here as 'likely', 'not expressed'. It is expected that this fault will be discussed more fully in a future report on the active faults of the Clutha District. It is assigned a recurrence interval in the range of ~250,000 to ~680,000 years by Villamor et al. (2018). To avoid pre-empting future assessment of active faults of the Clutha District, no slip rate or specific recurrence interval are assigned in this report, other than identifying the Tuapeka Fault as having a recurrence interval class of VI (greater than 20,000 years).

A2.48 Waihemo Fault Zone (feature 37; Figure 5.3)

This major northwest-striking fault lies along the southwestern foot of the Kakanui Mountains. It mostly lies in the Waitaki District and is discussed in detail by Barrell (2016). The most recent information on geologically-young activity is by Curran and Norris (2009) and Curran et al. (2011), from work in the Waitaki District sector of the fault zone. Within the Central Otago District, a prominent topographic step, up to the northeast by as much as ~10–15 m, runs across a mid-level alluvial fan surface of Old Hut Creek, about 13 km east-southeast of Naseby, and is interpreted as a 'likely', 'moderately expressed' fault scarp. The caveat on interpretation is that in the general area, there are low-lying knobs of hillocks of bedrock at the foot of the range, and the topographic anomaly could possibly be due to such a hillock having been partly overridden by the alluvial fan. However, for 3 km to the northwest, and 7 km to the southeast, there are short, discontinuous sectors of similar topographic anomalies, and intervening zones where the topography is such that geologically-young fault deformation could be obscured. On balance, the features are interpreted as the 'likely' result of past rupture of the Waihemo Fault Zone.

Towards the Kye Burn valley, the bedrock fault zones of the Stranraer, Dansey Pass and Waihemo fault structures all converge. As noted earlier in relation to the Dansey Pass Fault, the Stranraer fault (feature 37a) has offset geologically young middle to high terraces of the Little Kye Burn valley (see Figure 5.9 in the body of the report). Due to a general similarity of height and likely age of that 'definite' scarp of the Stranraer Fault and the 'likely' fault scarps on the Waihemo Fault Zone to the southeast, an interpretation is made that they are part of the same active fault structure.

For the purposes of quantifying fault activity, the aggregate length of the Stranraer Fault and Waihemo Fault Zone, extending southeast to the coast, is 80 km. Assuming that the middle terrace of the Little Kye Burn valley is nominally 100,000 years old, and has a vertical component of fault offset of 10 m, on a fault plane dipping 60° and assuming pure dip-slip motion, implies a net slip rate of 0.12 mm/yr. Using 2010 NSHM methodology, a recurrence interval of ~50,000 years is calculated.

A2.49 Waipiata Fault Zone (feature 38; Figure 5.3)

The northeast-striking Waipiata Fault Zone includes a number of complicated elements. For the purposes of description, its components are grouped into three stands.

A2.49.1 Waipiata strand

The western strand extends along the eastern margin of the Maniototo basin, from Patearoa northeast through Waipiata, and along the western foot of the Camp Hill anticlinal ridge and is identified as the 'Waipiata Fault Zone – Waipiata strand'. In the northeast, Cenozoic strata dip west at a moderate angle into the basin, and whether it is a fault or a monocline limb is unclear. It is identified as a fault in QMAP, and classified as 'possible', 'not expressed' in this dataset. At its north-eastern end, near SH 85, it projects across a high terrace, and there is no hint of a topographic step. For that reason, the north-eastern limit of this strand of the Waipiata Fault Zone is positioned ~2 km southwest of SH85.

For ~5 km between the Taieri River and Pig Burn, there is a topographic step of as much as 10 or 20 m, up to the SE, at the mapped location of the Waipiata strand. However, aerial photos show the terrain on the higher ground comprises moderately northwest-dipping Cenozoic strata, and the step may simply be a dip slope on the strata, with the dip-slope buried to the northwest by fluvial sediments. In that area, high-resolution aerial imagery has been used to slightly reposition the QMAP line to accord more closely with the topographic step, and it is identified as ‘possible’, ‘moderately expressed’.

About 7 km southwest of Waipiata, there is a distinct topographic step trends across river terraces extending for 2 km southwest of Pig Burn. It is as much as several metres high and is classed as ’well expressed’. However, it is conceivable it is a river-cut step, trimmed by drainage down-plain from adjacent tributary fans to the southwest. The reason for suspecting a river-cut origin of this step is that, were it the product of fault rupture, it is surprising it is not clearly evident across higher terrain northeast or southwest, where it should be reasonably prominently expressed. However, on balance, the tectonic origin seems likely and the step is classified accordingly.

Southwest of Patearoa, there is a topographic step at the likely position of the fault, but it is not clear whether it may just mark the boundary where fluvial sediment has accumulated against the margin of the schist rock forming the foot of the range. The step is classified as ‘possible’, ‘moderately expressed’, for 2 km southwest of Patearoa. Beyond there, along the mapped line of the fault in the QMAP dataset, the landscape comprises old alluvial fans and schist bedrock terrain, well suited for identifying geologically recent fault scarps, but there is no sign of any. A mapped extrapolation of the ‘possible’ fault, classified as ‘not expressed’, is extrapolated a further 2.5 km southwest and terminated there.

A2.49.2 Clunie strand

The central strand extends along the eastern side of the Camp Hill anticlinal ridge and is identified as the ‘Waipiata Fault Zone – Clunie strand’, after nearby Clunie Road. Mid- to high level river terraces along the western side of the Kye Burn valley are not matched on the other side of the valley, and one possibility is that the terraces on the western side of the valley have been elevated by tectonic movement. Two en-echelon monoclines, up to the west, are inferred to account for the elevated terraces, each positioned at the foot of the riser up to the terraces. Features in support of this interpretation are that along the more southern monocline, the terrace riser is surprisingly gentle for a river-cut feature. A feature of the northern monocline is the presence of what appear to be discontinuous fault scarps, up to the southeast, along the crest of the rise. All features associated with this structure are identified as ‘likely’. This strand is presumed to be associated with an underlying reverse fault dipping northwest, and if so is presumably a back-fault from the Waipiata strand.

A2.49.3 Hamilton strand

Shown in QMAP is an array of northeast-striking faults partway up the lower flank of the Rock and Pillar Range, upthrown to the southeast. There is indicated vertical separation of as much as several hundred metres on the peneplain. Being only a few kilometres southeast of the Waipiata strand, this fault array is interpreted to be a strand of the Waipiata Fault Zone, and named after Hamilton Diggings, that lie close to the fault. There is no indication of offset of geologically-young landforms. It is presumed to be a less active, perhaps older, part of the Waipiata Fault Zone, and is classified as ‘potentially active’, ‘not expressed’.

A2.49.4 Re-assessment of Waipiata Fault Zone Activity

Overall, there are few good geomorphic indicators to aid the assessment of activity of the Waipiata Fault Zone. Collectively, the suspected monoclines of the Clunie strand are assessed as being about 10 m high, and a nominal age of 100,000 years is assigned to the landform on the inferred uplifted side. This is taken, within error, as an indicative slip rate of 0.1 mm/yr. In conjunction with inferred fault dip of 60° and overall length of 35 km, a recurrence interval of ~24,000 years is calculated using 2010 NSHM methodology.

A2.50 Wanaka Fault (feature 13; Figure 5.1)

This north-northeast striking structure includes the Castle Hill Fault from QMAP Haast, and the Wanaka Fault of QMAP Wakatipu (different names were applied to the same fault structure). It also equates to the Makarora Fault Zone of the NZAFM, which was one of the Southern Alps 'potentially active' faults proposed by Cox et al. (2012), and to which no slip rate was assigned in the NZAFM. The Wanaka Fault is not in the 2010 NSHM.

For most of its length, the Wanaka Fault is concealed under Lake Wanaka or the floodplain of the Makarora River. It is inferred to be the structure that separates differing types and/or metamorphic grades of schist rock either side of the Wanaka/Makarora valley. Thus, it is likely that the fault originated during the Mesozoic Era. The Wanaka Fault is depicted in the QMAP dataset as curving east-southeast beneath Roys Bay and Wanaka township to meet the line of the NW Cardrona Fault. However, in this dataset the Wanaka Fault is stopped at the line of the Motatapu Fault due to indications that post-glacial rupture of the Motatapu Fault may have extended across the line of the Wanaka Fault. There are no known offsets of geologically young landforms on the Wanaka Fault, and it is classified as 'potentially active'. Using 2010 NSHM methodology, the Wanaka Fault is assigned a length of 60 km, a dip of 60° east-southeast and a nominal slip rate of 0.05 mm/year. A recurrence interval of ~85,000 years is calculated from those values.

A2.51 West Wakatipu Fault (feature 2; Figure 5.1)

This north-northwest striking fault is depicted on QMAP as separating semischist basement rock, upthrown to the east, from schistose greywacke rock to the west. The fault is mapped along the western side of the upper Wakatipu valley for ~27 km from the Greenstone/Caples river mouth north to just beyond the Route Burn valley. To the south the fault presumably extends under the lake. While it is not known whether there may be other faults hidden under Lake Wakatipu, the tentative interpretation made in this report is to equate the previously identified West Wakatipu Fault with the similarly striking Home Creek Fault near Mt Nicholas, which has a similar sense of upthrown, at least in the Late Cenozoic. Although there is no reported post-glacial offset on the Home Creek Fault, there is higher ice-sculpted bedrock terrain near the lakeshore, up to the east, along the approximate line of the fault. A connection is inferred between the West Wakatipu Fault under Lake Wakatipu and the Home Creek Fault, positioned along the western margin of that slightly higher terrain, named 'Fern Hills' on the topographic map. The inference made here is that the two prominent fault scarps east of Mt Nicholas, previously attributed to the Moonlight Fault, are associated with post-glacial rupture(s) of the Home Creek Fault a.k.a. the West Wakatipu Fault. The latter name is preferred here because the name Home Creek Fault has been previously regarded as part of the Moonlight Fault Zone (Turnbull et al. 1975).

The two fault scarps near Mt Nicholas are classified here as 'definite' active faults, while the Home Creek Fault, the West Wakatipu Fault, and an inferred connection between the two under Lake Wakatipu, are classified as 'likely'. The heights of the post-glacial fault scarps near Mt Nicholas have not been reported, but using colour aerial imagery, each is estimated here to be ~1.5 m high. Using 2010 NSHM methodology, the aggregate ~3 m vertical offset of landforms assumed to be as old as ~18,000 years, on a fault plane of inferred dip 60° east with pure dip slip motion, returns a net slip rate of 0.19 mm/year. In conjunction with an adopted overall length of 55 km for the West Wakatipu Fault, from the Moonlight Fault Zone north to the Route Burn area, a recurrence interval of ~20,000 years is calculated. If further work were to be undertaken to determine whether there has been any post-glacial offset on the Home Creek strand of the fault, and some is found, that would increase the slip rate and decrease the recurrence interval.

A2.52 Appendix 2 References

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Waitaki District Coastal Hazards

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Front page: View of the coastline between Bridge Point and Orore Point. [Jo Bind, NIWA]

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Executive summary

This study analysed the inundation and erosion hazards along the Waitaki District coast. The study, conducted by NIWA for the Otago Regional Council (ORC), found that while the erosion hazard is widespread, the inundation hazard only applies to relatively small parts of the populated area of the district (mostly Kakanui Estuary and Oamaru Port foreshore).

Coastal hazard zones were mapped for both the inundation and erosion hazards considering a 100-year planning time frame.

Inundation hazard zones are based on inundation extent across the populated area of the district and were adapted from previous work. Critical limitations in the available analysis, in particular with the estimates of extreme water levels and wave runup, constrained the use of the inundation hazard zone to low lying inland areas and does not allow the evaluation of the coastal inundation hazard in areas where wave impact is likely to be significant (e.g., Kaika, Karita, Katiki Road and Beach Road). Further study is recommended to refine the extreme water levels and wave runup and revise the inundation hazard zones.

The coastal erosion hazard zone was calculated for the entire length of the Waitaki District coast. This was based on extrapolation of historical erosion rates derived from analysis of aerial and satellite imagery and an allowance for short-term shoreline retreat due to storm erosion or cliff slumping/collapse. In areas where sufficient information was available, the erosion due to the future acceleration of sea-level rise was also taken into account. Separate simulation of the evolution of the cliffs north of Oamaru was undertaken using a numerical morphological model, and this showed that acceleration in sea-level rise should have little impact on the cliff retreat rate on that part of the coast.

The coastal erosion hazard zone was mapped for two outlook periods (50 and 100 years) and two risk levels: the CHZ95 zone mapped the line where there should only be a 5% chance that the erosion hazards could extend up to or landward of the line; and the less conservative CHZ50 zone mapped the line where there is a 50% chance that erosion hazards could extend up to or landward of the line. Decision makers should select the most suitable line depending on the planning horizon, value, and vulnerability of the assets potentially impacted by the predicted erosion.

The coastal erosion hazard zone width proposed for the 100-year outlook at 95-percentile confidence (CHZ95) is 65 m wide just north of Oamaru near Waitaki Boys High School. The CHZ95 width further north is close to 100 m which is similar to the 100 m width of the hazard zone previously proposed for the Waitaki District Council.

Much infrastructure (mostly roads) and many assets are within the CHZ95 zone. No new erosion hotspots were identified, with continued erosion expected at the current hotspots of Katiki Beach, Beach Road, Kakanui, and North Oamaru. Any plans to stabilise these shores with protective structures would need to ensure that the structures are properly built and maintained. Monitoring at these hotspots will help to refine estimates of the hazard zone widths and to better plan the nature and timing of hazard mitigation/adaptation.

The hazard zone estimates provided herein are based on a hybrid-probabilistic approach that can be reproduced and refined as new data become available.

1 Introduction

The Waitaki District is experiencing long-term retreat of its coastline. In particular, the coast north of Oamaru is experiencing a rapid recession of the soft sediment cliffs with reported retreat of 0.5 m/year (Gibb 1978). Coastal erosion in the District threatens communities, infrastructure, and assets. The Otago Regional Council is committed to better understanding of coastal hazards in the Otago Region. This focus in coastal hazards has come about through several recent drivers:

- Recent storm-related erosion events in Oamaru.
- The high cost associated with the repair and movement of coastal roads and breakwaters near Oamaru.
- The required update of the Waitaki District Plan.
- The need to address the effects of sea-level rise on coastal hazards as required by the NZ Coastal Policy Statement (NZCPS, 2010).
- A limited understanding of erosion rates along the coastline.

To address these concerns there is a need to understand and predict future coastal hazards and incorporate this understanding into future planning of development in the Waitaki District.

1.1 Project overview

The aims of this project are to:

1. Assess and update the existing coastal inundation information, including:
   - Provide feedback regarding the suitability of Lane et al. (2008) study
   - Advise the Otago Regional Council where additional information and studies are required
   - Update the inundation map with the new sea-level rise scenarios.
   - Convert the inundation information into hazard zoning for the 100-year average recurrence interval and two sea-level rise scenarios.
2. Evaluate the coastal erosion hazard for the Waitaki District including:
   - Map current shoreline position
   - Evaluate shoreline retreat rates using mapped shoreline position
   - Predict future shoreline position and construct hazard zones.

This project does not investigate the inundation related to tsunami, groundwater, river floods or urban flooding.

The study calculates the inundation hazard zone for a 100-year average recurrence interval (ARI) extreme water level. Coastal erosion hazard zones are calculated based on 50-year and 100-year projections of shoreline position following an adapted version of the shoreline recession approach proposed by Gibb (1982).

The study addresses coastal erosion for the entire Waitaki District and inundation hazards for Oamaru and the settlements of Kakanui, Hampden, Moeraki township and Boulders, and Shag Point/Matakaea (Figure 1-1).

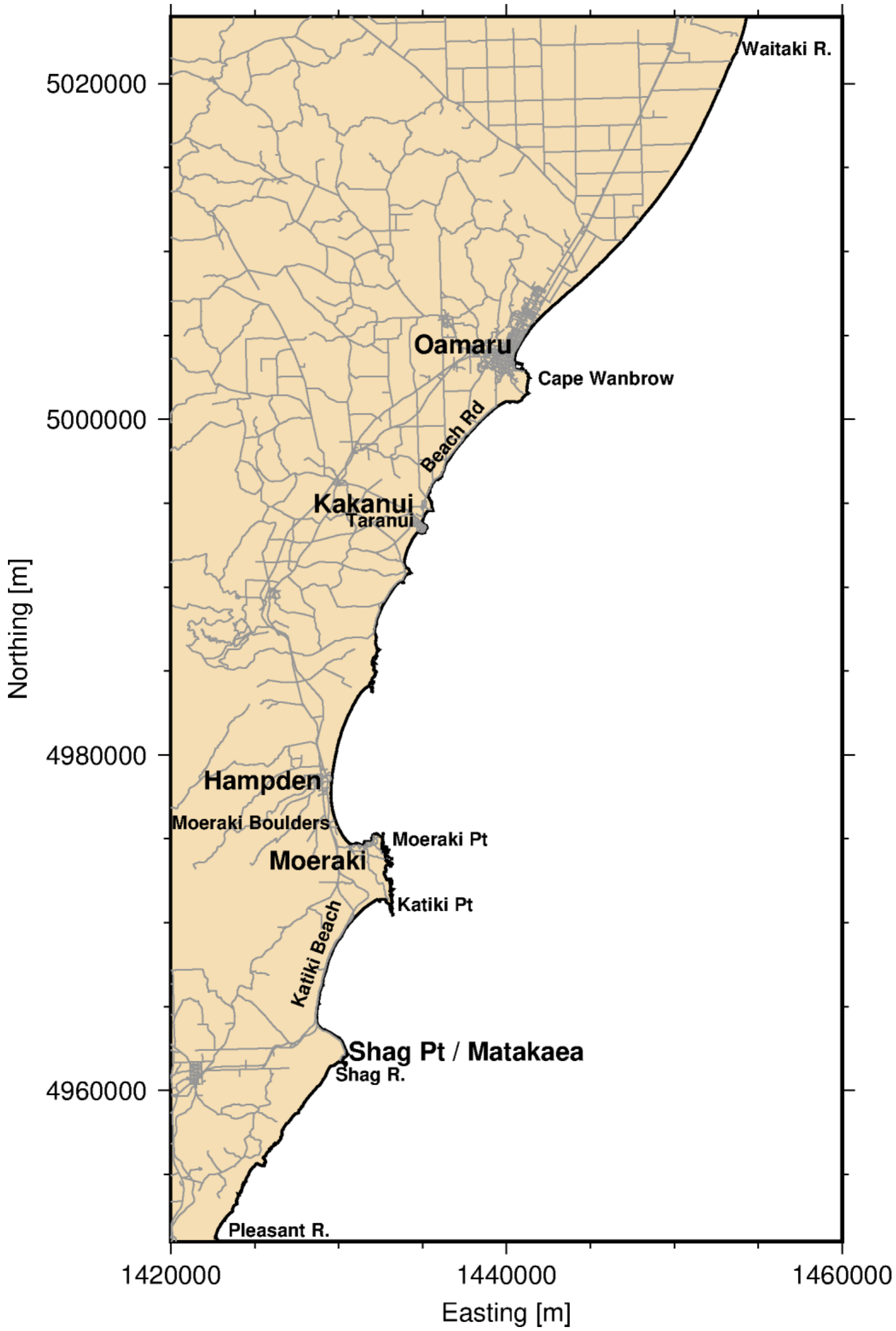

Figure 1-1: Location of the study area. Northing and easting are given in the New Zealand Transverse Mercator projection (NZTM).

Time constraints on the project did not allow for new field data collection nor even comprehensive field inspection of all the Waitaki District coast, but recommendations are made for future coastal hazard monitoring. This suggested monitoring is targeted to reduce the uncertainties where the coastal hazard risk is high and where communities and assets are more vulnerable.

The project outputs include:

- This report, which includes commentary on the methods and assumptions underpinning this hazard mapping.
- GIS files mapping the extents of the coastal inundation and erosion hazard zones.
- Four supplementary documents showing the different coastal inundation maps for storms with 20, 50, 100, and 500-year ARI and sea levels ranging from 0.0 to 1.3 m above present level.

Note that all the maps and all the northings and eastings in this report are given in the New Zealand Transverse Mercator projection (NZTM).

2 Coastal inundation hazard

Coastal inundation occurs when the elevation of the sea level exceeds that of the land, allowing water to flow inland and flood. Elevated sea levels are caused by a combination of normal tides (including neap and spring tides), storm surge due to the inverse barometer effect (i.e., lifting of the sea level by low atmospheric pressure) and wind, mean sea level anomalies (MSLA), and the release of wave energy at the coast causing wave setup and wave runup. The effects of future climate change, predominantly sea-level rise, will add to these factors.

For this project, the coastal inundation hazard due to storm tide (combined storm surge and tide), waves, and rising sea level was assessed in three steps:

- Review of Lane et al. (2008) for the prediction of coastal inundation extent from extreme water levels and waves in the Otago region. This step evaluated the suitability of the previous work for use in hazard zoning and advised on possible improvements.
- Updating the extents of the inundation hazard in Waitaki District by applying the results from Lane et al. (2008) to future sea-level rise scenarios that are in-line with guidance from the Ministry for the Environment.
- Convert the inundation extent into hazards zoning for the 100-year ARI extreme water level and two sea-level rise (SLR) scenarios.

2.1 Review of Lane et al. (2008)

Lane et al. (2008) used historical and hindcast data to describe the probability of extreme water levels from storm surge, tide, mean sea level anomaly and waves. Based on these probability distributions they calculated the 20, 50, 100 and 500-year ARI inundation events for the populated coastal areas of Oamaru, Kakanui, Hampden and Moeraki. Using the extreme water level and an estimate of wave runup, the report then shows inundation extent and inundation depths using a "bathtub"-type analysis applied over a coastal digital elevation model derived from the 2004 LiDAR survey gridded at a 10 m resolution. The report shows the impact of sea-level rise by applying sea-level rises of 0.3 m and 0.5 m to the bathtub analysis of the storm tide and wave runup.

The main finding of Lane et al. (2008) is that, in the Waitaki District, only the Kakanui River mouth area is at high risk of coastal inundation from storm tide in the 100-year ARI storm event. Most other populated coastal areas (Oamaru, Hampden, Moeraki and Shag Point) are located sufficiently above the present mean sea-level to avoid storm surge flooding.

The general methodology used in Lane et al. (2008) is sound but contains significant limitations in the analysis of wave runup, analysis of extreme water level and in the inundation mapping. The wave setup included in the extreme water levels is non-conservative, the analysis of wave runup is non-conservative (i.e., low), and the inundation mapping method (bathtub) is conservative. So, the results from Lane et al. (2008) potentially underestimate inundation depth along the coastline where wave runup occurs but overestimate the inland extend of inundation. The main other limitations are the short historical record, a simplistic approach to combining wave setup and storm surge, and lack of process-based simulation of storm surge and wave propagation over the bathymetry. Despite these limitations, improving the accuracy of the methodology used in Lane et al. (2008) is unlikely to significantly change the inundation mapping in the most populated locations in the Waitaki District because most populated coastal areas are located high above the storm surge levels. Kakanui and

Oamaru Port are the only areas where improvement to the extreme analysis and inundation simulation would refine the predicted inundation extent. This is because Kakanui is near the river mouth, is relatively low lying, and is only protected from elevated sea levels by a 20 m wide gravel/shingle barrier. The results from Lane et al. (2008) do not apply to rural parts of the Waitaki coast, thus the available information about topography and extreme water levels is insufficient to evaluate the coastal inundation hazard along these parts of the coast.

For the purposes of this work, we have used Lane et al. results, but as requested by ORC a detailed review of four aspects of the methodology (historical data, statistical model, inundation simulation and climate change impact) used by Lane et al. (2008) to assess the coastal inundation hazard is provided below. In addition, we note the potential improvements to the work that could be considered in the future.

2.1.1 Historical data

The validity of extreme water level estimates depends on the initial data used to produce the probability density function (PDF) which is then used in the extreme statistical model. The data used in the 2008 analysis were derived from a combination of wind, tide record and hindcast model results.

The historical storm surge (1961 – 2005) was reconstructed by combining the inverse barometer and wind setup component following Wild et al. (2005) using atmospheric pressure and wind data from Taiaroa Head (75 km south from Oamaru). Tidal information was extracted from the tidal model of Walters et al. (2001). The wave height was extracted from the wave model from Gorman et al. (2003).

Potential improvements to the work that could be considered in the future: improving the reconstruction approach and extending the hindcast to include recent storms would improve the extreme statistical model. This would better constrain the empirical PDF of the storm surge and reduce the uncertainty for the estimated 100-year ARI extreme water level and wave height. Developing and implementing improved methods is out of scope for this project but could be considered in future studies.

2.1.2 Statistical model used to evaluate extreme water levels

The statistical model used in Lane et al. (2008) is a type of stationary bivariate analysis which assumes that storm surge and large waves do not occur independently. This is used to describe co-occurrence of extreme storm surge and wave setup. The joint probability of storm surge and wave setup are calculated for set return intervals and then combined with tide level and mean level of the sea to obtain extreme water levels. This method for estimating extreme water levels corresponds to the present standard methodology but more recent methodologies may be more robust (e.g., Stephens and Robinson 2016). However, these more robust approaches require more data and analysis beyond the scope of this report.

The extreme water levels calculated from Lane et al. (2008) appear to be consistent with those predicted with more robust analysis. For example, they estimated the 100-year ARI extreme water level (storm surge + tide + mean sea level anomaly + wave setup) south of Dunedin at 2.05 m (relative to Dunedin Vertical Datum 1958, DVD58). If we remove from this value the estimate of the wave setup component of 0.5 m for south of Dunedin (Figure 3.8 in Lane et al. 2008), the predicted storm tide from Lane et al. (2008) is comparable to the 1.58 m (above DVD58) storm tide estimates reported by Stephens and Robinson (2016) using a more modern extreme analysis.

Beyond the approach used in the 2008 study, recent developments in the analysis of extremes may improve the statistical robustness and reduce the uncertainty of the derived storm surge distribution. Recent methods use multivariate analysis (e.g., following Gouldby et al. 2014 or Rueda et al. 2016) that account for multiple wave parameters (wave height, period and direction), separate components of the storm surge (wind setup and inverse barometer) and mean sea level anomaly.

Recent developments in coastal inundation research also aim to include seasonal and inter-annual variability in extreme distributions, with the aim of better understanding how a changing climate affects extreme events. This methodology often relies on weather pattern analysis and the non-linear relationship between the weather pattern and the interdependent components that contribute to the total water level and wave parameters. Although the necessary data is available in the Waitaki region through weather, wave and storm surge hindcasts, this type of analysis is laborious and generally applicable to large regions. Preliminary work by Rueda et al. (in review) applied this methodology to analyse the wave climate of New Zealand's South Island and found strong inter-annual variability of large wave events.

Potential improvements to the work that could be considered in the future: Improvements to the method used in the 2008 report should better reflect the actual joint-occurrence of waves, storm surges and mean sea level anomaly along the Waitaki coastline. In addition, these modern methods are less conservative in predicting extreme events and would likely reduce the predicted extreme water levels. Developing and implementing improved methods is out of scope for this project but should be considered in future studies.

2.1.3 Wave runup calculations

The wave runup estimates from Lane et al. (2008) were calculated based on the empirical formula from Stockdon et al. (2006) using hindcasted wave conditions for the Waitaki coastline from Gorman et al. (2003). While the wave hindcast and empirical formula are robust, the values presented for runup in Lane et al. (2008) appear lower than expected when compared to nearby observations of beach morphology and runup estimates from South Canterbury. For example, the value for the maximum runup presented for the 100-year ARI event at Oamaru is 1.38 m (excluding wave setup), which is far smaller than the 6.0 m wave runup presented by Stephens et al. (2015) for Wainono Lagoon. It is likely that Lane et al. (2008) underestimated the beach slope or miscalculated how the extreme waves were determined, and therefore underestimated their runup predictions.

Table 2-1: Wave runup prediction. *Source*: Lane et al. (2008).

Location	Averaged predicted wave runup (m)	Maximum predicted wave runup (m)
Moeraki	0.28	0.85
Hampden	0.36	1.09
Kakanui	0.44	1.33
Oamaru	0.46	1.38

Potential improvements to the work that could be considered in the future: The wave runup results presented by Lane et al. (2008) are not realistic and require new calculations. This analysis is beyond the scope of this project but is critical for inundation hazard assessments.

2.1.4 Inundation simulation

The total water level calculated at the coast is extrapolated over land using a bathtub analysis where the total water level is assumed to reach a uniform elevation, and depth of inundation is then the difference in elevation between the water level and the land. This methodology cannot take into account how the storm surge flows over the land and underestimates attenuation of the propagating storm surge as it spreads inland over vegetation (Sheng et al. 2012), around obstructions (e.g., buildings) or interacts with permeable surfaces (e.g., gravel barriers), nor does it account for morphodynamic changes during such a storm. These two factors result in conservative estimates of inundation extent and depth, particularly at greater distances inland.

In addition, the analysis in Lane et al. (2008) applies a single value of wave setup and runup to each DEM grid, underestimating (or overestimating) the runup where wave focusing locally produces higher (or lower) runup and overestimating (or underestimating) runup for areas locally sheltered (or exposed) to waves.

Another process that is not explicitly considered in the 2008 analysis is the contribution of infragravity waves on the runup. These low frequency waves are generated from the breaking of wave groups in the surf zone, and they can further raise the water level at the shore for several minutes. Although their behaviour is tied to swell dissipation, they can excite resonant modes in bays and harbours and locally cause a significant amplification of the maximum water level. Infragravity waves also play a significant role in triggering overtopping and landward "rollover" of gravel barrier beaches and overtopping of coastal structures (McCall et al. 2015).

The limitations of the methodology used in Lane et al. (2008) can be evaluated by comparing the inundation extent predicted by the report with the extensive inundation observed at Kakanui from the recent storm of July 2017. Drone footage by Robertson (2017) collected immediately following the storm on 21st July 2017 was used to identify the maximum extent of inundation as indicated by debris (driftwood, seaweed etc.). The July 2017 event was a "compound" event, with coincident high storm surge (equivalent to the 1-year ARI storm tide in Timaru based on the Stephens et al. (2015) analysis) and river flooding stemming from heavy rainfall (largest recorded 24-hour rainfall accumulation in Oamaru since the record began in 1950), which renders the contribution of storm surge hard to separate from that due to river flooding. However, the extent of the inundation observed, in particular on the left bank of the river, appears to align best with the 20-year ARI inundation prediction with present day sea level (Figure 2-1). This result suggests that the inundation extent is more strongly controlled by topographical features on the floodplain than by the elevation of the storm surge.

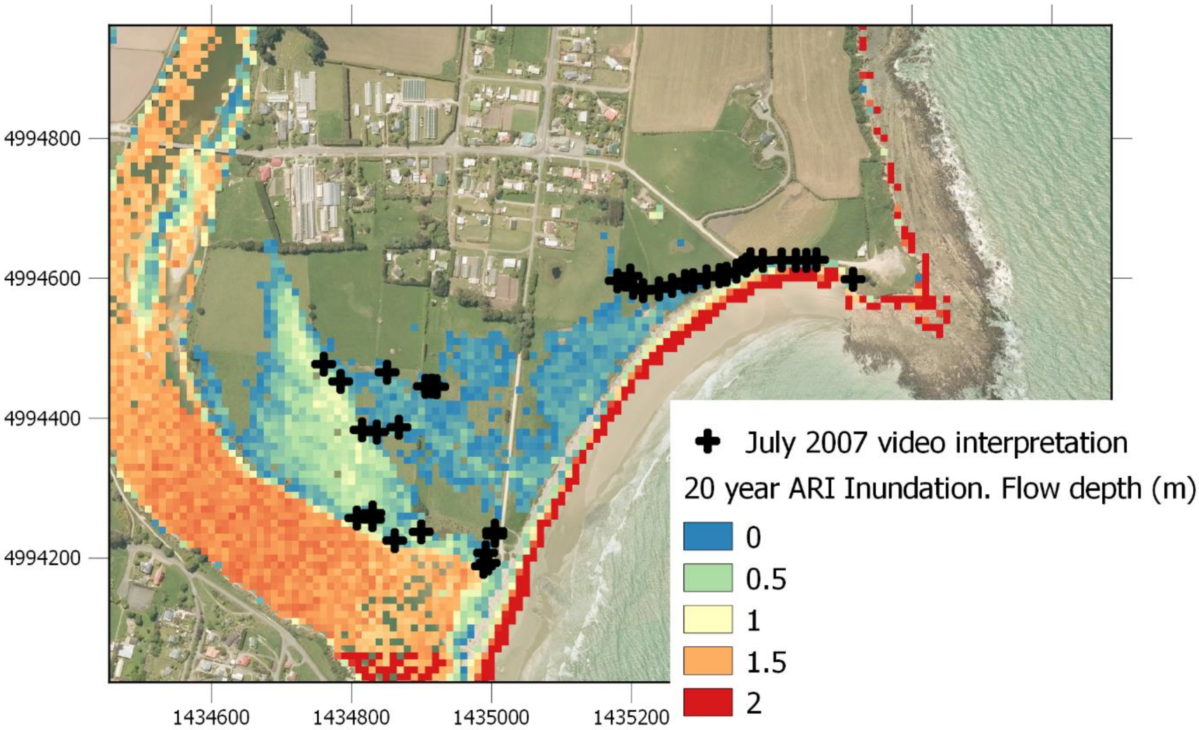

Figure 2-1: Comparison of measured and predicted inundation extent in Kakanui. Comparison of the predicted 20-year ARI inundation depths on present-day sea level (shading) with the observed July 2017 inundation extent (black crosses) at Kakanui. [Sources: modelled inundation extent Lane et al. (2008), inundation extent: Robertson 2017].

Potential improvements to the work that could be considered in the future: Improvement from using process-based simulations of the inundation is likely to lead to a somewhat smaller inundation extent for Kakanui, but the improvement may only be minor as the inundation extent is predominantly controlled by topographical features on the floodplain.

2.1.5 Climate change impacts

Lane et al. (2008) assume that the extreme distribution of storm surge would be stationary; that is, they assume (for lack of better information) that climate change is not going to significantly affect the distribution of waves, wind and storm surge. Challenging such an assumption is difficult because no regional scale climate model to date achieves a level of precision and accuracy that would allow an analysis of how climate change is going to affect these parameters. One solution to this issue is to analyse the relationship of the weather patterns and the distribution of processes that contribute to the water level and waves such as discussed above and apply these relationships to future weather patterns predicted from climate models. Ministry for the Environment (MfE 2017) recommends to "*undertake sensitivity testing for coastal engineering projects and for defining coastal hazard exposure areas out to 2100, using:*

- *A range of possible future increases across New Zealand of 0–10 per cent for storm surge out to 2100.*
- *A range of possible future increases across New Zealand of 0–10 per cent for extreme waves and swell out to 2100.*

- *Changes in 99th percentile wind speeds by 2100 and incorporating these for the relevant RCP scenario from MfE (2017) on climate change projections, to assess waves in limited-fetch situations, such as semi-enclosed harbours, sounds, fjords and estuaries."*

Although Lane et al. (2008) do not consider the effect of climate change on storm surge and waves, they do consider the effect of sea-level rise. Their report presents inundation hazard maps for three sea-level rise scenarios including a present day and two future scenarios:

1. Present mean level of the sea (MLOS).
2. MLOS + 0.3 m.
3. MLOS + 0.5 m.

However, no justification was given in the report for how the sea-level rise scenarios were selected.

Implications for this project: Further assessments of climate change effects is out of scope for this project but should be considered in future analysis and may be completed with a reanalysis of the predicted runup in a more detailed study of the extreme inundation hazards in the Waitaki district.

The future sea level scenarios are no longer in line with Ministry for the Environment recommendations. Updating the sea-level rise scenarios and the impact of sea-level rise on the coastal inundation extent is part of the scope of this report and is described in section 2.2 below.

2.1.6 Final remarks on Lane et al. (2008)

The general methodology used in Lane et al. (2008) is sound but contains significant limitations in the analysis of wave runup, analysis of extreme water level and in the inundation mapping. Addressing many of these limitations is beyond the scope of this report but should be considered in future analysis.

Improved sea-level rise estimates for New Zealand and guidance for councils of what sea-level rise scenarios to consider have been published since Lane et al. (2008). The present study uses up-to-date sea-level rise scenarios and updates the coastal inundation extent using the results of storm surge and wave runup from Lane et al. (2008).

2.2 Updated sea-level rise scenarios

The most recent national guidance on coastal hazards from the Ministry for the Environment (MfE 2017) recommends that different sea-level rise scenarios be used in an adaptive planning framework. This means that for different assets near the coast a different future timeframe and sea-level scenario may be used, with the timeframe and sea-level rise values proportional to the risk profile. For example, for the most high-risk assets, MfE (2017) suggest that: "Councils considering coastal subdivision, greenfield developments and major new infrastructure (Category A) should avoid hazard risk by using sea-level rise over more than 100 years and the H+ scenario[1]". For lower risk profiles (Category B, C and D), a shorter time frame and hazard outlook can be used.

To provide the Otago Regional Council with a range of options fit for the full range of assets, this study simulated additional sea-level rise scenarios, ranging from 0.3 m to 1.3 m above the present mean level of the sea, in increments of 0.2 m. Each of these scenarios corresponds to a different

[1] The H+ scenario is based on the RCP8.5 (83rd percentile) projection from Kopp et al. (2014)

timeframe for different IPCC emission scenarios (IPCC 2013) instead of simulating sea-level rise values directly tied to a single emission scenario and timeframe. The approximate timeframes for each simulated sea-level rise occurring under the different IPCC emissions scenarios are listed in Table 2-2.

Thus, in this study we consider sea-level rise up to 1.3 m above the present mean level of the sea, corresponding to the upper bound of the likely range of sea-level rise by 2115 under the RCP8.5 emission scenario, as well as intermediate sea-level rise values corresponding to earlier outlooks and/or lower emission scenarios.

Table 2-2: Sea level scenarios for coastal inundation prediction. Outlooks are based on emission scenarios from IPCC (2013). RCP2.6 is a low emissions, effective mitigation scenario; RCP8.5 is a high emissions, no mitigation scenario; the upper bound of the likely range of the estimate for RCP8.5 scenario is similar to the higher, more extreme scenario projection from Kopp et al. (2014) also referred to as H+ by MfE (2017).

Relative sea-level above present mean level of the sea (m)	Outlook for RCP2.6 Maximum likelihood	Outlook for RCP4.5 Maximum likelihood	Outlook for RCP8.5 Maximum likelihood	Outlook for RCP8.5 upper bound of likely range
+ 0.3	2070	2060	2055	2050
+ 0.5	2115	2095	2080	2070
+ 0.7	--	2125	2100	2085
+ 0.9	--	--	2115	2095
+ 1.1	--	--	2125	2105
+ 1.3	--	--	--	2115

2.3 Methodology for updated mapping of inundation hazard zones

In this study, we updated the coastal inundation prediction of Lane at al. (2008) by combining their results on extreme water level and wave runup (Table 2-3 and Table 2-1) with updated sea-level rise scenarios (Table 2-2). This was performed for the most populated areas of the coast (Moeraki, Hampden, Kakanui and Oamaru). Other areas of the Waitaki district may experience coastal inundation but the wave and storm surge information have not been calculated with sufficient details to assess inundation extent in these areas.

As with the study from Lane et al. (2008), the inundation was calculated on a 10-m resolution Digital Elevation Model (DEM) created from the 2004 Lidar survey, with the vertical datum set to the mean level of the sea (2008), 0.11 m above the Dunedin Vertical Datum 1958.

In Moeraki, Hampden, Kakanui and Oamaru, the inundation depth was calculated as:

$$Inundation = ExtWL + Wrup \times ShoreFlag + SLR - Z_s \qquad (2.1)$$

where $Inundation$ is the inundation depth (i.e., the maximum depth of inundation). $ExtWL$ is the combined storm surge height, mean sea level anomaly, tide, and wave setup (Table 2-3), as calculated by Lane et al. (2008). $Wrup$ is the maximum wave runup as calculated by Lane et al. (2008) and is only applied where $ShoreFlag$ is 1. $ShoreFlag$ is a flag which includes or excludes the contribution of wave runup, and is only applied to those parts of the DEM grids that are located on the shoreface (i.e., beach, coastal defences, cliffs); it is excluded in parts of the DEM that are on land, in estuaries or inside marinas/ports. SLR is the sea-level rise, and Z_s is the ground elevation.

While LiDAR data provide high resolution topography information, it is important to consider the overall limitations of the Lane et al. (2008) analysis. Lane et al. wrote: "*The high resolution of the LIDAR allows the correct representation of smaller features such as sand-dunes which contain rises in sea level and protect the land behind. However, an important caveat to note is that due to the high resolution of the LIDAR data, very precise maps of inundation will be produced. The precision of these maps does not, however, imply an equivalent level of accuracy in the predictions, which may be affected by imprecise knowledge of sea-level phenomena. The simplifying assumptions involved in making the sea-level estimates, and the consequent limitations of the values produced, should be kept in mind when examining and interpreting the maps*."

Furthermore, the inundation is calculated as a "bathtub" model which only maps constant levels of water. It does not account for the propagation of the flood water, momentum and head loss due to the roughness of the environment, nor does it contain any information about the duration of the inundation. The model also does not account for any rainfall or river flow that may contribute to the inundation. Although the simulation includes allowance for future sea-level rise, it does not account for any change in the wave climate that may occur in the future. This type of simulation is a first order assessment that is well suited for identifying vulnerable areas, but more detailed assessments are required for risk assessment of assets and values in those areas.

Table 2-3: Predicted extreme water levels (m above MSL) for four average recurrence interval (ARI). Extreme water level here is a combination of storm surge height, mean level of the sea, tide, and wave setup. These values are given relative to the mean level of the sea (2008). [*Source*: Lane et al. 2008].

Location	20-year ARI	50-year ARI	100-year ARI	500-year ARI
Moeraki	1.60	1.67	1.71	1.83
Hampden	1.84	1.91	1.96	2.07
Kakanui	1.96	2.03	2.08	2.20
Oamaru	2.01	2.08	2.14	2.26

Maps of the modelled inundation depth were created for each of the four ARIs of extreme water level and seven sea-level scenarios at each site. Based on these maps, three coastal inundation hazard zones were created using the 100-year ARI extreme water level and three sea-level rise scenarios:

1. An intermediate emission scenario (RCP 4.5) sea-level rise for 2125 of 0.7 m;
2. A high emission scenario (RCP 8.5) sea-level rise for 2125 of 1.1 m; and
3. Extreme scenario of 1.3 m sea-level rise for 2125 based on the RCP 8.5 (upper bound of likely range) similar to the H+ scenario suggested by MfE (2017).

The results of the inundation modelling follow.

2.4 Results

For each area of interest (Oamaru, Kakanui, Hampden, Moeraki), we present below the maps of the predicted inundation for the 100-year ARI extreme water level at the 2008 mean sea level (referenced to Dunedin Vertical Datum 1958 + 0.11 m.) (+0.0 m SLR) and for the 100-year ARI extreme water level at future sea-level rise of 1.3 m (+1.3 m SLR) (forecast for 2115 for the RCP8.5 upper bound of likely range). The inundation for 20, 50 and 500-year ARI at present MLOS, +0.3 m, +0.5 m, +0.7m, +0.9 m, +1.1 m and +1.3 m SLR are presented in a supplementary document.

2.4.1 Oamaru

The inundation extent for the 100-year ARI event at present MLOS along Oamaru is limited to the coastal beach and extends up Oamaru Creek by approximately 300 m (Figure 2-2). The intermediate sea-level rise scenarios show a gradual increase to the inundation extent, with the areas landward from Esplanade Road only predicted to be inundated with the highest sea-level rise scenario of +1.3 m SLR (Figure 2-3).

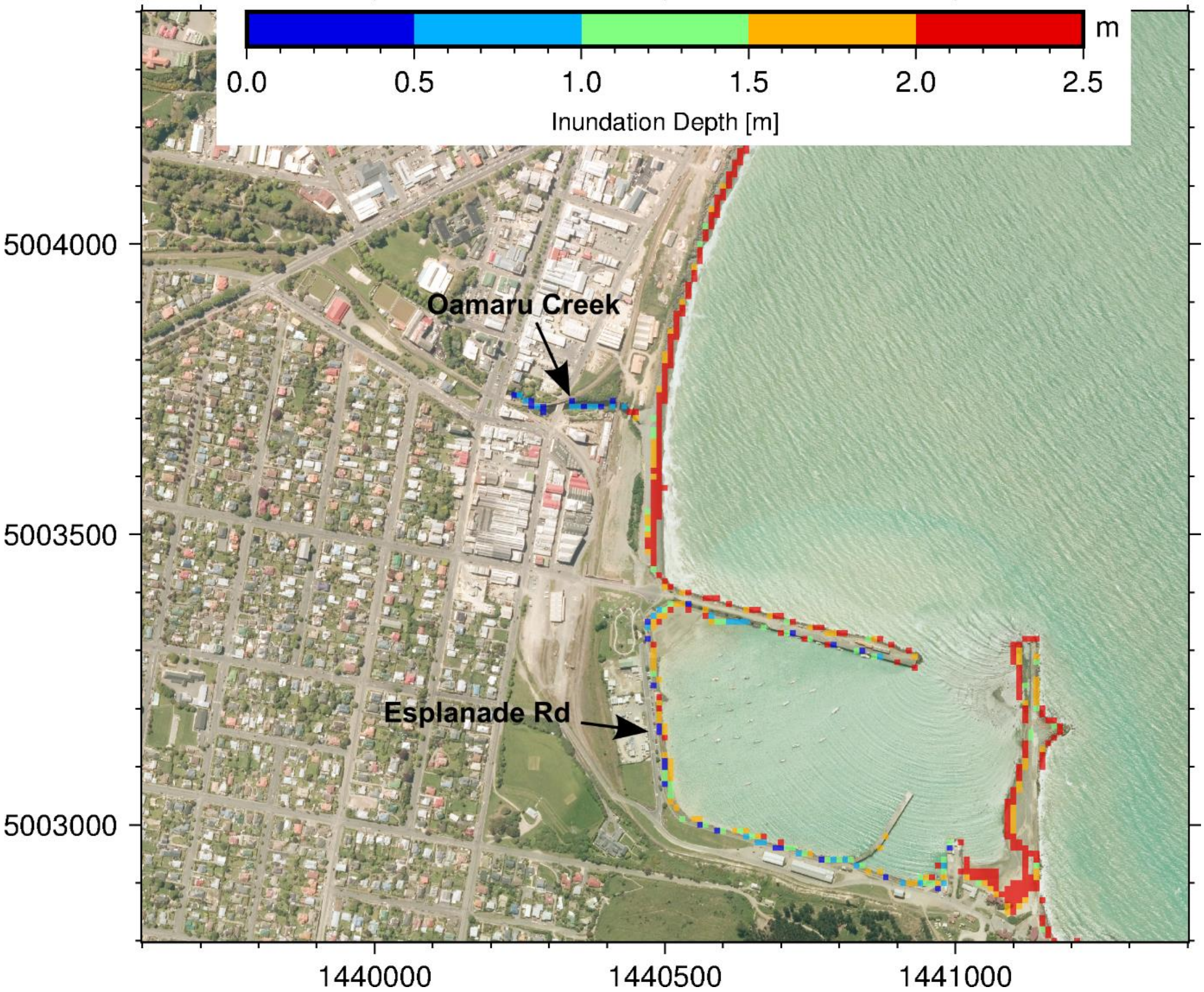

Figure 2-2: Predicted inundation depth for the 100-year ARI storm and +0.0 m SLR for Oamaru.

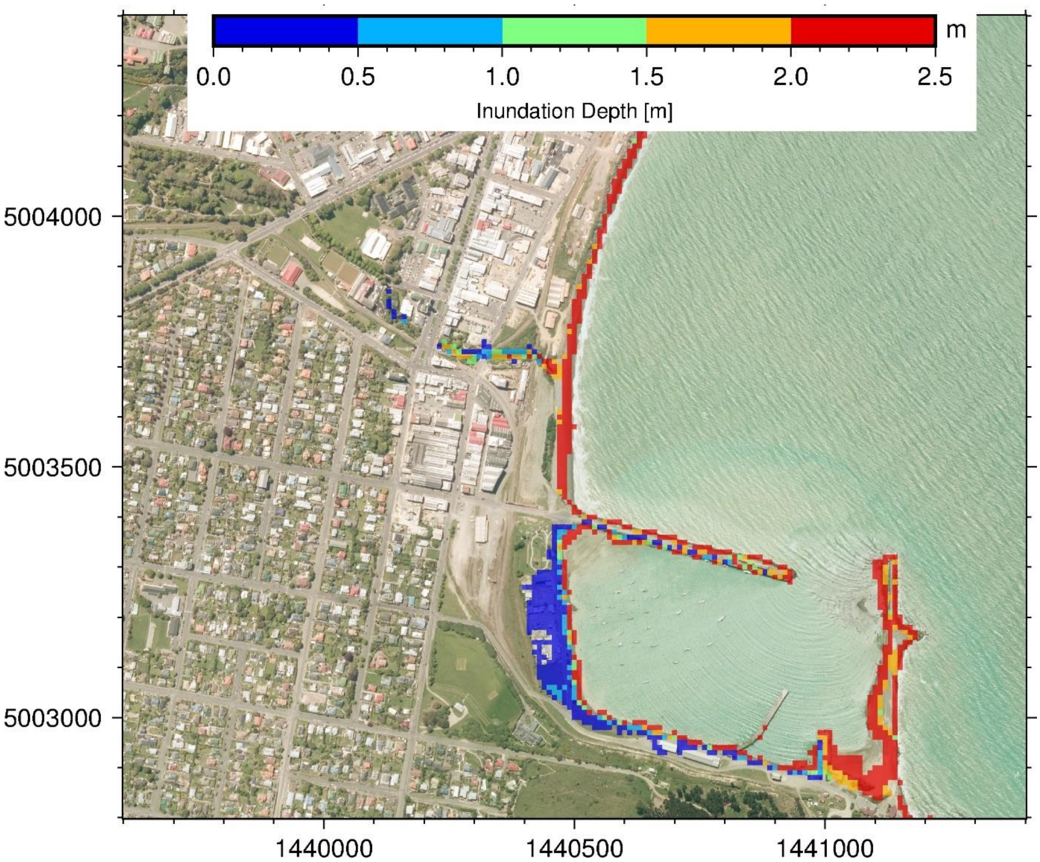

Figure 2-3: Predicted inundation depth for the 100-year ARI storm and +1.3 m SLR for Oamaru.

Sea-level rise increases the coastal inundation risk in Esplanade Road and the area of the port behind that road. However, the model shows inundation of Esplanade Road only for the higher sea-level rise scenario for the most extreme events (Table 2-4).

Table 2-4: Inundation depth for different extreme water level scenarios and sea-level rise scenarios at Esplanade Road. Double dash means no inundation. These values were extracted from a single point located near the center of Esplanade Road (E1440470, N5003200).

Sea-level rise (m)	20-year ARI (2.01 m) Extreme water level	50-year ARI (2.08 m) Extreme water level	100-year ARI (2.14 m) Extreme water level	500-year ARI (2.26 m) Extreme water level
+0.0	--	--	--	--
+0.3	--	--	--	--
+0.5	--	--	--	--
+0.7	--	--	--	--
+0.9	--	--	--	0.11
+1.1	0.06	0.13	0.20	0.32
+1.3	0.26	0.33	0.40	0.52

2.4.2 Kakanui

The inundation extent at Kakanui for the predicted 20-year ARI event closely matches the inundation extent of the recent 2017 storm (**Error! Reference source not found.**Figure 2-4). In both cases, the waves overtop the gravel barrier and gravel spit and significantly inundate the backshore, while inundation flows will also enter via the Kakanui River mouth. Sea-level rise increases the inundation extent, covering all the fields on the north side of the estuary and reaching the properties at the south end of Cobblestone Road. On the south side of the estuary, inundation is predicted near the bridge and in the area encircled by River Road (Figure 2-5).

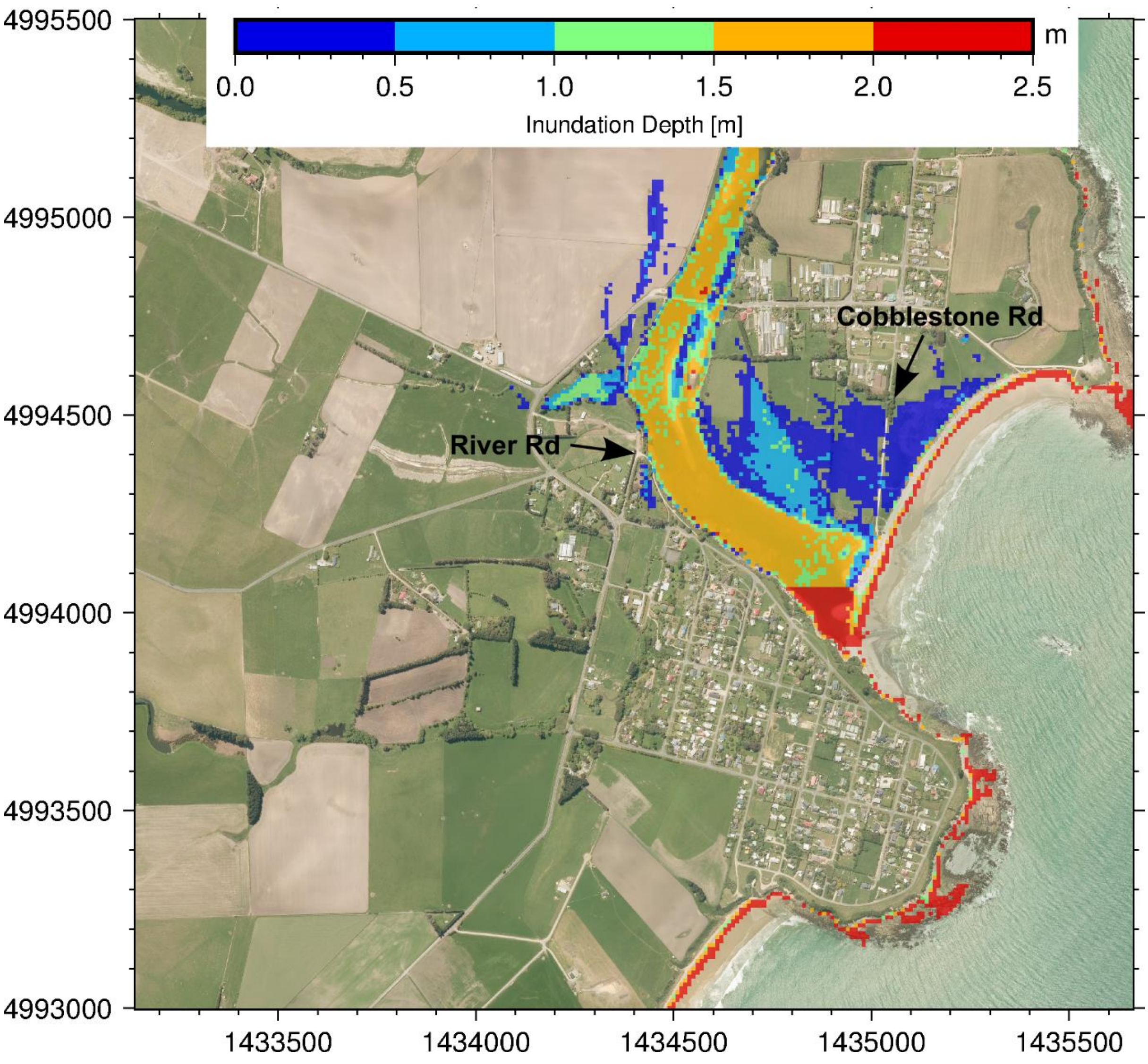

Figure 2-4: Predicted inundation depth for the 100-year ARI storm and +0.0 m SLR for Kakanui.

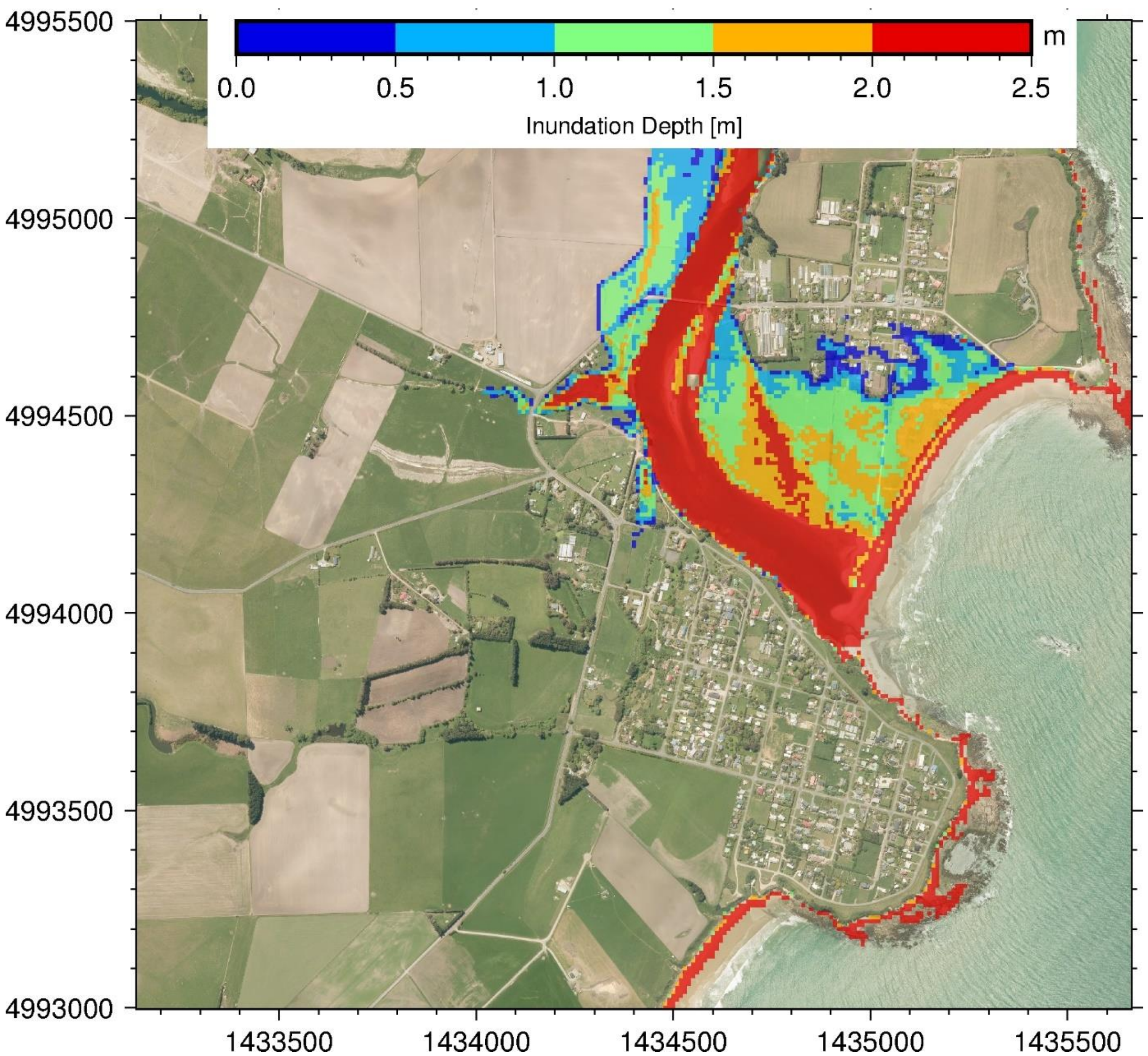

Figure 2-5: Predicted inundation depth for the 100-year ARI storm and +1.3 m SLR for Kakanui.

2.4.3 Hampden

The inundation extent in Hampden for a 100-year ARI storm at present day sea-level is limited to the coastal fringe and areas adjacent to and 200 m upstream from the mouths of Kurinui Creek and Kuriiti Creek (Figure 2-6). For the highest sea-level rise scenario (+1.3 m SLR) the inundation extends further inland to Carlisle Street and covers the wetlands located on the landward side of Carlisle Street and between the creek mouths (Figure 2-7). The intermediate sea-level rise scenarios are included in supplementary material and show a gradual increase of wetland inundation between the present day and the +1.3 m sea-level rise scenario.

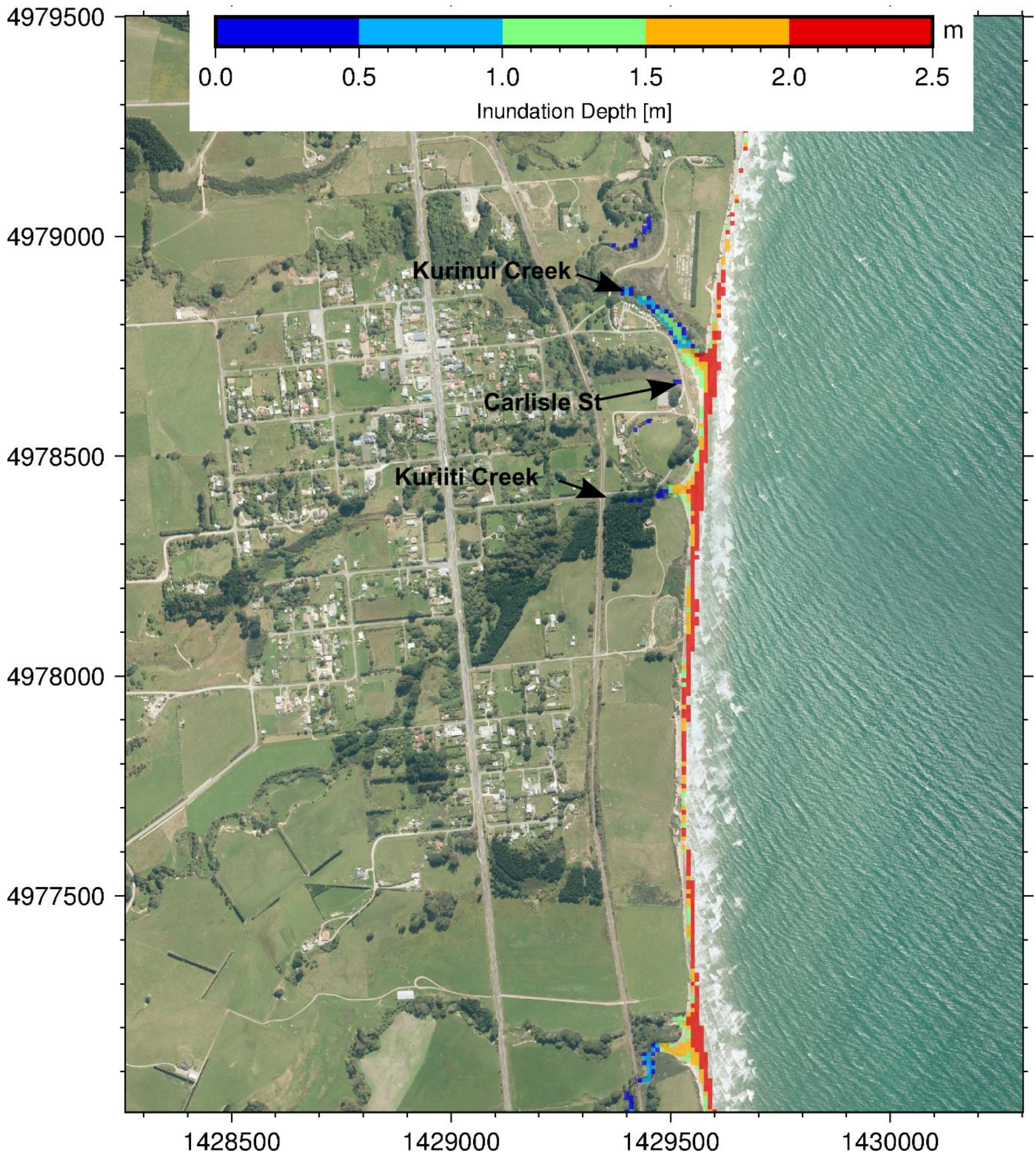

Figure 2-6: Inundation depth for the 100-year ARI storm and +0.0 m SLR for Hampden.

Figure 2-7: Inundation depth for the 100-year ARI storm and +1.3 m SLR for Hampden.

2.4.4 Moeraki

The predicted inundation extent at Moeraki for a 100-year ARI storm under the present-day sea level scenario is confined to the coastal fringe (Figure 2-8). The inundation extent for the highest sea-level rise scenario (+ 1.3 m SLR) increases slightly to cover the area between the old and new jetty (Figure 2-9).

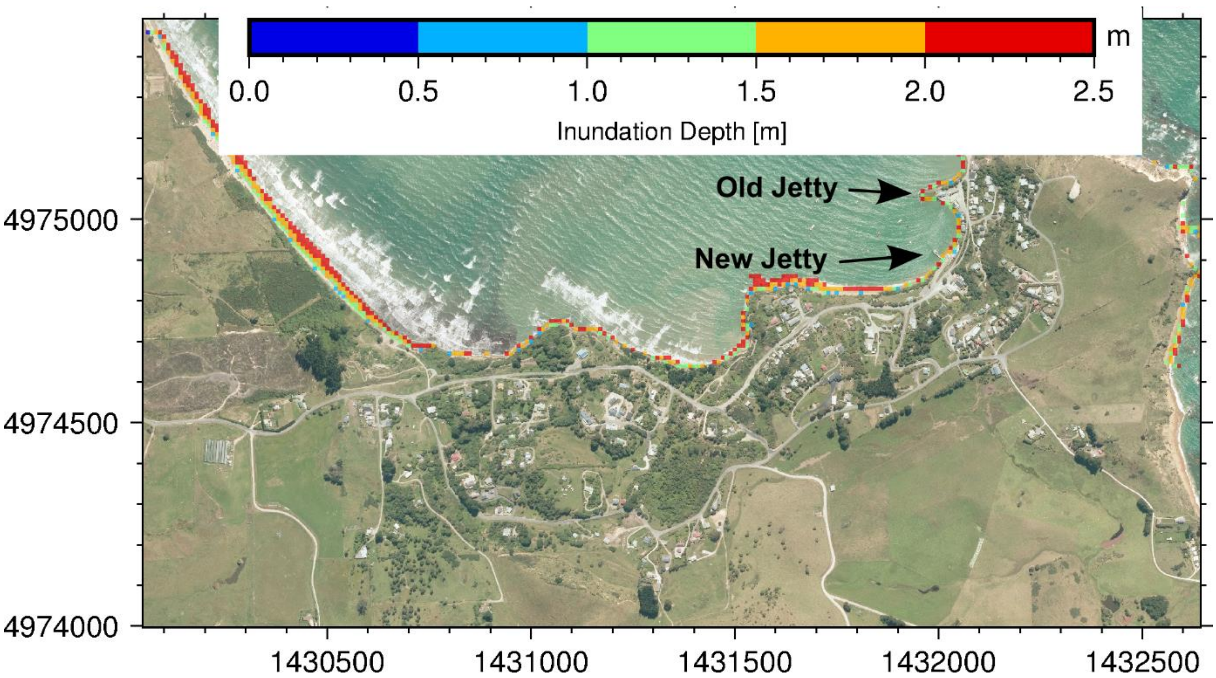

Figure 2-8: Inundation depth for the 100-year ARI storm and +0.0 m SLR for Moeraki.

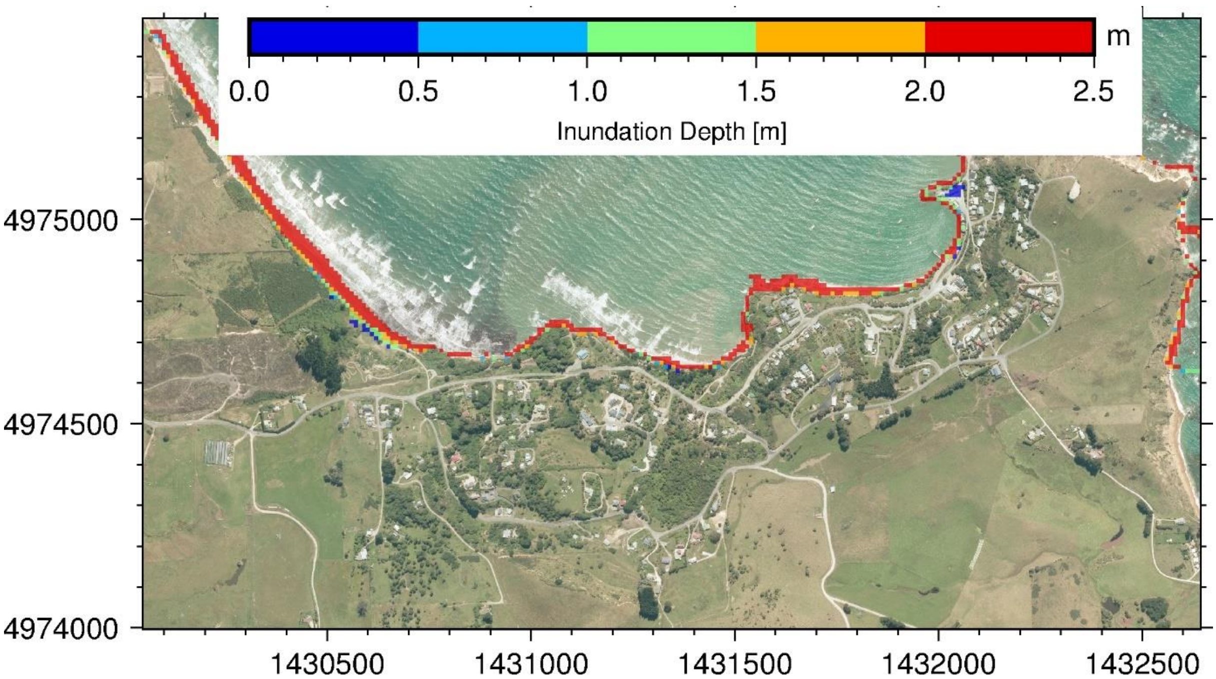

Figure 2-9: Inundation depth for the 100-year ARI storm and +1.3 m SLR for Moeraki.

2.4.5 Coastal inundation hazard zones

Coastal inundation hazard zones were developed using the predicted inundation depth for the 100-year ARI extreme water level event and considering three sea-level rise scenarios:

1. Sea-level rise of 0.7 m above present MLOS.
2. Sea-level rise of 1.1 m above present MLOS.
3. Sea-level rise of 1.3 m above present MLOS.

Note that the contributions to inundation from terrestrial (river and urban) and groundwater flooding are not included.

The hazard zones for each scenario are presented in Figure 2-10 to Figure 2-13. Showing the varying degree of area exposed to coastal inundation hazard when accounting for sea-level rise. Note only red areas are flooded under scenario 1; red and orange areas are flooded under scenario 2; red, orange and yellow areas are flooded under scenario 3; where only red is visible, all three zones coincide.

For the Ministry for the Environment's guidance to coastal hazards and climate change, Scenario 3 corresponds to the transitional response for development planning category A (Coastal subdivision, greenfield developments and major new infrastructure) whereas Scenario 1 and 2 are part of the information that can be used to define the transitional response for Category B and C of the development planning (MfE 2017).

Figure 2-10: Coastal inundation hazard zone extents for Oamaru. Zones are based on the 100-year ARI inundation event and a SLR of +0.7 m (Scenario 1), +1.1 m (Scenario 2) and +1.3 m (Scenario 3).

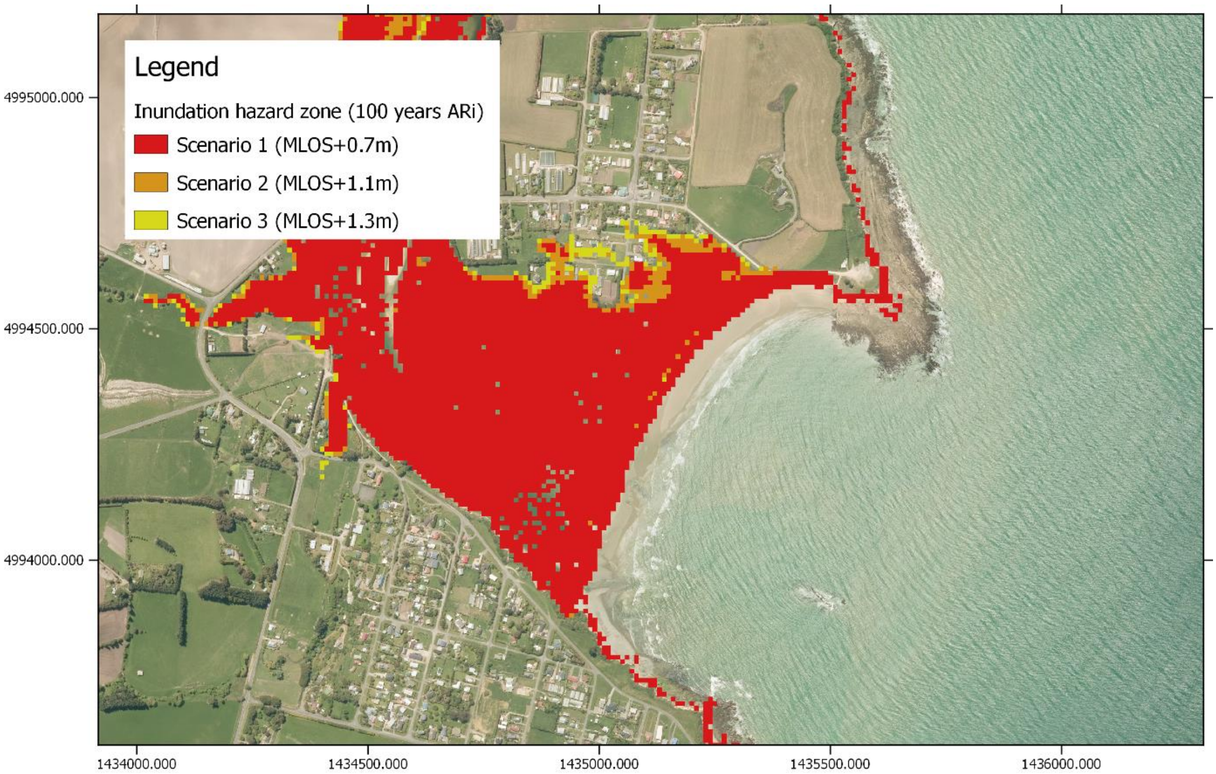

Figure 2-11: Coastal inundation hazard zone extents for Kakanui. Zones are based on the 100-year ARI event and a SLR of +0.7 m (Scenario 1), +1.1 m (Scenario 2) and +1.3 m (Scenario 3) above present day MLOS.

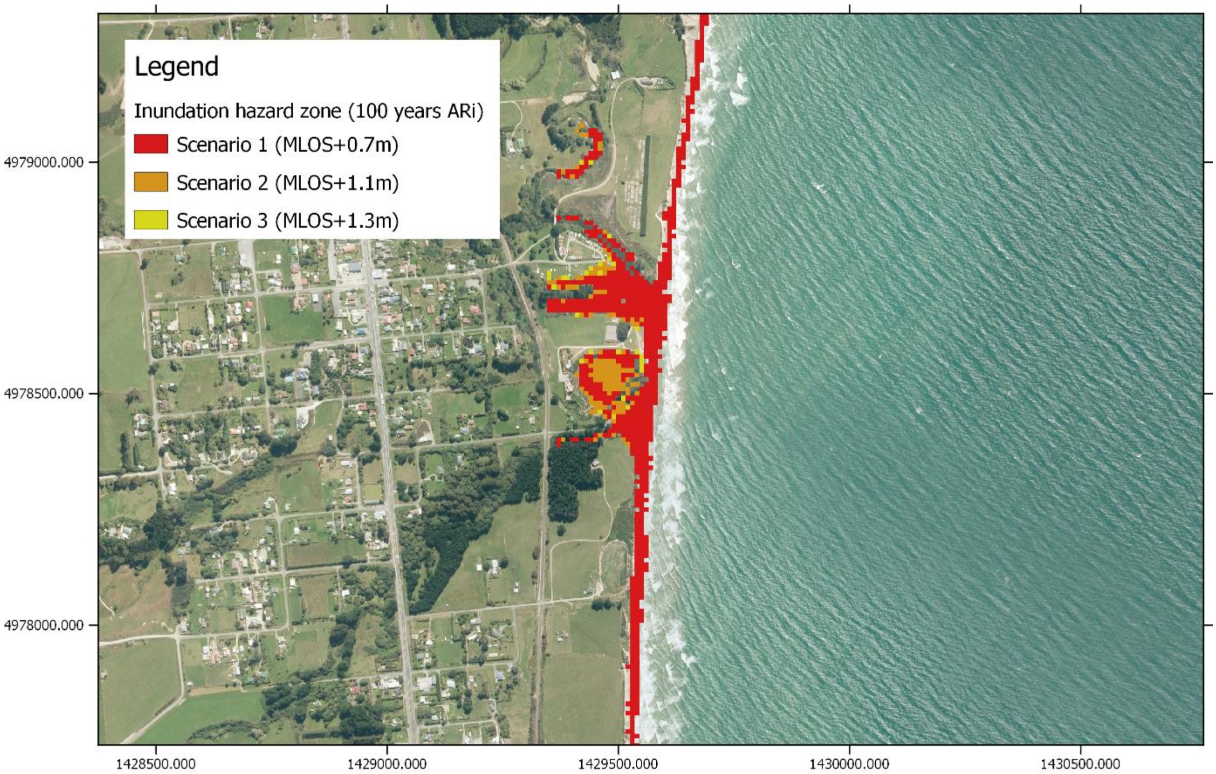

Figure 2-12: Coastal inundation hazard zone extents for Hampden. Zones are based on the 100-year ARI event and a SLR of +0.7 m (Scenario 1), +1.1 m (Scenario 2) and +1.3 m (Scenario 3) above present day MLOS.

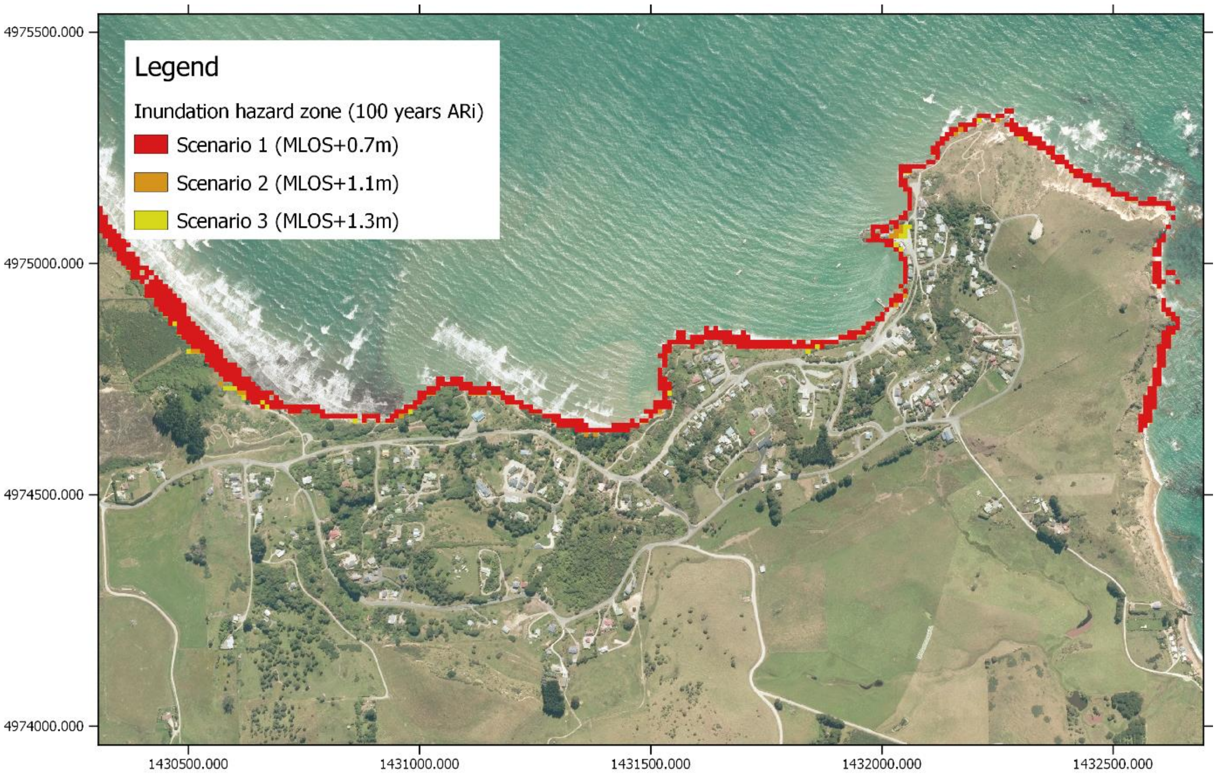

Figure 2-13: Coastal inundation hazard zone extents for Moeraki. Zones are based on the 100-year ARI event and a SLR of +0.7 m (Scenario 1), +1.1 m (Scenario 2) and +1.3 m (Scenario 3) above present day MLOS.

3 Coastal erosion hazard

3.1 Introduction

The shore of Waitaki District is very diverse, alternating between cliffs and beaches. High cliffs with hard bedrock dominate the landscape of Cape Wanbrow, Moeraki Point to Katiki Point, Shag Point, and most of the coast south of the Shag River. Cliffs formed in softer, sedimentary material (loess, gravel, or mudstone) occur between the Waitaki River mouth and Oamaru and along much of the shore between Moeraki and Beach Road, south of Cape Wanbrow. Sand, gravel, or mixed-sand-and-gravel beaches are present in most bays, often backed by low cliffs and sometimes fronted by reef platforms. The main estuaries are fronted with gravel or sand spits.

Waitaki District has historically experienced dramatic shoreline retreat. This has been focussed in several "hotspots":

- Oamaru to the Waitaki River.
- Beach Road.
- Kakanui.
- Hampden.
- Katiki Beach.

The area north of Oamaru was reported to be eroding as early as the 1870s when port development was begun at Oamaru (Carruther 1871). The reported erosion rates there have proven variable (1.4 m/y – 0.1 m/y), averaging around 0.5 m/y (Gibb 1978). Over decadal time scales, the erosion rates north of Oamaru vary alongshore and with time – in response to the occurrence of storms and localised cliff collapse. Over longer time scales, the rates would appear to be more uniform, as evident from the straight coastline.

South from Oamaru, the road to Kakanui (Beach Road) has experienced severe erosion events in recent years, with a retreat of 12 m between 2006 and 2014 and the closure of a section of the coastal road despite the protective armouring. Along this road, the erosion is cutting back into a low alluvial backshore flat, composed of interbedded lenses of fine rounded gravel with shelly coarse sand (estuarine/beach depositional-environment) and clay/silt lenses in places (swale deposits), with a loess cap topped by soil/peat, sometimes with a thin sand-dune cap. The beach material is coarse and of similar composition to the material within the cliff, suggesting that the beach is formed exclusively of the eroded material.

At Kakanui, the gravel barrier at the river mouth has been retreating landward, with rates of 5 m/y reported by Gibb (1978). This particularly high rate may be the result of both the removal/destruction of the pier in the bay in the 1970s and particularly severe storms in 1974 (Pattle 1974). More recent rates of erosion have lowered to 1 m/y (Johnstone 2001).

North of Hampden, a calcareous muddy sandstone and greensand capped by clay-rich gravelly sand is producing many slumps, with the top of the cliff retreating rapidly. The coast south of Hampden is formed in the same lithology and is also eroding (as evident by the Moeraki boulders being left on the beach) but no report has been made of the rates of erosion observed there.

Katiki beach is showing multiple spans of erosion, several reaching close to State Highway 1 (SH1). There, patches of riprap have been under construction (Figure 3-1). Older riprap was observed to be in a poor state (i.e., settled in the beach or partially dismantled by waves with scattered rock visible on the beach), implying that these are not performing as a long-term shoreline control.

Figure 3-1: Armouring of the backshore cliff on Katiki Road (7/12/2017).

The purpose of our study was to compile information on historical erosion rates and to develop coastal erosion hazard zones, with emphasis on these hotspots.

3.2 Methodology

Although existing reports of erosion provide information on erosion rates in the Waitaki District, they are insufficient for predicting future shoreline position and defining coastal erosion hazard zones. The prediction of future shoreline position requires up-to-date and systematic analysis of the time-trend in the shoreline position and a consistent analysis of the associated errors. The shoreline trend analysis undertaken here is based solely on the shoreline positions detected from aerial and satellite imagery. While this produced a consistent, uniform-alongshore dataset suitable to analyse shoreline trend for the whole coast of Waitaki District it does not account for site specific backshore geologies. Other estimates of shoreline evolution based on repeat LiDAR surveys, beach profiles and morphological model simulation are also used here to validate and complement the information calculated from the imagery-based shoreline detection.

3.2.1 Shoreline detection

Shoreline positions were manually extracted from historical aerial photography and satellite imagery (Table 3-1). The features extracted were the vegetation line along beach environments (often corresponds to the toe of dunes) or the cliff top along cliff-backed shores/beaches, following Boak and Turner (2005). In areas where coastal defence structures are present (e.g., rock wall in Oamaru) the rear-facing toe of the structure was used to define the shoreline.

More sets of historical imagery were found apart from those listed in Table 3-1, but these other sets were not used, either because the resolution of the imagery was too low or because distortion of the image would not allow for suitable geo-referencing.

For each set of imagery, the shoreline position was digitized at a scale of 1:600, with points digitised at a spacing that averaged 6.75 m (e.g., Figure 3-2). In each set of imagery, the error in the shoreline position was calculated as the sum of a shoreline-digitising error (typically 3 pixels width) and a geo-referencing error (measured as the offset of permanent features between georeferenced imagery and the LINZ 2014 baseline imagery). The error for each shoreline position was variable, ranging from 1.2 m to 7 m. The historical shorelines were archived as ArcGIS shapefiles.

For the span of shore between Oamaru and the Waitaki River, a valuable early historical shoreline fix from 1871 was also available. This was derived from photogrammetric analysis of cadastral maps (as reported by Hicks and Bind 2013).

Table 3-1: Imagery data source used in the shoreline detection.

Date	Area	Estimated error (m)	Source
1860s-1870s	Waitaki River mouth to Oamaru	20	Cadastral map
30 Aug 1955	Waitaki River mouth to Oamaru, Beach Road	6 – 8	Retrolens
12-13 Mar 1979	Waitaki River mouth to Oamaru, Katiki Rd, Hampden	5 – 8	Retrolens
Jan-Feb 2000	Waitaki River mouth to Oamaru	7 – 8	LINZ
Jan-Feb 2006	All of Waitaki	2	LINZ
02 Sep 2006	Moeraki, Hampden, Cape Wanbrow	7	DigitalGlobe
04 Dec 2007	Shag Point, Stony Creek	8	DigitalGlobe
19 Jan 2012	North Oamaru	6 – 8	DigitalGlobe
24 Mar 2012	Waitaki River mouth to North Oamaru	6 – 8	DigitalGlobe
03 Oct 2012	Beach Road, Kakanui, All Day Bay	6 – 8	DigitalGlobe
28 Oct 2012	Pleasant River to Waianakarua River	7	DigitalGlobe
26 Nov 2012	Te Hakapureirei Beach, Kakanui Point, Oamaru Port, North Oamaru	6 – 8	DigitalGlobe
22 Mar 2013	Oamaru	7	DigitalGlobe
Jan – Feb 2014	All of Waitaki	1	LINZ
14 Mar 2015	North Oamaru to Waitaki River	7	DigitalGlobe
09 Jun 2015	North Hampden	7	DigitalGlobe
27 Feb 2016	North Hampden to Beach Road	6	DigitalGlobe
20 Oct 2016	Beach Road to North Oamaru	6	DigitalGlobe

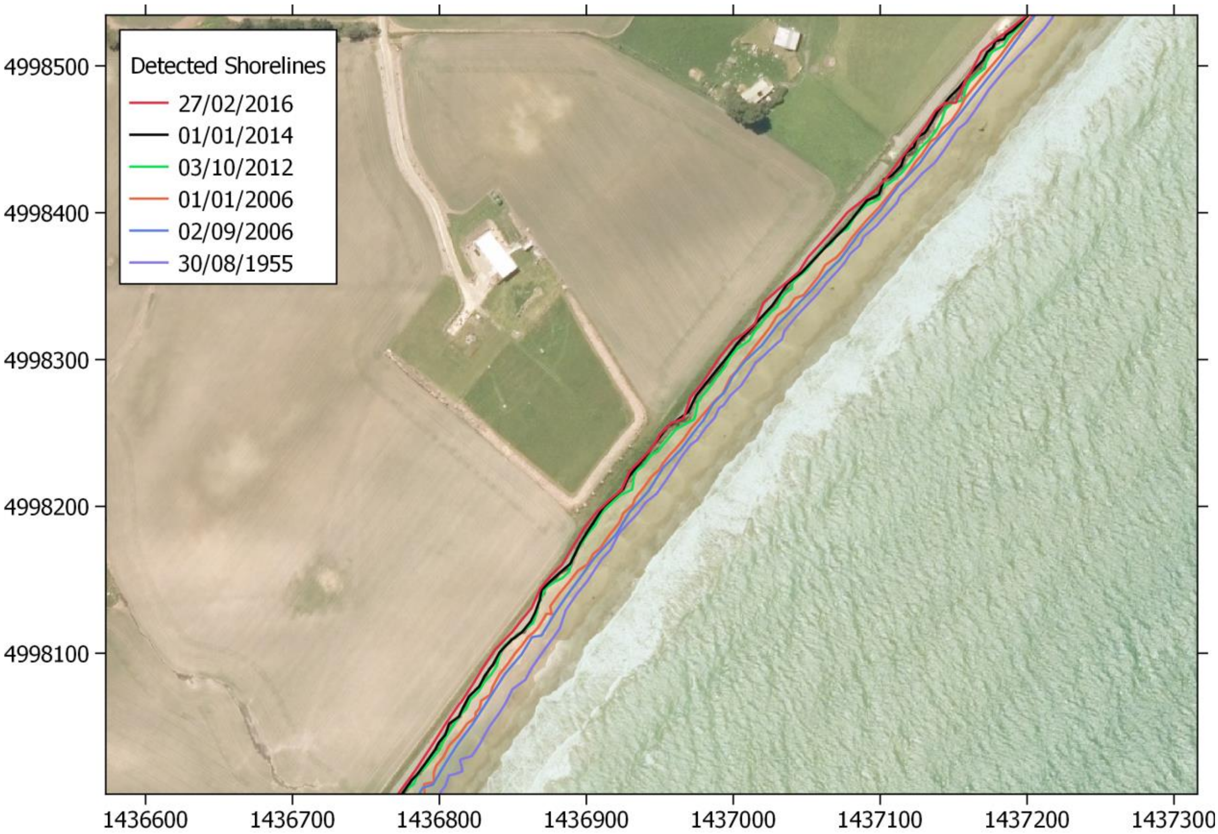

Figure 3-2: Example of shoreline detection along Beach Road, south of Oamaru. Black line shows the detected shoreline corresponding to the background image (Jan - 2014) [*Image source*: LINZ].

3.2.2 Shoreline analysis

The dataset of historical shoreline positions was used to calculate historical average retreat rates at stations every 5 m along the entire Waitaki District coast (19,408 stations in total). Transects perpendicular to the coast were constructed at each station using the AMBUR software (Jackson et al. 2012) (Figure 3-3). Then, the intersections between the mapped shorelines and each of the transects were captured and their offset from an arbitrary reference offshore was calculated (Figure 3-4).

Figure 3-3: Example of transects perpendicular to the coast. The distance alongshore between each transect is 5 m. [*Image source*: LINZ].

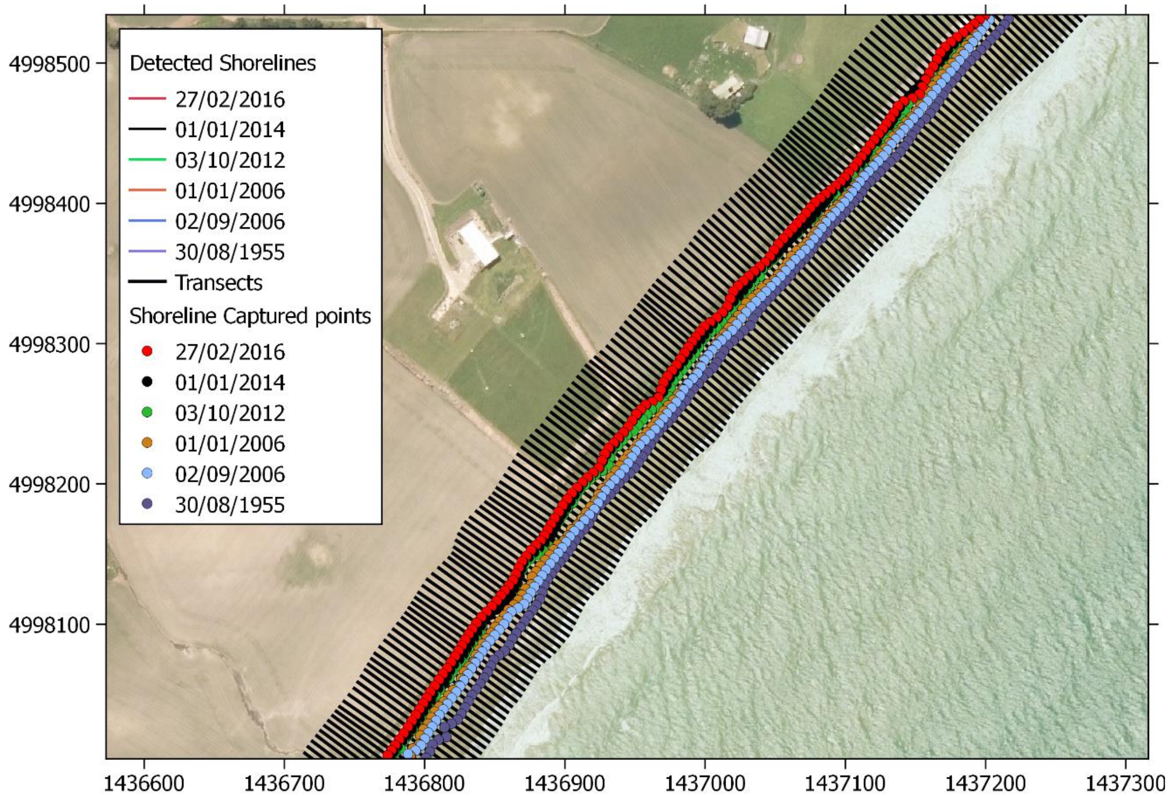

Figure 3-4: Example of intersection point between the transects and detected shorelines. The coloured points represent the intersection between shorelines and the transects. [*Image source*: LINZ].

For each of the transects, a weighted least square fit was used to calculate a linear time-trend in shoreline position, using the inverse of the shoreline position error estimate as the weighting factor (e.g., Figure 3-5). The trend rate and its standard error contained large alongshore variability which was smoothed using a moving-average filter with a width of 30 points along sections of uniform morphology (i.e., 15 points covering 75 m either side of the target point were averaged). The filtered shoreline trend and its standard error were recorded to be used in defining the coastal erosion hazard zones. In addition, for each transect, the residuals of the trend (distance between the trend and historical shoreline position) were also calculated for use in the coastal hazard zone calculations.

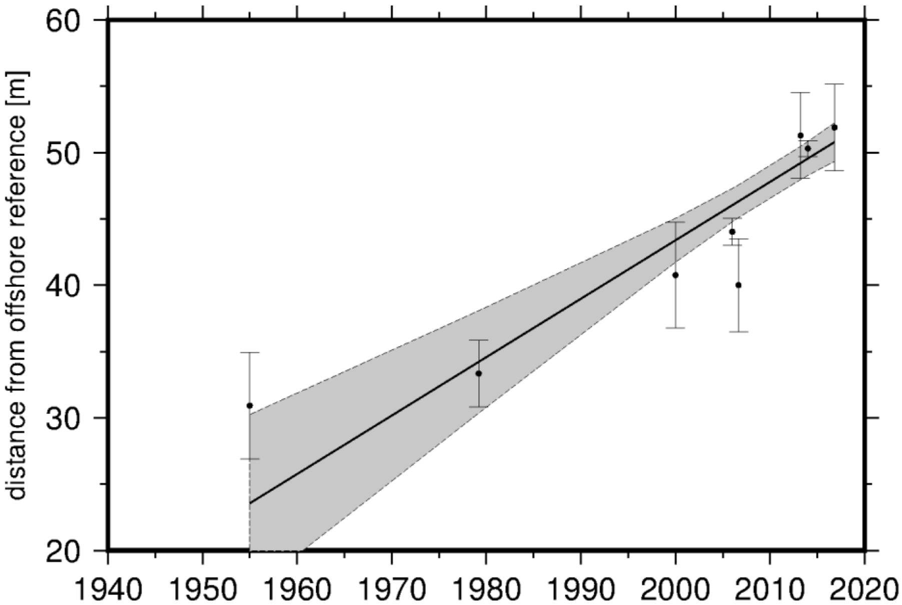

Figure 3-5: Example of shoreline trend analysis. The black line is the linear trend. The grey area represents the 95th percentile confidence interval around where the true trend-line could be. The black dots are the shoreline distance from the offshore edge of the transect, with associated error bars.

3.2.3 LiDAR volume change

For a number of areas along the coast, a recent LiDAR survey from 2016 existed in addition to an older LiDAR survey from 2004, which covered the entire Otago shoreline. The data of both surveys were used to create Digital Elevation Models (DEMs) with a ground resolution of 2 m. These DEMs were analysed in areas of particular interest (Oamaru township, Kakanui and Katiki Beach). This provided elevation changes to show a 2-dimensional overview of areas of erosion and accretion between the 2004 and 2016 surveys.

Results of the LiDAR volume change analysis are presented in section 3.3.3.

3.2.4 Beach profiles

Profile survey data for 12 sites north of Oamaru were provided by Otago Regional Council. Repeat surveys were available for some of these profiles which enabled independent analysis of the top-of-cliff retreat rates. The data from these profiles were also valuable for setting-up the shoreline simulation model. However, the limited number of repeat surveys meant that the profiles could not be used to assess the cliff erosion rate or the modes of erosion.

The surveyed beach profiles for Oamaru central are shown in Figure 3-6, with the top of cliff illustrated to show measured retreat rates.

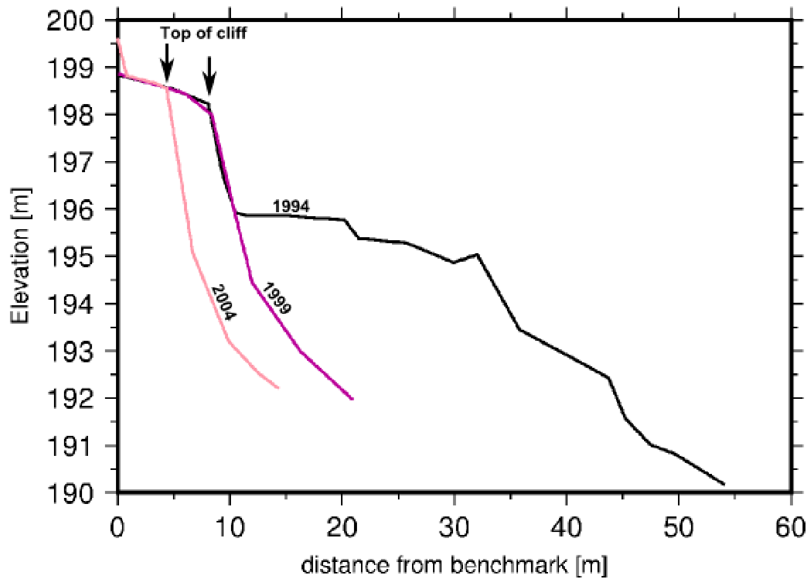

Figure 3-6: Oamaru (central) beach profiles surveyed by Otago Regional Council. Note: The vertical elevation is referenced to an arbitrary datum.

3.2.5 Shoreline simulations

SCAPE (Soft Cliff and Platform Erosion) is a coastal model designed to represent the mesoscale evolution of cliff-lined coasts (Walkden and Hall 2005). The SCAPE model was designed and thoroughly tested on the cliff/barrier coasts in Suffolk to assess the response of the cliff and barrier system there to accelerated sea-level rise (Walkden et al. 2015).

The SCAPE model is tested here to evaluate the response of the cliff-backed coast north of Oamaru to projected sea-level rise. While SCAPE allows for the simulation of a complex coastal system, the model implemented here remains simplistic as little environmental information is available to force and validate the model.

The model was set up for a 5 km-long span of shore, represented by 10 parallel and cross-shore transects spaced 500 m apart. The model shore trended 40 degrees east of north (i.e., transects are facing 130 degrees east of north). The model cliff heights were set to 12 m above present mean sea level (12.11 m DVD58). The beach crest level was set at 2.8 m above mean sea level. The daily tidal range and forcing variables (including storm surge and wave statistics) were taken from Gorman et al. (2002). The daily tidal range and forcing variables only spanned 20 years so it was repeated 505 times for duration of the simulation (1100 years).

The profile shape of the steep gravel beaches north of Oamaru was approximated using a 'Bruun constant' (Bruun 1962) of 0.8.

The SCAPE model has no option for specifying the rates of loss of material due to abrasion, which was previously shown to be significant (Hicks 2011). However, this can be approximated by reducing the proportion of material from the eroding cliff that can be retained on the shore (10 per cent). The alongshore flux of sediment was not allowed to exceed 150 m^3/tide, which is consistent with previous estimates of longshore transport rates for this shore (Hicks 2011).

The model assumed uniform cliff lithology both in the vertical (i.e., up the cliff height) and alongshore. This is in contrast with sporadic field observations that suggest that the loess layer (4-

5 m thick in Oamaru) thins towards the north. The data available are insufficient to directly evaluate how the lithology of the cliff affects the cliff recession and the development of the gravel beach.

The model was initially run for 1,000 years to allow it to reach an equilibrium. The rate of sea-level rise for this "running-in" period was set to 0.002 m/y, in keeping with the historical rates observed on the South Island east coast (Hannah and Bell 2012).

Model validation was achieved mainly by comparing the shore retreat rates over the last 100 years of the running-in period with those observed historically for this shore away from the armoured structures protecting the Oamaru port and town centre. The modelled rate for this period of 0.33 m/y compared well with the observed rates between 0.3 m/y and 0.4 m/y (see section 3.3.1). The SCAPE simulation also reproduced a variability of erosion rates driven by the occurrence of storms and cliff collapse which is similar to historical observation (Figure 3-7). The model also produced an equilibrium beach width similar to that observed by Dickson et al. (2009), providing additional validation.

Multiple simulations were run to assess the sensitivity of the results to the selected model parameters. The model was found to be very sensitive to the 'Bruun constant', slump period, talus slope, maximum longshore sediment flux and beach return ratio, but quite insensitive to the berm slope. This suggests that while the model produced valid results, more information about the dynamics of the cliff erosion are required to confirm the validity of the parameter selection.

We concluded from these validation results that simulation of the future shoreline position using SCAPE is reasonable and reproduced the dominant erosive trend, therefore giving confidence for use in the forecasting of future shoreline trends. However, the model is sensitive to parameters that are not well known, thus more data would be required to improve confidence in the model.

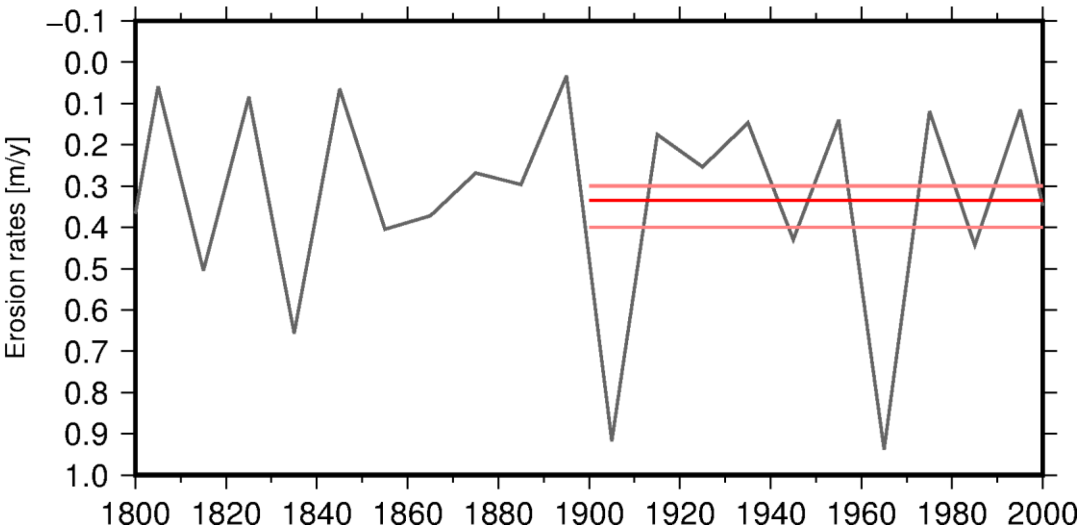

Figure 3-7: Erosion rates simulated for Oamaru using SCAPE+. The grey line shows the annual erosion rates, the light red lines the range of observed historical long-term rates for this section of the coast, and the bold red line is the averaged simulated rate.

The model simulation was then repeated (including the run-in period) and extended to 2115 using two sea-level rise scenarios: (1) the historical rate of sea-level rise of 0.002 m/y was applied from start to finish (1015 to 2115)with mean sea level reaching 0.22 m above present day mean sea level by 2115; (2) the historical rate of 0.002 m/y is applied from 1015 to 2015 and from 2015 the predicted sea-level rise associated with IPCC scenario RCP8.5 upper bound of likely range (+1.3 m by 2115 based on the IPCC 5-yearly sea level prediction) is applied. These two scenarios cover the range of expected shoreline responses over this timeframe.

3.2.6 Coastal erosion hazard zone mapping

Overview of approach

The coastal erosion hazard zone was created from estimates of the future shoreline position combined with an allowance for processes that cause short term shoreline fluctuations and/or backshore slope failure.

The base formula used to calculate the coastal hazard zone width (CHZ) was adapted from Gibb (1982):

$$CHZ = R \times T + S \qquad (3.1)$$

where CHZ is the hazard zone width, R is the long-term average rate of shoreline retreat which is based on the observed historical rate of shore retreat that, in some cases, can be adjusted to account for accelerated future sea-level rise, T is the time span for the hazard zone planning period (50 or 100 years in this case), and S is a factor to account for short term shoreline change due to storm erosion/accretion cycles or for slumps in cliffs in the backshore. The formula is applied at each shore station (every 5 m alongshore for this study), and the actual hazard zone is set back by the CHZ width from the 2014 shoreline position, which serves as a reference line.

A hybrid-probabilistic approach was used to manage uncertainty in the R and S terms in Equation 3.1. With a conventional probabilistic approach, both R and S in Equation 3.1 are represented by probabilistic distributions and (using what is termed a Monte Carlo approach) 10,000 realisations of the CHZ width are made by drawing values of R and S at random from their respective distributions. The resulting distribution of CHZ realisations (e.g., Figure 3-8) shows what the range in projected hazard zone width is, which width is most likely, and what the risk is that erosion could extend beyond any given width within the range. For example, if the CHZ line was drawn based on the 50th percentile of the realisations, which is the most likely outcome, then there would be a 50% chance that the erosion hazard would extend beyond that line by the end of the planning period. On the other hand, if the CHZ line was drawn based on the 95th percentile of the realisations, then there would only be a small (5%) chance that the actual future erosion hazard would extend beyond the line. It follows that for planning purposes, different percentiles may be chosen to match the value of assets and the level of risk. For example, if the land in the possible hazard zone range was farmland, then a reasonable risk of erosion could be accepted and a 50th percentile CHZ line might be used. However, in a township (with higher-valued assets), then only a small risk of those assets being eroded could be tolerated and so a 95th percentile CHZ line might best be used.

We term our approach "hybrid-probabilistic" for two reasons. First, while in an ideal case the type of probabilistic distribution function selected should be the one that best fits the available data, in the Waitaki coast case, because of the limited amount of historical data available, a normal distribution was assumed for all terms. A normal distribution is reasonably justified to account for error in digitization and shoreline detection that affect the estimation of historical shoreline retreat rates, but for short term shoreline fluctuations such as storm cut and slope failure, an extreme-value type of distribution is likely better suited but requires data on past extreme storm cut /slope failure that are not available.

Second, in the ideal case the procedures for determining the *R* and *S* terms in Equation 3.1 are well specified, so that the probability distributions assigned to them relate only to the uncertainties in the parameters used to derive them. This is the case, for example, with sandy beaches backed by dunes, where the effect of accelerated sea-level rise in the *R* term can be calculated from foreshore slope using the "Bruun rule", and the magnitude of short-term erosion "bites" can be assessed from repeated surveys of beach profiles. However, for other shore morphologies (e.g., rocky cliffs, perched beaches) for which neither the response to sea-level rise or the magnitude of shore erosion events are well formulated, the distributions associated with the *R* and *S* terms need to be estimated based on expert knowledge and approximation. Significant spans of the Waitaki District shore fall into this latter category because of the nature of the shore morphology and the availability of data.

The upshot is that these hybrid modifications introduce additional uncertainty in the hazard zone width that is not captured in the Monte Carlo probabilistic approach used herein. This additional uncertainty is difficult to quantify but can be managed in part at least by making a qualitative assessment of the reliability of the hazard zone width for each shore morphology type.

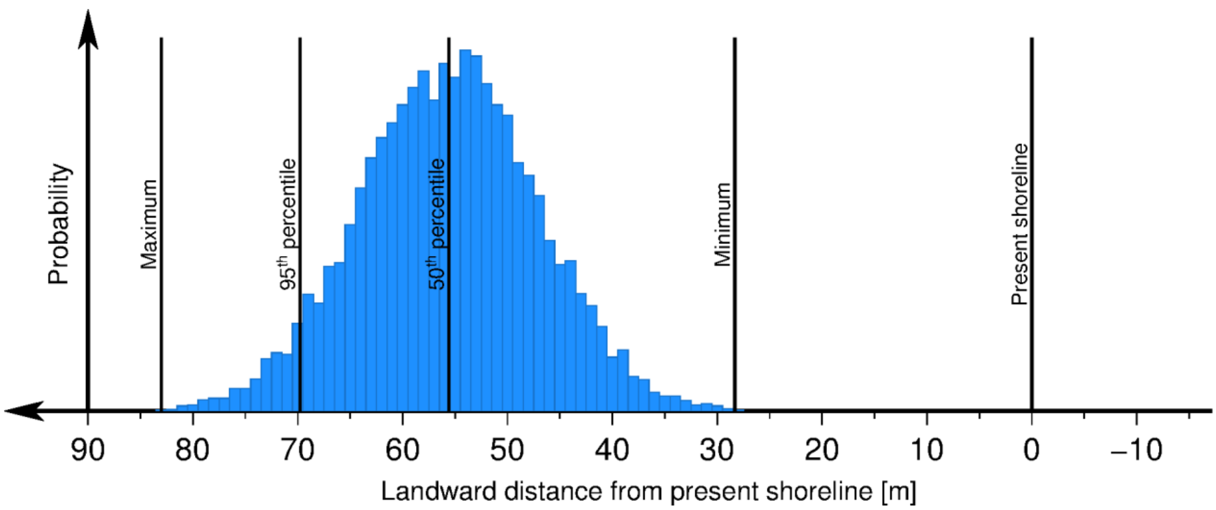

Figure 3-8: Example of probabilistic coastal hazard zone prediction. The vertical blue bars show the histogram of 10,000 realisations of the CHZ width made by drawing values of R and S at random from their respective distributions. The black bars represent statistical measures of the distribution. This distribution was calculated for a transect located on Beach Road.

Morphological diversity

The morphology of the coast in the Waitaki District is diverse and the base formula (Eq. 3.1) is not well suited for all morphologies because the data available and uncertainties around processes vary with morphology. To account for this diversity of coastal morphology, the base formula was adapted to account for six major types of morphology along the coast (mapped in Figure 3-9):

- Bedrock cliffs
- Unconsolidated cliffs
- Geologically controlled beaches (perched beaches)

- Wide gravel barriers
- Dune-backed beaches and thin sand/gravel barriers
- Major coastal structures (e.g., rock armouring, seawalls).

The approach used for each morphology type, and the modifications made to the base erosion hazard zone width formula, are detailed in the following sections.

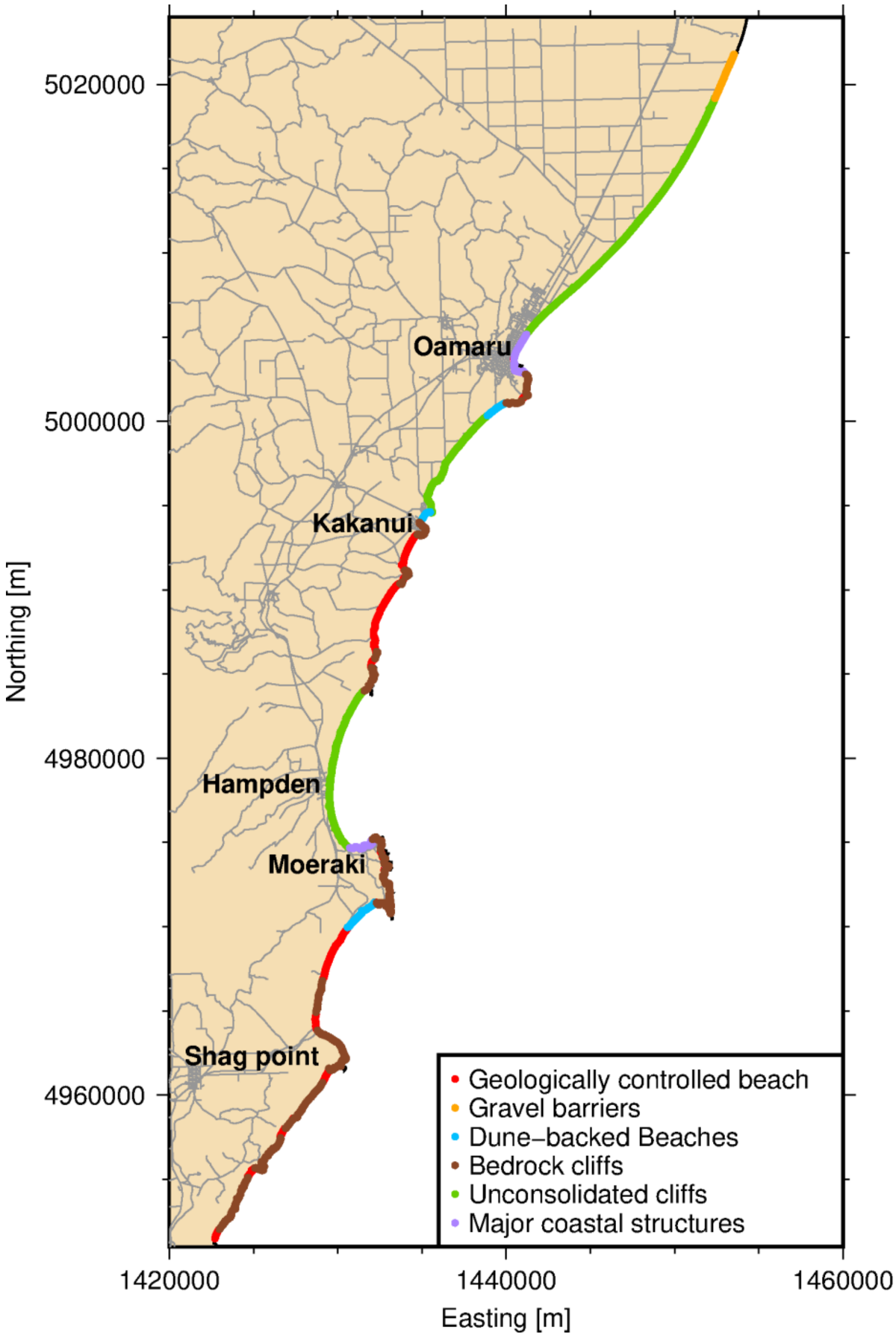

Figure 3-9: Coastal morphology types along the Waitaki District coast.

Bedrock cliffs

Bedrock cliffs describes the consolidated/hard-rock cliffs of high competency (HC) found at Cape Wanbrow, between Moeraki Point and Katiki Point, and between Pleasant River and Shag River (Figure 3-10). For these cliffs, future retreat is expected to be dominated by mass failures (e.g., slumps) and rock fall that are not directly affected by waves and sea level. The rate of retreat would therefore be dominated by the accumulation of all the slumps that occur within a given period. The geology and slope of these cliff must play a significant role in their retreat, but no information about their competence is explicitly taken into account in this study. Thus, their future shore positions are based only on projections of the observed historical trends.

The formula used to assess the coastal erosion hazard is:

$$CHZ = R_{HC} \times T + S_{HC} \qquad (3.2)$$

R_{HC} is the bedrock cliff erosion rate based on the calculated historical rates but using a running mean value smoothed over a 300 m span of shore. The shoreline detection on these high cliffs can be very unclear (e.g., Figure 3-10) and subject to errors in georeferencing and by misinterpretation of shadows and slumps. This results in the historical shoreline positions showing a high variability alongshore that is not representative of the variation in the position of the top of the cliff. To prevent these errors inducing erroneous coastal hazard zones, the historical shoreline trends were smoothed alongshore and 'clamped' to discard rates showing progradation (i.e., cliffs advancing into the sea). Uncertainties in the historical rate were accounted for by producing a normal probability distribution centred on the smoothed historical rate (clamped to remove any value less than 0.05 m/y) and with a standard error derived by similarly smoothing alongshore the standard error of the erosion trends. These smoothed standard errors ranged between 0.001 m/y and 0.003 m/y.

S_{HC} was originally conceived (in the Gibb, 1982 model) to represent the largest slump or slope failure observed in the field. However, without an adequate record of cliff failure or field mapping in Waitaki District, S_{HC} was selected as the average value of the maximum absolute shoreline position change for all the cliff profiles located within 150 m of the profile being analysed. This was represented by a normal distribution centred on the averaged value and with a standard deviation calculated as 1/3rd of the range of the absolute shoreline position change recorded off all the cliff profiles located within 150 m of the profile being analysed. This allows for a distribution of slump width that is representative of the cliff and is constructed independently for each transect. This approach was developed to avoid potential bias in just selecting the maximum between-survey change, since the number of historical shorelines captured at each profile is small (3—6 per profile) and a slow but steady retreat of the cliff occurring during a period when no aerial images are available will be mistaken for a single large slump, overestimating the largest slump during that period. In addition, S_{HC} and R_{HC} are not independent variable in our analysis, and in some cases S_{HC} may duplicate the retreat captured in R_{HC}.

While these estimates of coastal hazard zone for bedrock cliffs are conservative (mainly due to the S_{HC} distribution being conservatively wide), a conservative approach is warranted given that the data available do not allow account to be taken of all the cliff recession processes (e.g., drainage concentration factor). It is also recommended for this shore type that a minimum width of erosion hazard zone is adopted. This safety width would allow for cases where S_{HC} was mapped to be small because no significant slump could be observed from the imagery analysis but where slumps are known to occur based on geological evidence.

Note that for hard cliffs, accelerated sea-level rise is not expected to lead to acceleration of coastal erosion or slumping and is not taken into account.

Figure 3-10: Example of bedrock cliff morphology. Shag Point cliffs.

Unconsolidated cliffs

Cliffs formed in unconsolidated sediments (gravel, loess, clay, old sand dunes) have a low competency (LC) and their retreat is directly correlated to wave and sea-level actions. The sediment that falls off the cliff is reworked by waves and forms a beach at the foot of the cliffs, which, in turn, protects the cliff from waves. This morphology can be seen at the cliffs north of Oamaru (Figure 3-11), at Beach Road (Figure 3-12), and along most of the coast near Hampden (Figure 3-13). For these cliffs, which typically front old alluvial fans or coastal terraces, the location of the cliff top is typically more obvious than for bedrock cliffs with a rising backshore, leading to smaller shoreline detection errors. However, they also show a greater alongshore variability of erosion rate due to small slumps, which can mask or confuse the long-term erosion rate.

The formula used to assess the erosion hazard on low competency cliffs is:

$$CHZ = R_{LC} \times T + S_{LC} \qquad (3.3)$$

As with bedrock cliffs, R_{LC} is the erosion rate sampled from a normal distribution constructed using the historical erosion rates and their associated standard errors, both smoothed alongshore on a 300 m wide window to remove the contribution of short-term slumps to the long-term retreat. The normal distribution is justified when considering that the errors are due to digitization (for which a normal distribution is expected) and fitting the linear trends.

Unconsolidated cliffs could be affected by an acceleration of sea-level rise, especially if their elevation is comparable to the predicted rise of sea-level or if the rise of sea-level is affecting a new, less competent, geological layer. In this study the data necessary to properly account for cliff height and geology with acceleration of sea-level rise is not available throughout the district. However, the effect of the acceleration of sea-level rise was tested for the cliffs north of Oamaru using the shoreline dynamics model SCAPE (see Section 3.2.5). That simulation found that for those cliffs the acceleration of sea-level rise had little to no effect on the cliff erosion rates. Since this may not be true for lower cliffs or cliffs with a less competent geology, further study is recommended of the retreat mechanism of the unconsolidated cliffs elsewhere in the district and their sensitivity to an acceleration of sea-level rise.

S_{LC} was calculated the same way as for S_{HC}, with S_{LC} selected as a normal distribution centred on the averaged value of the maximum absolute shoreline position change for all the cliff profiles located within 150 m of the profile being analysed. The normal distribution standard deviation is calculated as 1/3rd of the range of the absolute shoreline position change recorded at all the cliff profiles located within 150 m of the profile being analysed. Again, with the approach we used S_{LC} and R_{LC} are not independent variables and in some cases S_{LC} may duplicate retreat captured in R_{LC} but is showing the sudden retreat that should be expected at any time.

The formulation here attempts at combining the effect of complex processes of cliff retreat into a normal distribution. While this is the most that can be achieved with available data, important processes of retreat may be ignored or underestimated. Therefore, it is also recommended to include a minimum width of the hazard zone. Discussion and recommendation of the minimum width is provided in section 3.2.7.

Figure 3-11: Example of unconsolidated cliff morphology: north of Oamaru. Note mainly gravel cliffs with loess cap.

Figure 3-12: Example of unconsolidated cliff morphology: Beach Road. Note remnants of the old coastal road on the cliff top and scattered light-coloured blocks from a failed rip-rap wall in the distance (circled).

Figure 3-13: Example of unconsolidated cliff morphology: Hampden. Note cliffs formed in soft mudstone containing scattered concretions.

Geologically controlled beaches (perched beaches)

The Waitaki District beaches are predominantly perched beaches that are often backed with low cliffs. Perched beaches are beaches that are underlain and/or fronted seaward by hard substrate (reefs, pavements, shallow bedrock, etc) (e.g.,Figure 3-15). The response of these types of beach to sea-level rise is poorly understood (Gallop et al. 2011) as the form and character of the nearshore substrate and backshore could either damp or amplify the effect of sea-level rise. In the case of the Waitaki District coast, there is not enough information to robustly assess the effect of an accelerated sea-level rise on these shorelines. Using the standard Bruun model or variations, developed for beaches with a sand-formed offshore profile and a sandy backshore, would lead to exaggerated shoreline retreat by predicting shoreline positions too far into the backshore. Therefore, for geologically controlled beaches, no acceleration of erosion due to sea-level rise was accounted for.

Thus, for perched beaches and beaches backed with low cliffs, the hazard zone formula used is:

$$CHZ = R_{PB} \times T + S_{PB} \qquad (3.4)$$

As previously, R_{PB} is the erosion rate sampled from a normal distribution constructed using the historical erosion trends and the associated standard error, both smoothed alongshore.

In these cases, the shoreline is expected to experience cycles of storm erosion and post-storm recovery (accretion/revegetation of backshore) superimposed on a long-term retreat trend, and S_{PB} is the short-term shoreline retreat of the vegetation line due to storms rather than the extent of slumps (e.g., as used to define S_{HC} and S_{LC}). The methodology of cliff slump-width estimation used for the cliffed morphologies will tend to overestimate this storm cut. A better approach is to estimate S_{PB} from the residuals of the linear long-term shoreline trends – which index the magnitude of short-term cycles. The S_{PB} distribution at each station (defined by a mean and standard deviation) was sampled from the pooled absolute values of the residuals from the shoreline trend analyses of all the transects within 150 m of the target transect. Unlike S_{HC} and S_{LC}, S_{PB} does not duplicate the erosion rates. It is likely that S_{PB} follows an extreme value type distribution, but not enough data is available to construct an accurate extreme value distribution, so a normal distribution was assumed.

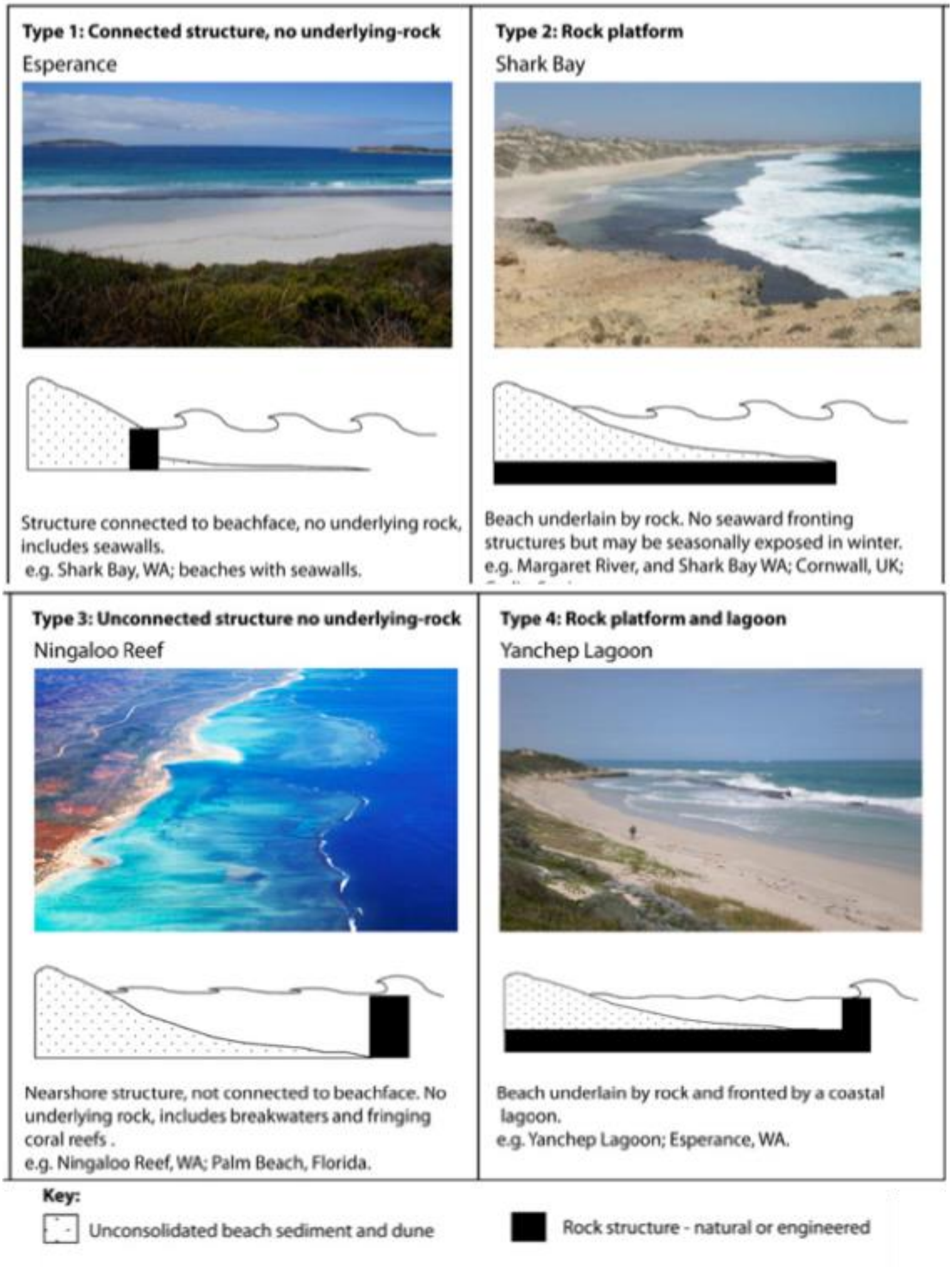

Figure 3-14: Four main types of perched beaches. The beaches of Waitaki District are often represented by Type 2 perched beaches but are generally a mix of the four main types. [Source: Gallop et al. (2011)].

Figure 3-15: Example of geologically controlled beach: South Katiki Beach. Note the outcropping reefs on the right and near the top of the beach.

Wide gravel barriers

The span of shore near the Waitaki River mouth is a wide gravel barrier. Gravel beach evolution in Canterbury and North Otago has been more extensively studied than the rest of the shoreline of Waitaki District. This allows us to use a more complex formulation than for most other beaches in the district. In this case the hazard zone formula is:

$$CHZ = (R_{Measures} + R_{Residual}) \times T + S_{RM} \qquad (3.5)$$

where $R_{Measures}$ represents the retreat rate due to sea-level rise. The retreat due to sea-level rise is based on the approach of Measures et al. (2014) for Kaitorete Spit. This approach is transferable to the gravel barriers of Waitaki District because it is based on a geometric calculation, and although Kaitorete Spit has a different wave climate the morphologies of both sites are similar. $R_{Residual}$ is the difference between the historical shoreline retreat rate and the shoreline retreat rate predicted by using a similar method as $R_{Measures}$ using an historical rate of sea-level rise of 0.002 m/y . $R_{Measures}$ is calculated as:

$$R_{Measures} = 0.01 * \Delta S \left(\frac{\Delta S}{2} + H_{bs}\right)\left(\frac{1}{\tan\alpha} + \frac{1}{\tan\beta}\right)/H_{fs} \qquad (3.6)$$

where ΔS is the expected sea-level rise over the period *of* 100 year, $H_{bs}$is the height of the backshore, α is the corresponding backshore slope, H_{fs} is the height of the foreshore using the toe of the gravel beach as a base, and β is the corresponding foreshore slope. This approach is equivalent to a Bruun-type response to sea level but bypasses the uncertainty of estimating the depth of closure. Lidar data of the Waitaki river mouth was used to measure the geometry parameters used in equation (3.6) at a single profile and assumed constant for the length of shoreline considered (Table 3-2).

Table 3-2: Wide gravel barrier geometry parameters used in equation 3.6 for the Waitaki River mouth. Parameters measured from LiDAR data.

Geometry parameter	Value
H_{bs}	5.7 m
H_{fs}	12.3 m
α	2.8°
β	4.7°

Dune-backed beaches and thin sand-gravel barriers

Beaches backed by a dune field are seldom present in Waitaki District. The northern section of Katiki Beach and the northern section of beach fronting Beach Road are the largest sections that are not strongly geologically controlled by nearby cliffs. Dune backed beaches as well as the thin gravel barrier in Kakanui (e.g., Figure 3-16) are expected to show a Bruun-type of response to sea-level rise. However, the shoreline retreat may not be solely due to sea-level rise and other historical effects may be acting (e.g., change in wave climate or coastal sand supply or adjustment of the shoreline due to the removal of the pier at Kakanui). In this case, the background/residual shoreline retreat needs to be accounted for. In these cases, the coastal hazard zone formula is:

$$CHZ = (R_{Bruun} + R_{Residual}) \times T + S_{PB} \qquad (3.7)$$

R_{Bruun} is the expected shoreline retreat rate based on future sea-level rise using the Bruun model. $R_{Residual}$ is the difference between the historical shoreline retreat rate and the shoreline retreat rate predicted by a Bruun model using an historical rate of sea-level rise of 0.002 m/y. S_{PB} is, as described above, the short-term shoreline retreat due to storms, and is sampled from a normal distribution based on the residuals of the shoreline trend analysis. R_{Bruun} was calculated as:

$$R_{Bruun} = \alpha_B \times R_{SLR} \qquad (3.8)$$

where α_B is the inverse of the active beach slope and R_{SLR} is the future average rate of sea-level rise. The active beach slope is usually calculated over the distance from the dune/barrier crest to the closure depth (i.e., the offshore depth where waves stop influencing the seafloor morphology) on the offshore profile, and is more generally calculated as:

$$\alpha_B = \frac{L_d + L_b}{h_d - h_b}$$

where L_d is the offshore distance to the depth of closure, L_b is the distance of the dune/barrier crest to the backshore toe, h_d is the depth of closure, and h_b is the elevation of the backshore. While h_b and L_b can easily be calculated from Lidar data, the depth of closure is not trivial to define and the offshore bathymetry in Waitaki is not well known. The closure point is likely located between 6 and 8 m depth which occurs between 500 to 800 m offshore for all three beaches of interest (Kakanui, north Katiki and north Beach Rd). Therefore, α_B was sampled from a normal distribution with a mean of 75 and a standard deviation of 7.3. A single scenario of accelerated sea-level rise rate (R_{SLR}) of 0.011 m/y was used. This corresponds to a sea-level rise of 1.3 m over the 100 years from 2015 to 2115 when the historical rate of sea-level rise (0.002 m/y) is included.

Kakanui gravel barrier is a thin barrier (as opposed to the wide, flat-topped barrier at the Waitaki River mouth) and is located on top of a sandy subtidal beach that may also show a Bruun-type response to sea-level rise. Therefore, the approach used for Kakanui Beach was similar to that used for a dune backed beach. In the Kakanui case, however, the Bruun-type response may overestimate the shoreline retreat due to sea-level rise because of the proximity of geological controls (i.e., nearshore substrate, adjacent rocky headlands) which are not taken account of by the Bruun model.

Figure 3-16: Example of thin sand/gravel barrier morphology: Kakanui barrier.

Major coastal structures

Near Oamaru Port, the coast has been protected by a seawall and heavy rock revetments since at least the 1920s, yet the reclamations and revetment are not perfectly stable, and small shoreline changes have occurred and need to be taken account of in the coastal hazard zone. These are calculated as:

$$CHZ = R_{hist} \times T \qquad (3.9)$$

where R_{hist} is the historical shoreline trend rate sampled from a normal distribution constructed using the alongshore-smoothed shoreline trend rates and their longshore-smoothed standard errors. The shore protection here is designed to prevent any sudden retreat of the shoreline during a single storm, but net shoreline retreat due to the cumulative effect of storms and successive repairs of the structure is captured by the R_{hist} term. Evidence from shoreline detection data and Lidar imagery in Oamaru confirm that the shore has crept inland slightly as the result of periodic damage and repair.

Note that this formula does not apply in the future if the coastal protection ceases to be maintained or is removed. It is assumed that the protective structures fronting Oamaru will be maintained at least for the next 100 years. However, short spans of small-scale/shallow-depth coastal protection, such as the riprap at Katiki Beach and along Beach Road and the seawalls at Kaika, were not considered in this analysis of hazard zones as we assume that in their present state they will not continue to hold the shoreline at its current position indefinitely as sea-level rises and erosion trends persist.

Also, note that the effect of acceleration of sea-level rise on the retreat rate has not been taken into account.

3.2.7 Caveat and limitations

The coastal erosion hazard zoning method outlined above attempts to define zones based on expected future shoreline retreat processes evaluated from shoreline detection from aerial imagery. As a consequence, many factors and processes (e.g., the geology of the backshore or foreshore, longshore sediment transport) locally important to driving or preventing shoreline retreat may be missed by the analysis or may be inaccurate. For example, apart from Waitaki River mouth, streams and estuaries are treated the same as the surrounding morphology (dune backed beach or perched beach) and sand/gravel spit retreat may be inaccurate because the influence of sediment supply by rivers is not explicitly accounted for.

There are large uncertainties associated with shoreline response to the acceleration of sea-level rise. The only established approaches are that soft sediment shorelines (beaches) and wide barriers are expected to respond following variations of the generalised Bruun model, but this study did not have available sufficient information on offshore profile geometry to implement this approach as robustly as it could have been. No such response model exists for beaches that are geologically controlled, such as perched beaches. Similarly, shoreline simulations using the SCAPE model suggest that the Bruun model would not be accurate for unconsolidated cliffs, so no estimate of the impact of acceleration of sea-level rise is taken into account on these morphologies.

Also, the dataset used to evaluate the historical shoreline and short-term erosion are based on a relatively few sets of imagery data. For most of the southern half of the coast (Kakanui and further South), the oldest imagery that could be used for shoreline capture (with low distortion of the georeferenced image and adequate resolution) is generally 2006 (with 1973 for Hampden). This means only about 10 years of shoreline record, which is unlikely to be adequate to isolate a long-term retreat trend from the signature of storm events. While some uncertainty is accounted for in the error estimate on the shoreline trend, it does not account for the short sampling period afforded by the data span. Therefore, the results of the analysis should be used with caution.

To account for these limitations, a minimum width should be set for the hazard zones. This minimum zone could follow practical landmarks (e.g., nearby road) or geomorphic limits (i.e., entire sand/gravel spit or coastal dune field). In a practical sense, the coastal hazard zone should not be narrower than the largest shoreline detection error of 8 m.

3.3 Results

3.3.1 Shoreline trends

Figure 3-17 shows the measured erosion rates for the wider Waitaki District. Figure 3-18 to Figure 3-22 show more detailed measurements of erosion rate for the urban areas. GIS data and digital files are available within the appended supplementary material.

The shoreline analysis off historical imagery shows that more than 60 % of the coast of Waitaki District is retreating at a rate of 0.15 m/y or more. The largest erosion rates of 2.0 m/y occur north of Hampden at the location of a large slump[2]. north of Oamaru, the entire coastline is retreating at rates between 0.3 and 0.9 m/y. Small pockets of accretion have occurred at the north end of Beach Road (0.3 m/y accretion), north of All Day Bay (0.16 m/y accretion), and the Shag River mouth spit (0.9 m/y accretion). Since these accretion cases are typically located at the northern end of bays, it may be the result of inter-decadal variability in wave direction rather than a long-term trend.

In the built-up areas, Oamaru shows erosion rates of 0.4 m/y near Waitaki Boys High School, 0.35 m/y near Foyle Street, and 0.3 m/y near Weaver Street. Even the area with rock protection shows retreat rates of 0.2 m/y (Torridge Street) - despite the coastal protection. Some parts of the port show accretion because of refurbishment of the seawall (Figure 3-18). At Kakanui, the gravel barrier is showing retreat rates of around 0.7 m/y. Near the Kakanui spit tip, the rates increase to 1.3 m/y (Figure 3-19). At Hampden, the erosion rates are around 0.10 m/y, a rate considerably less than the erosion observed at the large slump feature north of the town (Figure 3-20). At Moeraki, the shoreline change analysis suggests accretion, but the error estimates associated with these rates are high suggesting that it is likely influenced by an inter-decadal cycle or simply measurement error. At Shag Point, the rates appear to be variable (likely reflecting measurement error) but predominantly show no overall changes in the shoreline (Figure 3-21).

Elsewhere, the southern portion of Beach Road is an erosion hotspot, eroding at an average rate of 0.38 m/y (Figure 3-22), while the shore along the southern portion of Katiki Beach, alongside SH1, is eroding at 0.4 – 0.6 m/y.

[2] Here the shoreline has been defined as the scarp of the cliff and although the scarp has retreated 2m/y, the toe of the slump may have retreated more slowly.

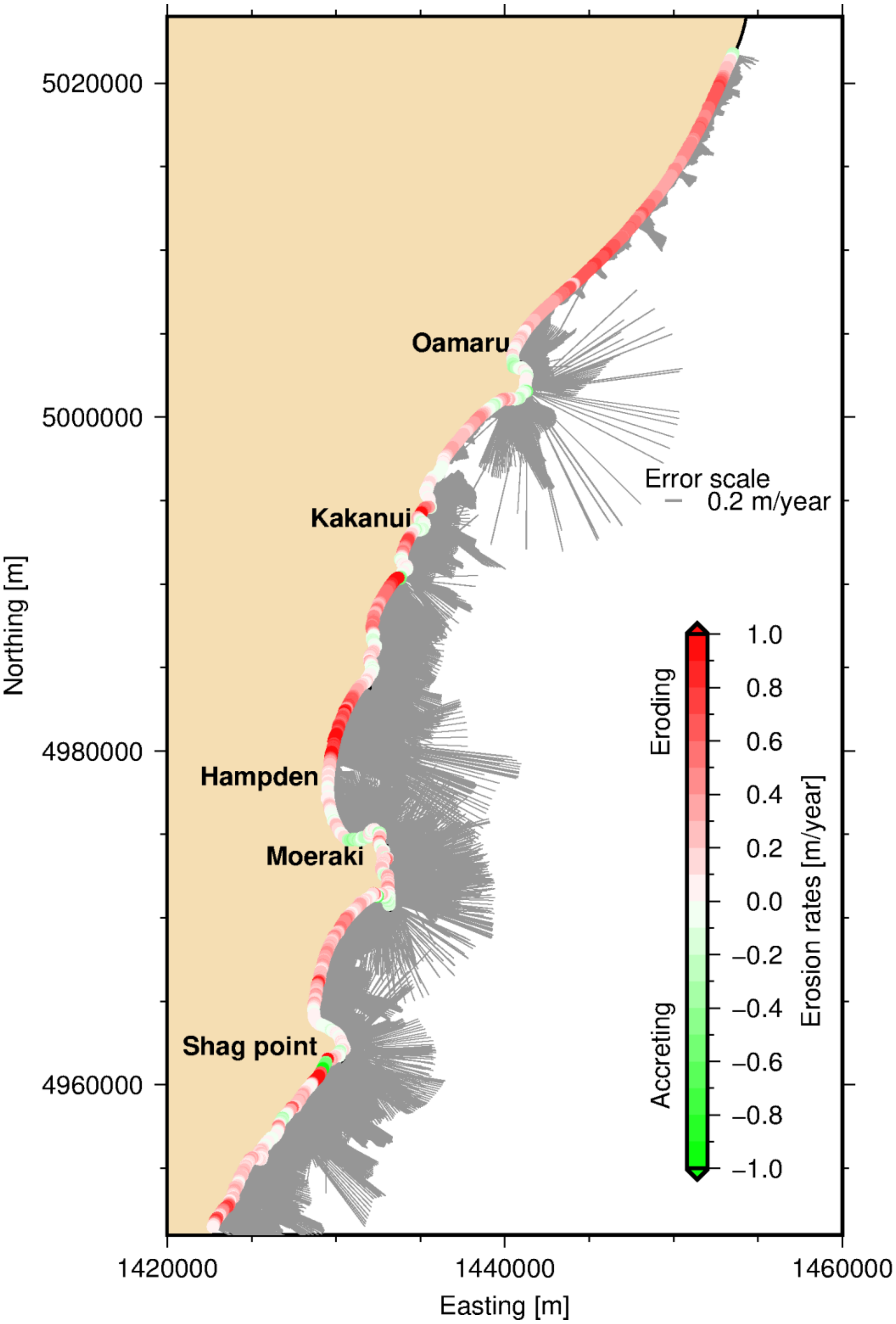

Figure 3-17: Calculated shoreline trends for the Waitaki District coast. Green and red shaded circles show the average erosion rate (m/year). The grey shaded lines show the standard error calculated for the erosion rate; their length scales as on the legend. High error may be due to lack of data or low resolution in shoreline fitting.

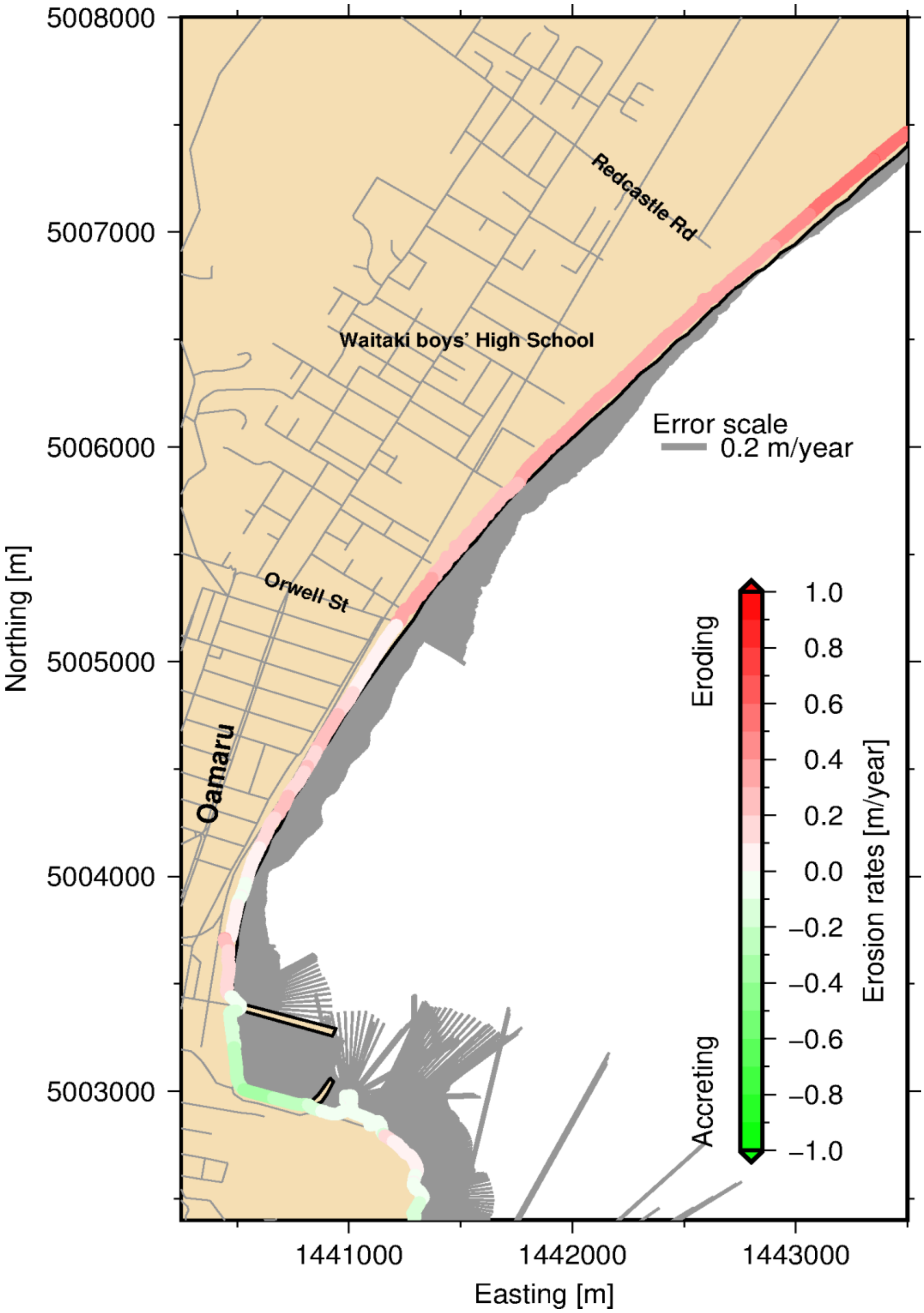

Figure 3-18: Calculated shoreline trends for the Oamaru area. Green and red shaded circles show the average erosion rate [m/year]. The grey lines show the standard error calculated for the erosion rate. High error may be due to lack of data or imprecise shoreline fixing.

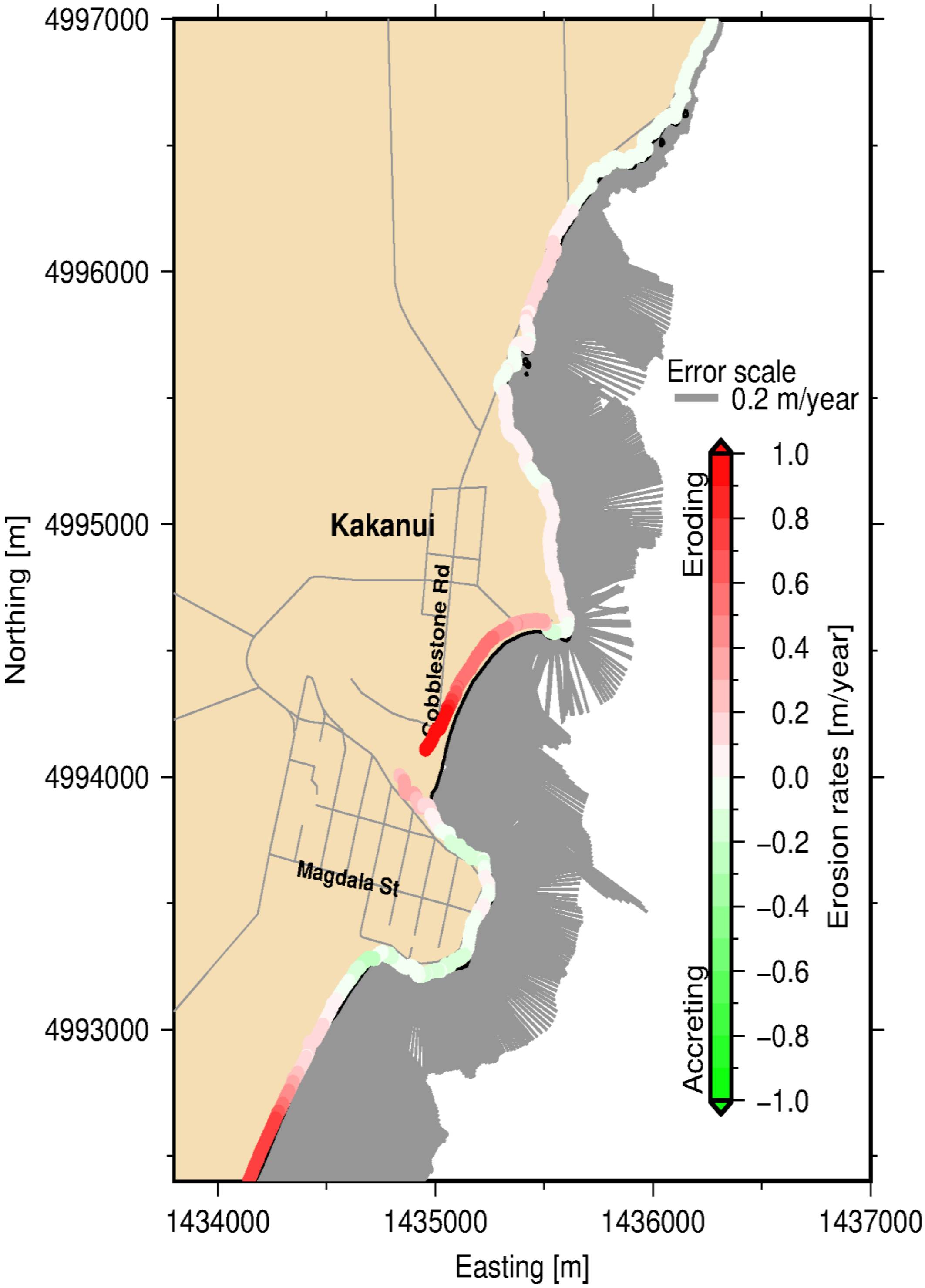

Figure 3-19: Calculated shoreline trends for the Kakanui area. Green and red shaded circles show the average erosion rate [m/year]. The grey lines show the standard error calculated for the erosion rate. High error may be due to lack of data or imprecise shoreline fixing.

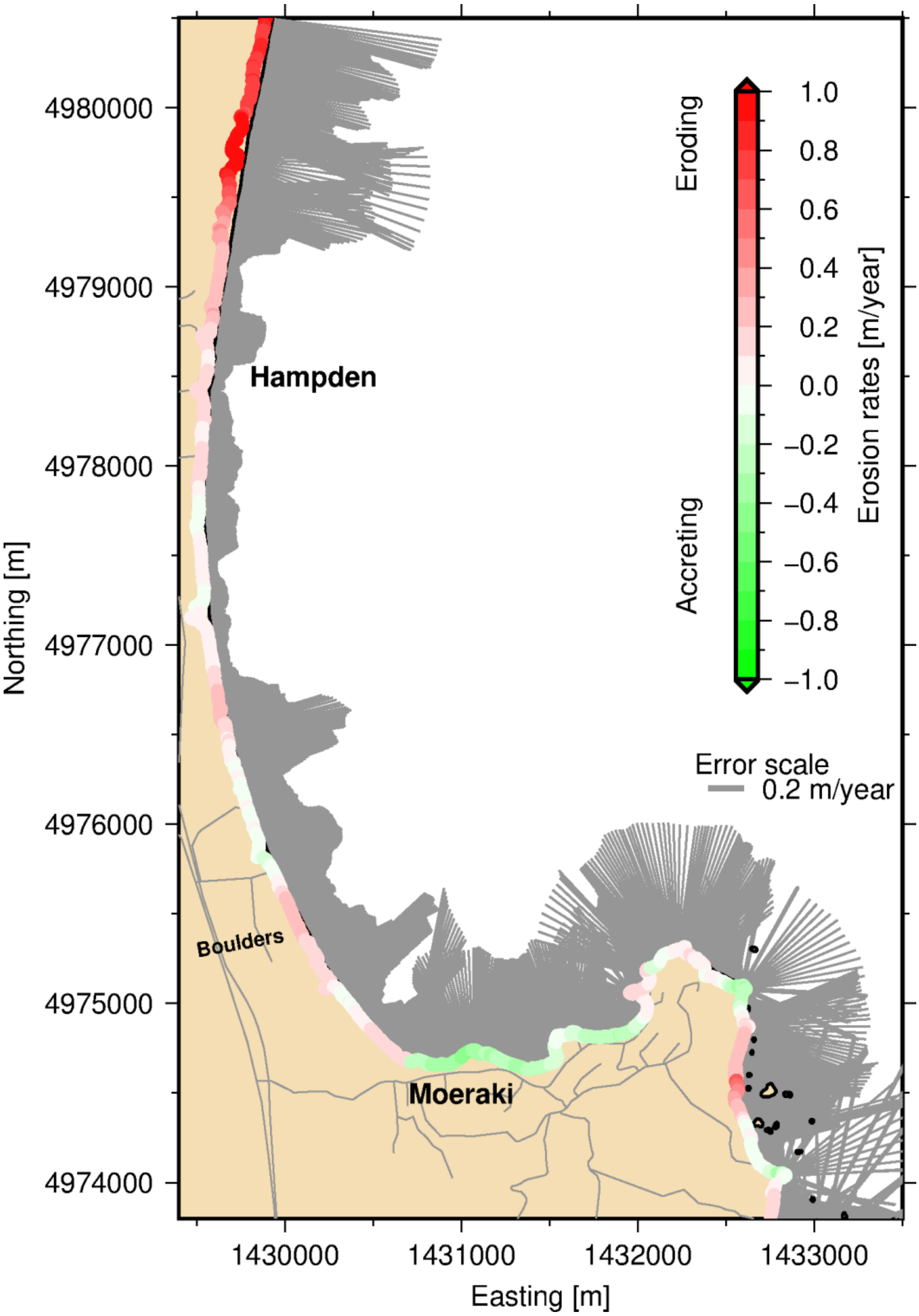

Figure 3-20: Calculated shoreline trends for the Hampden and Moeraki area. Green and red shaded circles show the average erosion rate [m/year]. The grey lines show the standard error calculated for the erosion rate. High error may be due to lack of data or imprecise shoreline fixing.

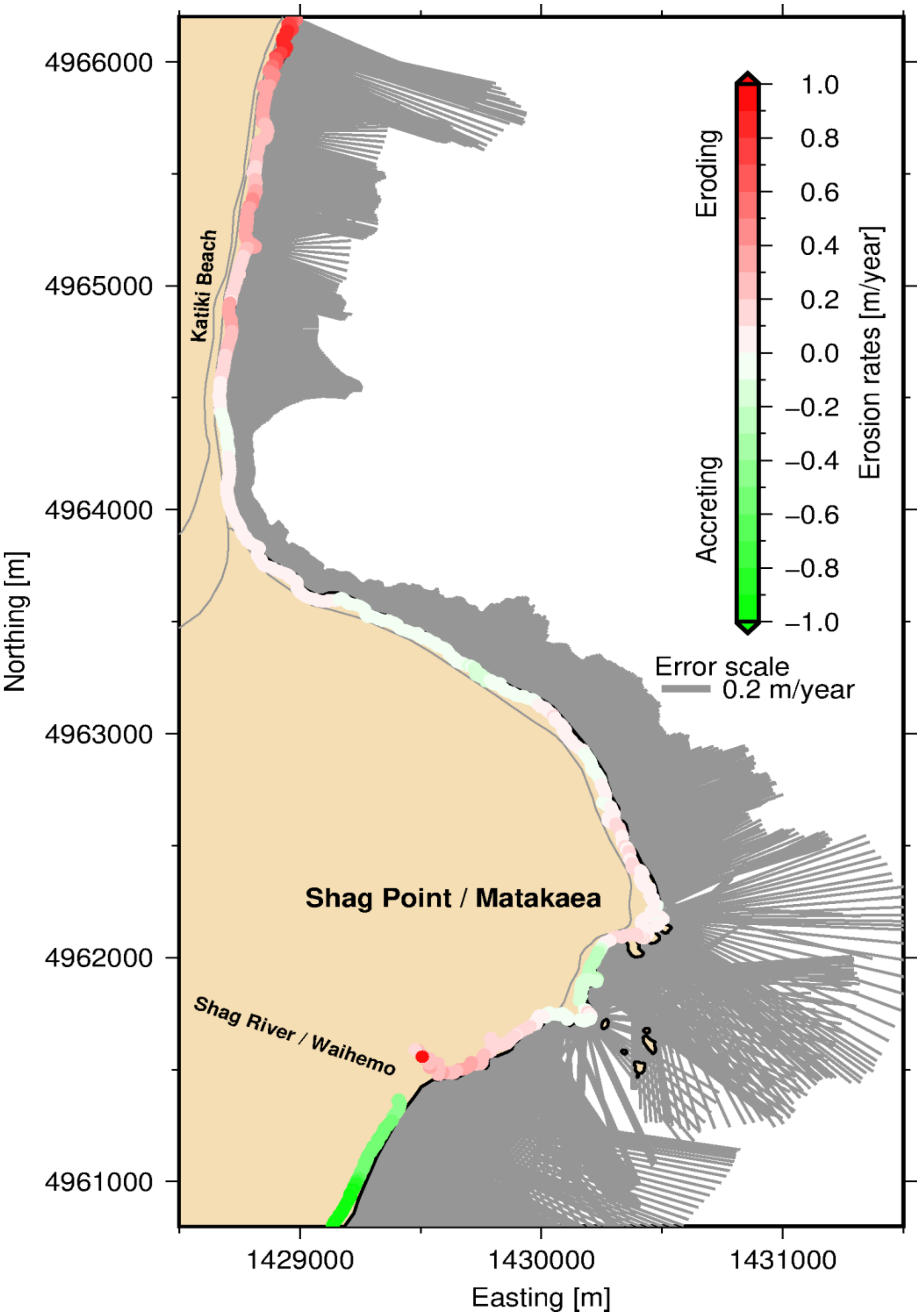

Figure 3-21: Calculated shoreline trends for the Shag Point and Shag River mouth area. Green and red shaded circles show the average erosion rate [m/year]. The grey lines show the standard error calculated for the erosion rate. High error may be due to lack of data or imprecise shoreline fixing.

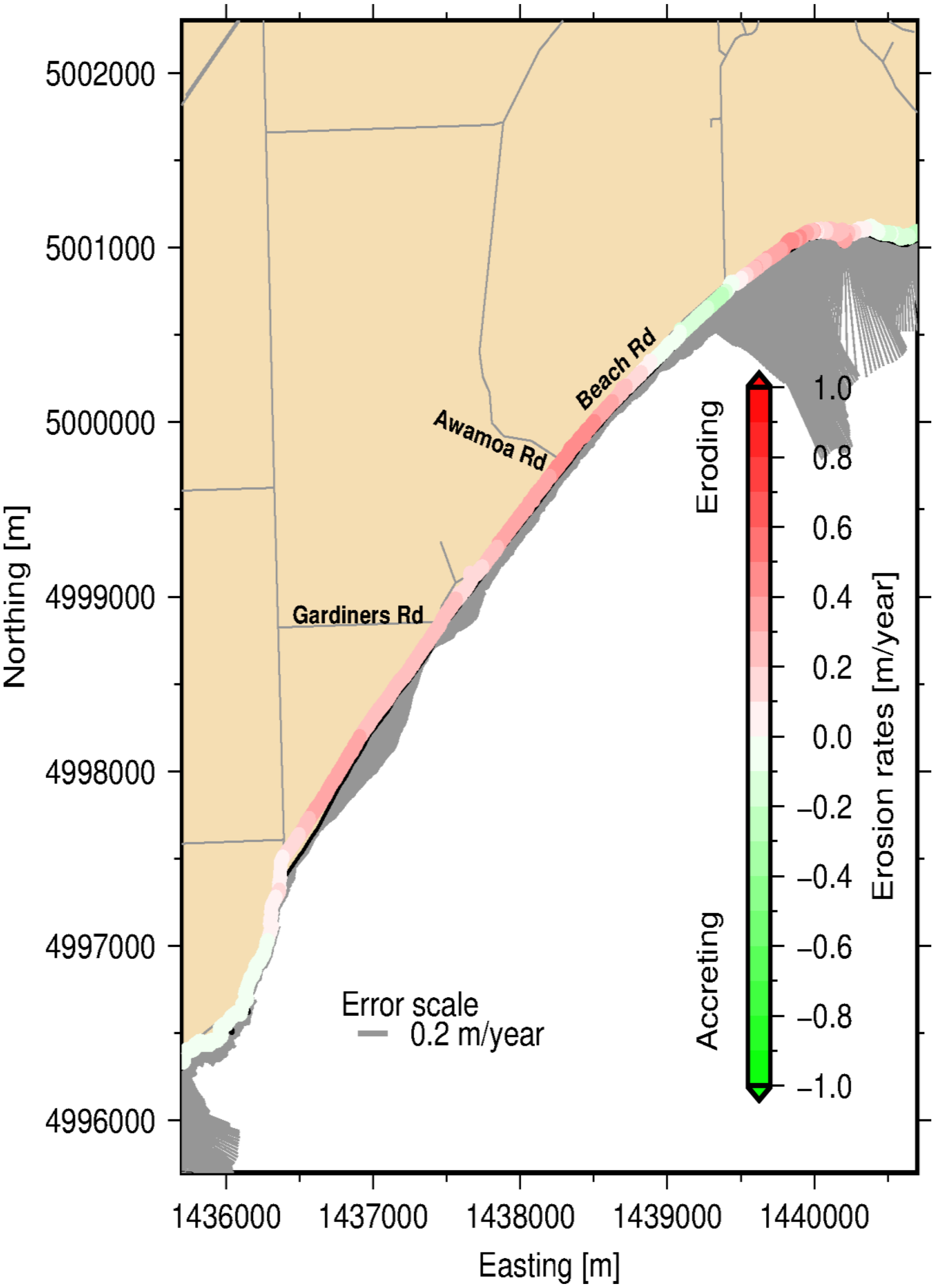

Figure 3-22: Calculated shoreline trends along Beach Road. Green and red shaded circles show the average erosion rate [m/year]. The grey lines show the standard error calculated for the erosion rate. High error may be due to lack of data or imprecise shoreline fixing.

3.3.2 Short term shoreline retreat

Short term retreat was estimated for different coastal morphology types as a component of the hazard zone. While a statistical distribution was used in the hazard zone definition, it is useful to evaluate the 95th percentile for short term retreat (Figure 3-23) to better understand the weight of this component in the overall hazard width. As with the rest of this report, the shoreline here refers to the vegetation line or cliff top line for cliffed shorelines. Short term retreat of the vegetation line due to a storm is expected to be much less than the retreat of the water line on a sandy beach. The largest short-term shoreline retreat is predicted for soft cliffs and in particular for the section north of Oamaru and Beach Road, contributing up to 1/3rd of the historical erosion rate contribution over 100 years. Small (~1 m) short term retreat is expected on the dune-backed northern segment of Katiki Beach; this is negligible compared to the 20-40 m expected retreat from the historical rates applied over 100 years.

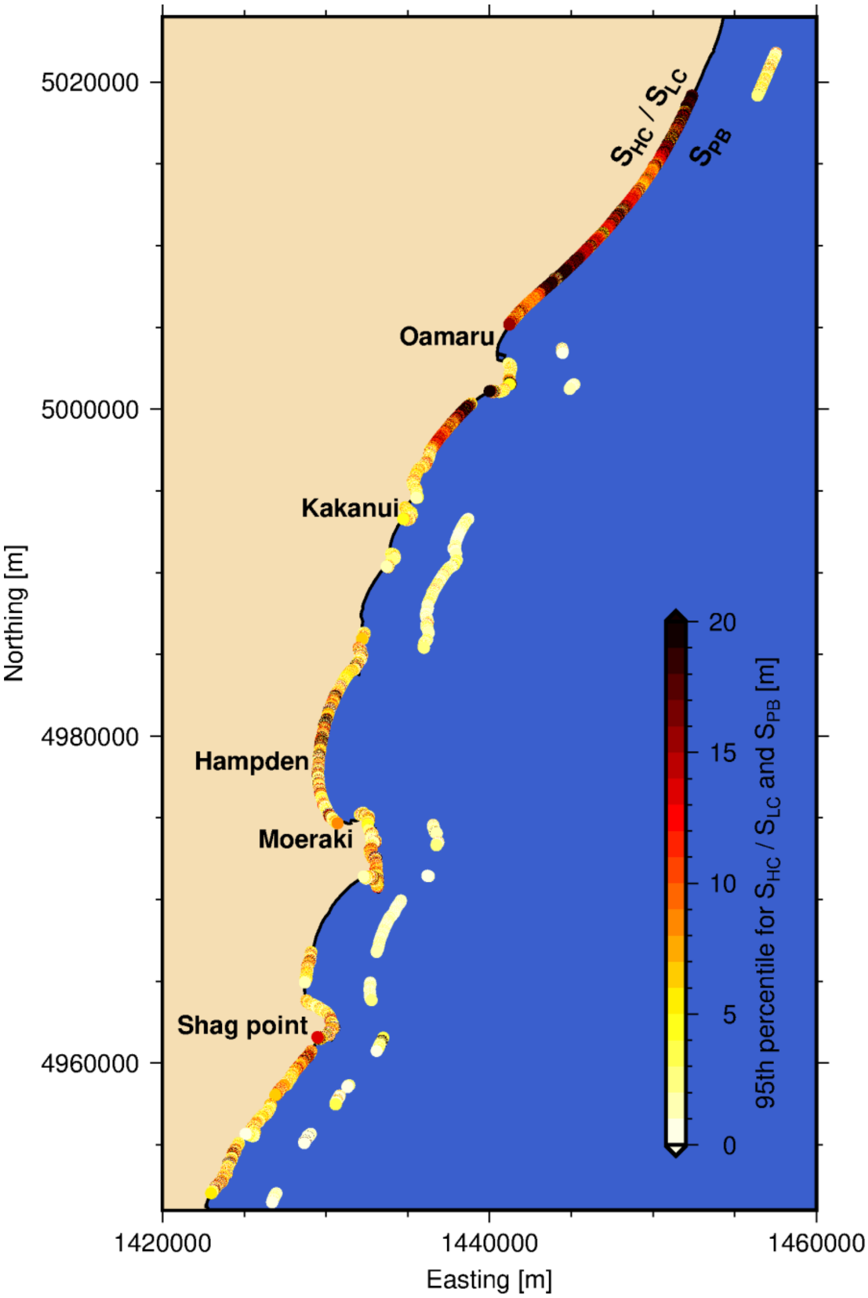

Figure 3-23: 95th percentile of the short-term retreat for beach and cliff shores. The hazard zone is defined using a statistical distribution of the morphology-dependent S (short term retreat) term. S_{HC} (bedrock cliffs) and S_{LC} (unconsolidated cliffs) are showed on the shoreline while S_{PB} (perched beaches) are showed intentionally shifted eastward of the shoreline for clarity.

3.3.3 LiDAR volume change

Shoreline topographical changes detected from the 2004 and 2016 LiDAR surveys provide another measure of rates of shoreline shift and may also show changes too subtle to detect from vertical imagery. In areas such as the eroding cliffs at the northern end of Oamaru (Figure 3-24, Figure 3-25), the cliff retreat rates indicated by the LiDAR are consistent with those from the shoreline analysis from aerial imagery. At central Oamaru, however, and surprisingly, the LiDAR analysis showed changes occurring on the rock protection beside the railway (Figure 3-24). In front of Eden Street, this rock protection lost up to 5.6 m in elevation between 2004 and 2016. The Lidar also shows the recent construction of the rock protection north of Oamaru Creek and accretion south of Oamaru Creek (Figure 3-24, Figure 3-27). This accretion was not reflected in the vegetation line observable on imagery.

At Kakanui, the LiDAR elevation changes clearly show the slump located at the end of Beach Road near the Coast Café restaurant (Figure 3-28 and Figure 3-29). The toe of the cliff retreated nearly 10 m at this feature between the 2004 and 2016 surveys. The LiDAR surveys also show the "rollover" process on the gravel barrier at Kakanui, where material on the front of the gravel beach is washed over onto the back of the barrier during storms, effecting a landward translation of the barrier (Figure 3-30). Despite this rollover, there appears to have been negligible net change in the volume of the gravel barrier between the two surveys (a 1 per cent net volume gain was detected).

The LiDAR elevation difference at Katiki Beach shows considerable variability alongshore (Figure 3-31). For example, Profile Katiki XS1 (Figure 3-32) shows a foreshore erosion/accretion pattern similar to that observed with storm-and-recovery cycles: with the high berm and narrow foreshore in 2004 typical of a post-storm profile, and the wider foreshore with a low berm in 2016 more typical of a recovered profile. In contrast, Profile Katiki XS2, backed by a cliff, shows cliff retreat since 2004 (Figure 3-33) but a slight net rise in the level of the beach fronting the cliff. This variable behaviour suggests that Katiki Beach may not behave like a simple sandy beach and that the nature of the backshore and the reefs outcropping in the nearshore and offshore play a significant role in the coastal processes there.

Figure 3-24: Difference in elevation between 2004 and 2016 near Oamaru based on LiDAR surveys.

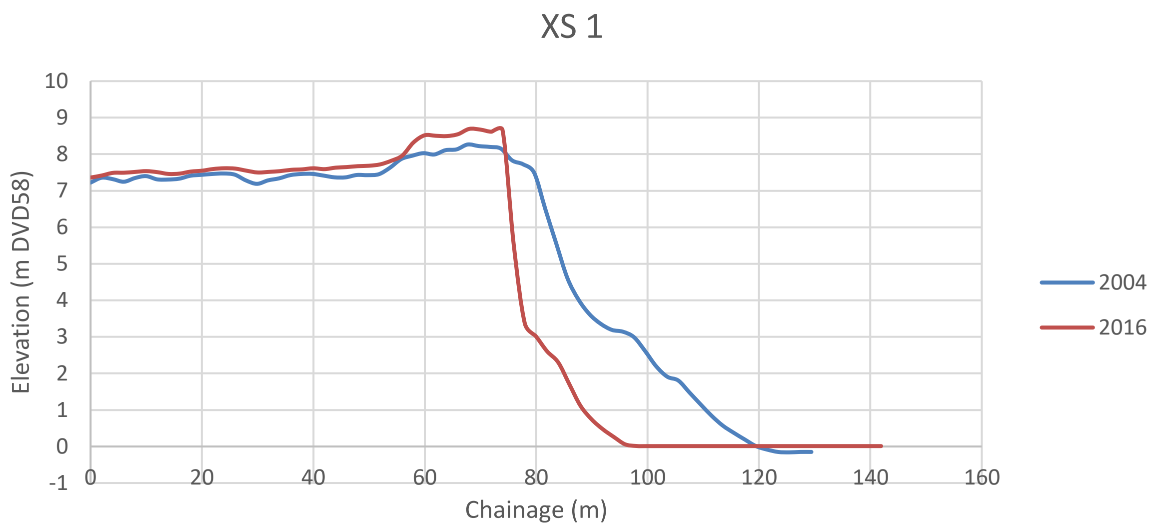

Figure 3-25: Elevation profiles near Weaver Road. Elevation was extracted from the 2004 and 2016 LiDAR survey. Profile location shown in Figure 3-24.

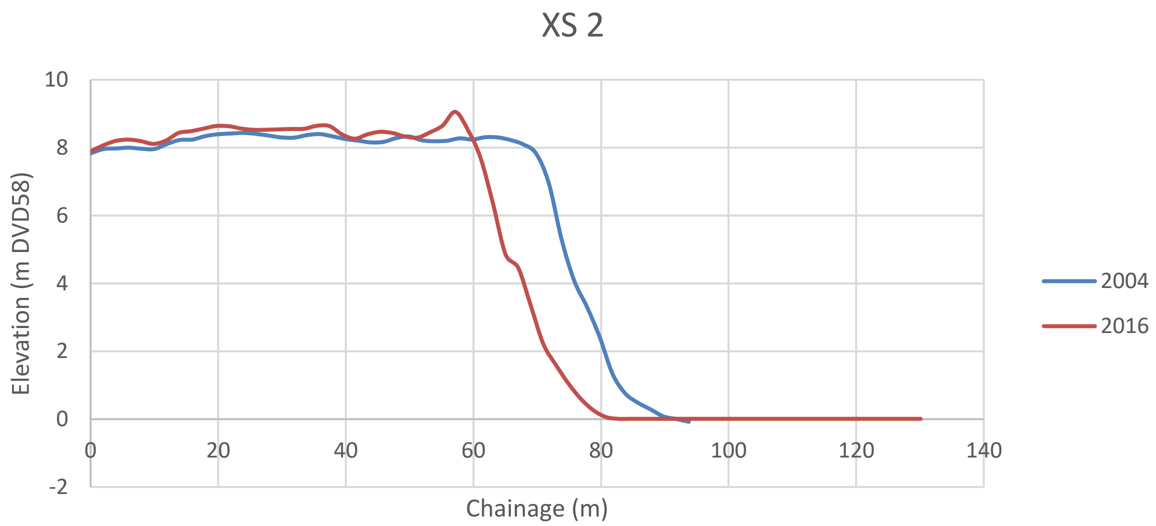

Figure 3-26: Elevation profile near Usk Street. Elevation was extracted from the 2004 and 2016 LiDAR surveys. Note that this profile is located on the armoured part of the coast and shows the degradation of the rock armouring between the two dates. Profile location shown in Figure 3-24.

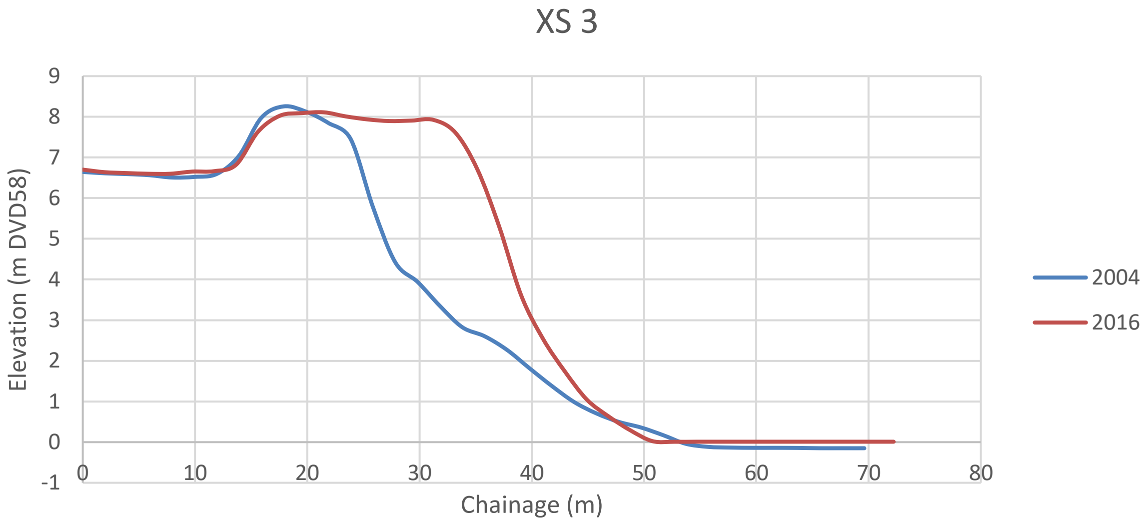

Figure 3-27: Elevation profile north of Oamaru Creek. Elevation was extracted from the 2004 and 2016 LiDAR surveys. Note the increased elevation here shows the recent placement of rock armouring. Profile location shown in Figure 3-24.

Figure 3-28: Difference in elevation between 2004 and 2016 near Kakanui based on LiDAR surveys.

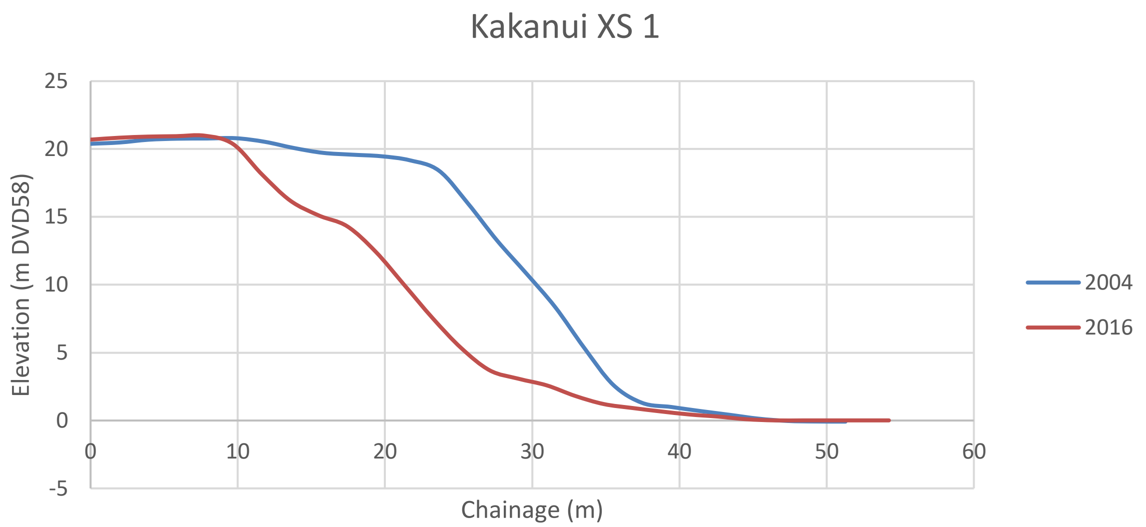

Figure 3-29: Elevation profile at Kakanui through a recent slump that removed part of the road. Elevation was extracted from the 2004 and 2016 LiDAR surveys. Profile located on Figure 3-28.

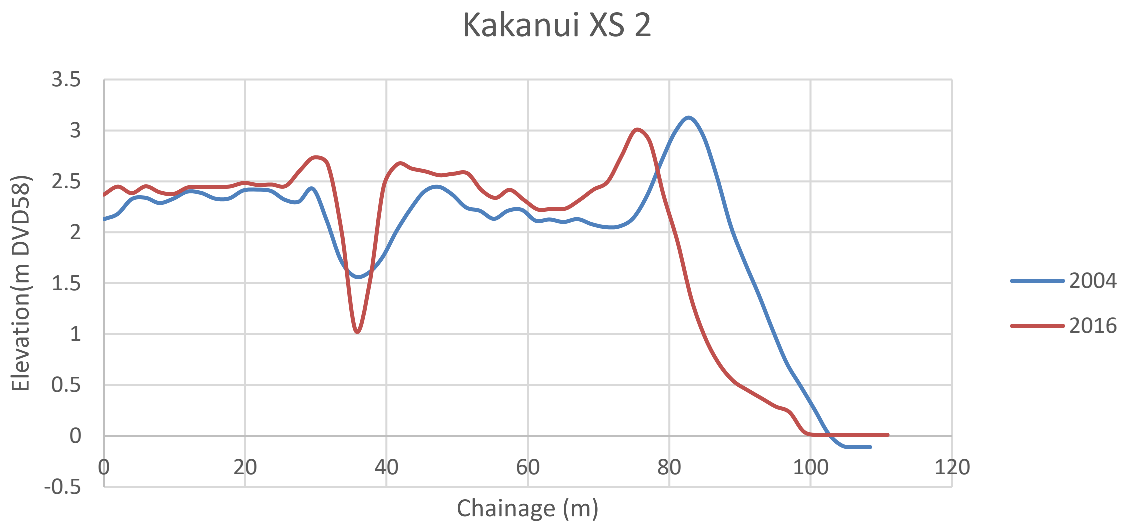

Figure 3-30: Elevation profile of the gravel barrier at Kakanui. Elevation was extracted from the 2004 and 2016 LiDAR surveys. Profile located on Figure 3-28.

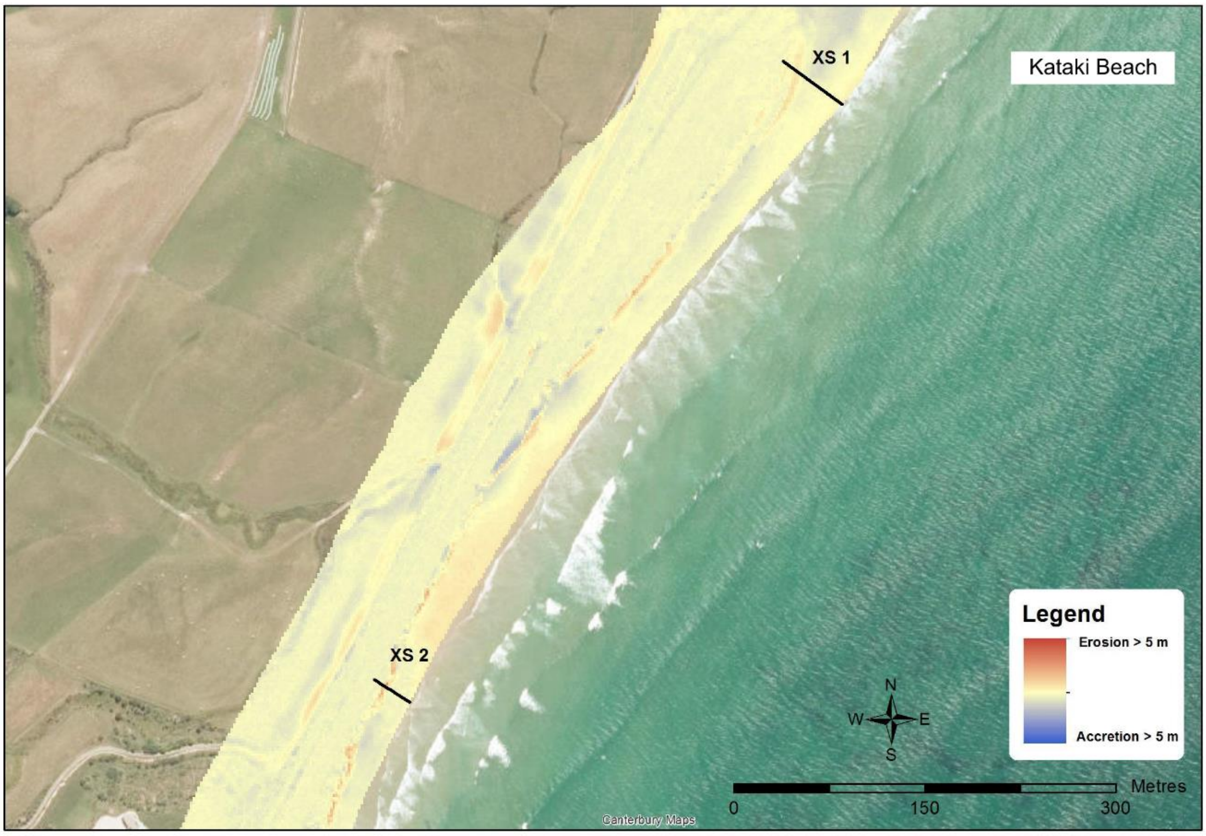

Figure 3-31: Difference in elevation between 2004 and 2016 on Katiki Beach based on LiDAR surveys.

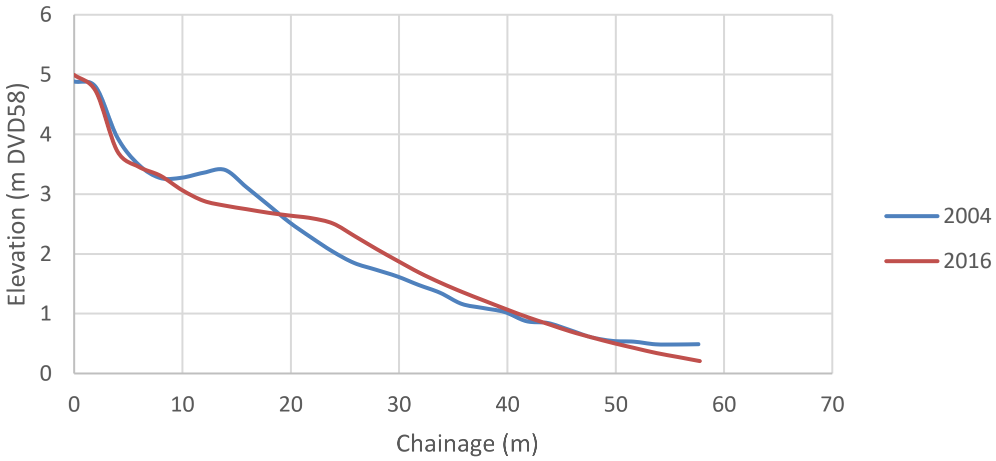

Figure 3-32: Elevation profile on Katiki Beach. Elevation was extracted from the 2004 and 2016 LiDAR surveys. Profile is located on Figure 3-31.

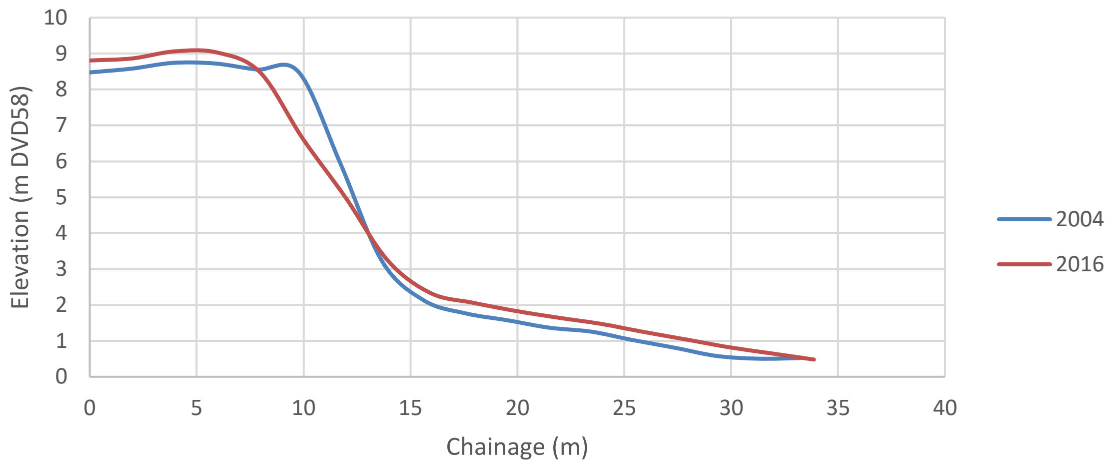

Figure 3-33: Elevation profile in Katiki Beach. Elevation was extracted from the 2004 and 2016 LiDAR surveys. Profile is located on Figure 3-31.

3.3.4 Profiles

Beach profiles monitored by Otago Regional Council only cover up to three dates (May 1994, March 1999 and March 2008) and 12 locations from Oamaru central to the Waitaki River mouth. The four profiles surveyed both in 1994 and 1999 show that the top of the cliff remained at the same location over that period (Table 3-2). The retreat of the cliff between 1994 and 2008, which varied between 3 m and 9 m, thus appears to have occurred during the period 1999-2008. This highlights that the cliff erosion is episodic and is driven almost entirely by storm events.

Table 3-3: Location of clifftop on profiles surveyed by Otago Regional Council.

Profile location	Distance seaward from benchmark 1994 (m)	Distance seaward from benchmark 1999 (m)	Distance seaward from benchmark 2008 (m)	Cliff retreat 1994-2008 (m)
Central	9.3	10.3	4.4	4.9
Foyle Street	6.7	6.4	1.7	5.0
Boys High School	6.6	6.5	2.9	3.7
Hedges Road	16.4		13.4	3.0
Bigg Road	34.1	34.2	27.4	6.7
Stewart Road	20.8		11.8	9.0
Corbet Road	25.8		21.9	3.9
Seacliff Road	20.5		11.9	8.6

3.3.5 SCAPE simulation

Simulation of the effect of accelerated sea-level rise on the cliff erosion near Oamaru using the SCAPE model was undertaken by first simulating the cliff erosion to 2115 using the historical sea-level rise rate of 0.002 m/y (0.2 m at 2115) and then repeating the simulation using the sea levels predicted by the RCP8.5 scenario (+1.3 m in 2115). The position of the cliff in both sea-level rise scenarios is very similar (Figure 3-34), suggesting that an acceleration of sea-level rise is not likely to significantly increase the cliff erosion rate. This result is consistent with the concept that storms are the largest driver of the erosion. Storm changes associated with climate change were not considered in this simulation.

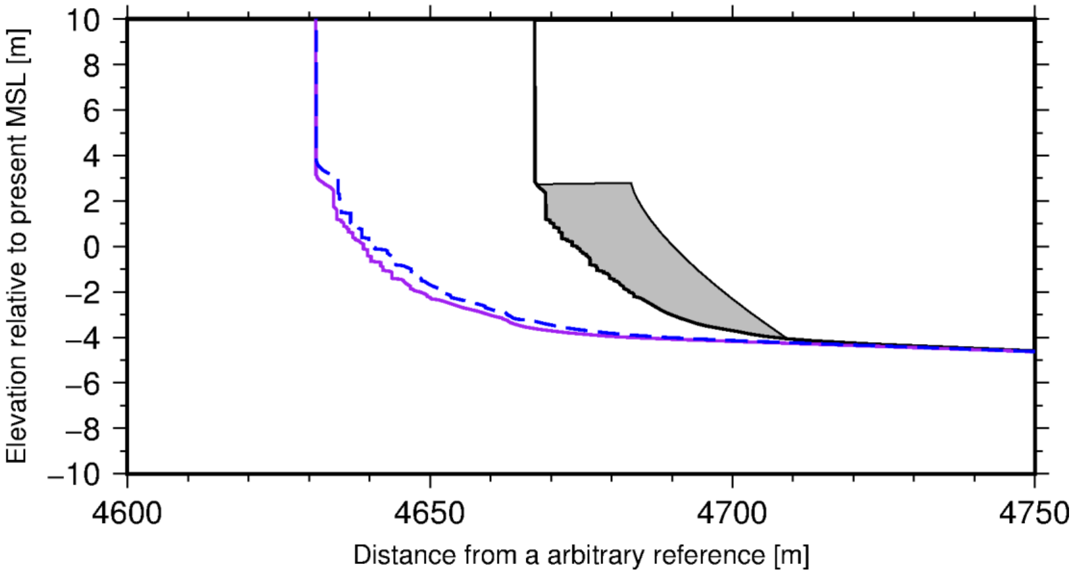

Figure 3-34: Result of the cliff erosion simulation for the shore north of Oamaru. The black line is the 2015 simulated bedrock profile. The grey area is the beach. The purple line is the simulated future bedrock profile for 2115 with a sea-level rise of 0.002 m/y, and the blue dotted line is the future bedrock profile for 2115 using the RCP8.5 upper bound of the likely range of sea-level rise.

3.3.6 Coastal erosion hazard zones

As detailed in Section 3.2, the coastal erosion hazard zones (CHZ) were mapped from shore-normal transects at 5 m intervals along the entire Waitaki District coastline, and its width was defined by different equations depending on the type of coastal morphology (section 3.2.6). The hazard zone includes predictions of shoreline position 50 and 100 years into the future, and to allow that these predictions are uncertain, 50th percentile and 95th percentile shoreline changes were calculated[3]. Overall for Waitaki District for the 100-year calculation, the 50th percentile predicted change in shoreline position varied between 6 m accretion and 213 m erosion, while the 95th percentile change varied between 11 m of erosion and 339 m of erosion.

The histogram of the coastal hazard zone widths shows that the CHZ50 width is mostly between 5 m and 95 m, with the most common width between 5 and 15 m (Figure 3-35). The CHZ95 widths were mostly between 5 m and 145 m with a most common value at 25-35 m (Figure 3-36), meaning that most of the coastal hazard zones calculated are wider than the minimum width suggested (8 m).

[3] With the 50th percentile prediction, there is a 50% chance that the actual future shoreline retreat would be larger (or less) than predicted, whereas with the 95th percentile prediction there would only be a 5% chance that the actual retreat would exceed the prediction. Thus the 95th percentile prediction is a conservative one, with a high likelihood that the actual retreat will be less.

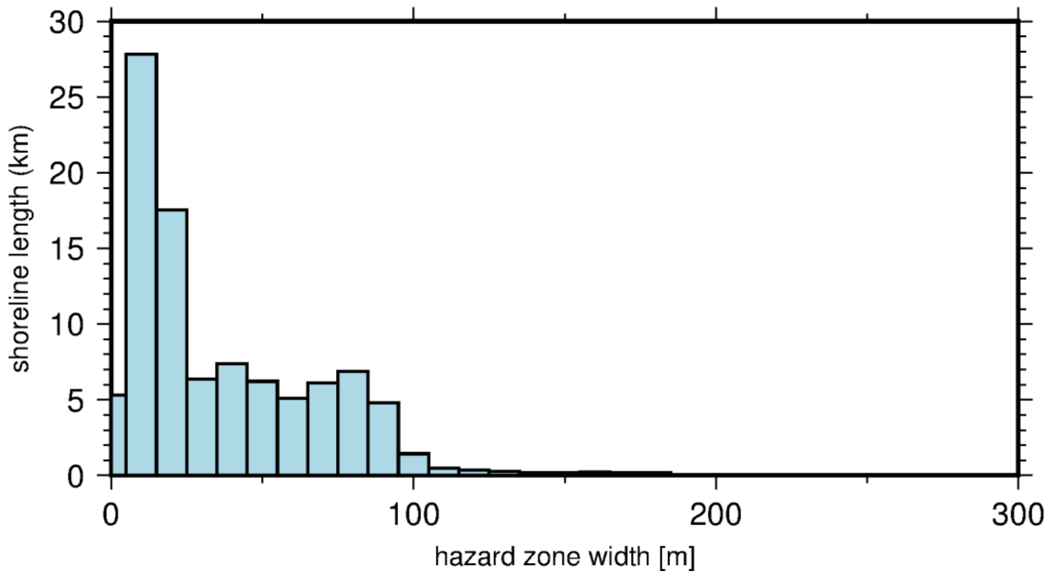

Figure 3-35: Histogram of predicted 100-year erosion hazard zone width for the most likely realisation (50th percentile).

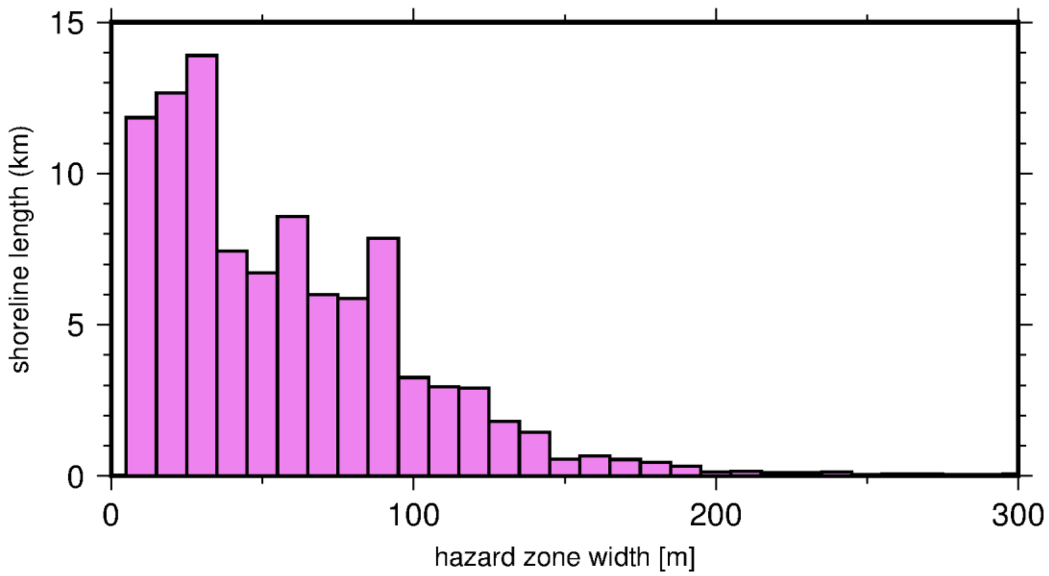

Figure 3-36: Histogram of predicted 100-year erosion hazard zone width for the 95th percentile realisation.

The hazard zone widths are mapped in Figure 3-37 whilst the hazard zone lines are included in the GIS supplementary material.

The description below outlines the general CHZ behaviour sequentially from north to south (Figure 3-37 to Figure 3-42).

The CHZ95 is less than 20 m wide at the Waitaki River mouth but it widens to 100 m at Seacliff Road. Further south the CHZ95 remains around 100 m until Simpson Road, where is starts to decrease to 60 m near Richmond Road. South of Richmond Road, the CHZ95 widens again to 120 m near McEneany Road. Further south, the CHZ95 remains close to 100 m wide until it starts to decrease south of Hedges Road. The CHZ95 width is 65 m at Waitaki Boys High School, 77 m at Foyle Street, and 60 m at Orwell Street. Behind the armoured coast at Oamaru, the CHZ95 narrows to less than 20 m by Oamaru central and 30 m at Oamaru Creek. In the inner harbour, the hazard zone width is less than 10 m.

At Beach Road, a current hotspot for coastal erosion south of Oamaru, the CHZ95 is close to 200 m wide on the northern section and 40 m wide along the southern section. Despite recent accretion trends (Figure 3-22) at the north end of the beach, the wide hazard zone there reflects the uncertainty of how the backshore dunes and cliffs respond in the short term. This section of the beach is also likely to erode in response to the acceleration of sea-level rise. The cliff section at the south end of Beach Road appears more stable but the extent of potential slumps is unclear. The slump that occurred in 2016 just north of the Coast Café was taken into account in the analysis but it is not clear whether other large slumps are likely on this stretch of coast.

Further south, at Kakanui, the rapid shoreline retreat and the expected vulnerability of the gravel barrier to sea-level rise creates a wide hazard zone for the whole beach, becoming wider southward toward the spit where the expected retreat is most uncertain. This is likely an overestimate of the shoreline retreat, but the estimated erosion hazard zone corresponds well to the estimates of the coastal inundation hazard zone there.

The coast north of Hampden is affected by a major slump. The slump appears to affect the entire hillside, while the toe of the slump is being washed away by the waves. The hazard is more of a geological hazard that is being kept active by coastal processes. The analysis used in this study is, however, not adequate to assess the hazard for such large slumps and the hazard zone is likely a conservative overestimate.

The slump does not affect Hampden town. In Hampden, the CHZ50 is 30 m wide and the CHZ95 is 55 m wide. These values remain similar most of the way south towards the Moeraki boulders, where the CHZ95 is extended to 80 m due to the presence of slumps in the cliff.

Moeraki town has experienced little historical changes in its shoreline and thus the CHZ95 is relatively narrow (35 m). The promontory to the old jetty may not be stable so the hazard zone was increased in this area. The town shoreline is currently stable because of the coastal defence structure preventing shoreline retreat, and it is assumed that it will be maintained in the future thus keeping the shoreline stable.

The coastal settlements of Te Karita and Kaika are located right on the beach edge and ad-hoc seawalls have been installed. This suggests that coastal erosion is a prominent problem for the two settlements. However, the presence of the seawall is hiding the natural movement of the shore, and the estimates of potential shoreline retreat are likely underestimated. There is, therefore, uncertainty in the future position of the shoreline at these locations - which is reflected in the CHZ95 widths of 70 m for Te Karita and 40 m at Kaika.

The northern end of Katiki Beach appears to be behaving similarly to an equilibrium sandy beach, and Bruun model predictions there of the impact of accelerated sea-level rise are considered reasonable. There, the CHZ95 extends between 100 m and 120 m. Further south, Katiki Beach is subject to greater geological control and the retreat rates become more variable but less overall - the CHZ95 width is typically 50 m to 60 m. At the southern end of Katiki Beach the beach transitions into a cliff and the CHZ95 width is reduced to less than 20 m. It is worth noting that of the 7 km span of SH1 along Katiki Beach, only 1.2 km is *not* in CHZ95 (and only 1.5 km is *not* in CHZ50).

The cliffs at Shag Point appear stable, with only slight changes detected in the shoreline analysis. This results in a CHZ95 of 15 m to 20 m from the existing cliff-line.

The cliffs south of the Shag River appear to have been stable with only small slumps detected, leading to a CHZ95 width of 30 m.

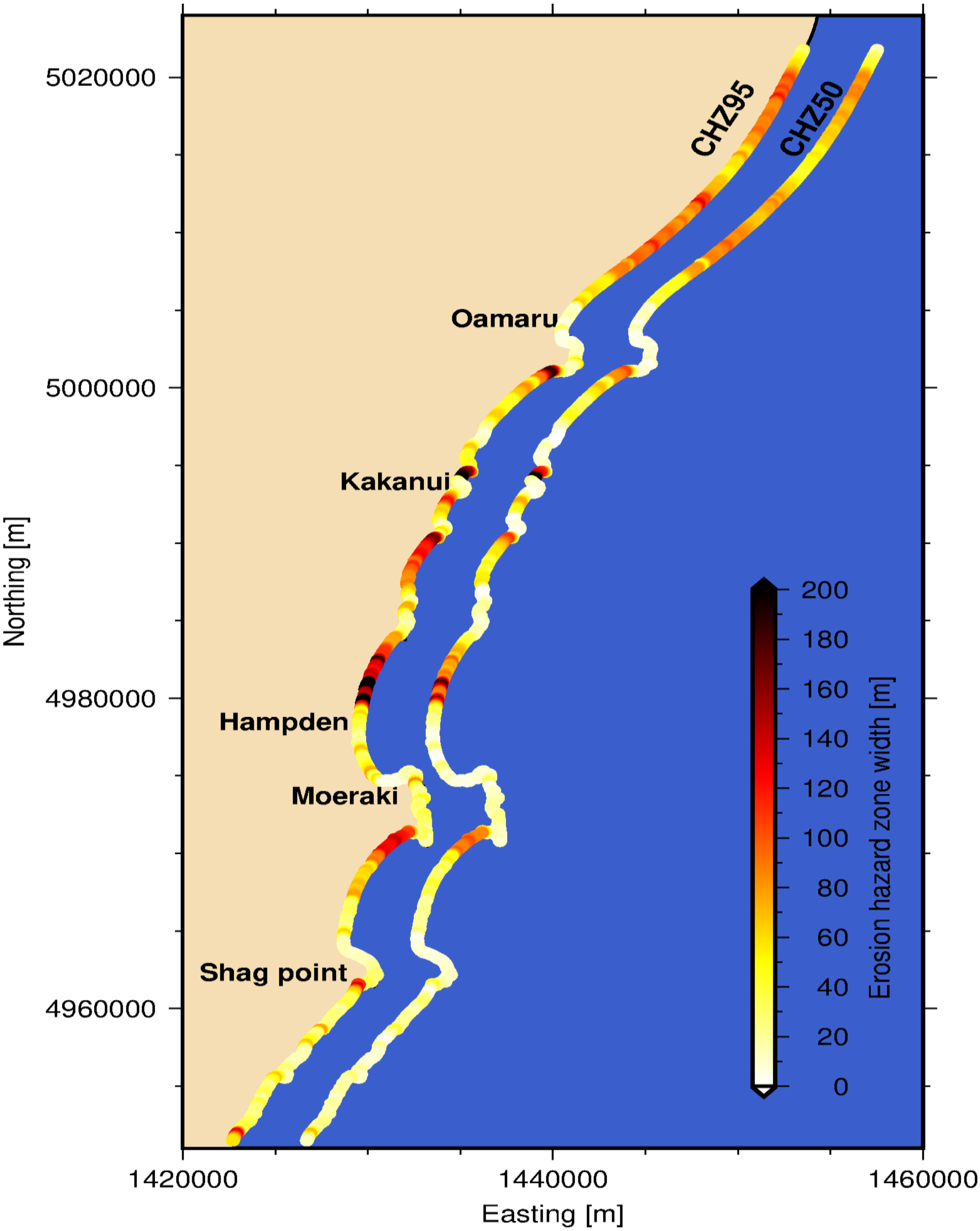

Figure 3-37: Coastal hazard zone width for 95th percentile (CHZ95) and for 50th percentile (CHZ50) for 100-year prediction for the entire Waitaki District coastline. Note the CHZ50 points are offset to the east.

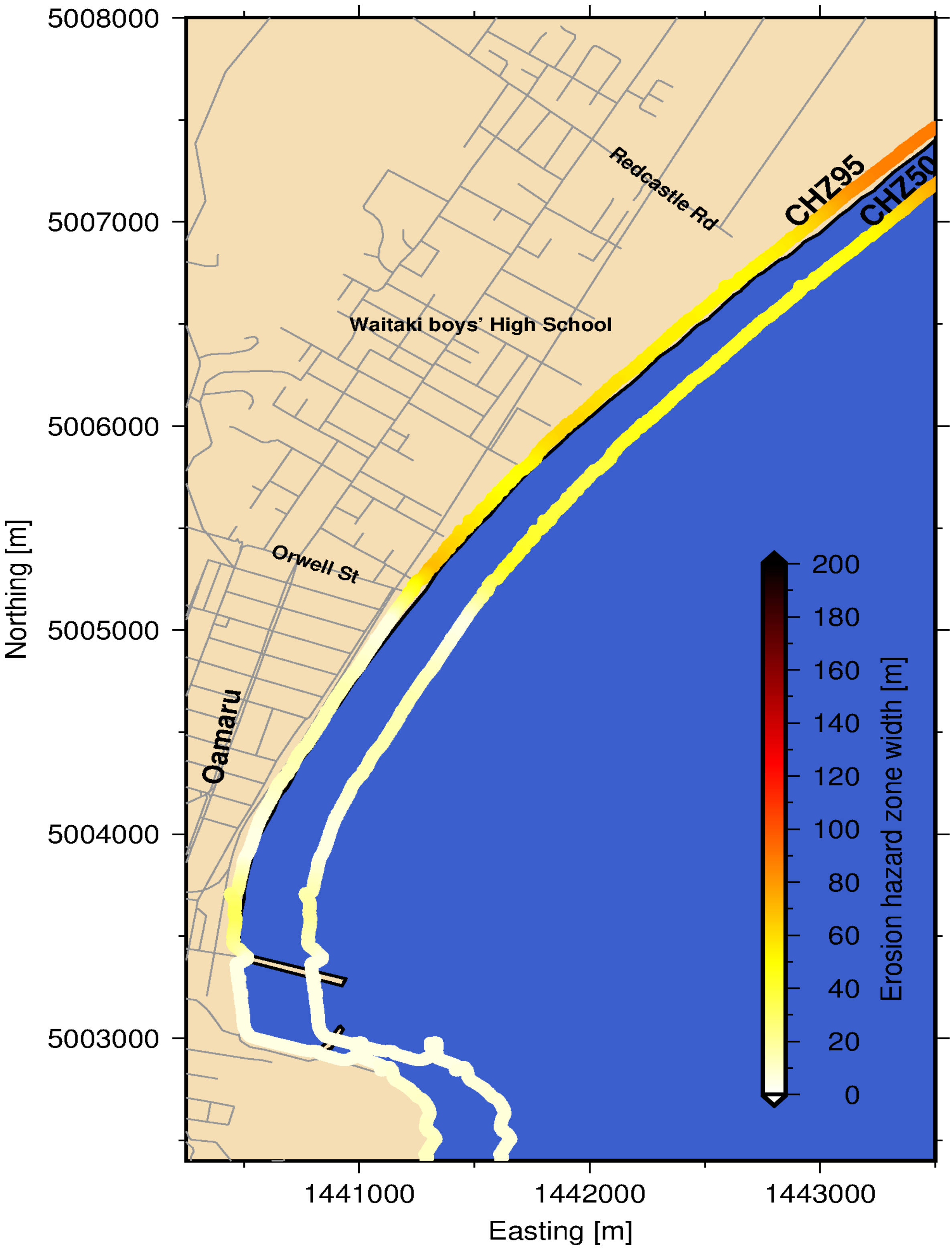

Figure 3-38: Coastal hazard zone width for 95th percentile (CHZ95) and for 50th percentile (CHZ50) for 100-year prediction for Oamaru. Note the CHZ50 points are offset to the east.

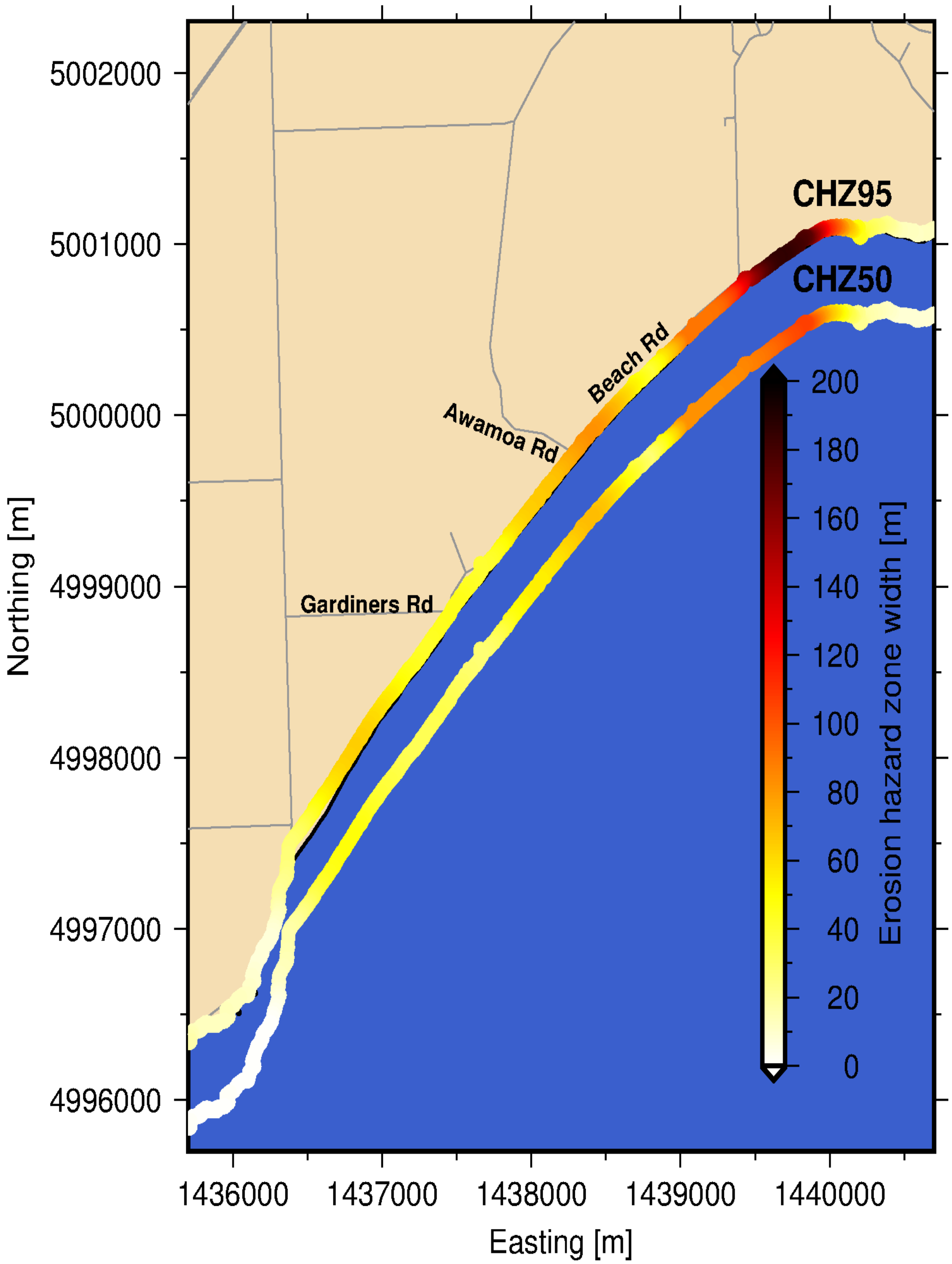

Figure 3-39: Coastal hazard zone width for 95th percentile (CHZ95) and for 50th percentile (CHZ50) for 100-year prediction for Beach Road. Note the CHZ50 points are offset to the south.

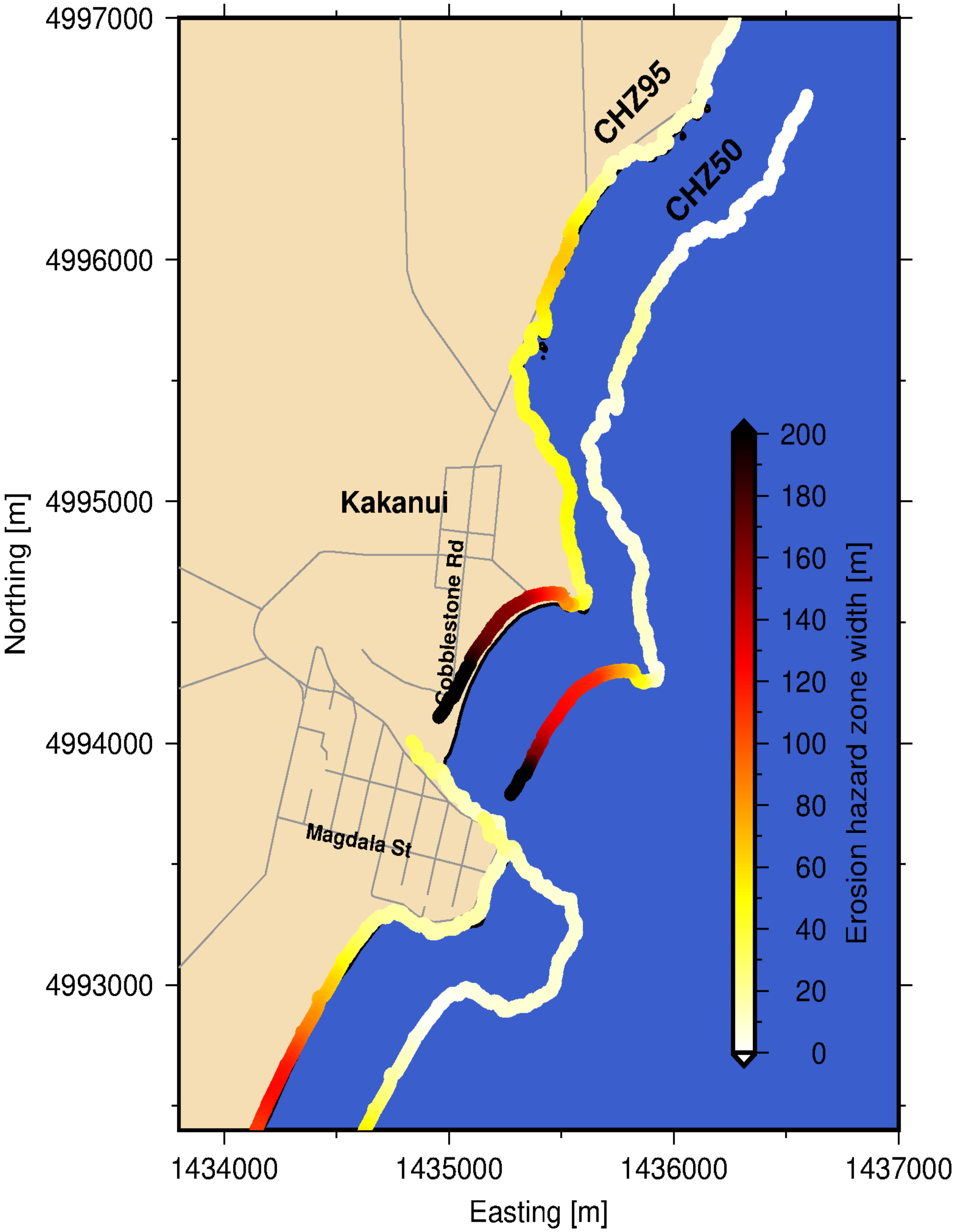

Figure 3-40: Coastal hazard zone width for 95th percentile (CHZ95) and for 50th percentile (CHZ50) for 100-year prediction for Kakanui. Note the CHZ50 points are offset to the southeast.

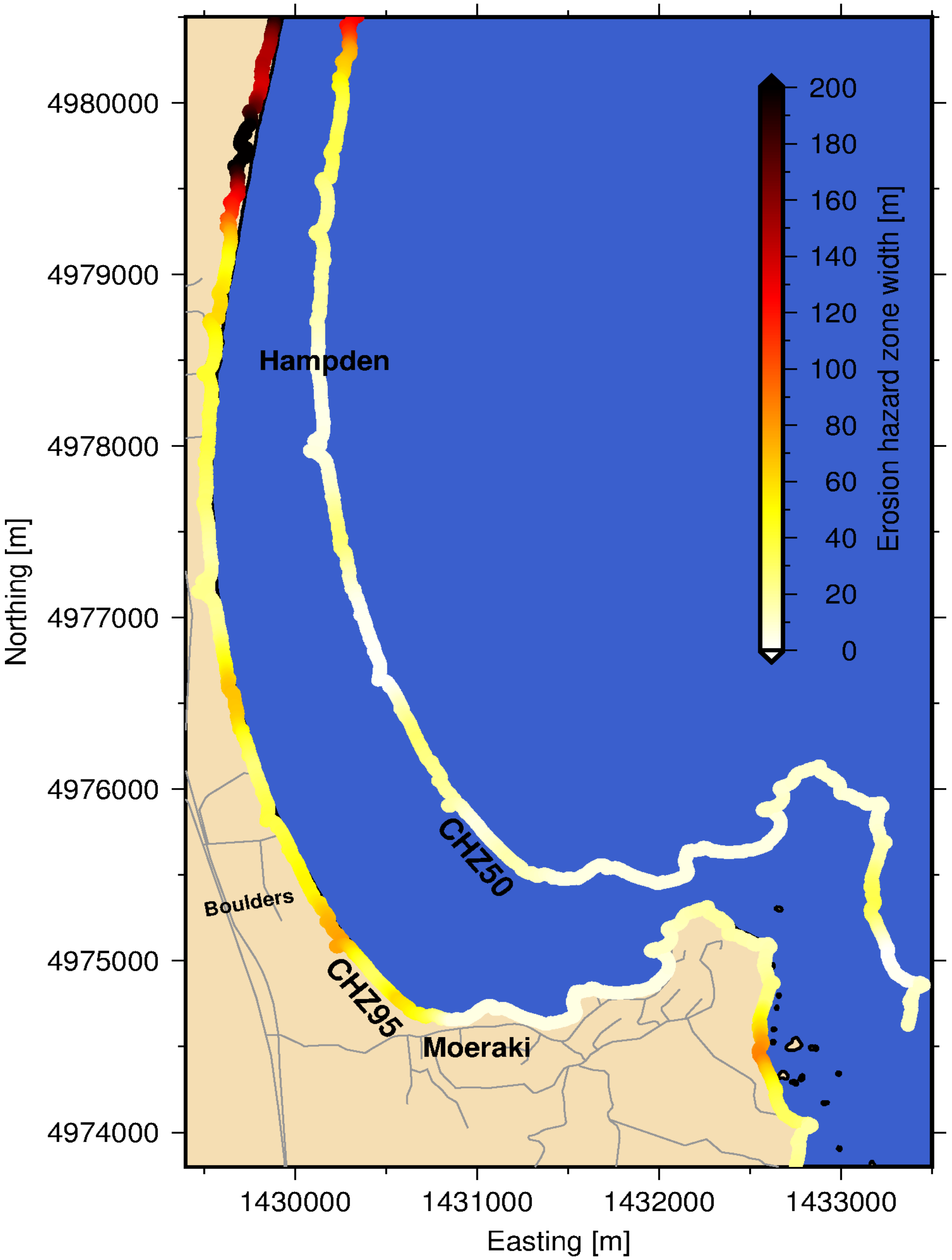

Figure 3-41: Coastal hazard zone width for 95th percentile (CHZ95) and for 50th percentile (CHZ50) for 100-year prediction for Hampden and Moeraki. Note the CHZ50 points are offset to the northeast.

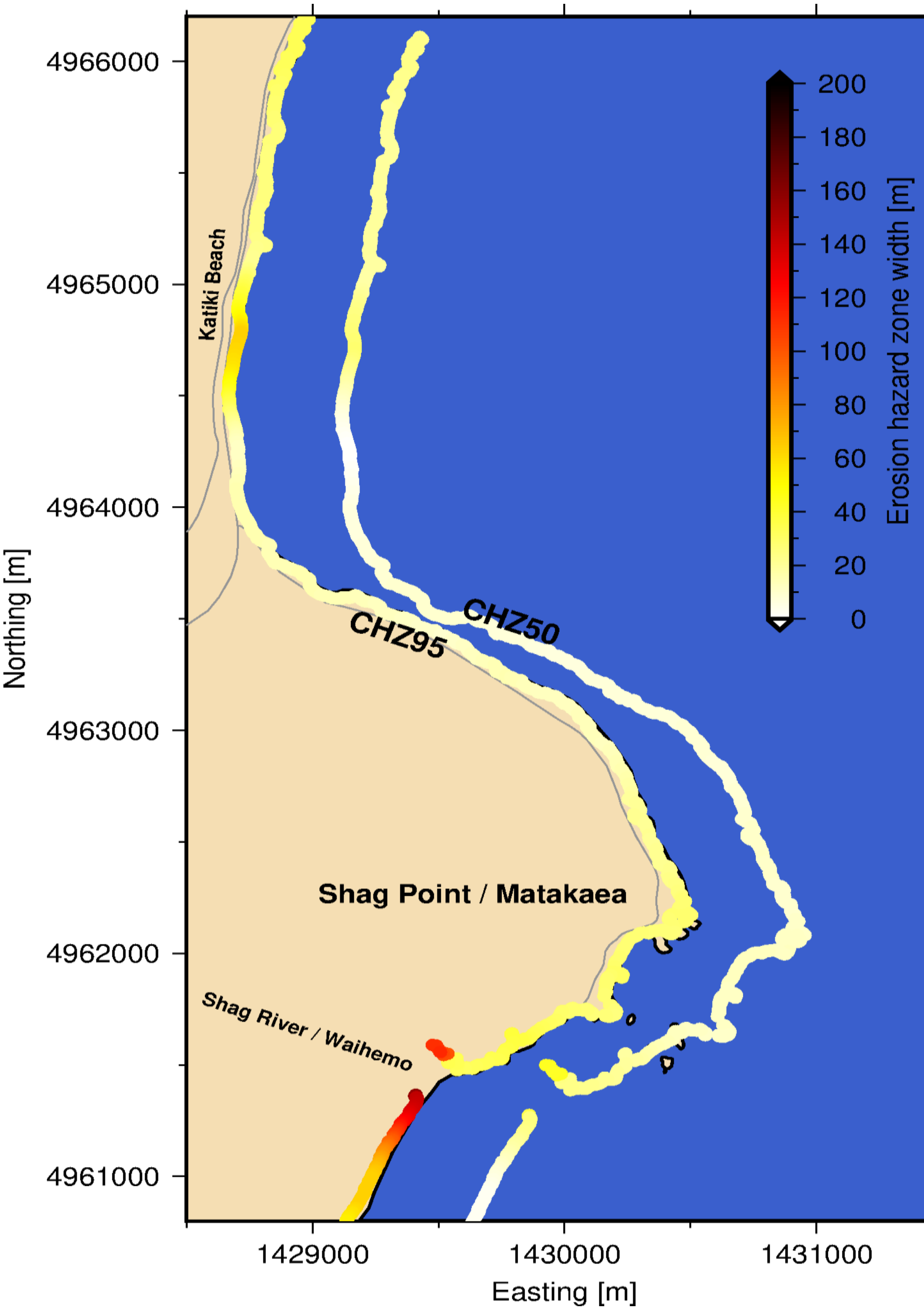

Figure 3-42: Coastal hazard zone width for 95th percentile (CHZ95) and for 50th percentile (CHZ50) for 100-year prediction for Shag Point / Matakaea. Note the CHZ50 points are offset to the southeast.

4 Discussion

4.1 Overview of the results

This study analysed the inundation and erosion hazards along the Waitaki District coast. The study found that while the erosion hazard is widespread, the inundation hazard only affects relatively small parts of the district (mostly Kakanui Estuary). This finding is consistent with the previous study of Todd (1997).

Limitations were found in the analysis of coastal inundation by Lane et al. (2008), and these limitations affect the reliability of the inundation prediction used in the coastal inundation hazard zone definition used herein. The limitations of the analysis of Lane et al. (2008) are non-conservative (i.e., they result in an inundation zone that is likely underpredicted) for the open-coast shore, where storm waves break, but are conservative on floodplains adjacent to estuaries. Improved extreme water level estimates are likely to show a reduction in the predicted inundation extent in Kakanui. Accurate predictions of wave runup are critical not only for inundation estimates in built-up areas but also for the small coastal settlements (e.g., Kaika and Karita) and infrastructure that is close to the shore (e.g., Katiki Road and Beach Road). Developing and implementing improved calculations for both extreme water levels and wave runup is out of scope for this project but should be considered in future studies.

The coastal erosion hazard zone was calculated using measured long-term erosion rates combined with potential short-term shoreline retreat due to storm-cut or cliff slumping/collapse. In areas where sufficient information was available, the contribution of the acceleration of sea-level rise has been taken into account. Simulation of the evolution of the cliffs north of Oamaru was undertaken using a morphological model, and this showed that acceleration in sea-level rise should have little impact on the cliff retreat.

The coastal hazard width proposed for the 100-year outlook with 95% confidence (CHZ95) is 65 m wide just north of Oamaru near Waitaki Boys High School and is similar to the proposed zoning by Johnstone (2001). Further north, to account for faster retreat rates and the occurrence of larger slumps on the cliffs, the CHZ95 width is close to 100 m, which is similar to the 100 m zone previously proposed for the Waitaki District Council.

It is noted that the erosion hazard zone estimates provided herein are based on a hybrid-probabilistic approach using the shoreline retreat data and short-term storm movement detected from aerial and satellite imagery and expert judgement where data is lacking and, in area north of Oamaru, also on a simulation of the cliff evolution with accelerated sea-level rise. The results presented here can be reproduced and refined when new data becomes available.

4.2 Impact of accelerated sea-level rise on the erosion hazard

Our SCAPE model simulations indicated that acceleration of sea-level rise over the next 100 years should have little effect on the erosion rate of the cliffs north of Oamaru. While this finding may appear counterintuitive, it is consistent with the expected dynamics of the cliffs. During fair weather, these cliffs are fronted by a gravel beach that can reach 5 m above mean sea level, and waves never reach the cliff toe, even at high tide; moreover, the gravel beach also acts as a retaining wall for the lower part of the cliff. During large and extreme coastal storms, this gravel beach is effectively removed, allowing waves to crash directly onto the cliff, undercutting it and producing large slumps. The gravel beach reforms quickly after the storm, again protecting the cliffs from waves. This is anecdotally confirmed by the lack of cliff retreat observed on profiles between 1994 and 1999. As sea-level rises and the shore retreats, the beach height and the substrate profile under the beach are expected to lift to match the rise in sea-level, thus the protective function of the beach should be maintained. However, this finding is not applicable to other parts of the coast where the backshore cliff is lower and the beach sediment size smaller.

At the northern end of Katiki Beach and at Kakanui, a Bruun-type model was applied to separate the background erosion rate from that attributed to historical sea-level rise. However, Bruun-type models do not account for the effect of geological controls, so they are likely to overestimate the impact of sea-level rise on beaches tightly enclosed by headlands, such as at Kakanui, and beaches perched above nearshore reefs and tidal platforms, as is the case with the southern half of Katiki Beach.

4.3 Effectiveness of coastal protection to reduce erosion hazard

Small-scale coastal protection, such as short spans of riprap or concrete seawall, have not been taken into account in this analysis. This is mostly because these structures are often built with a shallow footing (e.g., ~1 m deep at Katiki), and therefore they will have a limited lifespan. Many dislodged blocks of riprap litter the shoreline of Katiki Beach, which is a sobering example of the inability of these structures to hold the shoreline along Beach Road (e.g., Figure 4-1 and Figure 4-2). Moreover, repeated LiDAR surveys (2004 and 2016) show that even the heavy armouring used at Oamaru degraded and settled over the intervening 12 years (Figure 3-24). This experience warns that where structures may be chosen for protecting additional assets in the future, heavy, deeply-footed armouring and high maintenance would be required.

4.4 Coastal monitoring

In the hotspots of erosion, a monitoring program would help to better capture the hazard characteristics (e.g. steady slow retreat of the shore versus storm driven rapid erosion) and understand the long-term trend of the shoreline, the role of individual storms, and the response of the coast to annual and inter-annual variability of the wave climate. Towards this, we recommend extending the network of surveyed profiles to include profiles at Beach Road, Kakanui, Moeraki Boulders and Katiki Beach, and to repeat these annually. An alternative approach to profile surveying would be to use airborne LiDAR or a mobile laser scanner to capture the full 3d topography of the shore.

Records of water level and waves would also allow analysis of the relationship between storm intensity and coastal erosion and inundation in greater detail. Wave and water level hindcasts used in this study could be verified with local data, and any bias in the hindcast could be captured in revisions of the inundation hazard zone.

Water level records kept in key estuaries and water ways (e.g., Oamaru port, Kakanui estuary) would clarify the contributions to inundation from river floods, storm surge, and wave runup and overwash.

Figure 4-1: Riprap section on Beach Road viewed on satellite imagery of 02/09/2006. The riprap (circled in black) was installed prior to 2003. Imagery source: DigitalGlobe.

Figure 4-2: Riprap section on Beach Road viewed on satellite imagery of 03/10/2012. The view is the same as shown on Figure 4-1. Note the material of the failed riprap scattered on the foreshore (circled in black). Imagery source: DigitalGlobe.

5 Conclusion

This study analysed the coastal hazards in the Waitaki District. Results show that the coastal erosion hazard is widespread, with more than 60% of the coast in the district retreating, while any significant coastal inundation hazard was limited to Kakanui.

The inundation hazard zones presented herein are based on the inundation extents of Lane et al. (2008), since that is as far as the scope of this work extended. Critical limitations were found in the Lane et al. analysis. In particular, no consideration was given to infragravity waves, and wave runup were underestimated. This limitation constrains the use of the inundation hazard zone to low-lying inland areas not exposed to open-coast wave action (e.g., Kakanui estuary floodplain, Oamaru harbour); it does not properly allow evaluation of the coastal inundation hazard in areas where wave breaking and runup is likely to be significant (e.g., Kaika, Karita, Katiki Road and Beach Road). Further work is recommended to refine extreme water levels and wave runup together and revise the inundation hazard zones in such areas.

A coastal erosion hazard zone was defined using a projection of the future shoreline position over 100 years taking into account historical retreat rates, sea-level rise and slope failure. Taking a conservative approach, the coastal hazard zone width typically ranged from 5 m to 145 m but reached 300 m at some locations.

Much infrastructure and many assets are located within the erosion hazard zones. No new erosion hotspots were identified, with continued erosion expected at the current hotspots of Katiki Beach, Beach Road, Kakanui, North Oamaru, and Kaika and Karita settlements. Any plans to stabilise these shores with protective structures would need to ensure that the structures are properly designed, constructed and maintained to maximise their lifespan. With perhaps the exception of the heavily armoured Oamaru shore, existing protection works along the District's coast are generally not functional in the long-term; indeed, some minor shoreline retreat has been observed even on the larger structures near Oamaru.

Monitoring of beach morphology at erosion hotspots is recommended on an annual basis and will enable refined estimates of the hazard zone widths and to better plan the nature and timing of erosion mitigations. Monitoring of water level and waves is also recommended to better assess the inundation hazard and the erosion impact of large storms.

6 Acknowledgements

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8 List of supplementary material supplied separately from this report

Shapefile of digitized shoreline: Ambur_All_Shorelines_NZTM.shp

Shapefile of Calculated erosion rates: Shoreline_Retreat_Rates_Final.shp

Shapefiles with Coastal Hazard zone for 50-year and 100-year for both the 50th percentile and 95th percentile:

- CHZ50_50y_Final.shp.
- CHZ95_50y_Final.shp.
- CHZ50_100y_Final.shp.
- CHZ95_100y_Final.shp.

GIS raster files and figures for extreme water level inundation in Oamaru, Kakanui, Hampden and Moeraki for the 20-year, 50-year, 100-year and 500-year ARI and for sea-level rise scenarios of 0.0 m, 0.3 m, 0.5 m, 0.7 m, 0.9 m, 1.1 m and 1.3 m above present mean level of the sea.

Waitaki District Coastal Hazards

Response to specialist review

Prepared for Otago Regional Council

January 2019

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Quality Assurance Statement		
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	Approved for release by:	Helen Rouse

Contents

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1 Tonkin + Taylor review

Below in dark ink are the comment copied from the letter addressed to Otago Regional Council from Richard Reinen-Hamill Sector Director – Natural Hazard Resilience, Tonkin and Taylor. In red are the response from the Authors of the report.

1.1 Purpose

Otago Regional Council (ORC) commissioned Tonkin + Taylor (T+T) to carry out a peer review of the NIWA coastal hazard report entitled "Waitaki District Coastal Hazards" dated February 2018 along with their maps, figures and tables.

The NIWA study included erosion and inundation hazards along the Waitaki District for a 100 year timeframe using a probabilistic method and explicitly excluded tsunami, river floods or urban flooding and utilising the latest MfE guidance on sea-level rise (MfE 2017).

1.2 Project extent

The project extends along the entire Waitaki District although the scope included more detailed information for Oamaru, Taranui, Kakanui, Hampden, Moeraki township, Boulders and Shag Point/Matakaea.

1.3 Inundation

Baseline data

The baseline data relied upon for the inundation assessment was a storm surge study carried out in 2008 (Lane, et al, 2008) and the latest Ministry for the Environment (MfE 2017) guidance on sea level rise. LiDAR data from 2004 was used for mapping.

The authors of the coastal hazard report identify issues with regard to the Lane (2008) work with regard to storm surge estimates, the analysis of wave run-up, the omission of other processes such as infra-gravity waves and the selection of future sea-level rise values. The Lane results appear to be conservative for storm surge (i.e. predicting higher storm surge levels than might occur with more current approaches), non-conservative for wave run-up (i.e. predicting lower run-up levels than they might expect). However, the NIWA (2018) report authors still have used the results provided by Lane for storm surge and wave run-up as they conclude that the majority of the district shoreline is above the storm surge levels with the exception of Kakanui.

It would be useful to include some summary information on the length of the coast and the elevations along the coastal edge (possibly a frequency plot showing elevation frequency) that would support the authors assumptions.

For clarification, this statement was intended to apply only for the most populated coastal areas (Oamaru, Kakanui, Hampden and Moeraki) and not the rest of the district where the information for storm surge and topography is insufficient to evaluate the coastal inundation. This has been clarified in section 2.1.

Approach

Storm surge levels were extracted for four sites (Moeraki, Hampden, Kakanui and Oamaru). It is unclear what values were used for the remaining coast, but assume that inundation was limited to the beach areas and were not an issue on land areas.

The coastal inundation was calculated only for the most populated coastal areas (Oamaru, Kakanui, Hampden and Moeraki) and not the rest of the district where the information for extreme water level and topography is insufficient. This was clarified in section 2.1.

Inundation was assessed for the open coast at these locations by adding predicted storm surge for a 20, 50, 100 and 500--year ARI storms to the calculated wave run-up and selected sea-level rise value (0.3, 0.5, 0.7, 0.9, 1.1 and 1.3). For harbour/estuary areas inundation was assessed excluding the effects of wave run-up. Maps were produced for all these scenarios in terms of inundation depth.

Assessment

Inundation is only assessed at the four locations identified using bathtub modelling approaches and there is no district wide mapping of inundation. The process to limit inundation mapping to these areas could be better articulated in the report, but I understand that it is due to the remaining coastline elevation being higher than the storm surge levels.

Limiting the analysis to the most populated area of the coast is driven by the lack of information on the rural part of the coast rather than a perceived safety. This has been clarified further in the text in section 2.3.

The selected range of sea-level rise values provides a reasonable range of values to understand changing risk of inundation over the next 100 years resulting from sea-level rise. However, information of the ground levels along the coastal edge in terms of a frequency plot would have provided useful understanding of the potential for a "tipping point" type situation.

For Oamaru, where the inundation affects a developed area, a table summarising all the different scenarios was added (Table 2-4). It shows inundation depth at Esplanade Road. Inundation is predicted for the 50, 100, and 500y return interval only for the 3 highest sea-level rise scenarios. In other locations, the inundation is restricted to undeveloped areas where such graphical detail is unnecessary.

The approach of using wave run-up for mapping inundation extents away from the coastal edge is flawed, as run-up is a process that occurs at the coastal edge and the contribution of run-up in terms of overtopping volumes informs the potential for inundation. However, the approach also omits wave set-up that can be a more significant driver of inundation volumes and makes no allowance for processes such as infra-gravity waves that are identified as an exacerbating process.

Actually, the methodology used in the study does not apply wave runup away from the "coastal edge". The main text in section 2.3 was amended to clear this confusion.

Wave setup is already included in the extreme water level prediction used by Lane et al. 2008. The text in section 2.3 was amended to clarify this.

Bathtub modelling is a reasonable approach for a district wide inundation assessment to identify areas where more detailed analysis may be warranted based on vulnerability and risk assessments of assets and values in those areas.

Agreed. This statement was added to section 2.3.

For future sea-level rise scenarios the sea level is added to existing storm surge with no allowance for increased wave heights approaching the coast that can increase wave set-up/run-up. This approach is reasonably standard, but identifying this as a limitation would be useful.

This is clearly stated in section 2.1.5. An additional sentence was added in section 2.3 into the paragraph stating this limitation.

Both the flaws/omissions of the methodology may have been moderated by the use of a more conservative approach to evaluate storm surge and by using a method that may under-predict wave run-up, but does include wave set-up in the formulation (refer Lane (2008), section 2.5.2). However, the confidence of these approaches to offset the limitations is not able to be determined.

The storm tide estimates from Lane et al. are consistent with subsequent studies. However, it is unclear how much wave setup is underestimated in Lane et al. 2008 (wave runups are underestimated, and wave setups are calculated with the same variables and are therefore also expected to be underestimated). It is likely that the extreme water level at the shore are underestimated but still overestimated further inland were the bathtub prediction outweigh the underestimation of maximum water level.

Minor comments

Inundation depths are provided. However, frequently inundation levels are useful too.

No information is provided to the LiDAR survey accuracy or limitations on the map surfaces. This was done by Lane (2008) but should be included in this report.

Agreed - two paragraphs describing the caveat of the bathtub and LiDAR were added to section 2.3.

The location plan (Fig 1-1) does not locate all the areas identified in the introduction to the report.

Agreed - the location map was updated (Figure 1-1).

Table 2-2 includes an interpolation of the year that sea level will reach a particular level for RCP2.6, 8.5 and 8.5+. I note there are inconsistencies with the interpolation (for example 0.5 m is reached closer to 2110 than 2115 for the RCP2.6 scenario based on MfE.

The values in this table are taken from the IPCC 5th report. They vary slightly (few cm) from the values from Kopp et al. 2014 that were used in the MfE report (0.49m for RCP 2.6 in 2100 in IPCC report compared with 0.51m for RCP 2.6 in 2100 for Kopp et al. 2014) but are provided in greater detail in the IPCC report allowing the calculation on the date of the table.

Table 2-3 heading could be clearer. It provides predicted extreme levels for storms with different average recurrence intervals.

Fixed.

Variable approaches to bullet point format.

Formatting in the whole report has been revised.

Erosion

Baseline data

The baseline data relied upon for the erosion included historic erosion rates from previous reports, cadastral survey, aerial imagery, satellite data and LiDAR from 2004 (District wide) as well as more recent LiDAR from 2016 were available for Oamaru, Kakanui and Kaitaki Beach. Beach profiles at 12 sites were also available north of Oamaru (locations not provided), but it is unclear how the LiDAR and beach profile information was used in the assessment.

The LiDAR and beach profile data were not used in the calculation of the Coastal Hazard Zones. However the Lidar beach profiles data provided additional context and understanding of the hazard.

Limited information could be extracted from the surveyed profiles because they contained only 2 or 3 surveys over 14 years. A statement explaining the limitation of the profile data was added in section 3.2.4.

Approach

The overarching approach to establish the erosion hazard is to apply the historic rate of shoreline change (R) over the next 100 year period (T) with additional factors to take into account slumping (S) and the effects of sea-level rise, although a minimum set-back of 25 m was used. The following table summarises the approaches used.

Table 1-1: Erosion Hazard methodology comments.

Morphology	Formula	Variable definition/distribution	Comment
Hard Cliffs	CHZ = max (R_{HC} x T + S_{HC}, F)	R_{HC} = historic erosion rate, normal distribution.	No justification of normal distribution provided. Unclear of the number of profiles used to develop rate. A normal distribution of errors is adequate since the error is in part from the digitization error (which is expected to be normally distributed) and in part from the linear regression fit. Additional details were added to this paragraph and justify the choice of normal distribution.
		S_{HC} = normal distribution of absolute shoreline position for all cliff profiles within 200 m of profile being analysed.	Significant issues identified with mapping making establishment of this value difficult. This approach duplicates R_{HC} rather than address physical/observed process. Available data was not sufficient to identify the slump mechanisms in an accurate way. Only the shoreline detection provided a consistent approach to evaluate the largest slumps. The paragraph describing S_{HC} was rewritten to better describe the analysis.
		SLR = not taken into account.	Reasonable approach for hard cliffs.
		F = 25 m.	No justification provided for this value and it is applied across all morphologies. Safety factor has been removed from the calculation. Instead, the use of a minimum width is only suggested as an optional buffer for the final lines.
Soft Cliffs Now renamed: *Unconsolidated sediment cliffs* to	CHZ = max ((R_{LC} + R_{SLR}) x T + S_{LC}, F)	R_{LC} = historic erosion rate, normal distribution.	No justification of normal distribution provided. Unclear of the number of profiles used to develop rate. Additional information on this has been added to the paragraph to justify the normal distribution choice.

better describe the morphology		S_{LC} = normal distribution of absolute shoreline position for all cliff profiles within 200 m of profile being analysed.	Significant issues identified with mapping making establishment of this value difficult. This approach duplicates R_{HC} rather than address physical/observed process. Better description of the analysis was provided - see S_{HC} above.
		R_{SLR} = normal distribution of SCAPE results	No tabulated information provided. With 2 SLR scenarios for the lower and upper bound of SLR estimate, no description provided on how distribution developed or how this applies for different time periods. Assume R_{SLR} is the additional rate (i.e. subtracting the historic rate), but this is also unclear. RSLR was removed from the equations. Simulations from SCAPE suggested that the contribution of the acceleration of sea-level rise on the Oamaru cliffs is negligible. While this may not be the case for other lower elevation cliffs, this is the best assumption available at the moment. Further analysis is required to better understand this process in areas such as Beach Road or Katiki Beach area, where the variation in coastal geology is likely to play a major role.
Beaches backed by cliffs Renamed *Geologically controlled beaches* (Perched beaches)	CHZ = max (R_{PB} x T + S_{PB}, F)	R_{PB} = historic erosion rate, normal distribution.	I assume this is still the top of cliff. If so, would expect less erosion due to the presence of the beach, but no data presented to allow assessment to be made. If it is not the top of cliff, method not valid. These beaches may not be backed by a cliff. The shoreline (as for other locations) is the vegetation line at the cliff top or dune toe. This method is used for beaches that are strongly geologically controlled, where the Brunn assumption is questionable. The paragraph was rewritten to remove the confusion.
		S_{PB} = normal distribution of absolute values of residuals within 100 m of profile being analysed.	No justification of changed approach (100m vs 200 m) Unclear why absolute values on soft cliff works here and not

			on previous SC, unless actually on the beach. If it is the beach, this does not represent shoreline retreat of the cliff edge. More information is provided to justify the change of methodology here. For consistency, all profile smoothing now occurs over a 150m buffer regardless of the morphology.
		SLR	No allowance of SLR. This does not seem valid as there is likely to be increased erosion due to sea-level rise for soft cliffs. Agreed. But Bruun type shoreline retreat would grossly overestimate the shoreline retreat. In reality, the retreat will be erosion rate limited rather than governed by a Bruun-type equilibrium where the backshore sand supply keeps pace with the nearshore sand demand created by the rise in sea level. This is an active area of research. An explanation of the choice here was added to the paragraph.
Gravel Beach Renamed *Wide gravel barriers*	CHZ = max (R_{RM} x T + S_{RM} + SLR_{RM}, F)	R_{RM} = historic erosion rate, normal distribution.	Approach OK for present day. No allowance for increased rate for sea-level rise on long term trend (i.e. R_{Bruun} as used in following formula). Wide gravel barriers are expected to follow roughly a generalised Bruun response but the identification of the depth of closure is problematic. The method used by Measurse et al. for the Kaitorete barrier is similar to a Brunn model but by-passes the depth of closure uncertainty. More details were added in the method description.
		S_{RM} = normal distribution of absolute values of residuals within 100 m of profile being analysed.	No justification of changed approach (100m vs 200m) from previous approaches, but absolute values approach has merit for soft shores. Better justification added in the section on geologically controlled beaches. See also comment above.
		S_{SLRRM} = normal distribution of absolute values of residuals within 100 m of profile being analysed.	No justification why approach for Kaitorete Spit applies. Unclear if SLR values are relative (i.e., deducting historic SLR

			taken into account with S_{RM}. If not, this may be double counting. Indeed, historical sea-level rise contribution to shoreline retreat could be double counted but this effect is expected to be small (<5m) and it is conservative. More details were added to the methodology description.
Beaches backed by dunes *Renamed Sand-gravel thin barrier and dune backed beach*	CHZ = max ((R_{BRUUN} + R_{RES}) x T + S_{PB}, F)	R_{BRUUN} = shoreline retreat based on future sea-level rise of 0.011 m/y.	No justification of active beach slope values. No description of distribution variables. Only one SLR rate of 0.011 m/y included. Yes, only the RCP8.6 case of sea-level rise is used here. Description of the active slope was added to the text as well as a justification for the value chosen.
		R_{RES} = difference between historic shoreline retreat and shoreline retreat predicted by Bruun using a historic rate of 0.002 m/y.	This does not appear to make sense. This should be the historic rate of change. With the R_{BRUUN} providing the additional effect of SLR on the long term trend. Using the historical rate directly here would double count for the historic contribution of sea-level rise to shoreline change, since that is already captured in the surveyed historical retreat. Also, the historical shoreline change is not expected to be solely driven by sea-level rise so this method was selected to account for both non-sea level related erosion and future retreat due to sea-level rise assuming a Bruun response. The methodology text was changed to better explain the method.
		S_{PB} = normal distribution of absolute values of residuals within 100 m of profile being analysed.	Only evaluates present day storm effect and not future SLR. Appears inconsistent with S_{SLRRM} from above. Sea-level rise is accounted for in Rbruun so SPb is accounting only for storm effect. The climate change effect on future storm waves is not known and so future changes in this parameter are ignored.
Rock revetments	CHZ = max (R_{Hist} x T, F)	R_{HIST} = historical shoreline rate	Unclear if this rate is prior to the seawall (i.e. natural shoreline rate of change) or a combination. Method is not

			clear as if it is an indication of the potential extent of adjustment of the shoreline should the protection fail, it should also take into account SLR and S. The method accounts for the small retreat that occurs on the structure as it is repaired and does not account for failure or abandonment of the structure. These details were added to the methodology.
River mouths/ streams/ estuaries	No specific approach used for river mouths/streams /estuaries		It would be useful to delineate where the methodologies applied are valid and where other approaches are required. An excellent suggestion. A map of the morphology types used in this study was added to the start of section 3.2.6. Pictures were also added to show typical examples of each of the morphologies described.

Historic long term trend

The shoreline position from the imagery data was established as the top of cliff or vegetation line on beach systems and linear trends were calculated at 5 m sections along the coast, with smoothing applied to coastal sections of uniform morphology. With the range of historic data available this seems an appropriate approach, although it is unclear how uncertainty/errors are included in the hazard assessment.

Errors from the digitization were applied as a weight to the linear regression fit, and the standard error calculated in the least square fit was used to define the normal distribution in the historical rate. The error of the shoreline trend is now shown in the figures. Some text was added to the start of section 3.2.6 to clarify how the error was used in defining the hazard zones.

The normality of the probabilistic distribution of the historical rate can be validated by showing that the residuals of the trend are normally distributed. This is shown in the figure below for a section of uniform shoreline 300m wide North of Oamaru. Figure 1-1 shows the quantile values for the residual error in fitting historical rates and the quantile of a normal distribution created with the mean of the residual and the standard deviation of the residuals. In the Figure the percentiles for the measured residuals are comparable to the percentiles of a normal distribution with the same mean and standard deviation.

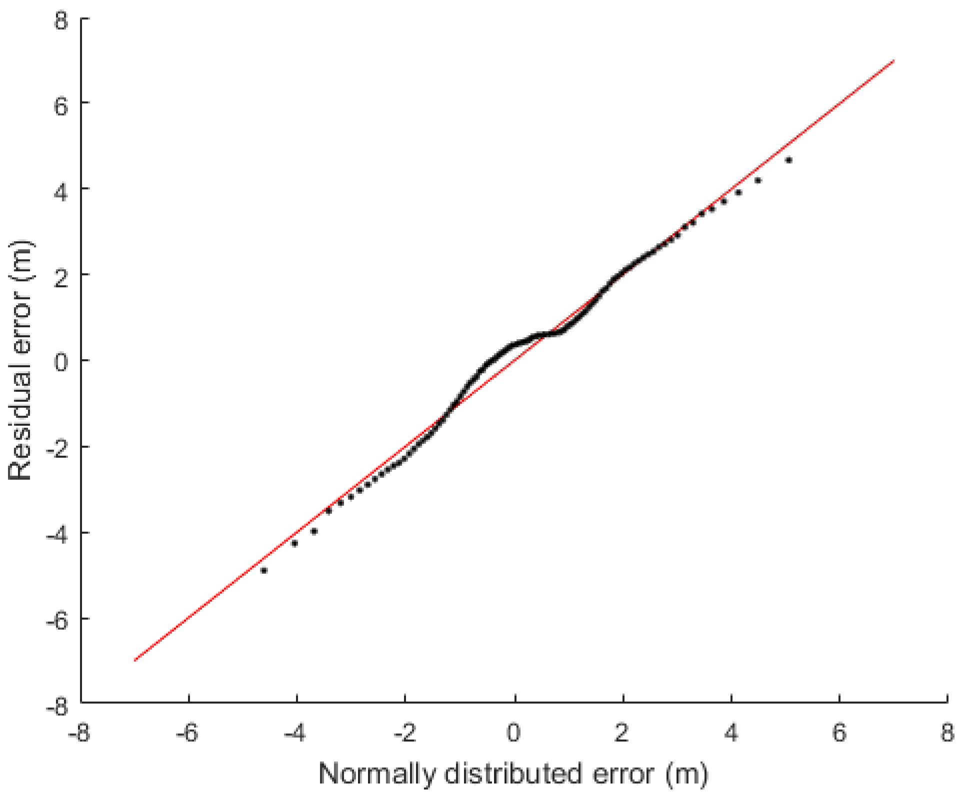

Figure 1-1: Quantile-quantile plot of historical erosion rate residuals and an equivalent normal distribution.

SCAPE

The SCAPE model has been used to assist in developing an understanding of the effects of future sea-level rise on the soft cliff shoreline and was used for a representative 5 km shoreline and calibrated with historic data, with the results applied in some other soft cliff areas, but apparently not all (a plan showing area where approaches used would be useful).

Only very summarised information is included in the report so no detailed review of the data and process used is possible. It is unclear how the two future sea-level rise scenarios were simulated, but it is assumed a linear extrapolation process was used.

The IPCC 5-yearly sea level prediction was used for future sea-level rise. This was added to the SCAPE methodology section (3.2.5). The shore morphology classification has been mapped in Section 3.2.6.

The conclusion that 1.3 m sea-level rise does not have a significant effect on soft cliff shore erosion, and indeed the results appear to show slightly less erosion during a 1.3 m sea-level rise than might occur with 0.22 m sea-level rise (refer Figure 3-25), is unusual. I would have expected larger waves occurring higher up the cliff face to result in greater erosion potential.

Indeed, this feels counterintuitive, but it is consistent with the expected dynamics of these cliffs. During fair weather, the cliffs North of Oamaru are fronted by a large gravel beach that can reach 5m above Mean sea level and waves and tide never reach the cliff. The gravel beach also acts as a retaining wall to protect the lower part of the cliff. During large and extreme storms this gravel beach is effectively removed, allowing waves to crash directly on the cliff producing erosion "bites". The gravel beach, partly with the new material added from the failed cliffs, reforms quickly after the storm protecting the cliffs from waves and tide. These processes will continue with a rising sea-level. This is anecdotally confirmed by the lack of cliff retreat between 1994 and 1999, as observed in the survey profiles. Also important is that the beach and nearshore is underlain by a ramp of substrate. This substrate profile is sculpted by wave action when exposed, and its surface will creep higher as sea-level rises and shore retreat proceeds. So as sea-level rises the overlying beach will rise in elevation, and the frequency of storm events with waves attacking the cliffs and the height of waves attacking the cliffs will not change (assuming the wave climate does not change with climate change). This statement was added to the discussion of the report (section 4.3).

Assessment

The methodology section is poorly laid out and hard to follow. There is limited data and information presented to enable an audit of the assumptions and values used. The selection of formulae and approaches seem to be highly judgement based and inconsistently applied across the different methodologies. For example, for soft cliffs (low cliffs) future sea-level rise is taken into account, while for cliffs fronted by beaches no assessment of SLR effects are included. This inconsistency is also evident in the treatment of soft shores.

It is correct that there is an inconsistency where the effect of the acceleration of sea-level rise is taken into account for soft shores backed by dunes but not for geologically controlled beaches. The reality is that the response of the latter is not well understood in the research domain, but the Bruun Rule is not to be trusted. A better explanation for this is now given in the text. Also, the methodology section describing the coastal erosion width has been rewritten describing the available data and processes better than in our previous version.

A more logical approach could have been to describe the coastal setting and the different morphologies and data available, then to work through the hazard methodologies for each specific morphology and then the quantification of the variables used. Tables providing the values of the distribution for each morphological section would have been useful to communicate the relative importance of each particular process.

Amendments to the text based on the above comments hopefully now show our approach more clearly. Because different values are used for each of the individual profiles to build the statistical distribution, it is not easy to show the values. The values for the estimated error in historical rates was added to the figure of the historical rates.

The use of a minimum set back (F) is a reasonable approach to manage uncertainty and limitations of the more detailed approaches. However, it would be sensible to document the uncertainties and limitations, which may vary from morphology to morphology (for example, changing cliff heights and observed slump angles combined with errors of interpreting image data may be a more robust way of determining F for sections of the coast).

The minimum setback was removed from the base formula and a section about the limitation and uncertainties of the base formula was added in section 3.2.7. This section addresses the use of a minimum setback width with a recommendation now made of what the setback should consider rather than imposing a constant arbitrary setback everywhere.

Minor comments

The location plan (Fig 1-1) does not locate all the areas identified in the introduction to the erosion section of this report.

Figure 1-1 was redone to include the locations mentioned in the methodology sections.

The extent of different morphologies (e.g. hard cliffs, soft cliffs, beaches) as well as the locations and extents of data used in the erosion assessment would have been useful on a plan and in a summary table.

A map of different morphologies was added at the start of section 3.2.6 as well as pictures typical of the morphology types.

Page 40. EQ 3.8 incorrectly referenced in previous paragraph.

Fixed.

Fig 3-11: The shoreline change at the spit in front of the estuary does not necessarily reflect the effect of the estuary. Best practice would be to identify all the spit as erosion prone.

Agreed, no spit-specific methodology is applied, and the end-of- spit erosion rate is unlikely to be accurate. Text has been changed to reflect this comment.

Main conclusions for the erosion hazard assessment

The stated probabilistic approach has limitations for this assessment due to the lack of data sets and knowledge of the system. My sense is the data is insufficient to confidently rely on the probabilistic outcome in absolute terms and the methodologies are not necessarily consistently applied across the different morphologies. The approach used is more a hybrid of deterministic and probabilistic approaches with expert judgement applied to the various parameters. A hybrid approach is reasonable for the available data and knowledge of the processes.

Agreed - the main text referring to the probabilistic approach has been altered to become hybrid-probabilistic. It should be appreciated that at least along some types of coast (e.g. the perched beaches) the deterministic response to sea-level rise is far from being quantifiable, and so there is additional uncertainty in the hazard lines that is not captured by the probabilistic approach.

At a high level the resulting erosion extents appear generally consistent and of a scale that we would expect for a “first pass” high order assessment. The information and output could be used to communicate relative hazards and to identify areas of more specific concern that could be subject to more robust assessment. However, we would be concerned regarding the robustness of the approach if its use lead to a legal challenges or to apply restrictions on property rights. We recommend some thought is given to the approach that could be used by individuals and/or smaller subsets of the shoreline to refine their understanding of coastal hazard.

Agreed. There are a lot of uncertainties associated with this analysis and caution should be used when applying restrictions. However, this analysis is a starting point for presenting coastal hazards to the public in Waitaki District and to discuss planning rules for costal zones in the district.

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.

2 Other comments from Waitaki District Council and Otago Regional Council

Below in black are comments that were collected during meetings and presentation of the results with Otago Regional Council and Waitaki District Council.

- Need some justification for the 25 m value chosen as the minimum hazard zone width. Should it be regarded as a safety factor? What other council do a similar thing and what value is used? Should the value vary by shore type?

  The safety factor has been removed from the main result but applying minimum width of 8m is recommended for planning purposes. It is recommended that the minimum hazard zone width should follow morphological boundaries (e.g. landward edge of dune field) or practical boundaries (e.g. roads).

- Guidance on how this should be communicated to public. Should more weight be placed on the 95% or 50% lines? We suggested explaining how the %tile approach and 95% and 50% lines help deal with the risk trade-offs between uncertainty and asset value. Who has used such lines elsewhere in NZ? Which %tile lines are typically used and by whom?

  Northland Regional Council is creating planning rules based on lines extracted from a similar analysis. The 95th percentile for the 100-year prediction and the 66th percentile for the 50-year prediction are available on their council website as an interim measure while the planning rules are being developed.

  Following further discussion with ORC on this topic it has been decided that further guidance on the selection of hazard lines for particular applications should be omitted in order to place the onus on the user of the lines to decide which is the most appropriate. In line with this we have omitted further discussion on this topic from the report.

- Do the inundation results take account of the existing breakwater at Oamaru?

  Yes. The breakwater in Oamaru does not show up in the inundation because of its size relative to the resolution. The breakwater is accounted for by assuming area inside the breakwater is not impacted by wave runup.

- What would happen if Kiwirail stopped maintaining their span of rock-wall in Oamaru?

  Our analysis did not consider this scenario - it assumed walls would be maintained. However, the data presented give a glimpse of the survival of the sea wall if maintenance is suspended. In the 12 years between 2004 and 2016 the forward edge of the structure receded by 10m. This suggests that in 30 years the full structure could disappear. Erosion rates without the structures will likely be at least similar to those for the unprotected part of the coast (~0.6m/year); however, there may be a phase of "catch-up" when the rates are higher until the shore alignment merges with the unprotected shore alignment.

- What lessons from coastal hazard mapping elsewhere in NZ have been captured in this study's approach?

The Ministry recommends developing flexible adaptation plans, rather than relying on a single scenario. The probabilistic approach and the framework used in this study are designed around this idea. The framework used also enables easy updates with improved/updated information and/or changed parameters. Not all coastal hazard mapping permits this.

- How confident are you in the line positions at different locations?

  The confidence level will vary with the different morphologies and available data. Area of Oamaru and northward have more historical shoreline data than the rest of the district so naturally the confidence level is higher there. The probabilistic approach is meant to take this in account and the 95th percentile line is meant to reflect a fairly uniform confidence interval. However, there are processes that are not well captured for some morphologies (e.g. sea-level rise impact on perched beaches). These additional uncertainties are difficult to quantify but are likely larger than those for soft sediment shores.

- What to do about gaps in the data on inundation zones.

  DEM data gaps were removed by interpolating the topography data. The model resolution was selected not at the highest possible resolution but to create a DEM that minimize the gaps and still provide useful results. It is worth noting that most of the gaps occurred on water bodies.

- Explain in report why you sometimes get "islands" in the inundated areas under different SL scenarios (e.g. at Oamaru).

  While the islands may be really dry elevated point during storm inundation, the bathtub inundation calculation do not take into account the propagation of water over a seawall or dune. This is one of the main limitations of this inundation estimate.

Tonkin+Taylor

Job No: 1007054
25 July2018

Otago Regional Council
70 Stafford Street
Dunedin 9054

Attention: Ellyse Gore

Dear Ellyse

Waitaki District Coastal Hazards Report - Specialist Review

Purpose

Otago Regional Council (ORC) commissioned Tonkin + Taylor (T+T) to carry out a peer review of the NIWA coastal hazard report entitled "Waitaki District Coastal Hazards" dated February 2018 along with their maps, figures and tables.

The NIWA study included erosion and inundation hazards along the Waitaki District for a 100 year timeframe using a probabilistic method and explicitly excluded tsunami, river floods or urban flooding and utilising the latest MfE guidance on sea level rise (MfE, 2017).

Project extent

The project extends along the entire Waitaki District although the scope included more detailed information for Oamaru, Taranui, Kakanui, Hampden, Moeraki township, Boulders and Shag Point/Matakaea.

Inundation

Baseline data

The baseline data relied upon for the inundation assessment was a storm surge study carried out in 2008 (Lane, et al, 2008) and the latest Ministry for the Environment (MfE, 2017) guidance on sea level rise. LiDAR data from 2004 was used for mapping.

The authors of the coastal hazard report identify issues with regard to the Lane (2008) work with regard to storm surge estimates, the analysis of wave run-up, the omission of other processes such as infra-gravity waves and the selection of future sea level rise values. The Lane results appear to be conservative for storm surge (i.e. predicting higher storm surge levels than might occur with more current approaches), non-conservative for wave run-up (i.e. predicting lower run-up levels than they might expect). However, the NIWA (2018) report authors still have used the results provided by Lane for storm surge and wave run-up as they conclude that the majority of the district shoreline is above the storm surge levels with the exception of Kakanui.

It would be useful to include some summary information on the length of the coast and the elevations along the coastal edge (possibly a frequency plot showing elevation frequency) that would support the authors assumptions.

Approach

Storm surge levels were extracted for four sites (Moeraki, Hampden, Kakanui and Oamaru). It is unclear what values were used for the remaining coast, but assume that inundation was limited to the beach areas and were not an issue on land areas.

Inundation was assessed for the open coast at these locations by adding predicted storm surge for a 20, 50, 100 and 500--year ARI storms to the calculated wave run-up and selected sea level rise value (0.3, 0.5, 0.7, 0.9, 1.1 and 1.3). For harbour/estuary areas inundation was assessed excluding the effects of wave run-up. Maps were produced for all these scenarios in terms of inundation depth.

Assessment

Inundation is only assessed at the four locations identified using bathtub modelling approaches and there is no district wide mapping of inundation. The process to limit inundation mapping to these areas could be better articulated in the report, but I understand that it is due to the remaining coastline elevation being higher than the storm surge levels.

The selected range of sea level rise values provides a reasonable range of values to understand changing risk of inundation over the next 100 years resulting from sea level rise. However, information of the ground levels along the coastal edge in terms of a frequency plot would have provided useful understanding of the potential for a "tipping point" type situation.

The approach of using wave run-up for mapping inundation extents away from the coastal edge is flawed, as run-up is a process that occurs at the coastal edge and the contribution of run-up in terms of overtopping volumes informs the potential for inundation. However, the approach also omits wave set-up that can be a more significant driver of inundation volumes and makes no allowance for processes such as infra-gravity waves that are identified as an exacerbating process.

Bathtub modelling is a reasonable approach for a district wide inundation assessment to identify areas where more detailed analysis may be warranted based on vulnerability and risk assessments of assets and values in those areas.

For future sea level rise scenarios the sea level is added to existing storm surge with no allowance for increased wave heights approaching the coast that can increase wave set-up/run-up. This approach is reasonably standard, but identifying this as a limitation would be useful.

Both the flaws/omissions of the methodology may have been moderated by the use of a more conservative approach to evaluate storm surge and by using a method that may under-predict wave run-up, but does include wave set-up in the formulation (refer Lane (2008), section 2.5.2). However, the confidence of these approaches to offset the limitations is not able to be determined.

Minor comments

Inundation depths are provided. However, frequently inundation levels are useful too. No information is provided to the LiDAR survey accuracy or limitations on the map surfaces. This was done by Lane (2008) but should be included in this report.

The location plan (Fig 1-1) does not locate all the areas identified in the introduction to the report.

Table 2-2 includes an interpolation of the year that sea level will reach a particular level for RCP2.6, 8.5 and 8.5+. I note there are inconsistencies with the interpolation (for example 0.5 m is reached closer to 2110 than 2115 for the RCP2.6 scenario based on MfE.

Table 2-3 heading could be clearer. It provides predicted extreme levels for storms with different average recurrence intervals.

Variable approaches to bullet point format.

Erosion

Baseline data

The baseline data relied upon for the erosion included historic erosion rates from previous reports, cadastral survey, aerial imagery, satellite data and LiDAR from 2004 (District wide) as well as more recent LiDAR from 2016 were available for Oamaru, Kakanui and Kaitaki Beach. Beach profiles at 12 sites were also available north of Oamaru (locations not provided), but it is unclear how the LiDAR and beach profile information was used in the assessment.

Approach

The overarching approach to establish the erosion hazard is to apply the historic rate of shoreline change (R) over the next 100 year period (T) with additional factors to take into account slumping (S) and the effects of sea level rise, although a minimum set-back of 25 m was used. The following table summarises the approaches used.

Morphology	Formula	Variable definition/distribution	Comment
Hard Cliffs	CHZ = max (R_{HC} x T + S_{HC}, F)	R_{HC} = historic erosion rate, normal distribution.	No justification of normal distribution provided. Unclear of the number of profiles used to develop rate.
		S_{HC} = normal distribution of absolute shoreline position for all cliff profiles within 200 m of profile being analysed.	Significant issues identified with mapping making establishment of this value difficult. This approach duplicates R_{HC} rather than address physical/observed process.
		SLR = not taken into account.	Reasonable approach for hard cliffs.
		F = 25 m.	No justification provided for this value and it is applied across all morphologies.
Soft Cliffs	CHZ = max ((R_{LC} + R_{SLR}) x T + S_{LC}, F)	R_{LC} = historic erosion rate, normal distribution.	No justification of normal distribution provided. Unclear of the number of profiles used to develop rate.
		S_{LC} = normal distribution of absolute shoreline position for all cliff profiles within 200 m of profile being analysed.	Significant issues identified with mapping making establishment of this value difficult. This approach duplicates R_{HC} rather than address physical/observed process.

Morphology	Formula	Variable definition/distribution	Comment
		R_{SLR} = normal distribution of SCAPE results	No tabulated information provided. With 2 SLR scenarios for the lower and upper bound of SLR estimate, no description provided on how distribution developed or how this applies for different time periods. Assume R_{SLR} is the additional rate (i.e. subtracting the historic rate), but this is also unclear.
Beaches backed by cliffs	CHZ = max (R_{PB} x T + S_{PB}, F)	R_{PB} = historic erosion rate, normal distribution.	I assume this is still the top of cliff. If so, would expect less erosion due to the presence of the beach, but no data presented to allow assessment to be made. If it is not the top of cliff, method not valid.
		S_{PB} = normal distribution of absolute values of residuals within 100 m of profile being analysed.	No justification of changed approach (100m vs 200 m) Unclear why absolute values on soft cliff works here and not on previous SC, unless actually on the beach. If it is the beach, this does not represent shoreline retreat of the cliff edge.
		SLR	No allowance of SLR. This does not seem valid as there is likely to be increased erosion due to sea level rise for soft cliffs.
Gravel Beach	CHZ = max (R_{RM} x T + S_{RM} + SLR_{RM}, F)	R_{RM} = historic erosion rate, normal distribution.	Approach OK for present day. No allowance for increased rate for sea level rise on long term trend (i.e. R_{Bruun} as used in following formula).
		S_{RM} = normal distribution of absolute values of residuals within 100 m of profile being analysed.	No justification of changed approach (100m vs 200m) from previous approaches, but absolute values approach has merit for soft shores.
		S_{SLRRM} = normal distribution of absolute values of residuals within 100 m of profile being analysed.	No justification why approach for Kaitorete Spit applies. Unclear if SLR values are relative (i.e. deducting historic SLR taken into account with S_{RM}. If not, this may be double counting.

Morphology	Formula	Variable definition/distribution	Comment
Beaches backed by dunes	CHZ = max ((R_{BRUUN} + R_{RES}) x T + S_{PB}, F)	R_{BRUUN} = shoreline retreat based on future sea level rise of 0.011 m/y.	No justification of active beach slope values. No description of distribution variables. Only one SLR rate of 0.011 m/y included.
		R_{RES} = difference between historic shoreline retreat and shoreline retreat predicted by Bruun using a historic rate of 0.002 m/y.	This does not appear to make sense. This should be the historic rate of change. With the R_{BRUUN} providing the additional effect of SLR on the long term trend.
		S_{PB} = normal distribution of absolute values of residuals within 100 m of profile being analysed.	Only evaluates present day storm effect and not future SLR. Appears inconsistent with S_{SLRRM} from above.
Rock revetments	CHZ = max (R_{Hist} x T, F)	R_{HIST} = historical shoreline rate	Unclear if this rate is prior to the seawall (i.e. natural shoreline rate of change) or a combination. Method is not clear as if it is an indication of the potential extent of adjustment of the shoreline should the protection fail, it should also take into account SLR and S.
River mouths/ streams/ estuaries	No specific approach used for river mouths/streams /estuaries		It would be useful to delineate where the methodologies applied are valid and where other approaches are required.

Historic long term trend

The shoreline position from the imagery data was established as the top of cliff or vegetation line on beach systems and linear trends were calculated at 5 m sections along the coast, with smoothing applied to coastal sections of uniform morphology. With the range of historic data available this seems an appropriate approach, although it is unclear how uncertainty/errors are included in the hazard assessment.

SCAPE

The SCAPE model has been used to assist in developing an understanding of the effects of future sea level rise on the soft cliff shoreline and was used for a representative 5 km shoreline and calibrated with historic data, with the results applied in some other soft cliff areas, but apparently not all (a plan showing areas where approaches used would be useful).

Only very summarised information is included in the report so no detailed review of the data and process used is possible. It is unclear how the two future sea level rise scenario's were simulated, but it is assumed a linear extrapolation process was used.

The conclusion that 1.3 m sea level rise does not have a significant effect on soft cliff shore erosion, and indeed the results appear to show slightly less erosion during a 1.3 m sea level rise than might occur with 0.22 m sea level rise (refer Figure 3-25), is unusual. I would have expected larger waves occurring higher up the cliff face to result in greater erosion potential.

Assessment

The methodology section is poorly laid out and hard to follow. There is limited data and information presented to enable an audit of the assumptions and values used. The selection of formulae and approaches seem to be highly judgement based and inconsistently applied across the different methodologies. For example, for soft cliffs (low cliffs) future sea level rise is taken into account, while for cliffs fronted by beaches no assessment of SLR effects are included. This inconsistency is also evident in the treatment of soft shores.

A more logical approach could have been to describe the coastal setting and the different morphologies and data available, then to work through the hazard methodologies for each specific morphology and then the quantification of the variables used. Tables providing the values of the distribution for each morphological section would have been useful to communicate the relative importance of each particular process.

The use of a minimum set back (F) is a reasonable approach to manage uncertainty and limitations of the more detailed approaches. However, it would be sensible to document the uncertainties and limitations, which may vary from morphology to morphology (for example, changing cliff heights and observed slump angles combined with errors of interpreting image data may be a more robust way of determining F for sections of the coast).

Minor comments

The location plan (Fig 1-1) does not locate all the areas identified in the introduction to the erosion section of this report.

The extent of different morphologies (e.g. hard cliffs, soft cliffs, beaches) as well as the locations and extents of data used in the erosion assessment would have been useful on a plan and in a summary table.

Page 40. EQ 3.8 incorrectly referenced in previous paragraph.

Fig 3-11: The shoreline change at the spit in front of the estuary does not necessarily reflect the effect of the estuary. Best practice would be to identify all the spit as erosion prone.

Main conclusions for the erosion hazard assessment

The stated probabilistic approach has limitations for this assessment due to the lack of data sets and knowledge of the system. My sense is the data is insufficient to confidently rely on the probabilistic outcome in absolute terms and the methodologies are not necessarily consistently applied across the different morphologies. The approach used is more a hybrid of deterministic and probabilistic approaches with expert judgement applied to the various parameters. A hybrid approach is reasonable for the available data and knowledge of the processes.

At a high level the resulting erosion extents appear generally consistent and of a scale that we would expect for a “first pass” high order assessment. The information and output could be used to communicate relative hazards and to identify areas of more specific concern that could be subject to more robust assessment. However, we would be concerned regarding the robustness of the approach if its use lead to a legal challenges or to apply restrictions on property rights. We recommend some thought is given to the approach that could be used by individuals and/or smaller subsets of the shoreline to refine their understanding of coastal hazard.

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.

Yours sincerely

Richard Reinen-Hamill
Sector Director – Natural Hazard Resilience

5-Mar-19
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Tonkin+Taylor

Job No: 1007054
4 March 2019

Otago Regional Council
70 Stafford Street
Dunedin 9054

Attention: Ellyse Gore

Dear Ellyse

Waitaki District Coastal Hazards Report - Specialist Review: Final Assessment

Otago Regional Council (ORC) commissioned Tonkin + Taylor (T+T) to carry out a peer review of the NIWA coastal hazard report entitled "Waitaki District Coastal Hazards" dated February 2018 along with their maps, figures and tables. T+T completed the review (T+T letter dated 25 July 2018) and NIWA has subsequently updated their report dated January 2019 taking into account the peer review findings. NIWA has also provided a separate report titled "response to specialist review" also dated January 2019.

We confirm that the NIWA report has considered and taken account of our review of their draft report. Their report provides coastal inundation extents from storm surge and sea level rise for a range of sea level rise scenarios as well as coastal erosion hazards extents along the Waitaki District coastline. Their assessment has used an appropriate methodology that combined existing data, empirical assessments and expert judgement to provide an assessment of both these hazards over the next 100 years.

We note the identified limitations and caveats on the methodologies. These are appropriate given the scale and complexity of the geology but should not be considered a reason for not accepting the hazard extents. We also support the approach not to consider small scale protection works as effective over the planning timeframe. We support NIWA's recommendations on monitoring beach morphology at the identified erosion hotspots and to continue monitoring of water level and waves to improve confidence of results with a longer dataset.

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.

Yours sincerely

Richard Reinen-Hamill
Sector Director – Natural Hazard Resilience

4-Mar-19
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