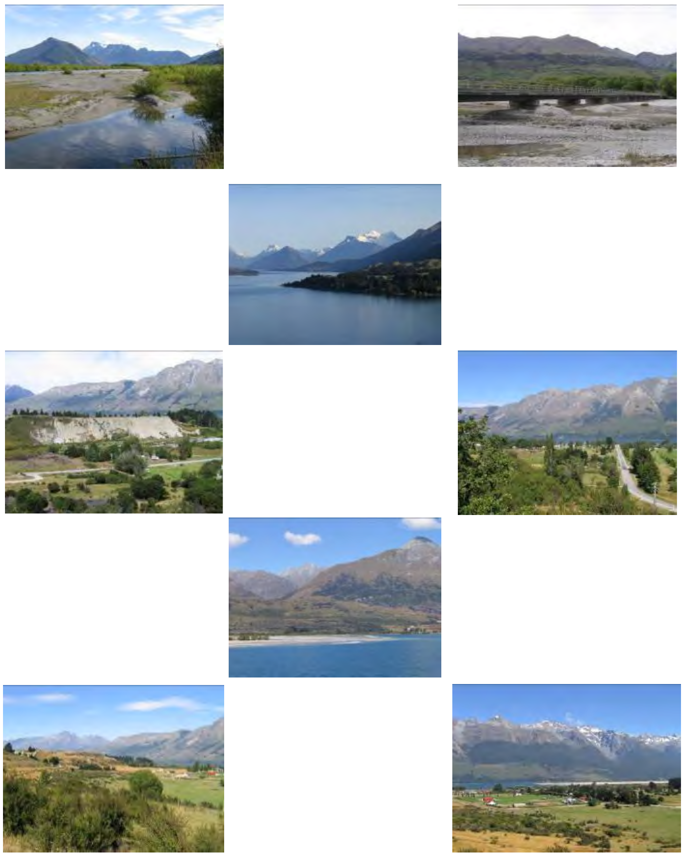
REPORT

Glenorchy Area Geomorphology and Geo-hazard Assessment



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Otago Regional Council

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ES 1 Dart River floodplain and fairway

- The Dart River floodplain and fairway are typical of a large braided river. Over the past 140 years the fairway has moved across the valley floor recycling floodplain deposits and eroding in-channel islands.
- Erosion of the true right floodplain area north of Kinloch has occurred since at least 1977 due to the continued presence of major braid channels flowing along this side of the fairway. This has removed ~100 ha of farmland.

ES 2 Rees River floodplain and fairway

- The lower Rees River floodplain and fairway are unusual as the main fairway is 1 – 2 m above its adjacent floodplain, and in the lower 1.6 km reach before flowing into Lake Wakatipu, it splits into three distributary channels. The western distributary (#3) carries water directly into the Dart River fairway.
- Deposition of gravel bars in the main fairway in the area where the distributaries diverge affects the balance of flow in these channels. Since about 1995 the main flow of the Rees River has been in the eastern (#1) distributary, and this brings it directly past Glenorchy.
- Weighted mean bed level analysis of the fairway of the distributary #1 indicate a stable bed since 1999 in its lower reaches near Glenorchy, and slight aggradation of <20 cm one kilometre upstream.
- A large quantity of gravel is situated in the fairway at the head of distributary #1. If this migrates downstream it is likely to increase the potential for the Rees River to shift its channel and flow directly into the Glenorchy Wetland/Lagoon area; and/or to cause aggradation near the mouth leading to loss of freeboard on the Rees/Glenorchy floodbank and an increased risk of flooding through the northern parts of the town.

ES 3 Delta progradation

- The Dart River delta has advanced 180 – 200 m since the mid 1870s.
- Since the late 1970s the main area of deposition has been on the western side near Kinloch where up to 150 m of advance has occurred. This has been in response to the main flow of the river being on this side of the fairway, and the significant floodplain erosion that has occurred upstream.
- The Rees River delta adjacent to Glenorchy only began to form at the mouth of this distributary (#1) after about 1890. Since then it has advanced 90 – 175 m.
- Initial growth was slow, as the river appears to have mainly occupied distributaries #2 and #3 that do not discharge through here. Between 1937 and 1966 the northern sector showed the most significant advance (70 – 100 m), while the southern sector advanced most significantly from 1966 – 2001 (85 – 100 m).
- The Buckler Burn delta has advanced up to 215 m from 1864 – 2001. Growth was mainly along the northern sector close to Glenorchy until 1966. Since then the growth has been along the southern sector in response to Buckler Burn occupying a more southerly route across its lower floodplain and causing significant undercutting and erosion of the terrace face here.

ES 4 Glenorchy Wetland

- The Glenorchy wetland and lagoon area was originally an arm of Lake Wakatipu, which did not become drained until after the late 1880s. Historical photographs and survey plans show that by 1905 the area was occupied by numerous braids of the Rees River.
- By 1937 the Rees River no longer flowed into the wetland area, and four small lagoons covering 13.75 ha had developed in the lowest parts. Over succeeding years this open water area has expanded slowly to now (2001) cover 15.73 ha.
- The wetland is fed by small streams and shallow groundwater inflow. The Rees River flows nearby in distributary #1, and this is probably a significant source.
- Changes in open water area are probably related to changes in inflows, and outflow. While the Rees River occupies distributary #1, it will augment groundwater flows. However, should flow shift away from this to distributaries #2, and #3, this source would be reduced. Drainage of farmland and the Bible Stream diversion will also have contributed to increased inflows.
- Outflows are controlled by the discharge efficiency of the outflow channel that runs at the base of the Rees/Glenorchy floodbank. In addition, the level of the Rees River bed where the outflow stream joins will also influence outflow efficiency.
- There is a significant risk that the Rees River could change its course to flow directly into the lagoon area. While this may initially increase the open water area, within a few decades the area would probably become silted up.

ES 5 Bible Stream

- The Bible Stream gully is an unusual landform that does not have any significant surface water source, and has probably been formed by erosion of the gully head due to groundwater outflow.
- An alluvial fan landform has been formed at the mouth of the erosion gully. This covers about 4 ha, and aerial photographs show that since the 1930s most of the fan surface has experienced overland flow, and associated sediment deposition has extended nearly 200 m across the fan surface in 10 m wide corridors. However, it is unlikely that significant depths of overland flow would ever extend much beyond these limits as the discharge volume and declining slope gradient are unlikely to be able to sustain such flow.
- A dry channel runs to the northwest through the former gravel pit and landfill area, and this will be a preferential path for any flood discharges that are large enough to overtop the existing flood bund. Several buildings at the end of Shiel Street would be in the path of this flow should it extend more than about 220 m.

ES 6 Buckler Burn

- Buckler Burn has formed much of the area now occupied by the Glenorchy township, particularly west of Oban Street. Overbank deposits were formed north of a line between Coll Street to Forbes Place, and braid channels were formed south of here. These surface micro-relief patterns have been largely removed by urban development.
- The present Buckler Burn channel has undergone a number of changes since 1864. The stream has migrated through 340 m across its lower floodplain, alternately threatening Glenorchy on its north bank or eroding terraces on its south bank.
- Erosion of the north bank in the upper reach downstream of Campbelltown has threatened the Glenorchy-Queenstown highway, and bank protection works have been constructed.

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- This section has also been subject to considerable aggradation, which is currently managed by gravel extraction.

ES 7 Seismic hazard

- The Glenorchy area has a seismic hazard that is moderately high for Otago. Significant damage will be sustained by buildings during an earthquake exceeding an average recurrence interval of 100 years.
- There is limited data on subsurface conditions at Glenorchy, but our model for the development of the surface landforms indicates there is a high likelihood of liquefaction occurring during a large earthquake, and a high likelihood of this affecting property along the lake edge.

ES 8 Landslide hazard

- Although large landslides occur in the mountains near the study area, these present negligible risks to Glenorchy as they are not adjacent to the town.
- Slope instabilities most likely to affect Glenorchy are cut slope failures along the Queenstown-Glenorchy Road which could block the road and isolate the area from road access.
- Additional slope instability issues that are considered unlikely to directly affect Glenorchy township include: landslide damming of Buckler Burn or Precipice Creek; toppling of a section of the high gravel cliffs cut in fan gravels along Buckler Burn; or reactivation of the rockfall above the Glenorchy-Paradise Road.

Section 1 Introduction

1.1 Purpose of this report

This report addresses aspects of the geomorphology, landslide risk and seismic hazard setting of the Glenorchy area. It accompanies a flood hazard assessment report for Glenorchy, also prepared by URS New Zealand Ltd.

The purposes of this report are therefore:

- Document the geomorphic environments in and around Glenorchy;
- Assess landslide risk and seismic hazards; and
- Provide a setting for the flood hazard assessment report.

Specific areas of concern are:

- Landform mapping;
- Rees/Dart Rivers delta progradation;
- Glenorchy lagoon and wetland;
- Buckler Burn;
- Bible Creek;
- Landslide risk; and
- Seismic hazards.

Figure 1-1 Glenorchy Area Geomorphology and Geo-hazard Study Area

1.2 Study area

The study area covers some 23 km^2 at the eastern side of the head of Lake Wakatipu, stretching ~8 km north from Stone Creek to Precipice Creek, and ~3 km west from Chinaman Flat on the eastern slopes of the Wakatipu basin, to the western edge of the Rees River floodplain where it merges with the larger Dart River floodplain. This area is shown in Figure 1-1.

There are three main elements of this landscape: the steep west-facing slopes of the Richardson Mountains; the floodplain of the Rees and Dart Rivers; and Lake Wakatipu. In the study area, smaller elements of the landscape include the valleys of the tributary streams such as Precipice Creek, and Buckler Burn.

These broad landscape features are described below in Section 3.

1.3 Settlement, land use and population

The geomorphology and geo-hazards of the Glenorchy area have influenced patterns of settlement, land use and population. For many years a relatively quiet area accessible only by steamer to Queenstown or a rugged overland cattle track, the area has started to grow significantly. The following descriptions have been obtained from published local histories such as Hooper (1884), Duncan (1888), Chandler (1984), Bradshaw (1997), and Paulin (2003) (see also Section 2.1.6).

1.3.1 Settlement and land use

European settlement of the area began in 1861/62 when the area was opened up for grazing. Farming has remained a major occupation, most intensively on the flat lands of the Rees and Dart river floodplains. Use of the floodplains has resulted in issues of loss of productive land as the rivers shift their courses (in particular the Dart River).

Timber milling was a significant occupation in the early decades of European settlement, based mainly at Kinloch across the lake from Glenorchy. The lower slopes of the Humboldt Mountains were cleared in places by this industry, and the timber exported by steamer back to Queenstown. Bush clearance also occurred on Mt Alfred Ari, and from patches of forest that occurred on the river flats. The Richardson Mountains being drier were naturally not as well forested, although large patches of bush are shown on early survey plans, and the presence of numerous burnt stumps and logs attest to a former wider tree cover here (Thomson *pers comm* 16/7/2007). *Patches* of bush remain here in the deep gullies formed by the larger streams such as Buckler Burn and Precipice Creek. Removal of this forest cover has probably contributed to increased sediment loads in the affected stream catchments.

Mining has also been a significant occupation at the Head of the Lake. Gold miners investigated the area during the Otago gold rush of the 1860s, and there were alluvial workings in the Rees River, Buckler Burn, and Precipice Creek, but there were no major finds. Gold was also sought in underground mines such as the Invincible Mine in the upper Rees Valley that was moderately successful in the 1880s. There was also an attempt to operate a gold dredge in the bed of the Dart River between 1890 and 1904, but this was never successful. Of more lasting effect was the mining of scheelite deposits in the Richardson Mountains above Glenorchy. There were several phases of activity, mostly triggered when the price of scheelite was high enough during overseas wars for the efforts to be marginally economic. The most recent activity was in the late 1960s and early 1970s when several mines, tenements and alluvial deposits were drilled and investigated (Thomson *pers comm* 16/7/2007). A significant effort was put in by Alex Harvey Industries (AHI), but they did not proceed with a new phase of mining. However, they did construct dwellings on land close to Buckler Burn, and these required protection from flood risk, and most were eventually removed in the late 1990s.

Tourism has long been popular in the area. The head of Lake Wakatipu became reasonably well known from the 1870s, and the landscape photography of the Burton Brothers brought images of Diamond Lake and Paradise to a wider public. Three large accommodation hotels operated at Glenorchy, although all were eventually lost to fires by the early decades of the 20th Century. The completion of the road to Queenstown in November 1962 further opened the area up to tourism, providing road access from

Queenstown to the Mt Aspiring National Park and Routeburn Track. Today the area is the gateway to this park, and a destination in its own right with attractions like the Dart River jet boat tours.

In recent years there has been a trend towards subdivision of land for dwellings. This has occurred at Glenorchy in the parts of the town area that had not previously been built on, and on the lower slopes of the Richardson Mountains on the eastern side of the road both to the north and south of the town.

1.3.2 Population

The changing population of Glenorchy and district is shown in Table 1-1, with data sourced from the New Zealand Census of Population. The township has fluctuated in size over the years, but has generally been quite small at between 20 and 150 people. Influxes occurred when scheelite mining increased and the small satellite settlement of Campbelltown (just north of the Buckler Burn bridge) was active. The opening of the road to Queenstown in 1962 has allowed a steady growth in Glenorchy's population and in recent years as Queenstown has grown rapidly there appears to have been a spin-off in Glenorchy. However, the town did not consistently number over 100 people until the 1990s, and even now at approximately 275 is not large.

Table 1-1: Glenorchy and Queenstown population, 1874 – 2006 (Data from New Zealand Census of Population Reports)

Census	Glenorchy	Queenstown
1/3/1874	62	705
3/3/1878	34	574
3/4/1881	37	735
28/3/1886	74	733
5/4/1891	40	779
12/4/1896	27	781
31/03/1901	18	690
29/04/1906	33	665
2/04/1911	126	696
15/10/1916	150	657
17/04/1921	158	751
20/04/1926	54	804
24/03/1936	104	931
25/09/1945	114	854
17/04/1951	117	1013
17/04/1956	82	1198
18/04/1961	78	1321
22/03/1966	65	1634
23/03/1971	131	2159
23/03/1976	98	3133
24/03/1981	123	3367
4/03/1986	87	3659
5/03/1991	147	5883
5/03/1996	195	7518
6/03/2001	225	8535
7/03/2006	*275*	10422

Section 1 Introduction

Glenorchy has always been the main settlement in the district at the head of Lake Wakatipu. Kinloch on the west side of Lake Wakatipu has never numbered more than a few dozen people, and a similar population was scattered up the Rees Valley and around Paradise. In the 2006 census, the Glenorchy district usually resident population stood at 465, although this included all the western shores of Lake Wakatipu south to Kingston.

The growth of Queenstown has been very rapid since the late 1980s, and this has and will continue to significantly affect Glenorchy through the flow of tourists, and pressure for residential and life-style subdivisions to service this large population centre.

1.4 Geomorphic environmental changes

The head of Lake Wakatipu district and Glenorchy is affected by several dynamic geomorphic systems including the Dart and Rees Rivers, Buckler Burn, and Lake Wakatipu. The productive valley floor is traversed by the large Dart River, and this dynamic braided fairway can carry dramatic floods and erode its floodplain. The Rees River is smaller, but also dynamic, showing patterns of fairway aggradation in upper reaches (see Section 3.4), and closer to Glenorchy it flows in a potentially unstable channel that is above its floodplain, and can flow in three distributary channels. Buckler Burn on the southern outskirts of Glenorchy has a steep catchment that can deliver significant flood flows. Lake Wakatipu has a large catchment, but only one outlet (the Kawarau River). Regional flood inflow events can cause the lake to rise resulting in significant flooding of low lying shoreline areas.

Historically a number of environmental events have occurred that reflect the nature of this geomorphic and geo-hazard setting. These have included:

- Floods of September – October 1878, affecting both the major rivers and the lake.
- In-filling of the Glenorchy lagoon embayment of Lake Wakatipu that occurred between the late 1880s and early 1900s.
- Aggradation of the Rees River delta required the steamer jetty be moved to deeper water in the mid 1930s.
- Threat of flooding by the Buckler Burn forced relocation of the Glenorchy school in 1939.
- Erosion of the west side of the Dart River fairway resulted in various flood protection works, stopbanks, and training banks constructed between late 1950s and mid 1980s.
- Buckler Burn threatened the south parts of the town, and the Queenstown road from the 1970s onward. Various flood protection works have been built, and gravel removed from the channel.
- Flood of January 1994 destroyed the Stone Creek bridge.
- The flood of 1999 inundated parts of the town as the lake rose to a record level.
- Rees River floodbank constructed in 2000 to protect the northern side of the town.
- Floodbank and new channel for the Bible Stream constructed to take this creek away from the landfill and Shiel Street area of Glenorchy.

All of these have resulted from the natural geomorphic process regimes, and have in part provided stimulus for this study. Most of the issues relate to flooding, and thus this study links to the accompanying flood study carried out by URS as the landforms set the boundaries within which the hydrological processes take place.

Section 2 Data Sources and Methodology

The geomorphological and geo-hazard assessments have used a variety of data sources and employed various methodologies. Historical data has been used to document geomorphic changes in the river systems and delta fronts. This has included use of survey plans, historical photographs, topographic maps, aerial photographs, and scientific papers and reports. These are outlined below.

2.1 Data Sources

Data on river floodplain changes and delta front positions have been derived from historic survey plans, photographs, topographic maps and aerial photographs as described below.

2.1.1 Survey plans

Survey plans dating from the 1860s – 1955 were obtained from the LINZ website *Landonline*, and the Lakes District Museum. The following plans were used.

Plan #	Title	Date	Notes
na	Compiled plan of the Town of Glenorchy by E.M. Barr	November 1864	Shows proposed Glenorchy town street layout, Buckler Burn, and lake shoreline near Glenorchy
SO 1833	Topographical Plan of the Upper Wakatipu District	August 1871	Shows lower reaches of the Dart and Rees Rivers and Lake Wakatipu shoreline. Topographical details do not appear to be accurately placed.
SO 1835	Block I Upper Wakatipu and Glenorchy Districts	September 1871	Shows land parcels and topographical details between eastern valley side and Rees River. Does not show Glenorchy.
SO 1836	Part of Block I Upper Wakatipu District	December 1874	Shows land parcels and topographical details between Rees and Dart River.
SO 1837	Compiled Map of Block I Upper Wakatipu District	No date	Is a compilation of SO1835 and SO 1836. Shows part of Rees/Dart delta near Glenorchy.
na	Topographical Map of part of Dart, Earnslaw, U. Wakatipu and Glenorchy Districts	April 1881	Shows Dart and Rees River basins, but does not extend to Lake Wakatipu.
SO 4460	Plan of Buckler Burn mining reserves	September 1890	Survey plan of lower Buckler Burn channel
SO 4464	Plan of the Glenorchy Railway Reserve	June 1905	Shows Glenorchy, Rees River and delta, Buckler Burn
SO 11999	Plan of the Glenorchy commonage area	1955	Detailed topographical plan of Glenorchy wetland area

These showed mainly cadastral information with some topographic details of river and stream channels, and lake shorelines. Where possible, land parcel boundaries were used to overlay these plans on modern maps, and changes were documented.

2.1.2 Historical photographs

Historical photographs taken between 1875 and 1905 have been sourced from collections at Te Papa and the Lakes District museums. These all come from the large Burton Brothers (subsequently Muir and

Moody) catalogue. This Dunedin based firm of photographers was active from 1868 to 1912, and many of their works survive in public collections as negatives or prints.

Photographs were taken around the Head of Lake Wakatipu area in 1875, 1883, 1886, 1889/1890, and 1898. These have been used to corroborate interpretations derived from the survey plans, and a selection of these is shown in Appendix A.

2.1.3 Topographic maps

Topographic maps at suitable scales were available from the 1960s onwards. Information on these is derived from aerial photographs, which are documented below. Maps consulted included

NZMS 1 Hollyford S122 (2nd Edn, 1980), scale 1:63360 (based on 1966 aerial photography)

NZMS 1 Skippers S123 (1st Edn, 1973), scale 1:63360 (based on 1966 aerial photography)

NZMS 260 Queenstown E14 (1st Edn, 1994), scale 1:50,000 (based on 1988 aerial photography)

NZMS 260 Queenstown E14 (2nd Edn, 2002), scale 1:50,000 (based on 2001 aerial photography)

2.1.4 Aerial photographs

Aerial photographs provide the most detailed source of information, and the following were consulted for this project.

Survey/Run/Number	Scale	Date	Source	Notes
SN 40/Run Y/#s 16-29	1:8,000	01/04/1937	NZ Aerial Mapping	Only covers eastern valley side
SN 1843/Run F/#s 1-2	1:11,000	05/03/1966	NZ Aerial Mapping	Only covers Glenorchy, Buckler Burn, and the Rees delta.
SN2016/Run 3985/#s 18-24	1:75,000	12/03/1966	NZ Aerial Mapping	
SN5062/Run A/#s 9-10	1:25,000	12/02/1977	NZ Aerial Mapping	
SN8426/Run H/#s 4-6	1:50,000	03/12/1984	NZ Aerial Mapping	Rees and Dart Rivers north of Glenorchy
SN9996/Run E/#s 18-19	1:50,000	15/12/1988	NZ Aerial Mapping	Flood in Dart and Rees Rivers, Lake Wakatipu at high level
(No ID number)		12/01/1994	ORC	Flood in Dart and Rees Rivers, Lake Wakatipu at high level
SN12325/RunE41/#s P/05-P/09	1:50,000	27/11/1998	Aerial Surveys Ltd	Colour
		22/11/1999	ORC	Flood in Dart and Rees Rivers, Lake Wakatipu at high level
SN25055	1:50,000	19/02/2001	NZMapToaster	

2.1.5 Satellite Images

Satellite imagery is available in the MapToaster software, but this is low resolution and does not provide detailed coverage. Some high resolution imagery was available in Google Earth, and one scene covered much of the Dart and Rees River floodplain areas to just north of the delta front and Glenorchy. This was dated 13th April 2006.

2.1.6 Reports and Papers Consulted

Old reports of settlers, surveyors and geologists were consulted for historic details of the Head of Lake Wakatipu environment prior to the availability of aerial photography as these provided useful details on some of the significant environmental changes that have occurred. These are listed below.

Local histories contained material that provided some insights into environmental changes in the area. These included:

Hooper, R.S. (1884) *The descriptive guide to Lakes Wakatipu and Wanaka and the Southern Alps of Otago, New Zealand* Evening Star Office.

Duncan, A.H. (1888) *The Wakatipuans or early days in New Zealand*. Edition of Lakes District centennial Museum Inc, 1964, 60 p.

Chandler, P.M. (1984) *Head of Lake Wakatipu schools centennial 1884 – 1984* Central Otago News Ltd, Alexandra, 56 p.

Bradshaw, P. (1997) *Miners in the clouds*. Caxton Press, Christchurch, 106 p.

Paulin, P. (2003) *Dart River gold dredge 1890 to 1904, 44 p.*

A number of topographical survey and geological reports were also consulted for scientific accounts of the area. These included:

McKerrow, J. (1864) *Reconnaissance survey of the Lake Districts of Otago and Southland, New Zealand.* Journal of the Royal Society London 34: 56 – 82.

Hector, J. (1869) *On mining in New Zealand* Transactions of the New Zealand Institute 2: 361 – 384.

McKerrow, J. (1870) *On the physical geography of the lake districts of Otago* Transactions and Proceedings of the Royal Society of New Zealand 3: 254 -263.

Higginson, H.P. (1877) *On floods in lake districts and flooded rivers in general with methods adopted for their prevention and control. Transactions* and Proceedings of the Royal Society of New Zealand 10: 180-189.

McKay, A. (1881) *District west and north of Lake Wakatipu.* Reports of geological exploration during 1879-80. p 118-147. Colonial Museum and Geological Survey Department.

Henderson, J. (1937) *Glenorchy district* Annual Report of the Department of Scientific and Industrial Research 1936-37, Geological Survey Branch, p 16 – 22.

Healy, J. and R.W. Willett (1938) *Glenorchy Subdivision* Annual Report of the Department of Scientific and Industrial Research 1937-38, Geological Survey Branch, p 12 – 16.

Reed, J.J. (1945) *The scheelite deposits at Glenorchy* Transactions of the Royal Society of New Zealand 75(3): 271 – 393.

Barrell, D.J.A., B.W. Riddolls, P.M. Riddolls, R. Thomson (1994) *Surficial geology of the Wakatipu Basin, Central Otago, New Zealand.* Institute of Geological and Nuclear Sciences science report 94/39, 31 p.

ORC made several reports from their archives available. These included:

Rees River sedimentation Report 24p.

Johnstone, N (1999) *Queenstown-Lakes District floodplain report*

OPUS International (2004) *Wakatipu floodbank stability survey*. Unpublished letter report to ORC dated May 2004.

2.1.7 Fieldwork

Geomorphological and hazards assessments were carried out during field visits on 18th January, and 12th – 15th February 2007.

Discussions were held with long term local residents Mr P Lucas formerly of Wyuna Station, and Mr R Reid, formerly of Precipice Creek Station who provided anecdotal reports of various flood events.

2.2 Documenting Delta Growth

Documenting delta growth would ideally track the advance of the submerged delta front. However, this would only be possible from repeated detailed bathymetric surveys. Bathymetric surveys have been carried out in 1902 (chart scale 1:200,000), 1968, (chart scale 1:63,360), and 2003 (chart scale 1:100,000), but these scales are not conducive to detailed analysis[1]. Delta advance has therefore been assessed from changes in the position of the shoreline across the delta front. These have been documented from historical survey plans, maps, and aerial photographs. However, this mapping is compromised by a number of factors including:

- Historic survey plans mainly show land parcel boundaries, and topographic details were incidental to this primary aim of the mapping;
- Scale of aerial photographs. At less that ~1:20,000 information becomes difficult to observe;
- Water clarity. Sediment plumes obscure information, while clear water makes it difficult to determine whether a surface is above or below the water line;
- Black and white photographs “see” deeper into the water than colour photographs;
- Lake level changes will vary the position of the apparent shoreline; and
- Shoreline morphologies may not be clearly related to lake levels.

Only the 1937 aerial photographs are at a scale of greater than 1:20,000 and this set only covers the eastern part of the delta. However, this was partly offset by scanning the other photographs and working with them digitally at around 1:5,000 scale, although details are lost at these higher magnifications.

The 1988, 1994, and 1999 photographs were taken during major floods, and sediment plumes obscured most shoreline details. In addition, lake levels were high at these times, and the shoreline shown would only have been a transient one. The 1st edition of the 1:50,000 scale topographic map was made from the 1988 aerial photographs, and no allowance was made for the higher lake levels at that time. As a result, the 1994 map indicated there had apparently been over 250 m of delta front retreat since 1966.

The actual boundary between dry land and the lake is not well shown on the aerial photographs. This is due to the photograph “seeing” into the water column, which in the case of black and white photographs can be more than 1 m if the water is clear. This effect can be reduced by mapping the shoreline along beach landforms that would have formed by wave action while the lake level remained in a narrow range for a period a few weeks or months. The 1966, 1998, and 2001 photographs showed reasonably clear beach landforms.

Varying lake levels will have a significant effect on the position of the apparent lake shoreline in areas where the land surface slope is gentle. The slope of the lower part of the Dart/Rees River floodplain

[1] Chart sources: 1902 bathymetry from Thomson *pers comm.* 16/7/2007; 1968 bathymetry from Irwin, J. 1972 *Lake Wakatipu Bathymetry* NZOI Lake Series; 2003 bathymetry from LINZ 2006, *Chart NZ262 Lake Wakatipu*.

measured from the 1:50,000 topographic map is about 1:360, thus a change in lake level of 1 m would result in the apparent shoreline shifting 360 m. From 1962 – 2004, Lake Wakatipu level[2] varied through range of 3.46 m, with a mean level of 309.95 m above sea level (asl), as shown in Table 2-1.

Table 2-1 Summary levels, Lake Wakatipu (1962 - 2004) (Figures rounded to nearest cm from original data in mm)

Level	Height
Maximum	312.78 m
Upper quartile	310.15 m
Mean	309.95 m
Median	309.88 m
Lower quartile	309.70 m
Minimum	309.32 m
Std Dev	0.36

Across land sloping at 1:360 the apparent shoreline at the lowest recorded lake level would be horizontally 1,245.6 m from the shoreline at the highest recorded lake level. Thus, the delta shoreline position could change horizontally through more than 1 km from variations in lake level alone, although this would be an extreme case. The variation in delta shoreline position due to lake level changes can be estimated for the aerial photographs by applying the 1:360 ratio identified above. The time the aerial photographs were taken is known from the instrument panel on the photographs, the lake level at those times can be determined from the lake level database, and the apparent change in shoreline position can be determined as shown in Table 2-2. This shows where the delta shoreline would be if it had always been at the 2001 position, and only varied in apparent position due to changes in lake level. In all cases the apparent shoreline of the delta would have been north of the 2001 position, and it shows that the shoreline position can change significantly due to water level variations alone. The 1977, 1988, 1994, and 1999 lake shoreline positions will have been most affected by this issue.

Table 2-2 Apparent shoreline change at times of aerial photographs relative to the 2001 photographs

Date	Lake level (m asl)	Apparent delta shoreline change from 2001 position
01/04/1937	310.00	-79
05/03/1966	309.95	-61
12/03/1966	309.86	-29
12/02/1977	310.11	-119
15/12/1988	310.97	-428
12/01/1994	311.48	-612
27/11/1998	309.92	-50
22/11/1999	312.42	-950
19/02/2001	309.78	0

It can be seen that the most recent 2001 photographs were taken at the lowest water level of all the available aerial photographs, and this will have the effect of at least partly exaggerating apparent delta progradation. For this study the 1937, 12/3/1966, and 2001 aerial photographs have been used as these

[2] Data supplied by ORC.

are generally less affected lake level variations. In addition, given the relatively small amount of movement recorded, they give a clearer picture of delta movement without the clutter of data from intervening years when little relative change appears to have occurred.

2.3 Mapping process

Rectified aerial orthophotographs from 2001 available in the MapToaster software were used to create base maps for mapping purposes. Details from older aerial photographs were manually transferred to the rectified photographs.

2.3.1 Delta mapping

Aerial photographs were used to map delta front positions. These were scanned and analysed on-screen at a scale of about 1:5,000, and shoreline positions were mapped where possible along beach landforms. Reference points were then selected on the 2001 aerial photographs. These points included such things as road junctions, trees and rocky shoreline headlands. At least four points were identified on each image, and they were chosen to be spatially well separated, and as close as possible to lake level. Using the x-y co-ordinates of these points, the older photographs were then geo-referenced using GIS software. It is estimated that the uncertainty in this geo-referencing would have been about ±10 m.

A similar process was followed for the older survey plans. The corner x-y co-ordinates of several land parcels were derived from the Terraview Platinum software and the old plans geo-referenced to these positions. Lake shoreline positions were then overlaid on the 2001 aerial photography, as shown in Figure 5-1.

2.3.2 Landform mapping

Landforms were initially mapped from stereo aerial photographs, and these interpretations checked in the field. Three groups of landforms were identified that resulted from largely glacial processes, fluvial deposition into lakes, and stream erosion and deposition as follows. Landform maps are shown in Figures 4-1, and 4-2.

1. Landforms resulting directly and indirectly from glacial processes. Glacial deposits occur on the slopes of the mountains, and various erosional and depositional landforms were mapped. Ice smoothed slopes were identified where rock slopes had been smoothed into streamlined low ridges oriented sub-parallel to the valley axis. Till-mantled slopes were mapped where the mountainsides were mantled with loose boulders, gravel, sand and silt. Fluvio-glacial features deposited close to the ice margin by meltwater were also identified, including alluvial fans and meltwater channels. These features are perched high on the valley sides, well apart from present-day drainage systems. Ice-marginal lake shorelines were also mapped where narrow level benches occur that cut across older glacial and fluvio-glacial landforms.

2. Fan-delta landforms occur where tributary streams entered ice marginal lakes, or the greater Lake Wakatipu. They are identified by their fan-shaped surface form, with the fan apex at the mouth of the tributary valley where it leaves the mountain front. Deltaic deposits below the fan surface can be seen in stream cuttings. Level benches interpreted as lake shorelines occur on the front edges of some fan deltas.

3. Fluvial landforms occur in association with the present river and stream systems. The bare gravels of the presently active channel and braided river fairways are mapped separately from the adjacent vegetated floodplains. Some higher terraces occur indicating previous floodplain levels.

Landslide landforms occur on steeper slopes, and were assessed from aerial photographs and field inspection. These stand out as features where the slope has failed and disrupted the trend of the pre-existing slope landforms.

2.4 Glenorchy Digital Terrain Model

The Queenstown Lakes District Council made available a digital terrain model that had been prepared by GeoSmart Ltd using photogrammetric methods and based on 1996 aerial photography. Data was also available from December 2006 and February 2007 ground surveys carried out by OPUS International Consultants, and Glasson Potts Fowler Ltd for ORC and QLDC. These three data sets were merged by New Zealand Aerial Mapping to create a combined dtm, and 0.5 m contour plots were developed from this model. These data were used for the detailed mapping of landforms around the Glenorchy township. The area covered by these data extended from the north bank of Buckler Burn, along the Lake Wakatipu shoreline, and around the north side of the town adjacent to the Glenorchy wetland.

Section 3 Landscape Setting

3.1 Head of Lake Wakatipu

For many years the study area was known as the Head of Lake Wakatipu, and Glenorchy, Diamond Lake, and Paradise were well known destinations for the more adventurous nineteenth century tourist, while today the area is the gateway to the Routeburn Track. The head of the lake area is a large basin, flanked to the east by the Richardson Mountains, to the west by the Humboldt Mountains, and Mt Alfred Ari to the north.

The Richardson Mountains rise steeply above the eastern shores of Lake Wakatipu to 2,300 m above sea level (asl), which is some 2,000 m above the lake. However, only the lower 400 m of these slopes are of concern to this study. These slopes are largely devoid of trees except in the floors of the larger tributary streams. The Humboldt Mountains are on the western side of the basin, and also rise to 2,348 m, although the whole lower slope area here is forested. Mt Alfred Ari is an isolated block between the Richardson and Humboldt Mountains, and is flanked by the Dart and Rees River valleys.

The floor of the basin is 3.6 km across at the head of the lake, expanding to 5.6 km across in the north of the study area where the valleys of the Dart and Rees Rivers merge. The basin floor is mostly occupied by the combined floodplains of the Dart and Rees Rivers, and these large braided rivers are building a delta that is slowly infilling the lake. The Dart River is the largest, with the present fairway ranging from 1.0 – 1.5 km across, while the Rees River fairway is only 160 m – 400 m wide. Despite the Dart River and its fairway being much the larger, the broader floodplain environments of each river are more similar in size, with the Dart floodplain occupying about 55 – 60 % of the basin floor, and the Rees floodplain 40 – 45 %.

Lake Wakatipu is the other main element of this landscape, marking the southern boundary of the study area. Its mean level is today at about 310 m asl, although it varies through a range of nearly 3.9 m (see Section 2.2). Mostly the lake is within a one metre range from 309.5 m to 310.5 m where it is found 87.8 % of the time. The lake level has fluctuated in this range for at least the last 145 years, but there is clear evidence for a much larger Lake Wakatipu in the more distant past when it was at least 60 m deeper than at present (see below, Section 4.2). Although the lake reaches depths of over 300 m, it is mostly less than 50 m deep between Glenorchy and Kinloch. However, the bathymetric survey from 1968[1] show there is a steep sub-lake delta front sloping down at 1 in 24 to merge with the flatter lake floor at 150 m depth around 3.4 km south from Glenorchy[2].

Tributary streams enter the basin from the Richardson Mountains, and the larger ones have formed suites of landforms at the side of the basin. The largest is Buckler Burn, which along with Stone Creek has built a suite of landforms 1.4 km wide by 2.7 km long around and to the south of Glenorchy (see Figure 4-2). These comprise alluvial fans, terraces, deltas, and lake shorelines. Precipice Creek at the northern end of the study area has formed a similar but much smaller set of landforms.

Numerous other small streams flow off the Richardson Mountains, but these have not constructed significant landforms, except for Bible Creek, and an unnamed stream between Buckler Burn and Stone Creek. These two streams have formed unusual erosion gullies cut into the fan-delta deposits of Buckler Burn. These are discussed below in Section 8.

3.2 Floodplain changes

The Rees River, and to a lesser extent the Dart River are major influences on the flood hazards existing at Glenorchy. The geomorphic history of the floodplains has influenced the pattern of flood hazard and this is described in this section. Data has been obtained from the survey plans, historical photographs,

[1] Irwin, J. 1972 *Lake Wakatipu Bathymetry* NZOI Lake Series Chart, 1:63360.

[2] Brodie, J.W. & J. Irwin 1970 NZ Journal of Marine and Freshwater Research 494): 479-96.

aerial photographs, and topographic maps as described above, and for the Rees River repeated cross section surveys are available.

Long-term hydrological data is not available for the Dart River as hydrological records only start in 1996. Johnstone (1999)[3] compiled a list of floods from newspaper records and personal accounts, identifying events that he rated as the greatest experienced in the Dart and Rees Rivers. These were in January 1924, February 1952, October 1978, January 1983, January 1994, and December 1995. Other well-known floods occurred in September-October 1878, and November 1999. Large flood events like these are likely to have significantly affected floodplain geomorphology.

3.3 Dart River floodplain changes

The Dart River sector of the head of Lake Wakatipu area is about 2.0 – 2.7 km across, and is separated from the Rees River by a strip of grassed floodplain 0.2 – 1.3 km across, except for the 80 m wide gap that allows the Rees River to enter the Dart fairway about 1.6 km north of Glenorchy. The area is shown in Figure 1-1. Most of the sector is occupied by the braided fairway that is 0.8 – 1.7 km wide. In December 2006 OPUS surveyed a transect across the fairway near the delta front and this shows at least 9 braid channels, some up to 30 m wide and 2 m deep.

3.3.1 Dart River floodplain changes 1871 - 2006

Adjacent to the fairway are areas of grassed floodplain. On the western valley side these areas show a distinctively braided pattern reflecting their origin as former elements of the active fairway. However, on the eastern side this braiding pattern is absent, and it is reported that this area comprises deep silt deposits (Russell Reid, *pers comm*). It is therefore interpreted as an area of overbank flood deposition.

A number of changes have occurred across the Dart River fairway and floodplain since the first survey plans were complied in the 1870s.

The Dart River floodplain is shown in the 1871 survey plan (SO 1833). The fairway was 1.0 – 1.6 km across, similar to its width today, but there was a large 90 ha vegetated island 2.7 km long, and up to 640 m wide on the eastern side of the fairway and extending down to about opposite Glacier Burn on the Humboldt Range. On the western side of this island the main braided fairway was up to 1.2 km wide and extended to the base of the Humboldt Mountains on the western valley side. The edge of the grassed floodplain separating the Dart and Rees Rivers was about 150 m west of its present position.

The next available sources of floodplain information are the 1966 aerial photographs, and these show the whole Dart River area. In the 95 years since 1871 the fairway had moved to the east, and the large island in the floodplain had been eroded away. A large grassed area had developed on the western side of the fairway, extending some 1.2 km out from the valley side, and the eastern side of the fairway had moved about 150 m into the grassed area between the Dart and Rees Rivers. The braid pattern shows flow distributed reasonably evenly across the fairway.

In the 1977 aerial photographs there is a large main braid that meandered across the fairway, and enters the lake through the central and eastern sectors of the delta. In the eleven years since 1966 there had been only one major flood in December 1967.

By 1998 the fairway had been significantly reorganised. The main braid no longer meandered across the fairway, but was close to the western side from at least 5 km north of the lake, and the main discharge of Dart River water into Lake Wakatipu was in the western sector adjacent to Kinloch. In the eleven years since 1977 there had been five major floods and 16 events greater than the mean annual flood. In addition, in 1978/1979 there had been five floods in ten months. This active period of floods caused significant channel change in the Dart River fairway.

[3] Johnstone, N. 1999 *Queenstown-Lake District Floodplain Report*. Otago Regional Council Report.

The main braid pattern was similar in 2001. The 1999 flood, the largest on record, had not significantly altered the arrangement of the fairway. Satellite imagery from 2006 in Google Earth shows continued concentration of braid channels on the western side of the fairway, particularly in the lower 1.4 km of the fairway where the main braid was adjacent to true right bank.

This pattern of change shows that since 1966 the fairway as a whole has been widening by eroding the previously grassed floodplain on its western side. This is likely to be due to the main flow being on this side of the valley here from after 1977. Considerable areas of productive land have been lost. In the north opposite Turner Creek a strip of land over 450 m wide has been lost, covering a total area of ~40 ha. Closer to the lake in the 2 km long strip between Woodbine Station and Kinloch, 330 m has been lost, covering ~ 60 ha. Most of this erosion occurred between 1977 and 1998.

This loss of land along the western side of the fairway is reflected in the more prominent recent growth of the Dart River delta at its western side as discussed below.

3.3.2 Causes of Floodplain Changes

The above analysis of aerial photographs does not permit an assessment of potential increases in bed load movement, and repeated cross section surveys of the Dart River fairway have not been carried out from which bed aggradation could be measured. Thus, it is not known whether there has been an acceleration of bedload movement, and the lack of clear evidence of an increase in delta growth (see Section 5) suggests this has probably not been occurring. Furthermore, there is little evidence for widespread fire or bush clearance in the Dart catchment that could have resulted in an increased supply of gravel, and while tributary streams like Glacier Burn, Turner, Kowhai and Scotts Creeks do carry significant volumes of sediment from the steep slopes of the Humboldt Mountains down to the Dart floodplain, this material does not appear to have been transported to the Dart River fairway.

The floodplain changes documented above are largely ones of erosion, related to the migration of braid channels across the fairway. It is considered most likely that this erosion has been driven by the normal oscillations of a large braided river, and it is therefore a natural process.

3.3.3 Future Floodplain Changes

The data presented above shows a braided river behaving in a manner typical of such systems. Based on trends to the present day, it is expected that future floodplain changes would follow similar patterns. Aggradation within the fairway does not appear to be occurring, and the river seems to be able to transport the sediment supplied to it to its delta front. Erosion of the banks of the fairway will continue to occur where major braid channels impinge on the banks. At present, much of the true right bank for about 5 km north of the lake is threatened by this process.

3.4 Rees River floodplain changes

3.4.1 Lower Rees River Floodplain

The Rees River occupies the eastern 1.7 km of the Dart/Rees River floodplain, and the lower section discussed in this report is shown in Figure 3-1. This smaller river has been subject to fewer changes than exhibited by the Dart River. When first mapped in the 1870s (SO 1835 – 1837), the river flowed generally south in a 300 m wide fairway. The fairway became narrower downvalley, particularly downstream from the Precipice Creek junction. At about 1.6 km north of the lake, the river split into two branches, with the larger eastern distributary flowing southeast into the Glenorchy Lagoon area, and the smaller western branch flowing in a course 0.5 km to the west, directly south to Lake Wakatipu. These two river courses are shown as Distributaries 1 and 2 on Figure 3-1. There does not appear to have been any connection between the Dart and Rees Rivers at this time, although there was only a narrow 30 m neck of land between them about 1.6 km from the lake.

The 1937 aerial photographs cover the Rees River and show that while there had been some re-organisation of the channel margins, the fairway was essentially in the same place as 62 years previously, and there had been no significant changes in width. However, the lower 1.6 km of the river had been re-organised as there were now three distributaries here. There was a direct connection through to the Dart River fairway (distributary #3 on Figure 3-1), which was probably active during floods. Distributary #2 was small but actively carrying water south towards the lake. Distributary #1 was the largest channel, carrying most of the Rees River flow along the western side of the old lagoon area to discharge into Lake Wakatipu adjacent to Glenorchy. The location of this fairway had shifted about 200 m to the west.

From 1937 to 2001 there have been few changes in the Rees River floodplain, although the balance of flow in the three distributaries has varied. Survey plan SO11999 shows the lower Rees River in 1955. Only the distributaries 2 and 3 are shown carrying water, and there is no flow going into the former Glenorchy lagoon area. This pattern persisted in 1966 and the main river flow appeared to pass through the gap to the Dart River fairway and distributary #1 was narrower and only active during floods.

In 1977, the general arrangement is very similar, with most Rees River flow passing through the gap into the Dart River fairway. The 1988 photograph is taken during flood conditions, and the bulk of the Rees River flow is passing southwest in distributary #3 through the gap into the Dart River.

By 1998, there had been a significant change, and the bulk of the Rees River flow now entered distributary #1 to flow to Lake Wakatipu past Glenorchy. A large tongue of gravel appears to be advancing into the head of this channel. Distributary #2 was by this time very small, and did not appear to

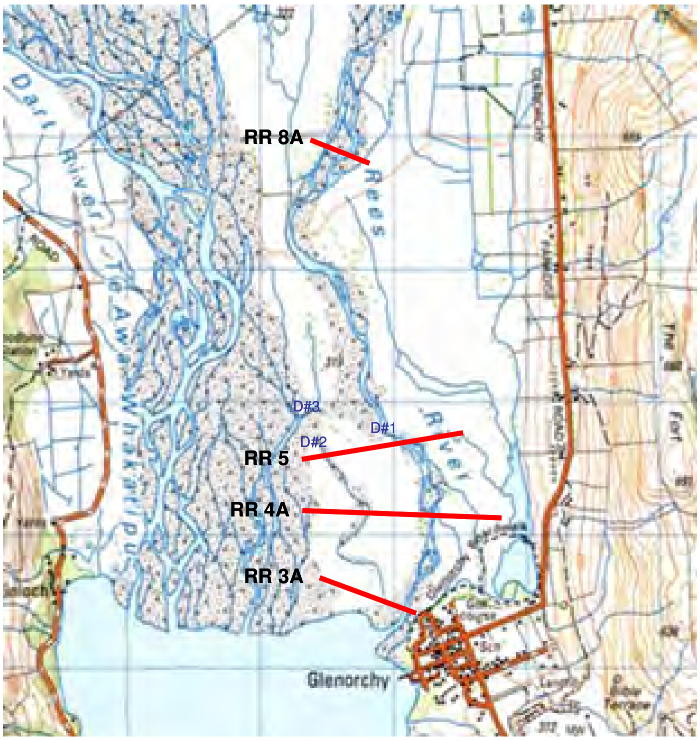

Figure 3-1 Lower Rees River floodplain (Transects labelled RR. Distributary channels D#.)

carry significant flow. In 2001 the gravel tongue is still in place, having not been significantly altered during the 1999 flood. Distributary # 2 was almost dry, and all Rees River flow is now passing down the eastern channel (Distributary #1) past Glenorchy.

The 2006 satellite image in Google Earth shows the Rees River flow approximately evenly divided between Distributary #1 and Distributary #3. The gravel tongue has not advanced further into the head of Distributary #1, rather the whole front of the tongue from Distributary #1 across to Distributary #3 (a distance of 480 m) has advanced 15 – 20 m south across the northern edge of the floodplain island that separates the Rees fairways.

The balance of flow in the distributaries is believed to be related to the arrangement of gravel bars in the area where the three channels originate about 1.5 km north of Glenorchy. This natural pattern of change is important, as it shows that over the last two decades there has been a re-organisation of gravel lobes in the Rees River at the point where the distributary channels diverge. When gravel builds up at the head of a distributary, flow will tend to be directed to other channels. Thus, gravel accumulation in the heads of distributaries 2 and 3 is now directing most Rees River flow into distributary #1. If the gravel tongue at the head of this channel begins to migrate downstream, a significant phase of aggradation could occur along this reach, and this would adversely affect the viability of the Rees/Glenorchy stopbank.

3.4.2 Bed Level Changes

Cross sections have been surveyed across the Rees River floodplain on several occasions since 1984 by Otago Regional Council. The transects relevant to this study, and their locations are shown on Figure 3-1. At each location the surveys show there has been reorganisation of the locations of bars and channels within the fairways as would be expected in a fluvial system. Changes in weighted mean bed levels of the four transects that cross the fairway of distributary #1 are shown in Table 3-1.

Table 3-1 Changes in Lower Rees River Fairway Weighted Mean Bed Levels, 1999 - 2006

Cross section #	Distance from lake (km)	Width of fairway (m)	7/06/1984	11/08/1990	5/05/1999	1/07/2003	20/12/2006	Rate of change* (mm/yr)
			Weighted mean bed level (m)					
RR8A	4.35	330	320.32		320.43	320.48	320.53	9
RR5	1.68	180		313.93	313.85	313.99	314.02	6
RR4A	1.05	150			312.57	312.60	312.57	ns
RR3A	0.28	155			311.12	312.04	311.02	ns
Lake	*0.00*						*310.00*	

* Linear regression. Trend for RR8A is strong (R^2 = 0.98), and weak for RR5 (R^2 = 0.31). No significant trend for RR4A and RR3A.

This shows that despite the shifts in bar and channel locations, and the large flood of November 1999, there has only been a trend towards slight fairway aggradation in two cross sections. At cross section RR8A the bed level has risen 0.21 m since 1984, at a rate of 9 mm/yr. There has been a consistent trend of aggradation here for the past 22 years, although the total increase of 0.21 m is not great. At RR5 the bed has risen at a rate of 6 mm/yr since 1990, although this trend is not statistically strong. The bed level dropped between 1990 and 1999, but rose after the 1999 flood, and has continued to rise since then. As noted above, there is a large accumulation of river gravel just upstream of this site, and the changes documented here may show that this material is being transported slowly downstream. This issue is discussed below in Section 6.4.

Cross sections RR4A and RR3A are close to Glenorchy. There is no significant trend of fairway weighted mean bed level change at these sites since 1999.

3.4.3 Upper Rees River Floodplain

The upper Rees River floodplain runs for 7.5 km north of Precipice Creek. This has not been examined in detail as it is outside the main study area. However, some observations were made, and bed level changes have been documented from the OPUS cross section surveys as shown in Table 3-2.

Table 3-2 Rees River fairway weighted mean bed level change (1978 - 2006)

Cross section # and location	Distance from lake (km)	Width of fairway (m)	2/08/1978	7/06/1984	16/07/1987	24/04/1996	5/05/1999	1/07/2003	20/12/2006	Rate of change (mm/yr)+
			Weighted mean bed level (m)							
RR18A Below Lovers Leap	14.62	360	367.42	367.58				367.70	367.67	8
RR17	14.02	105	363.58	363.56		363.40	363.70	363.61	363.75	
RR15	12.30	440*		353.69	353.71#	353.85	354.01	353.83	353.65	
RR14A Twelve Mile Creek	11.84	450*			351.04#	350.87		351.04	350.93	
RR14	11.19	300*		347.43		347.45	347.54	347.59	347.54	6
RR13 Davidsons Creek	10.08	680*				341.19	341.27	341.39	341.30	12
RR12 Upstream of bridge	8.84	430*		334.65		335.08	335.09	335.23	335.23	27
RR11 Downstream of bridge	7.83	390*		330.63		330.91	330.96	331.00	330.97	16

* Width constrained by stopbank(s)
# full width of fairway not surveyed
+ Linear regression. Trend for RR18A is strong (R^2 = 0.83), RR14 is moderate (R^2 = 0.69), RR13 is moderate (R^2 = 0.50), and RR12 is strong (R^2 = 0.95). No significant trend for RR17, RR15, and RR14A.

The Rees River leaves its narrow valley between the Richardson Mountains and the Mt Earnslaw massif near the Lovers Leap peak, some 13.5 km from Lake Wakatipu, and 7.4 km north of Precipice Creek. In this reach it is joined from the true left by Twelve Mile Creek, which has a small hydro power station, Davidsons Creek, and Precipice Creek, all of which drain from the Richardson Mountains, and the river channel runs close to the base of these mountains. When in flood, these streams deliver significant bed load to the main river.

On the true right side the river flows past an open valley between Mt Earnslaw and Mt Alfred Ari, and Diamond Creek is the only tributary. Despite draining a large catchment that includes Earnslaw Burn and Diamond Lake, this stream delivers very little sediment to the Rees River due to the flood buffering and sediment trap effects of the lake. The road to the Routeburn Track and Paradise crosses the river 1.25

km upstream of the Precipice Creek junction. This bridge was opened in March 1957, replacing a much older structure that had been built in 1921 some 5 km upstream. This has been damaged during the January 1952 flood. Old piles from this bridge can still be seen in the river bed (Thomson, *pers comm* 16/7/2007) suggesting limited aggradation here over the last 50 years.

This western side of the Rees Valley contains numerous terraces up to about 40 m above river level. These had probably been formed in the late retreat stage of the Rees and Dart glaciers around 13,000 years ago, and during the following period when greater Lake Wakatipu (see Section 4.1.4) probably extended into this area. The present floodplain of the Rees River is constrained between these terraces and the lower slopes of the Richardson Mountains. It is up to 1 km wide on places, although the active fairway is narrower, varying from about 300 m to more that 750 m, although this has been narrowed between stopbanks constructed along much of this reach.

Photographs in the Burton Brothers catalogue taken in the early 1880s (BB1840, 1841, 1843) show the Rees River fairway in the upper part of this reach around transects RR18A and RR17. It is very similar to today's fairway showing a braided channel that had recently been swept clean by a large flood, possibly the 1878 event of a few years earlier. When the original bridge was constructed in the early 1920s close to the location of transect RR17 the fairway was somewhat different as it was incised in a single channel some 3 m below the level of the floodplain[4]. By the time the bridge was replaced, the fairway had built up to be level with the floodplain. From Table 3-3 it can be seen that apart from small build up at RR18A, this 2.5 – 3 km reach covering transects RR17, RR15, and RR14A has not aggraded since 1978.

From transect RR14 downstream there has been fairway aggradation, and this increases downstream reaching a peak at RR 12 of over 2.6 cm/yr, and declines again downstream of here. The increased rate of aggradation coincides with the part of the reach most affected by stopbanks, and this is consistent with observations reported by Davies and McSaveny[5], who note that where rivers are constrained between stopbanks they commonly then show trends of bed aggradation. However, in this case, the downvalley pattern of fairway aggradation could reflect a wave of bed sediment moving down the channel, and this would be consistent with the changes in fairway character implied by the historical photographs and anecdotal evidence noted above.

The aggradation at the Rees River bridge is causing problems there as in places there is only 2 m clearance between the bridge deck and the river bed. Local reminiscence suggests it was possible to drive a bulldozer under the bridge when it was first built, and this is clearly not possible now. If the aggradation here is part of a wave of sediment moving downvalley, the rate could begin to slow in future years. However, if this sediment wave effect is the case, it would likely continue to move downstream and could cause significant problems when it passed Glenorchy. Aggradation of the fairway there would significantly increase flood risk in the northern parts of the town. It is recommended that a regular programme of transect surveys be continued to document future patterns of aggradation.

[4] Chandler, P.M. 1984 *Head of Lake Wakatipu Schools Centennial 1884 – 1994.* Central Otago Newspapers Ltd, Alexandra, 56 p.

[5] Davies, T.R. and M.J. McSaveney 2006 Geomorphic constraints on the management of bedload-dominated rivers *Journal of Hydrology (NZ)* 45(2): 111-130.

Section 4 Definition and Analysis of Landforms

Landforms in the study area are shown in Figures 4-1 and 4-2. Three groups of landforms are identified (from oldest to youngest):

- Landforms of the glaciated slopes of The Fort ridge;
- Landforms of the fan-deltas of Buckler Burn and Precipice Creek; and
- Landforms of the Rees River floodplain.

4.1 Landforms of the glaciated slopes

The steep slopes of the Richardson Mountains have been extensively affected by glacial action. The Wakatipu Glacier flowed past here on numerous occasions over the last 2.5 million years, the most recent glacial advances occurring between about 20,000 and 14,000 years ago. A number of glacial landforms were formed and deposits have accumulated, along with other fluvial and lacustrine features formed in close association with the glacier.

4.1.1 Ice smoothed slopes (I)

The middle slopes of the Richardson Mountains have been extensively ice-smoothed, and this presumably happened over numerous glacial cycles. The smoothing has exploited weaker layers in the schist foliation and produced low ridges a few metres high, oriented north-south parallel to the direction of the main valley, ice flow, and the strike of the schist foliation.

4.1.2 Till mantled slopes (Tm)

Below the Fort ridge, the lower slopes of the Richardson Mountains are mantled with glacial till, a poorly sorted, non-bedded mixture of boulders, gravel, sand and silt. This appears to be no more than about 1 – 5 m thick, and is plastered over the underlying schist. It was deposited as basal till beneath the glacier, and was left behind as the ice level shrank after the last main advance. On the lower parts of these slopes this material has been eroded by running water to form small linear gullies

4.1.3 Ice marginal alluvial fans (Imf) and meltwater channels (Imw)

During the last main ice advance the glacier level was at about 600 – 650 m asl, more than 300 m above the present lake level. The Fort ridge stood just above the ice surface, and ice marginal meltwater streams drained from Precipice Creek and Buckler Burn along the Chinamans Flat valley. Both of these streams formed high level alluvial fans that block the northern and southern ends of the valley. The Buckler Burn fan is pock-marked with small depressions that are interpreted as kettle holes formed by blocks of melting ice, indicating the close presence of nearby glacial ice during fan formation.

4.1.4 Lake bench (L)

Near the base of the Fort ridge is a prominent bench up to 200 m across, and lying at an altitude of 370 – 380 m above sea level. It can be traced for some 4.5 km from above the Glenorchy Wetland north towards Precipice Creek. It is interpreted as a lake bench, cut by wave action along the shoreline of a lake. It is probably in part structurally controlled by the underlying rock, but the inner side at the base of the steep slopes of the Fort Ridge shows characteristics of a wave cut bench and low cliff. It is interpreted as having been formed at the same time as fan-delta #1, which is graded to a similar level (see Section 4.2).

Section 4 Definition and Analysis of Landforms

Numerous high lake shorelines are known from around the Wakatipu Basin[1], and these are interpreted as belonging to expanded versions of Lake Wakatipu that had formed after the glacier had retreated, and before the present outlet through the Kawarau River had been established. The end moraine at Kingston would have dammed this lake, and the lowest outlet level there is at 355 m asl. Shorelines at around this height are known from various locations, and these are believed to be related to a greater Lake Wakatipu.

There is a small rockfall deposit on the upper slopes of the Fort ridge, and this is described in more detail below in Section 9. Much larger landslide landforms occur on the upper slopes above the Fort and Chinaman's Flat. These occur outside of the study area, and along with the small rockfall feature do not have any direct bearing on landslide hazards at Glenorchy.

4.2 Fan-Delta landforms

Fan-deltas are fluvial landforms that develop where larger streams carrying significant volumes of gravel enter a lake. Initially the landform was deposited directly into water to form a delta, while the later upper parts were deposited above lake level as an alluvial fan landform. Fan delta landforms occur at the mouth of Buckler Burn, and Precipice Creek.

At Buckler Burn, three phases of fan-delta accumulation can be identified, and these are identified on Figure 4-1 as FD. The present delta is described below in Section 4.2.4 and Section 7.

4.2.1 Fan-deltas (FD1, FD2, FD3)

Fan-delta #1 is preserved on the south side of Buckler Burn just as it leaves the mountains. The apex of the fan is just to the north of Wyuna Station at ~ 400 m asl, and it slopes down to 375 m asl some 700 m to the southeast. It is crossed by the Queenstown Glenorchy Road, and cuttings in the road side just south of the Buckler Burn bridge show it is underlain at 40 m below the surface by a poorly sorted diamict interpreted as basal (or lodgement) till. From this it is interpreted that the fan was initially formed in the early stages of retreat of the Wakatipu Glacier, and may have been built out against the retreating ice margin.

Fan-delta #2 is prominently preserved on both sides of Buckler Burn, and forms the high surface of Bible Terrace. This extensive landform occurs between 365 and 375 m asl, and remnants of it occur between Buckler Burn and Stone Creek, and also to the south where the Glenorchy airstrip is situated on this surface. On the south side of Buckler Burn the surface has three distinct levels, separated by 5 m high terraces. The maximum extent of these surfaces is to about 1.2 km out from the valley side, and there are 30 – 40 m high near-vertical slopes on all of the outer parts of these features.
Exposures of the sub-surface gravels in the sides of the Bible Stream gully and on the south side of Buckler Burn show ~20 m of foreset-bedded deltaic gravels, overlain by ~10 m of horizontally bedded alluvial gravels.

Fan-delta #3 is only preserved in the outer part of the suite of terraces that forms a northwest trending peninsula between Buckler Burn and Blanket Bay. They occur between about 355 and 325 m asl, the lowest of which is only about 5 m above the present bed of Buckler Burn. There are five different terrace levels, and the surfaces are distinctively patterned with braid channels. In some places, the top ~1 m of these sediments show characteristics of well sorted beach gravel. As the greater Lake Wakatipu environment became established after the formation of fan-delta #2, Buckler Burn started to cut a wide valley into these older fan-delta deposits, and a new fan-delta was formed graded to the 355 m lake surface level. Gradually, as the lake levels continued to fall, lower fan-delta landforms were formed graded to the new base levels, and the top surfaces of the landforms were slightly re-worked by wave action.

[1] Barrell D.J.A. *et al* 1994 *Surficial geology of the Wakatipu Basin, Central Otago, New Zealand*. Institute of Geological and Nuclear Sciences Report 94/39. 31 p.

4.2.2 Lake Shorelines (Ls)

A distinctive suite of high lake shorelines is seen on the north face of the Bible Terrace, and their very level linear form apparently was the source of the name Bible. Similar shorelines are preserved on the south-facing slope overlooking the north of Blanket Bay, and on the west facing slope that drops down to the lake beside the airstrip.

At Bible terrace there are three distinct shoreline levels at 353 m asl, 344 m asl, and 332 m asl. They range in width from 7 – 25 m. The shorelines at the other two locations are similarly arranged. These features are believed to be related to greater Lake Wakatipu, around which several shorelines were formed from a top height of 355 m asl.

4.2.3 Lake Strand Plain (Sp)

A lake strand plain is mapped at Glenorchy between the base of the Fort ridge, out to about the end of the Bible Terrace and extending north to the Rees/Glenorchy floodbank. This landsurface slopes north from about 325 m down to 311 m asl, and is generally devoid of micro-relief forms except for small areas south of Shiel Street, and through the golf course. Here the ground surface has small lineations that show clearly on the 1937 aerial photographs. These small ridges are oriented approximately east-west, are several hundred metres long, 2 – 3 m apart, and no more than a few tens of centimetres high. There are some 15 – 20 of these in both areas. They are interpreted as strandlines formed by small waves as greater Lake Wakatipu fell quite quickly through the last 14 m to its present level.

4.2.4 Buckler Burn alluvial fan (BAf)

The Buckler Burn alluvial fan is in effect a presently forming fan-delta. However, the delta part of the fan is of restricted extent out from the shoreline of the present floodplain, and it is described in more detail below in Section 7. The main bulk of the alluvial fan extends north from the present stream floodplain to the Rees River floodplain area, and most of Glenorchy is built on this landform.

The Buckler Burn alluvial fan consists of two main elements. An older set of terracettes, and overbank deposits (BAf_1), and a younger suite of braid channels (BAf_2) just to the north of the present floodplain.

The older suite of landforms (BAf_1) is subtly developed, and has been largely obscured by urban development. They are best seen on the 1937 aerial photographs. The outermost extent is marked by the bulge that juts out into the Glenorchy wetland just west of the shallow depression that cuts through the middle of the rugby grounds/golf course area. This then sweeps around in an irregular arc to the west past the old jetty, and south along Benmore Place to the edge of the present Buckler Burn delta. It can be traced south into the valley of Buckler Burn and occurs on the lower terrace below Campbelltown. The eastern side of the fan-delta (mainly to the east of Oban Street) comprises overbank deposits that have been laid down about 0.5 m deep over an older lake strand plain (described above). West of this the fan surface is patterned with terracettes and braid channels that show flow paths that trend around from northwest to west, and entered the lake across the area now occupied by Benmore Place.

The younger suite of alluvial fan landforms (BAf_2) occur below a 1 m high terrace that runs north about 50 – 75 m east of Oban Street, crosses between Shiel and Coll Streets, then swings west across Argyll Street. The surface here is patterned with braid channels.

From this arrangement of landforms, it is interpreted that as Lake Wakatipu fell to its present level, Buckler Burn established a course mainly to the northwest, and it formed a low angle alluvial fan. During floods, the stream extended to the east, depositing the overbank sediments on top of the older lake strand plain landforms. Gradually the trend of stream flow moved westwards and southwards as Buckler Burn shifted towards its present course along the south side of the township.

These fan delta landforms set the boundaries of the environments within which present hydrological systems operate. The features of the Buckler Burn alluvial fan are important as most of Glenorchy is built on this landform, and the surface micro-relief of braid channels and terraces will control the direction of movement of any overland flow.

4.3 Floodplain landforms

The floodplains of the Dart and Rees Rivers contain a number of landform types, and these were described in more detail above (Section 3). Much of the Dart floodplain is occupied by the presently active braided river fairway (F). Away from this area, the floodplain is different on the true left and true right banks. On the true left the floodplain comprises and area of overbank deposits (Fo) consisting mainly of silt. On the true right, the floodplain comprises an abandoned fairway with well preserved braid channel landforms.

The Rees River floodplain is different in character as the braided fairway occupies only around a third of the floodplain width. Along much of its length south of Precipice Creek, the fairway is above the general floodplain level. There are some overbank flood deposits away from the main channel, but much of the floodplain is poorly drained swamp and wetlands (Fw, and where these have been drained Fwd).

4.3.1 Gullies (G)

Gullies have been eroded into the terrace landforms of fan-delta #2. These occur on the Bible Terrace, and to the south above Blanket Bay, and are described in detail in Section 8 below.

4.3.2 Alluvial fans (Af)

A number of streams flowing into the Head of Lake Wakatipu basin area have formed small alluvial fans. Two in particular are relevant to this study, the Bible Stream fan (see Section 8), and the Precipice Creek fan. They are identified separately from the larger fan-delta landforms associated with Buckler Burn as they do not form deltas in Lake Wakatipu.

4.4 Sequence of Landforming Events

From the arrangement of the various landforms described here, a relative sequence of landforming events can be defined (from oldest to youngest)

1. Lateral basal till deposits and high level alluvial fans in Chinamans Flat formed when the Wakatipu Glacier had advanced during the last glacial maximum about 14,000 to 20,000 years ago.
2. The Wakatipu Glacier then began to shrink, and ice marginal lakes formed along the valley side. The 375 m lake bench between Bible Terrace and Precipice Creek was formed at this time, along with fan-delta #1. Continued shrinkage of the glacier, resulted in the deposition of fan-delta complex #2. These events probably took place over about 2,000 years so that by 12,000 years ago the Wakatipu Glacier had ceased to exist, having retreated out of the Wakatipu basin into the headwaters of the Dart and Rees Rivers.
3. As the glacier retreated it was replaced by greater Lake Wakatipu, and shorelines were formed at 353 m – 332 m asl on the north face of Bible Terrace and to the south at Blanket Bay and the airstrip. As the lake level lowered, Buckler Burn was able to form fan-delta complex #3. By this time the Dart and Rees Rivers were also beginning to infill the lake with delta sediments, although how far upvalley from the present delta is unknown.
4. As the lake level fell to its present height, the Glenorchy strand plain was formed on the gentle slopes north of the Bible Terrace.
5. Buckler Burn then began to form fan-delta #4, flowing to the north and northwest and reworking the western parts of the strand plain. Occasional floods deposited overbank sediments on the eastern parts of the fan-delta. The stream then formed a new floodplain level that extended about

250 m north of the present fairway and the edge of this marked by a 1 m high terrace. The Bible Terrace gully was also probably initiated during this phase.

6. The present phase of landform development is associated with Buckler Burn in its current floodplain environment to the south of Glenorchy, and it is actively forming a significant delta in Lake Wakatipu. This phase probably began several hundred years ago. The Dart/Rees delta environments are also advancing much closer to Glenorchy, and in future centuries will move past Glenorchy.

Section 5 Delta Progradation

5.1 Head of Lake Wakatipu Delta Environments

Ever since the earliest recorded observations of the Head of Lake Wakatipu area it has been noted that the combined deltas of the Dart and Rees Rivers have been advancing into the lake[1]. However, the rate of progradation has not been documented. In this section, data on delta front positions is complied, and processes of delta growth are described. In addition, growth of the nearby Buckler Burn delta is examined.

The direct distance from Glenorchy across to Kinloch is 2.7 km, but following the shoreline it is 3.11 km, and four different shoreline types can be identified. The main aggrading shoreline elements are the large Dart River delta front, and the smaller Rees River delta adjacent to Glenorchy. On the western valley side adjacent to Kinloch is a short section of stable shoreline, while a further section of more stable shoreline occurs between the Dart and Rees River deltas.

On the western side the shoreline extends 415 m from Kinloch and comprises a well formed beach landform. Early survey plans and historic photographs show that originally there were gaps in this beach that opened into small lagoons behind. These have been in-filled, but the position of the main lake shoreline appears to have changed little over the last 130 years.

The active delta front of the Dart River extends for 1,920 m and now forms a gentle arc across most of the head of the lake shoreline. When first seen, it formed a straight line across the head of the lake, appears to have been some 180 – 200 m back from its present position. On the 2001 aerial photographs this delta shoreline comprises numerous sections of wave-formed beach ridges, separated river braid channels. The ridges are up to 200 m long and 15 – 20 m wide, and in total occupy ~910 m of the delta shoreline. Earlier aerial photographs show similar patterns. The eastern ~350 m of the Dart delta is in part formed of Rees River-derived sediment as the Rees River enters the Dart fairway during flood conditions through a gap 1.5 km north of the lake.

There is a short 200 m section of more stable shoreline between the Dart and Rees deltas. Aerial photographs from 1937 onwards show this is usually a beach landform up to 25 m across, and it often encloses a small lagoon. The shoreline here has only advanced a few tens of metres since 1937.

The Rees River delta forms the eastern side of the head of Lake Wakatipu shoreline. It is 575 m across, and reaches almost to the Glenorchy jetty. Growth of this delta had probably begun by the 1890s, and by the mid 1930s it had probably advanced ~300 m necessitating the original Glenorchy jetty be moved 200 m south into deeper water.

On the south side of Glenorchy the Buckler Burn enters Lake Wakatipu in a broad delta front. It is over 800 m across, and has grown significantly since first mapped in 1864.

These three deltas are shown in Figure 5-1.

5.2 Dart River Delta

Information on delta growth can be derived from the 1875 survey plans, and 1937, 1966, and 2001 aerial photographs. These allow definition of the general pattern of delta advance. Information was also obtained from the 1977 and 1998 aerial photographs; however, due to the difficulties in identifying shoreline positions, detailed data from these years has not been included in this analysis.

The first detailed map of the Dart delta is a topographic survey plan SO 1833 dated 1871. There are some land parcel boundaries marked on the western side near Kinloch, and some of these still appear on modern plans. By overlaying these it suggests the delta may have grown 350 – 400 m between 1871 and 2001. However, the topographic details on the 1871 plan are not accurately shown and they do not

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[1] McKerrow, J. 1864 *Journal of the Royal Society London* 34: 56 – 82.

correlate well with more detailed plans made just four years later. Therefore, this mapping has not been relied on for this analysis.

Survey plans S) 1835-1837 were originally complied between 1871 and 1875. These show land parcel boundaries and some topographic details on the eastern half of the Dart/Rees valley. The land parcel outlines correlate well with modern plans, and thus the adjacent topographic details such as river positions, and the lake edge are considered to be reasonably accurately placed. Unfortunately only the eastern side of the area from Glenorchy across the mouth of the Rees River and then to the eastern side of the Dart delta shows on these plans (see Figure 5-1). They show there has been 180 – 200 m of Dart delta front advance here from 1875 – 2001. Survey Plan 1833 shows a uniform delta front alignment across the head of the lake, thus it is assumed that the portion shown on plans 1835-1837 is representative of the whole delta front.

The 1937 aerial photographs show the same eastern section of the delta as the 1875 plans. The Dart River delta front has advanced 85 – 145 m, although the shoreline between the Dart delta and the new Rees River delta appears to have only advanced about 30 m.

The 1966 aerial photographs and topographic maps NZMS 1 sheets S123 and S122 show the whole Dart/Rees delta environment. The eastern Dart delta had grown 25 – 55 m.

The 2001 aerial photographs and topographic map NZMS 260 sheet E41 show the most recent available information on the delta position, and it has continued to grow. The eastern third of the delta had advanced ~40 m since 1966, while the central third was in about the same position, or may have retreated slightly. However, the western sector had been more active, advancing up to 150 m. Most of this occurred between 1977 and 1998. It is interpreted that this rapid delta advance resulted from the loss of floodplain land that had occurred along the western side of the Dart River fairway particularly between 1977 and 1998.

From these data it can be calculated that the overall rate of delta advance from 1875 – 2001 was about 1.4 – 1.6 m/year. From 1875 to 1937 the eastern part of the delta advanced at between 0.9 – 1.6 m/year, and from 1937 to 1966 this part grew at 0.89 – 1.9 m/year, and from 1966 to 2001 it grew at about 1.1 m/year. The western sector grew at up to 4.3 m/year between 1966 and 2001.

5.3 Rees River Delta

Information on delta growth can be derived from the same plans and aerial photographs described above for the Dart delta. In addition, a 1905 survey plan also shows the delta front.

The Rees delta is immediately adjacent to the northwest part of Glenorchy township. It is a relatively recently developed landform, having only been present here since about 1890 – 1900. Prior to this time the area upstream of the delta had been an arm of Lake Wakatipu, as described in more detail in Section 6 below. The first survey plan showing the new Rees River delta is SO4464, and it is positioned very close to the original Glenorchy jetty that was located at the junction of Jetty Street and Lake Road. From this plan it is apparent that the overall delta advance between 1905 and 2001 has been 90 – 175 m

The 1937 aerial photographs show the delta in some detail, and it is in much the same position as in 1905. However, there must have been some advance of the delta as by that time the old jetty had been abandoned and a new jetty constructed some 220 m to the south[2].

The 1966 aerial photographs and topographic maps NZMS 1 sheets S123 and S122 show the Rees delta had advanced 70 – 100 m since 1937, mostly along the northwest sector.

The 2001 aerial photographs and topographic map NZMS 260 sheet E41 show the most recent information on the delta position, and it has continued to advance, growing some 85 – 105 m along its

[2] Henderson, J. 1937. Glenorchy District *Geological Survey Branch of the Department of Scientific and Industrial Research* 31st Annual Report, pp 16 – 22.

southeast parts since 1966. This growth appears to have been most rapid between 1977 and 1998. There was little or no growth on the northwest side of the delta.

From these data it can be seen that the delta grew very little from 1905 to 1937, but since then it has grown at an overall rate of about 1.4 – 2.7 m/year. From 1937 – 1966 growth was mainly in the northwest part at 2.4 – 3.4 m/year, and from 1966 to 2001 the southeast section advanced at 2.4 – 3.0 m/year.

5.4 Buckler Burn Delta

Growth of the Buckler Burn delta can be documented from a wide variety of plans, maps and aerial photographs, and is therefore the best known of the three deltas.

The original survey of the Glenorchy township street layout was made in 1864, and this showed the position of the shoreline along about two thirds of the Buckler Burn delta. Survey plan SO4460 shows the delta in 1889, and it had apparently advanced 60 – 75 m in the previous 25 years. A 1905 plan (SO 4664) shows the shoreline in the same position. By 1937 the delta had grown a further 45 – 90 m along the northern section. The southern 235 m section remained in the same position as in 1889 and 1905. By 1966 the shoreline had again advanced, this time by 20 – 45 m along most of the delta front. The 2001 aerial photographs show significant advance in the southern sector where up to 60 m growth has occurred. Across the central sector growth was around 20 m, while the northern 250 m had not changed since 1966.

The maximum growth from 1864 to 2001 has been 215 m at an average rate of 1.6 m/year. Growth has changed from being dominantly in the north sector of the delta from 1864 – 1966, to the south sector from 1966 to 2001. This reflects the changing positions occupied by Buckler Burn on its lower floodplain, and growth here was rapid during the floods of the 1990s that caused significant erosion of the terraces along the south side of the floodplain (see below Section 7.3).

5.5 Processes of Delta Growth

Deltas grow by deposition of river sediments, in particular the bedload transport of sand and gravel material. The sources of this material will include both sediment derived from tributary inputs, and erosion of the bed and banks of the main river. Typically, it would be expected that sediment that is delivered to the delta front will be carried over the edge and deposited down the advancing delta front to form foreset beds, and the shoreline would thus slowly advance. However, the process on the deltas at the head of Lake Wakatipu appears to be slightly different. In many of the aerial photographs, beach ridge landforms can be seen along considerable parts of the shoreline. It is postulated that these are formed by wave action during times when the lake level is relatively stable. These ridges then become of sufficient size to last for many months or years. Small lagoons can often be seen behind these ridges, and over time these are infilled with river-deposited sediment, and the shoreline of the delta thus advances. Typically, up to half the delta shoreline can exhibit these beach ridge landforms, while the remainder appears to be developing as the normal model suggests.

Evidence for broader patterns of sediment transport to the delta fronts can be interpreted from the above data. In recent decades about 100 ha of floodplain has been recycled into the Dart River along its true right bank. Topographic map contours indicate this bank could be up to 2 m high, thus about 2 million cubic metres of material may have been added to the bedload here. Transport of material to the delta front resulted in rapid advance of the shoreline here between 1977 and 1998. About 8 ha of new delta area has formed, and assuming this water was 25 m deep, the whole 2,000,000 m^3 of bank erosion sediment could have been accommodated here. This suggests that recycling of floodplain sediments could be a significant source of delta sediment at least locally and at times of fairway widening. However, these calculations are necessarily crude, particularly in the absence of detailed topographic and bathymetric information. It considered more likely that long term rates of delta growth will be related to the rates of sediment delivery from tributary inputs. This is consistent with observations that many of New

Section 5 Delta Progradation

Zealand's large rivers are under-supplied with bedload sediment and the rate of sediment transport is therefore strongly related to the rate of sediment supply[3].

The overall advance of the Rees delta has been much more rapid than for the Dart, particularly since 1937, although the delta area is much smaller. The relative balance of bedload transporting capacity of the two rivers is not known. However, it is unlikely that the Rees is a more active river than the Dart, and the greater amount of delta advance may simply be related to shallower lake water at its mouth. The rate of delta advance will also be related to the balance of flow in the three distributaries. The very slight change between 1905 and 1937 could be due to distributary #1 not being active during that time. However, the establishment of distributary #1 as the main Rees River channel from after 1988 does not appear to have resulted in an increased rate of delta growth.

Significant delta growth had occurred on both deltas up to 1998, and this includes the major 1994 and 1995 floods. However, from 1999 to 2001 there was little change in either delta, despite the major 1999 flood. This probably relates to the high lake levels at that time. The effective delta shoreline was more than a kilometre up-valley, and sediment transported down river may not have reached the actual delta front. In addition, the floods may not have carried much sediment having flushed their beds in the previous floods.

In summary, it can be seen that the natural rates of delta growth over the last 140 years have not been spectacular, and have proceeded at various rates in response to broad scale patterns of sediment delivery, and more localised patterns of floodplain erosion, and braid channel location. While it is expected that future climate change may result in greater flood frequency, sediment delivery to the delta front will still be limited by sediment supply. Unless climate changes result in greater delivery of sediment by tributaries, it is unlikely that future river sediment regimes and delta growth rates will be detectably different from the recent past.

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[3] Hicks, M. 2004 *NIWA Report CHC2004-053*.

Section 6 Glenorchy Wetland

6.1 Glenorchy Lagoon and Wetland

The Glenorchy wetland and lagoon area is identified in Schedule 9 of the Otago Region Water Plan as a significant wetland. Administered by Department of Conservation as a Wildlife Management Reserve, it is a regionally significant habitat for waterfowl and swamp birds, including paradise/mallard/grey ducks, black swan, grey teal, pukeko and oystercatcher. Water depth in the lagoon is about 0.5 m, and it covers about 16 ha. It is part of a wider wetland area that covers over 350 ha at its maximum extent from Glenorchy north to near Precipice Creek and lies 1 – 2 m below the adjacent Rees River. This area comprises drained farmland, swamps, irregularly flooded grasslands, small stream channels, and open water areas.

6.1.1 Catchment area and inflows

The catchment area for the lagoon covers 1,030 ha comprising 605 ha on the hillsides on the lower slopes of the Richardson Mountains, and 425 ha of floodplain environments adjacent to the Rees River. The hillside catchment area extends from near Precipice Creek south to the Bible Creek catchment. This latter 60 ha area was added to the catchment in 2000 when the Bible Creek diversion was constructed. A large northern part of the floodplain catchment covering 195 ha is farmland now intersected by over 10 km of deep drains that direct water into the main northern stream that feeds into the lagoon.

There are a number of streams that feed into the lagoon. A northern stream carries water from the slopes south of Precipice Creek and the drained farmland on the Rees River floodplain. Close by is a stream entering from the northwest that carries water from a large area of the Rees River floodplain, although there is no direct surface flow connection to the river. When the water table is high, a dense network of small tributary channels can be seen feeding into this stream. A further small stream drains into the northwest part of the lagoon. Along with the larger stream to the north, this inflow is considered to be from shallow groundwater fed by the Rees River that skirts along some 4 km of the north and west side of the wetland area. The Rees River fairway is 1.5 – 2 m above the wetland area, and this will provide the head difference to support this flow.

A stream also enters the lagoon from the south through a culvert under the Glenorchy-Paradise Road. This carries water from the southern slopes of the Fort ridge, and as noted above has recently been augmented by flow in the Bible Stream diversion.

6.1.2 Outflow from the Lagoon

Outflow from the lagoon is through a channel that carries flow about 1 km around the outside of the Rees/Glenorchy floodbank to the Rees River about 300 m from where it enters Lake Wakatipu. The outlet stream runs back through a small delta landform in the southern end of the lagoon. The grade of this stream is very gentle and appears to allow flow to reverse when water levels rise above about 311.25 m asl in the lower Rees River fairway.

In its downstream reaches the outlet stream carries significant flow, estimated to be several cumecs. Some of this may be augmented by surface or groundwater flow from the lower reaches of the Rees River, as the topographic map shows two distributary channels from the Rees River joining this outlet stream.

6.2 Environmental history of the wetland area

The Glenorchy wetland is a relatively recent development in this landscape, having only formed within the last 100 years. The environmental history of this area is documented below.

Section 6 Glenorchy Wetland

6.2.1 Wetland from 1860s – 1900s

When Europeans first arrived in the area in the early 1860s most of this area was a shallow lagoon that formed an arm of Lake Wakatipu. Alfred Duncan's account[1] of grazing stock at Glenorchy for William Rees in 1861/62 includes a map showing the lagoon, and Survey Plans 1836 and 1837 dating from 1874 show parts of the western and northern shores of the lagoon. From these it is estimated that the lagoon covered about 100 ha, and was connected to the main lake through a 250 – 300 m wide gap between Glenorchy and the Dart delta.

The survey plans show a branch of the Rees River flowing towards the northwest corner of the lagoon. However, this was probably not the main branch of the river as there is no obvious delta landform here, and the surveyor James McKerrow noted in 1864 that the Rees River entered Lake Wakatipu only a few yards east of the Dart River[2]. Likewise, Duncan's map shows the two rivers side by side, and he comments that he had built a hut opposite the mouth of the Rees River, where a large lagoon opened off the lake.

Photographs in the Burton Brothers catalogue show parts of this lagoon quite clearly in 1875 (BB492, BB496), in 1886 (BB 4410, 4411) and in 1888 (BB 4819). However, by the early 1890s the area appears to have begun to dry out. Image BB5113 dating from about 1891 shows the southern end of the lagoon area largely dry with numerous river channels and cattle grazing on the flats. (Images BB496 and BB5113 are shown in Appendix A). A 1905 survey plan covers the southern part of the lagoon area next to Glenorchy, and shows four channels of the Rees River flowing in from the north and combining to flow in a main channel along the whole northern town boundary where the floodbank now is. From these early maps, photographs and accounts, it is interpreted that over the forty year period from the 1860s to the turn of the 20th century, the lagoon area progressively ceased to be permanently occupied by Lake Wakatipu[3]. This probably resulted from a combination of aggradation raising the level of the entrance to the lagoon near the mouth of the Rees River adjacent to Glenorchy, and some infilling of the lagoon area by sediment influx during floods in the Rees River. By the early years of the 20th century several braid channels of the Rees River were actively flowing through the now dry lagoon area. With the area having turned to dry land, it became part of a "commonage" grazing area, and at least until the mid 1950s the area was referred to this way.

6.2.2 Wetland in 1937

The 1937 aerial photographs allow a detailed assessment of the area, and by this time there had been further significant changes. The main flow of the Rees River was confined in a braided fairway along the western side of the wetland area, and there were no visible active or dry channels into the eastern part of the wetland. The northwest part of the wetland area contained a dense network of small channels draining eastwards. These did not connect with the Rees River, but appeared to be sourced from shallow groundwater.

There was no obvious outlet for the lagoon. A small channel flowed along the southern end adjacent to what is now the Glenorchy golf course and this probably carried water in both directions. A small delta landform was developing at the lagoon end of the channel, presumably built by Rees River inflow during flood conditions. The open water area was in four discrete ponds, and covered 13.75 ha (see Table 6-1). There were very few trees in the wider wetland area, or around the shores of the lagoons.

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[1] Duncan, A. *The Wakatipuans or Early Days in New Zealand*, re-printed by Lakes District Centennial Museum Inc, 1964.

[2] McKerrow, J. 1864 *Journal of the Royal Geographical Society of London* 34: 56-82.

[3] In the course of the present study, other maps from the early years of the 20th Century were sighted that continued to show the lagoon. However, the photographic evidence of dry land here in the early 1890s suggests these maps may have been incorrect.

6.2.3 Wetland in 1966

The 1966 aerial photographs show a few changes to the wetland area. The open water area has formed into one lagoon covering 14.86 ha, an increase of just over 1 ha (see Table 6-1). The delta at the southern end of the lagoon is now fully formed, and there were a few trees on and around this landform. The channel network that drained shallow groundwater across the northwest end of the wetland area was no longer visible, and along the remaining water courses a few groups of trees were beginning to form. The nearby Rees River fairway had reduced in size and was no longer carrying much water as the main flow was passing west into the Dart River fairway.

Table 6-1 Change in open water area in Glenorchy Wetland, 1937 - 2001

Date	Open water area (ha)
1/04/1937	13.75
12/03/1966	14.86
12/02/1977	15.48
15/12/1988	8.50
27/11/1998	15.56
19/02/2001	15.73

6.2.4 Wetland in the 1970s – 1980s

In the 1977 aerial photographs many more small trees are evident on wetland flats, along water courses and in the southern lagoon area. The open water area has increased to 15.48 ha (Table 6-1). The Rees River fairway had reduced further in size and the main flow was still directed into the Dart River. However, the shallow channel network in the northwest part of the wetland area was again visible, presumably due to a higher water table level at the time. For the first time, a few farm drains can be seen in the area to the north of the wetland, and these take carry water south towards the lagoon.

The 1988 aerial photographs show a much smaller open water area, which appears to cover only 8.5 ha. The southern part appears to be dry or very shallow, and the delta landform here is now densely covered with trees. The Rees River fairway is still small, and most flow is passing into the Dart River. There are more trees lining the water courses that drain into the lagoon, but those out on the wetland flats are no longer present. More farm drains have been dug to drain the wetland area to the north.

6.2.5 Wetland since 1998

In the 1998 aerial photographs the open water area had recovered to 15.56 ha (Table 6-1). Large groups of trees occur around the margins, along the wetland watercourses, and the wetland flats area again support many small trees. The nearby distributary now carries the bulk of the Rees River flow, and more farm drains have been constructed north of the wetland.

During the 1999 flood the open water area greatly expanded in size, extending a further 1.2 km north and covering a total area of 70 ha. The normal open water area was occupied by sediment laden flood waters from the Rees River that covered about 54 ha. This is interpreted as a backwater effect due to the raised level of Lake Wakatipu at the time.

By 2001 the open water area had again increased slightly to 15.73 ha, and there had been continued expansion of tree cover in all areas. The main Rees River flow continues in the nearby distributary, and the network of farm drains appears to be unchanged.

In the 64 years since 1937 the open water area had grown by nearly 2 ha (a rate of ~300 m^2/year). However, the large reduction in area in 1988 shows the open water area is sensitive to changes of inflow.

6.3 Assessment of Wetland Change

The wetland area occupies a shallow depression that was formerly an arm of Lake Wakatipu. The lake appears to have ceased occupying this area by the end of the 19th Century, and this probably resulted from a combination of Rees River processes. There does not appear to be any impediment to the Rees River flowing directly into the wetland/lagoon area. However, this only appears to have occurred early on during floods when some aggradation would have occurred. The river does not appear to have had a permanent course into this area, instead occupying the three distributary channels to the west. As a result of this flood aggradation, this low lying area would have become increasingly shallow. In addition, aggradation and then delta growth by the adjacent distributary of the Rees River would have raised the level of the narrow entrance to the depression and closed off its direct connection to the lake. Lake Wakatipu now only enters this area during high flood levels above about 311.25 m asl.

Water level in the open water lagoon area reflects the local shallow groundwater regime, and this appears to be influenced by a number of factors that will affect both inflows and outflows from the lagoon, including:

- Climate related changes to inflow regime. Long dry spells will reduce inflows from all sources, while increased rainfall will augment inflows.
- Rees River flow paths. The Rees River is a source of shallow groundwater inflow to the lagoon. If it changes course to flow directly into the Dart River fairway, this groundwater source may be reduced.
- Farm drains. The construction of farm drains to the north of the wetland area since the 1970s has resulted in increased surface water flow to the lagoon. Further development of this network of drains will augment this effect.
- Diversions. The diversion of the Bible Stream has added a small volume of inflow to the lagoon; however, it is unlikely that any further diversions will be possible.
- Reduced capacity of the outflow channel due to sedimentation and or vegetation encroachment.
- Rees River aggradation. Build-up of the Rees River bed near Glenorchy could raise the outlet level causing the lagoon to enlarge.
- Change in regional groundwater level due to long term change in the mean level of Lake Wakatipu.

The main factors that could result in lower lagoon levels and thus reduce the open water area are likely to be related to inflows. If there is a shift to a drier climate, surface and groundwater inflows will be reduced, and lagoon water levels will decline. Similarly, if the Rees River changes course to direct more flow westwards into the Dart River fairway, the lower one kilometre reach of the eastern distributary will not be acting as an effective source of shallow groundwater, and lagoon water levels may fall.

Factors that could result in increased groundwater levels and expanded lagoon area are likely to be reduced outflow channel capacity, and aggradation at the junction with Rees River. Continued growth of willows along the outlet channel will reduce flow capacity, although this is likely to be a small effect for all but the larger outflows during storm conditions. Removal of these trees would readily mitigate this effect.

Continued delta growth has been suggested as a possible effect on lagoon water levels. However, this is considered unlikely unless there is also aggradation by the Rees River at its junction with the lagoon outlet. This could reduce the discharge capacity of the outflow. To date, this process does not appear to be occurring as analysis of bed levels in cross section RR3A at this point shows there has been no bed level increase between May 1999 and December 2006. This period included the November 1999 flood.

Climate change that leads to increased inflows to the lagoon is unlikely by itself to cause a long term increase in the open water area. Increased inflows would only result in raised water levels if the outlet channel was unable to carry the increased discharge, and the present outlet appears large enough to carry potential increased baseflow.

6.4 Potential for Loss of Glenorchy Wetland

As noted above, the Glenorchy wetland lies in a low area adjacent to the Rees River. Over the last 140 years the river has largely maintained a course along the western side of the wetland, at a level 1.5 – 2 m above the lagoon. There is no evidence that the river has ever flowed into the Glenorchy area. Should the course of the Rees River change so that it flowed directly into the wetland area, the lagoon would initially increase in size, then be filled with sediment. Assuming the current lagoon area is on average 0.5 m deep, approximately 80,000 m^3 of sediment would be required to fill it, and this could take less than 10 years.

It is not known why the Rees River does not flow directly into the wetland/lagoon area. Transect RR5 crosses the river at the same level as the north end of the lagoon. This shows the main fairway here is as little as 0.4 m below the floodplain, and at least one metre above the wetland. In the seven years from 1999 to 2006 the weighted mean bed level here increased 0.17 cm (see Table 3-2). If the large tongue of aggradation gravel in the fairway just 250 m upstream of this cross section were to move downstream, the river could easily shift course out of its present fairway and directly into the lagoon area. This sequence of events is considered highly likely to occur within the next few years if the main flow of the Rees River remains in this channel (distributary #1).

Section 7 Fluvial Geomorphology of Buckler Burn

7.1 Catchment

Buckler Burn drains the eastern slopes of the Richardson Mountains, from peaks in excess of 2,000 m elevation. The catchment area upstream of the Queenstown-Glenorchy highway bridge covers 50 km^2, and the upper eastern part is in two main branches: Buckler Burn to the north (17.3 km^2), and Wallers Creek to the south (14.7 km^2). The lower western parts are covered by three smaller catchments (Browne Jean Creek, Long Gully, and Chinaman's Creek).

The total catchment length is about 16 km. The lower 6.5 km part of the course is in a narrow gorge about 400 m wide at the top, and 150 – 200 m deep, cut into the base of a broader more open valley that had a floor at about 700 m asl. (This hanging valley landform is discussed below.) The gorge is cut in schist upstream of the bridge, but the last 1.8 km to the lake is cut through lacustrine and alluvial gravel deposits.

The catchment has been extensively glaciated. During the glacial periods, the Wakatipu Glacier flowed through the lake basin, and glaciers also flowed from cirques in the Richardson Mountains including the Buckler Burn catchment. In earlier glaciations, the Buckler Burn glaciers joined the Wakatipu Glacier and formed a hanging valley landform with the base of the valley at about 600 - 700 m asl where it joined the main glacier. The floor of this hanging valley cuts across the southern end of the Fort ridge.

During the last glacial advance between about 20,000 and 14,000 years ago the Wakatipu Glacier filled the lake basin to ~600 m above sea level (~300 m above present lake level), but the Buckler Burn glacier did not join the Wakatipu glacier. Instead, its meltwater stream discharged to the side of the Wakatipu Glacier, bringing sediment and forming a number of landforms, particularly as the main glacier retreated (see Section 4.2). Initially, Buckler Burn formed an ice marginal alluvial fan landform, and remnants of this block the southern end of Chinaman's Flat valley at about 600 m asl. This fan landform is prominently pockmarked with shallow depressions or kettle holes, formed by the melting of blocks of glacial ice that had been buried by the alluvial fan deposits. A similar landform occurs at the northern end of the valley, built by Precipice Creek.

The geomorphic history of the Buckler Burn area has been described above (Section 4). This section is concerned with the present Buckler Burn floodplain and channel in the downstream 1.8 km of its course from the highway bridge to Lake Wakatipu.

7.2 Buckler Burn Valley

Buckler Burn downstream of the highway bridge has cut a valley through its older fan-delta deposits. The upper section from the bridge to the end of the Bible Terrace is 1 km long and 300 – 450 m across (see Figure 7-1). On both sides the main banks are steep rising in near vertical faces to 40 m above the valley floor and formed in deposits of fan-delta #2 (see Section 4). However, there are a number of lower terraces rising 5 – 15 m above the valley floor, and the stream only cuts in under the main slopes in one location on the true left bank 220 m downstream of the bridge. Here a 270 m length of terrace face is undercut during flood events, and the slope above is bare gravel that delivers sediment to the valley floor. Buckler Burn then swings across the valley to cut in very close to the base of Bible Terrace about 670 m west of the bridge. At present there is only about 20 m between the river and the base of the terrace, and this 160 m long section carries the highway into Glenorchy. It is vulnerable to stream erosion that has taken 40 – 50 m from this area since 1937.

The lower 830 m section of the valley runs from the end of the Bible Terrace to the lake, and only constrained by terraces on its southern side. These are formed in the lower level deposits of fan-delta #3 and are 5 – 10 m high. On the north bank there is a low terrace about 3 m high near Bible Terrace, declining downstream to disappear before the end of Benmore Place. The valley floor expands downstream from 200 m to 445 m at the end of the terraces on the south bank, and in the last 290 m to the lake it expands further to be 750 m wide across the delta front. During the 1990s the true left valley side lost several metres during flood erosion events, particularly at the downstream end of the terraces. However, the true right valley side, although much lower has not been eroded as Buckler Burn has not flowed in this direction for some years. This is discussed in more detail below.

The upper valley floor longitudinal slope is1:59, while the lower valley gradient is a little flatter at 1:75.

7.2.1 Floodplain

The present floodplain of Buckler Burn is mapped on Figure 4-2. It lies about 2 m above the general level of the present fairway, and is likely to be inundated during large floods. As can be seen on figure 7-1, this is a remnant of a much more extensive landform that existed here seventy years ago. The 1937 aerial photograph shows a grassed well developed floodplain along the south side of the stream. Since then, much of this has been eroded away, and the remnant floodplain areas have become heavily vegetated with scrub. This loss of floodplain has largely resulted from the stream fairway shifting south from its previous course close to the southern side of Glenorchy.

7.2.2 Fairway

The active fairway of Buckler Burn increases in width downstream. At the road bridge near the downstream end of its gorge it is 10 m wide, but it quickly expands to 100 m across a few tens of metres downstream. It maintains this width for a further 900 m, and from where it passes out from under the high Bible Terrace it expands to be ~ 450 m wide where it enters the lake.

The upper reach contains a shallow single thread low sinuosity low-flow channel up to 10 m wide. In the lower reach the channel splits into 2 or 3 braids.

7.3 Landform Changes

Floodplain and fairway history can be interpreted from various survey plans, maps and aerial photographs that give snapshots of the stream in 1864, 1889, 1905, 1937, 1966, 1977, 1988, 1994, 1998, 1999, and 2001.

The 1864 town survey plan shows the proposed layout of Glenorchy. The main lower channel of Buckler Burn was then more than 200 m away from Jura Street that was to be the east running street that marked the southernmost edge of the town (it has never been formed). The stream probably ran along the base of the fan-delta #3 terrace. By the late 1890s, it had shifted over 200 m to the north to run across the end of Benmore Place. By 1905, it was again back on the south side of its fairway under the fan-delta #3 terrace.

The 1937 arrangement of the fairway and floodplain is shown in Figure 7-1. Of note is the narrow fairway through the upper reach where it was less than 50 m wide in many places. The lower reach had numerous channels, and there were several large braids along the north side. The Glenorchy School was situated very close to the bank of the fairway, and by 1940 it had been moved away from here due to the flood risk from Buckler Burn.

Since 1937 the stream fairway has moved southwards. The 1966 photograph shows this process had begun, with an expanded upper reach fairway, and large areas of south bank floodplain had been eroded. There had also been significant erosion of the floodplain adjacent to the road where it passed under the southern slopes of Bible Terrace. Here some 35 – 45 m of erosion had occurred, bringing the stream bank to within 20 m of the road. There has been further loss of floodplain here, particularly after 1977, and during the floods of the 1990s. Now this bank has had to be reconstructed and has rip-rap protection as described below in Appendix B.

As the fairway has migrated southwards, the terrace along fan-delta #3 has been significantly eroded, particularly during the floods of the 1990s. Here 40 – 70 m has been lost along the western 300 m of the terrace, and this has resulted in rapid delta growth downstream (see Section 5.4).

Although the fairway has moved to the south, there continues to be concern regarding the southern parts of Glenorchy, as a flood channel persists in this area (see Figure 7-1). Flood water can enter this just downstream of the groyne, and it swings downstream across the end of Benmore Place. The floodbank constructed in the early 1980s to protect the AHI dwellings was a response to this hazard.

7.4 Geomorphic Assessment

The landform changes documented above are typical of a steep alluvial fan environment, particularly in the wide fluctuations of channel position seen in the lower reach near the lake.

The upper catchment of Buckler Burn has seen considerable human activity with grazing of stock, and scheelite mining likely to contribute to significant sediment loads in the channel. In addition, the 40 m high face cut in fan-delta #2 just downstream of the bridge contributes large volumes of gravel to the stream during floods. Thus there is often significant aggradation in the channel during flood events. However, over the long term, this is likely to be a temporary effect as the lower end of the fan is unconstrained, and sediment can be carried out of the system into the delta environment.

In the short-term, floods will continue to cause both erosion of the floodplain and aggradation. Current practices of clearing the aggradation material from the upstream parts of the lower reach are appropriate. If the material is not needed it can be spread on lower floodplain near the lake shoreline, or stockpiled in areas that will not encourage flow towards Benmore Place.

The Glenorchy-Queenstown road runs very close to the stream, and this area will continue to be at risk from undercutting as the main flow from upstream is directed at this bank. Aggradation can also occur here during floods. Over time, this aggradation could reduce the channel capacity and Buckler Burn, and if this was to lead to the stream leaving its channel during a flood, it could flow down the highway towards Glenorchy. The contour information in the dtm indicates this could reach beyond Shiel Street, but would likely then begin to swing west towards Invincible Drive and Lochburn Avenue. It should not extend further north than Coll Street where it would be limited by the terrace separating the Buckler Burn fan surfaces (BAf_1 and BAf_2). However, as discussed in the URS Glenorchy Flood Hazard Assessment this scenario is considered unlikely given the present form of the channel cross section here.

Section 8 Fluvial Geomorphology of Bible Stream

8.1 Bible Stream

The Bible Stream catchment and erosion gully is a distinctive feature of the Glenorchy area. It is an unusual suite of landforms as the small hillside catchment has a very poorly defined stream network that is indistinctly connected to a large erosion gully cut into the north flank of Fan-delta #2, and the stream that flows out of this gully does not have a defined natural channel out onto the Glenorchy flats.

8.1.1 Catchment

The Bible Stream drains from a 40 ha catchment at the southern end of the Forts ridge. When observed in February 2007, flow was estimated at a few litres per second, but landform evidence indicates there can be more significant flow during floods (see accompanying flood assessment report). The catchment comprises two slope elements. The upper catchment steep slopes fall some 220 m from 620 m asl in only in 880 m horizontal distance. Only one small shallow valley can be seen on this slope, although several smaller depressions probably also carry water during heavy rainfall. These steep slopes pass abruptly onto the gently sloping Bible Terrace landform at about 375 m asl. This terrace is a remnant of the Buckler Burn fan-delta #2. The above mentioned stream passes across this surface in a very shallow flow path for 250 m before dropping into one of the tributary arms of the gully.

8.1.2 Gully

Despite the small size of the catchment and the very small stream that feeds into it, Bible Stream has formed a large erosion gully that cuts deeply into the terrace. It is 425 m long, up to 95 m wide, and covers about 2 ha. In its lower reaches the gully floor is 25 m across and there is a prominent terrace 1.5 – 2 m above the present channel which is 1 m across. The gully has three short tributaries, one of which connects with the stream channel, while the other two have no apparent surface source. These gullies are about 5 m deep at their heads, and they merge 130 m downstream to form the main gully. This deepens rapidly to be 35 m deep where it exits from the terrace. The sides are steep and largely bare gravel, although in recent years some scrub has become established in its upper reaches. A similar landform occurs 1.3 km to the south where a tributary to Stone Creek likewise has no obvious surface catchment, but a deep erosion gully complex has been formed that flows into Blanket Bay.

8.1.3 Alluvial Fan

At its mouth the Bible Stream gully issues out onto the flats southeast of Glenorchy township, and a small alluvial fan landform has been formed from the materials eroded out of the gully. This landform covers about 4 ha, extends ~180 m from the foot of the terrace, and drops about 15 m from its apex at 330 m down to the flats behind the Glenorchy cemetery. The outer perimeter of the fan is about 650 m long. A former gravel pit and informal landfill, the eastern end of Shiel Street, and a number of dwellings have been built on the western side of this landform.

8.2 Landform Changes Since 1937

Bible Stream gully can be seen in historic photographs from the 1870s, so despite its freshly eroded appearance, is a relatively long-standing landform. However, there have been some changes in the gully and its associated alluvial fan landform over the past 70 years, indicating it is still a potentially dynamic feature.

In the 1937 aerial photographs, the main gully had only two upper tributaries, and the longest of these had no apparent source of surface water flow. All of the gully side slopes were devoid of vegetation. The alluvial fan had numerous tongues of bare gravel, although these were partly covered by scrub vegetation. About 1.5 ha of the fan surface was bare gravel. Recent deposition had extended in five tongues radiating across the whole fan surface, and extending out to a maximum distance of ~110 m from the apex.

Section 8 Fluvial Geomorphology of Bible Stream

The 1966 aerial photographs showed a similar pattern to 1937. The longer tributary gully had grown ~ 20 m in length, and still had no visible surface water flow entering it. The gully sides supported a few patches of scrub. The alluvial fan surface had less bare gravel, (~0.9 ha), and denser scrub coverage. The main recent flow paths had been to the north-northeast and northwest, with this latter path extended some 140 m from the fan apex.

Little change had occurred in the gully area by the time of the 1977 aerial photographs. However, the flow paths on the alluvial fan had been active, with the northwest one extending 190 m as far as the edge of the Cemetery shelter belt. Scattered scrub was still present on the fan, and on the gully sides.

By 1988 a gravel borrow pit had been established and covered ~0.75 ha on the western side of the fan. Scrub had been cleared from the fan surface. The gravel pit obscures the northwest flow path, but the northeast flow path had been active out for a distance of ~170 m.

In 1996 the gravel pit covers about 1 ha. This area was also used as a local rubbish dump and periodically burnt (Thompson *pers comm.* 16/6/2007). A 10 m wide by 1 m deep channel flowed through this area, carrying water about 100 m beyond the fan apex. Scrub cover had returned and the northeast flow path was still present and extended 90 m in a 10 m wide path, although it had not cut into the fan surface. The 1998 photographs show more of the upper part of the gully, and scrub vegetation is starting to take hold on about 20 % of the slope area.

The 2001 aerial photographs show a new 30 m long tributary gully has been eroded into the terrace surface. Much of the upper gully area is vegetated and about 60 % of the whole gully side slopes have some vegetation cover.

8.3 Geomorphic Assessment

The Bible Stream gully is an unusual landform. It appears to be fed mainly by subsurface flow as there are no significant surface streams that drain into its tributaries. Observations of sediments beneath the terrace surface show there is a 1 m thick layer of silts at about 1 m below the surface, and this may impede water percolation and cause lateral subsurface flow to the gully heads. The gully presumably originally formed at the main terrace face, and has grown through headward sapping by groundwater flow along the top of the silt horizon to capture the drainage channels issuing from the steep hillside part of the catchment.

The aerial photographs show that since 1937 the Bible Stream has occasionally flowed across all parts of its alluvial fan, although typically in flow paths only 10 – 20 m across. This shallow overland flow did not appear to form a channel, and was able to extend up to 190 m from the apex before percolating into the ground.

Today, the Bible diversion bund and channel should direct most small and medium flows east away from former landfill area and the new houses on Shiel Street. However, the bund and diversion channel bank could easily be overtopped, either by a large flood, or when aggradation occurs and reduces the freeboard on the bund. If the stream overtops the bund it will flow down the channel that now exists through the former gravel pit and landfill area, and could extend 200 m to Shiel Street, and may impact the new houses on the other side. It is unlikely that water or sediment would flow much further than this as the discharge and energy gradient would be unlikely to sustain this flow, and it will percolate to ground.

Section 9 Geological Hazard Assessment

9.1 Introduction

As part of the current Glenorchy Floodplain Flood Hazard Study, a geomorphic assessment has been completed along with an assessment of seismic and slope instability hazard. It follows an earlier study of seismic risk in the wider Otago Region by OPUS (2004)[1]. The following sections discuss these hazards with respect to the study area shown in Figure 1-1.

9.2 Seismic Hazard

The seismic hazard that affects Glenorchy is characterised by:

- Large Alpine fault earthquakes
- Infrequent distributed small earthquakes that are generally shallow (<40 km) but deepen to the west.
- A few known active faults within about 40 km

The Alpine Fault is located along the western edge of the Southern Alps (Figure 9-2) and it contributes significantly to seismic hazard because it is thought to generate very large earthquakes (~M_w 8.0) relatively frequently (estimated return period of 200 to 300 years), and currently has a high probability of occurrence (85% in the next 100 years) (Yetton *et al* 1998[2]). The Alpine Fault passes within about 55 km of Glenorchy and an M8 earthquake is expected to generate peak ground accelerations of about 0.25 g in Glenorchy (using the attenuation relation of McVerry *et al* 2006[3]). The duration of shaking is expected to be up to about 2 minutes for an earthquake of M_w 8.0 (Yetton *et al* 1998).

The nearest significant active fault to Glenorchy shown on the current regional geology map (Turnbull 2000) is the Nevis - Cardrona Fault system, which reaches to within about 45 km east of Glenorchy (Figure 9-2). The Cardrona Fault has a return period for M_w7.1 of between 5000 and 10 000 years (Stirling *et al* 2002[4]).

Historical seismicity is summarised in Figure 9-3. This shows earthquakes of magnitude three and greater. M3.0 is usually the minimum magnitude that can be felt, and then only if the observer is very close to the earthquake epicentre. Typically engineering studies ignore anything smaller than M5.0 to M5.5 because smaller earthquakes are not recognised to be capable of damaging engineered structures. For example the NZ National Seismic Hazard Model (Stirling *et al* 2002) has a minimum magnitude of M5. Including earthquakes between M3.0 and M5.0 in Fig 9-3 helps to illustrate that the whole region is tectonically deforming and that random larger earthquakes could occur anywhere.

Figure 9-3 shows that most of the relatively few earthquakes that have occurred in the vicinity of Glenorchy are shallow (<40 km depth) and of less than M5.0. The large number of earthquake epicentres to the southwest of Glenorchy relate to the location of the northern limit of the Australian Plate subducting beneath the South Island.

The New Zealand National Seismic Hazard Model (Stirling *et al* 2002) is a probabilistic model that predicts the average rate of a range of different magnitude earthquakes on a regional basis. The model

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[1] OPUS, 2004 *Seismic Risk in the Otago Region.* Unpublished report to Otago Regional Council 5C0656.00.

[2] Yetton, M.D., Wells, A and Traylen, N.J., 1998: *The Probability and Consequences of the next Alpine Fault Earthquake*, EQC Research Report 95/193.

[3] McVerry, G., Zhao, J. Abrahamson, N and Somerville, P., 2006: New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering 39(1).*

[4] Stirling M. W., McVerry, G. H. and Berryman, K. R., 2002: *A New Seismic Hazard Model for New Zealand.* Bulletin of the Seismological Society of America, 92(5).

includes information about known active faults, rates of historical seismicity and rates of crustal deformation. A lack of detailed fault studies in the western Otago and Southland areas led to the inclusion of several hypothetical faults to account for crustal deformation in the region. As future active fault studies improve the quality of information on active faults in the region, the accuracy of the model will improve. For this study the data presented by Stirling *et al* (2002) is believed to be adequate because it is consistent with the rate of crustal deformation. However, future developments that require rigorous seismic hazard assessment should consider a site specific seismic hazard assessment that incorporates the latest information about active faults in the region.

The New Zealand National Seismic Hazard Model predicts the ground motions for any location in New Zealand for a range of return periods using a probabilistic assessment approach (Stirling *et al* 2002). Probabilistic estimates for peak ground acceleration are summarised in Table 9-1. Deterministic estimates for peak ground acceleration during an Alpine Fault earthquake of M_w8.0 are also presented.

Table 9-1 Summary of peak ground accelerations for a Class B or C site at Glenorchy predicted by the NZNSHM along with estimated peak ground acceleration from a M_w8.0 Alpine Fault earthquake

Probabilistic estimates		Deterministic scenario estimates		
Return Period	pga (g)	Fault parameters	Percentile level	pga (g)
150 years	0.35			
475 years	0.55	Alpine Fault M_w8.0 @ 55 km	50^{th} percentile	0.12 to 0.16
1,000 years	0.75	RI ~ 300 years	84^{th} percentile	0.20 to 0.26

Note: Probabilistic estimates from Figure 6 of Stirling *et al* (2002) for a shallow soil site. Alpine Fault deterministic estimates calculated using McVerry *et al* (2006) with the range covering Class A-D (strong rock to deep or soft soil).

OPUS (2004)[4] present earthquake shaking estimates for Otago in terms of Modified Mercalli Intensity for a range of return periods and earthquake scenarios. Modified Mercalli Intensity rates the degree of shaking in terms of felt effects and damage. Intensity estimates for Glenorchy from the Opus study are presented in Table 9-2.

OPUS estimate Modified Mercalli Intensities based on the accelerations from NZS1170.4 (2002 draft). The results suggest that significant damage will be sustained by buildings in Glenorchy during an earthquake with an average return period of 100 years.

McVerry *et al* (2006) present attenuation relationships predicting peak ground acceleration for a range of distances from an earthquake epicentre. That study also describes the attenuation relationships for a range of ground conditions from strong rock to very weak soil (refer to Table 9-3 for descriptions of the ground condition classes). For crustal earthquakes (most damaging earthquakes that Glenorchy experiences will be crustal earthquakes) the McVerry *et al* (2006) attenuation relationships predict similar peak ground accelerations across a range of magnitudes for Class A and Class B sites. The model predicts that Class C sites will experience peak ground accelerations about 25% higher than for Class A or B. For Class D sites, the model predicts peak ground accelerations up to 20% less than Class A or B at epicentral distances of less than 10 km, but similar to Class A or B at greater distances. These generalisations hold for earthquake magnitudes between M_w 5.0 to 8.0.

Table 9-2 Predicted Modified Mercalli Intensity earthquake shaking for Glenorchy (OPUS 2004)

Average recurrence interval or earthquake scenario	Modified Mercalli Intensity
From probabilistic seismic hazard assessment	
100 year average recurrence interval	VII
2500 year average recurrence interval	IX
From deterministic seismic hazard assessment	
Akatore Fault earthquake (M_w 7.0)	IV
Alpine Fault earthquake (M_w 8.0)	VIII
Dunstan Fault North earthquake (M_w 7.0)	VI
Dunstan South Fault earthquake (M_w 7.0)	VI

Summary of Modified Mercalli Intensity effects:

MMIV	Felt indoors and not outdoors. Rattles doors and crockery.
MMV	General alarm. Little property damage.
MMVI	General alarm, difficulty in walking steadily. Objects fall from shelves, slight damage to Type I buildings (buildings dating before earthquake design).
MMVII	Difficulty experienced in standing. Substantial damage to fragile contents of buildings. Unreinforced stone or brick walls cracked, chimneys damaged. Some liquefaction.
MMVIII	Alarm may approach panic. Type I buildings heavily damaged, some collapse. Liquefaction and lateral spreading.
MMIX	Many Type I buildings destroyed. Other buildings heavily damaged. Liquefaction can be widespread and landsliding on steep slopes.

9.3 Local variation in ground shaking intensity

The intensity of earthquake shaking can vary locally due to variation of ground conditions. Ground conditions that are relevant to local shaking intensity have been defined in the NZ Building Code (NZS1170.5:2004) as shown in Table 9-3.

Table 9-3 Ground class definitions (after NZS1170.5:2004)

Class name	Geological Description	Simplified Engineering Description (for full description refer to NZS1170.5:2004)
Class A	Strong rock	Strong to extremely strong rock with no weak layers
Class B	Rock	Very weak to moderately strong rock with surface soil less than 3 m thickness
Class C	Shallow soil	Soil sites with natural period less than 0.6 seconds.
Class D	Deep or soft soil	Soil sites with natural period greater than 0.6 seconds. More than 20 m thickness of soil, though thickness defined by strength or density of soil.
Class E	Very soft soil	More than 10 m of very soft soil

9.3.1 Subsurface conditions

Only shallow boreholes (<20 m depth) have been completed in the Glenorchy area, and none that have encountered rock are known to ORC. No drilling was undertaken as part of the current study.

Based on surface geology, the soils that directly underlie Glenorchy are interpreted to be mainly deltaic silty or sandy gravels, possibly to a depth of about 100 m, underlain by schist bedrock. The groundwater table is shallow (approximately at lake level) under Glenorchy. Similar subsurface conditions are anticipated underlying the flood-plain of the Rees and Dart Rivers. The depth of soil overlying rock is expected to reduce away from the lakeshore. The slopes east of the flood plain are underlain by schist with a relatively thin (<10 m) cover of glacial till.

Based on the geological model described above and using the ground classification in Table 9-3, the town of Glenorchy would be classified as Class D near to the lake edge and Class C near to the base of the hill slopes. Defining the distribution of these ground classes would require significant subsurface data.

9.4 Liquefaction assessment

Liquefaction is the loss of strength that can occur when saturated, cohesionless soil (usually sand or silt) experiences strong earthquake shaking. Liquefaction has occurred in several large earthquakes in New Zealand and much of the country is thought to have a significant risk of damage due to liquefaction. Significantly, liquefaction was reported around the margins of Lake Te Anau following the 2003 Fiordland earthquake. Liquefaction can damage buildings due to settlement (particularly differential settlement) and underground services due to flotation, lateral or differential movement. OPUS (2004) indicate that Glenorchy, along with much of the land adjacent to Lake Wakatipu is “possibly susceptible” to liquefaction due to the presence of unconsolidated sediments.

Prediction of liquefaction hazard requires knowledge of the seismic hazard that a site will be subjected to and a detailed knowledge of subsurface conditions including characterisation of the near surface soil types, density and groundwater levels. Usually a liquefaction assessment requires a rigorous drilling investigation to collect soils data. In the case of Glenorchy we have undertaken a simple, qualitative assessment based on our knowledge of the near surface soils.

The following points characterise the propensity of the near surface soils underlying Glenorchy to liquefy during sufficiently strong earthquake shaking:

- The deltaic soils underlying Glenorchy were deposited in a low energy environment and consequently there is a high likelihood of at least part of the soil profile being in a ‘loose’ condition.
- The deltaic soils mainly comprise sands and silts, though they have significant gravel content also.
- Groundwater levels are near to ground surface.

Given the seismic hazard described in Section 9.2 we believe that there is a high likelihood of liquefaction occurring in the soils underlying Glenorchy. Liquefaction is particularly likely in the case of an Alpine Fault earthquake which is expected to generate about 2 minutes of high intensity shaking (Yetton *et al* 1998). As described above, a more definitive assessment of liquefaction would require collection of some detailed characterisation of the physical properties of the soil profile.

9.4.1 Anticipated effects of liquefaction at Glenorchy

Liquefaction of part of the soil profile underlying lightweight, residential dwellings usually results in some deformation of the building, but rarely collapse. As a result, liquefaction does not often cause fatalities in this type of building. However, Glenorchy is adjacent to a lake edge and may experience lateral spreading as a result of liquefaction. Lateral spreading occurs when soils that are not laterally confined liquefy allowing the liquefied soil and everything above it to move laterally. This phenomenon often occurs at the margin of water bodies where the ground slope is locally steep.

Lateral spreading is commonly highly damaging to underground services as large lateral movements are possible (up to several metres).

9.5 Existing slope instability

9.5.1 Queenstown-Glenorchy Road immediately south of Buckler Burn

The project scope called for an assessment of sites of possible landslip along the Queenstown-Glenorchy Road immediately south of Buckler Burn. Observation of road cuttings and other exposures along the road and review of aerial photographs were made prior to and during the field investigations.

Geology in the vicinity of Buckler Burn comprises fine grained glacial till overlying schist. Schist outcrops in the bridge abutments and gorge of the Buckler Burn Bridge, and till is exposed in a road cutting immediately south of the bridge. Post glacial fan gravels overlie both of these units.

Our investigations indicated no significant slope instability affecting the road; however a review of existing slope instability over the wider area of the study follows.

9.5.2 Existing slope instability affecting the wider Glenorchy study area

Several distinct types and scales of slope instability occur in the study area and surrounds. These can be characterised as:

- Large, creeping schist landslides,
- Bedrock failures on steep slopes resulting in rockfalls,
- Postglacial slumping of deltaic sediments and overlying fan materials.

Schist landslides

Large creeping landslides are very common throughout Otago in the areas underlain by schist bedrock. These landslides can be very large (several square kilometres in area), and typically move extremely slowly, often averaging a few centimetres per year or less.

This type of landslide is restricted to the slopes of the mountains outside the study area, where they are relatively common (see Figure 9-5, Figure 9-1 Photographs 9-1 and 9-2). These landslides are considered to represent negligible risk to the current Glenorchy township and associated infrastructure.

Evidence for smaller, more rapid rock slope failures have been observed in the vicinity of Glenorchy, including:

- Rock slope failure above Glenorchy Paradise Road on a steep schist slope.
- Schist slope failure depositing debris as a dam across Buckler Burn (Thomson, 2006[5]).

The slope failure above Glenorchy Paradise Road appears to be a discontinuity controlled rock slope failure on foliation (unfavourably oriented with respect to the slope) and joints acting as release surfaces (see Figure 9-5 for location and Figure 9-1 Photographs 9-3 and 9-4). This is a relatively small failure (10 000m^3) that has occurred post glacially (<10 000 years old). The failure does not represent a high risk to residents or infrastructure in Glenorchy.

Glacial sediments

Deltaic sediments (identifiable by the characteristic cross bedding observed in outcrop) underlie fan alluvium from Buckler Burn and Precipice Creek. The deltaic sediments were deposited relatively loosely in still water compared to the fan alluvium which was deposited by river currents.

[5] Thompson, R. 2006 Letter report to ORC regarding potential damming of Buckler Burn by a rockfall.

Arcuate scarps or terraces can be observed adjacent to the modern channels of these rivers (Figure 9-1 Photograph 9-7), which have incised into the fans by 50+ m. Deformation of bedding was observed in fan alluvium of Buckler Burn (Figure 9-1 Photographs 9-5 and 9-6) suggesting that slumping or settlement had occurred in the fan alluvium and underlying deltaic sediments. This may have occurred in response to a combination of the rapid downcutting of the rivers during post-glacial lake level lowering and relatively slow reduction in groundwater pressures within the lower permeability deltaic deposits. It is also possible that the scarps partly relate to historical gold mining as the extent of mining has not been ascertained at this stage.

Slumping or settlement is not expected to occur in the near future due to the relative stability of lake levels in Lake Wakatipu. However, ongoing fretting of the sub-vertical ‘cliffs’ cut in fan gravels by Buckler Burn is expected downstream of the Queenstown-Glenorchy road bridge.

9.5.3 Earthquake-induced slope instability

Strong seismic shaking is a common trigger of slope failure. Large creeping schist landslides are relatively insensitive to earthquake shaking, but slopes can experience new or renewed slope failure. Rockfalls are a common result of earthquake shaking. Most slope failures resulting from earthquake shaking are relatively small, but occasionally, very large slope failures can occur. Very large earthquakes can generate a large number of landslides throughout a region (for example the 1929 Buller earthquake). A large number of landslides are expected to occur in western Otago as a result of a large Alpine Fault earthquake, and this could include landslides that affect Glenorchy.

Slope failure scenarios that could affect the study area resulting from strong earthquake shaking include:

- Reactivation of the rock slope failure that resulted in a landslide dam on Buckler Burn,
- New rock slope failure resulting in a landslide dam either on Buckler Burn or Precipice Creek,
- Reactivation of the rock slope failure above Glenorchy Paradise Road north of Glenorchy (refer Figure 9-1 Photographs 9-3 and 9-4),
- Toppling of a section of the steep cliffs cut in fan materials adjacent to Buckler Burn (refer Figure 9-1 Photograph 9-5),
- Slope failure of road cuttings of the Queenstown-Glenorchy Road outside the study area, but preventing road access to Glenorchy. This is the most likely slope failure scenario that could affect Glenorchy.

The likelihood of earthquake induced slope failure affecting other slopes within the study area is considered to be very low.

Section 10 Limitations

URS New Zealand Ltd (URS) has prepared this report in accordance with the usual care and thoroughness of the consulting profession for the use of Otago Regional Council and only those third parties who have been authorised in writing by URS to rely on the report. It is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this report. It is prepared in accordance with the scope of work and for the purpose outlined in the Proposal dated 17th January 2007.

The methodology adopted and sources of information used by URS are outlined in this report. URS has made no independent verification of this information beyond the agreed scope of works and URS assumes no responsibility for any inaccuracies or omissions. No indications were found during our investigations that information contained in this report as provided to URS was false.

This report was prepared between February and May 2007 and is based on the conditions encountered in the field in February 2007, and information reviewed at the time of preparation. URS disclaims responsibility for any changes that may have occurred after this time.

This report should be read in full. No responsibility is accepted for use of any part of this report in any other context or for any other purpose or by third parties. This report does not purport to give legal advice. Legal advice can only be given by qualified legal practitioners.

Appendix A Historical Photographs of the Glenorchy Area

Figure A-1: Glenorchy Lagoon and Rees Valley, 1875

Photo #496 *Mt Earnslaw from Glenorchy* from the Burton Brothers catalogue. The original glass negative is now in the Te Papa Photographic Collection (Reference number C.016731).

This scene of the Glenorchy Lagoon and Rees Valley area was photographed in the early winter of 1875 by Alfred Burton. It looks north towards Mt Earnslaw and was taken from about the position of the old jetty west of Jetty/Mull Streets. The open water area is the Glenorchy Lagoon, now occupied by the Rees River.

Appendix A Historical Photographs of the Glenorchy Area

Figure A-2: Glenorchy and Mt Earnslaw from south side of Buckler Burn valley, 1889/1890

Photo #5108 *Mt Earnslaw from Birley's Hotel* from the Muir and Moodie (Burton Brothers) catalogue. The original glass negative is now in the Te Papa Photographic Collection (Reference number C.016632).

Mt Earnslaw is the snow-capped mountain in the background, and Birley's Hotel is the large building in the middle ground. The image was taken by George Moodie sometime in 1889 or 1890. The open water in the foreground is part of Lake Wakatipu, which at this time formed a small embayment in the downstream end of the Buckler Burn valley. The stream floodplain and delta has now built out across much of this area. The hotel was built in 1880, and destroyed by fire in July 1959.

Appendix A Historical Photographs of the Glenorchy Area

Figure A-2: Glenorchy wetland area, 1889/1890

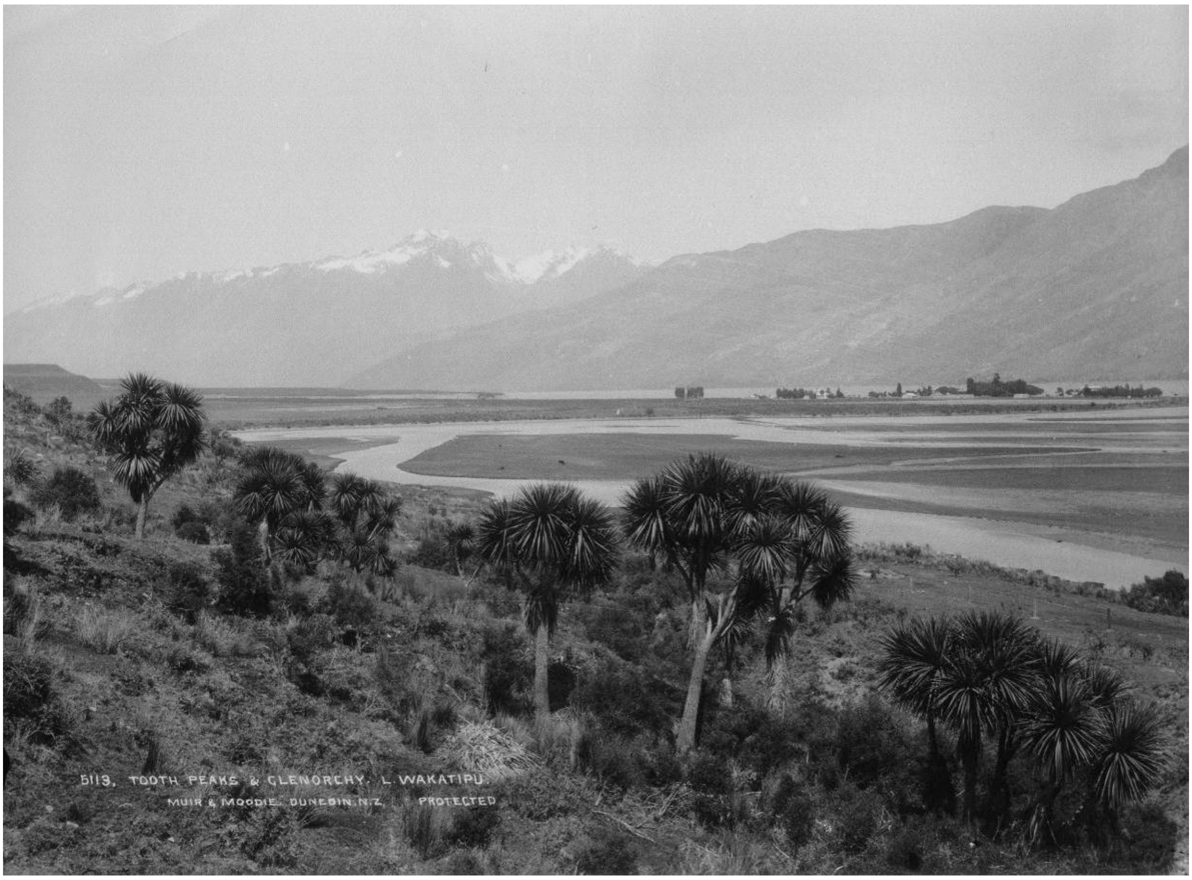


Photo #5113 *Tooth Peaks and Glenorchy, Lake Wakatipu* from the Muir and Moodie (Burton Brothers) catalogue. The original glass negative is now in the Te Papa Photographic Collection (Reference number C.016627).

The Tooth Peaks are the snow-capped mountains in the background. The image was taken by George Moodie, probably on the same expedition as BB# 5108. The view is to the south from a position about 2 km north of Glenorchy. Distributary channels of the advancing Rees River delta flow into what is today the Glenorchy Lagoon and wetland area. Cattle are grazing on the commonage areas of grassy river flats.

Appendix B

Geotechnical Assessment of Glenorchy Flood Protection Works

B.1 Introduction

As part of the evaluation of the effectiveness of the current scheme a geotechnical assessment of the existing embankments around Glenorchy was completed.

The geotechnical evaluation included a site visit to inspect the stopbanks (12 to 14 February 2007), a review of regional geological maps[1] and review of an earlier assessment of floodbank stability conducted by OPUS[2].

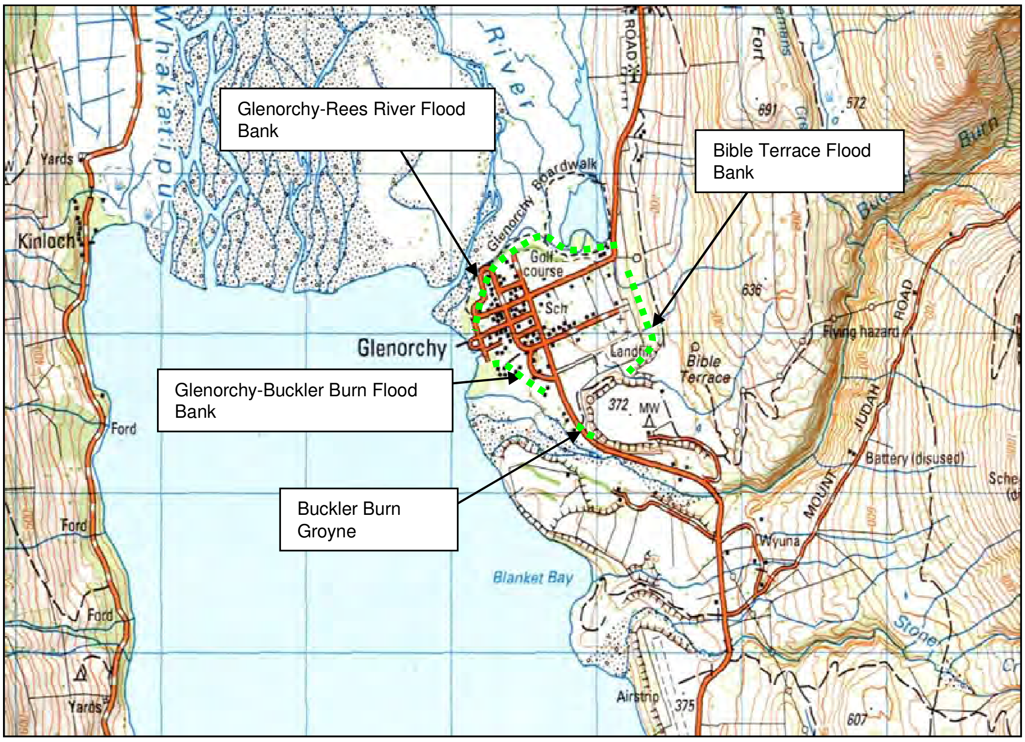
The existing flood defences around Glenorchy referenced by OPUS include the following elements:

- Glenorchy-Rees River Flood Bank, located along the north side of Glenorchy separating the Rees River Floodplain from Glenorchy.
- Glenorchy-Buckler Burn Flood Bank, separating Glenorchy from the lower reaches of Buckler Burn, which flows around the southern margin of the town, and
- The Bible Flood Bank, which diverts surface water from a small stream around the east side of Glenorchy.

In addition to these, Buckler Burn Groyne is located along the edge of the Buckler Burn approximately 900 m from the river mouth and this structure attempts to divert flood water away from Glenorchy.

The locations of the structures listed above are shown in Figure B-1.

Figure B-1: Glenorchy flood protection works



[1] Turnbull, I. M. (compiler) 2000: *Geology of the Wakatipu area*. IGNS 1:250 000 geological map 18.

[2] OPUS, 2004: *Wakatipu Floodbank Stability Survey*. Unpublished letter report to Otago Regional Council dated May 2004.

B.2 Glenorchy-Rees River Flood Bank

B.2.1 General description

The Glenorchy-Rees River Flood Bank was constructed during 2000 to protect Glenorchy from flood inundation by the Rees River. The structure is about 1400 m long and separates the wetland from the golf course at the eastern end and separates the outlet from the wetland from residential properties at the western end. Photographs B-1 to B-6 in Figure B-2 illustrate the structure.

B.2.2 Construction

The embankment is constructed from well-graded, schist-derived gravel, which is exposed at various locations along its length. The source of the material is unknown, but it is expected to be locally extracted alluvium, probably from Buckler Burn. The maximum gravel clast size observed was about 150 mm in maximum dimension, and the gravel clasts are tabular in shape, which is typical of schist. The gravels have a relatively high silt content (Photo B-5), reflecting the close proximity of glacial activity that was the direct material source. The estimated grading characteristics of the gravels used to construct the embankment are presented in Table 1.

The maximum height of the embankment is about 1.5 m above the surrounding area and the crest width is about 3 m. The crest of the embankment is generally very level (photographs B-2, B-3, B-4 & B-6) and has no obvious low areas. Side slopes are about 2H:1V in places, and the downstream slope is very flat along the golf course section of the floodbank (Photos B-4 & B-6).

Based on our assessment of the regional geology, the embankment is probably founded on material with a similar grading to the embankment, and was either deposited as a delta front or lake bed, though some disturbance by subsequent wave or stream action has probably occurred. As a result, the foundation materials are expected to have suitable bearing capacity for the embankment, and the lack of any evidence of slumping is consistent with this assessment. However, the foundations are expected to be relatively permeable and to allow significant leakage if the maximum head were developed across the embankment for an extended period.

Table B-1: Estimated Grading Characteristics of Glenorchy Stopbank Materials

Grading	Estimated Range	Comments
% cobbles/boulders (> 60 mm)	0 – 25%	Gravels and cobbles are typically tabular with minimum dimension 20-50% of maximum dimension
% gravel (2 – 60 mm)	50 – 90%	
% sand (0.06 – 2 mm)	20 – 50%	
% silt/clay (< 0.06 mm)	10 – 20%	Fines are non-plastic, very little clay
d_{75}	10 – 100 mm	Estimated average d_{75} is 30 mm

B.2.3 Erosion resistance

The embankment is generally well vegetated with grass, and is some areas protected with willows. The only area protected with rip-rap is the western end of the embankment, where the Rees River flows against the toe (Photo B-1). This area is protected with schist boulders up to about 1 m across, though schist typically forms a poor quality rip-rap, as the tabular boulders do not interlock well and easily dislodge.

The schist gravel from which the embankment is constructed is a relatively erodible material, as can be seen from natural exposures. Where unprotected by rip-rap, the embankment is unlikely to sustain direct river flows against the fill.

B.2.4 Ability to withstand overtopping by Rees River

Several factors suggest that the existing flood bank should withstand a small amount of overtopping:

- the embankment is constructed of well compacted, well graded material
- the crest and slopes are generally well vegetated (mainly with short grass)
- the average height is only about 1 m, and
- flood loading is transient.

However the floodbank will not withstand sustained overtopping due to the erodibility of the embankment material.

B.3 Glenorchy-Buckler Burn Flood Bank

B.3.5 General description

The Glenorchy-Buckler Burn Flood Bank is a series of low stopbanks that were constructed during the 1980's to protect cottages on the southern side of Glenorchy from flooding in Buckler Burn. OPUS reported that this floodbank was in poor condition in 2004 noting that it was not "well formed" and appeared to have "spread and subsided" since construction.

The area where this floodbank was constructed is now heavily overgrown with broom and little evidence of the embankment was found during the site visit (Photos B-7 and B-8).

B.3.6 Construction

The embankment was observed along the south side of the Dart River Safaris workshop where it is between 0.5 and 1.0 m in height. The embankment is heavily overgrown with broom though it appears to have a quite rounded cross section as shown in the 2004 OPUS report.

The grading of the material described in the OPUS report is similar to the description of the material in Table B-1. The material source is also expected to be the lower Buckler Burn floodplain.

The flood bank is discontinuous in several locations, e.g. about Benmore Place and about a drainage channel southeast of the Dart River Safaris workshop. Flood water will pass through both of these locations unimpeded.

Foundation conditions for the flood bank are expected to comprise Buckler Burn alluvium.

B.3.7 Erosion resistance

This flood bank is discontinuous and does not have an armour layer. The poorly compacted gravel that this flood bank is constructed of is expected to present little resistance to erosion by the Buckler Burn in flood.

B.3.8 Ability to control flood flows in Buckler Burn

The Glenorchy-Buckler Burn Flood Bank is expected to be quite ineffective in controlling high water levels in Buckler Burn for the following reasons:

- crest elevation is typically only 0.5 m above the adjacent ground

- the embankment is discontinuous
- the embankment is constructed from loosely compacted gravel that is expected to be easily eroded by flood water.

B.4 Bible Terrace Floodbank

B.4.9 General description

A small stream has eroded a deep channel in Bible Terrace and is constructing a fan at the southeast margin of Glenorchy township (Photo B-11). The stream has a very small catchment and was flowing at an estimated 1 to 2 l/sec on 13 Feb 2007. Presumably this stream would carry a much greater flow during heavy or prolonged rain.

In an attempt to control water and sediment discharge onto properties on and adjacent to the fan, some control structures have been built. These structures comprise an embankment across the stream (Photo B-9) and a small diversion channel (Photo B-10) that diverts surface flow around the east side of Glenorchy and into the Rees River Wetland.

B.4.10 Construction

The embankment is up to 3 m high and 30 m long and is founded on fan alluvium. The abutments are deltaic gravels (Photo B-12). It is constructed from fan alluvium excavated from the adjacent fan. The crest width is about 5 m and the side slopes are approximately 2H:1V. Schist boulders up to about 1 m across have been placed on the upstream slope, which has a freeboard of about 1 m (Photo B-9).

The storage capacity of the embankment is estimated to be a less than a few hundred cubic metres when full. The embankment does not have an engineered spillway, but discharges directly into the diversion channel (Photo B-9).

The diversion channel has a base width of about 1 m with channel side slopes of 1H: 1V. The maximum depth of the channel is about 0.75 m. There is armouring of schist slabs along part of the channel. Rabbits have burrowed into the channel sides in several places. These dimensions give the channel a potential capacity of about 1 m^3/sec. However, it is considered likely that the banks would be unstable when the channel was carrying this magnitude of flow.

B.4.11 Effectiveness of the Bible Terrace Diversion Channel

This structure is expected to be effective at diverting normal flows away from the dwellings to the north of the dam, however without erosion protection on the ‘spillway’ or channel, it is expected that the stream would not be controlled during high flows and would resume a northerly course.

B.5 Buckler Burn Groyne

B.5.12 General description

The Buckler Burn Groyne comprises a length of elevated road about 50 m long that attempts to direct Buckler Burn away from Glenorchy (Photos B-13 and B-14). The groyne is oriented approximately east west and intersects with Glenorchy-Queenstown Road near the southern margin of the town.

B.5.13 Construction

The groyne is typically about 2 m high and the crest is about 3 m above the normal river level of Buckler Burn (as observed on 14 February 2007). At the western end, the road ramps down onto a terrace of Buckler Burn.

The crest of the embankment is about 5 m wide and the side slopes are about 1.5H:1V. The southern slope has a layer of unknown thickness of schist boulders to help reduce the likelihood of erosion during flood events (Photo B-15).

The groyne is probably constructed on Buckler Burn alluvium, which is expected to be a relatively stable foundation.

East of the groyne a similar layer of schist boulders has been placed on the terrace riser between the Glenorchy-Queenstown Road and the river (Photo B-16). It is understood that this work was in response to severe erosion that threatened the road during the floods of the late 1990s.

B.5.14 Ability of the groyne to control flood flows in Buckler Burn

The Buckler Burn groyne is not a continuous structure and cannot contain flood water within the bed of Buckler Burn, but may have the intended effect of diverting the most erosive flood flows away from infrastructure immediately downstream on the true right bank.

The groyne may also have the effect of encouraging aggradation of the adjacent river bed due to constriction of the flood plain at this narrow point[3].

The armouring adjacent to the Glenorchy-Queenstown Road will have a positive effect on resisting erosion by flood water, but the armour is likely to move during sustained flood flows owing to the tabular shape of the schist slabs.

[3] Davies, T.R. and M.J. McSaveney 2006 Geomorphic constraints on the management of bedload-dominated rivers *Journal of Hydrology (NZ)* 45(2): 111-130.

Photograph B-1 View of Rees River flowing against western end of the Glenorchy-Rees River Floodbank. Some schist boulders can be seen offering some erosion protection. Photograph taken 13 February 2007 (photo Tim McMorran)

Photograph B-2 View (to the northeast) of Glenorchy-Rees River Floodbank near the western end showing the 3 m wide, relatively level crest and significant vegetation cover. Photograph taken 13 February 2007 (photo Tim McMorran)

PROJECT

Glenorchy Geomorphic and Geo-hazard Assessment

URS New Zealand

Engineering and Environmental Management

Otago Regional Council

TITLE

Figure B-2: Geotechnical assessment of existing flood protection

PROJECT:**42162267** REV: **A**

Photograph B-3 View (to the west) of the Glenorchy-Rees River floodbank about half way along its length. Photograph taken 13 February 2007 (photo Tim McMorran)

Photograph B-4 View (to the east) of Glenorchy-Rees River Floodbank near the eastern end showing a very gentle downstream slope, relatively level crest and good grass cover of the golfcourse. Photograph taken 13 February 2007 (photo Tim McMorran)

PROJECT

Glenorchy geomorphic and Geo-hazard Assessment

URS New Zealand

Engineering and Environmental Management

Otago Regional Council

TITLE

Figure B-2: Geotechnical assessment of existing flood protection

PROJECT:**42162267** REV: **A**

Photograph B-5 Upstream slope of the Glenorchy-Rees River floodbank at photograph 4 location. Note steep slope, lack of vegetation and high fines content. Photograph taken 13 February 2007 (photo Tim McMorran)

Photograph B-6 View (to the east) of Glenorchy-Rees River Floodbank along golf course showing a very gentle downstream slope, relatively level crest and good grass cover. Photograph taken 13 February 2007 (photo Tim McMorran)

PROJECT	TITLE
Glenorchy Geomorphic and Geo-hazard Assessment URS New Zealand *Engineering and Environmental Management* Otago Regional Council	**Figure B-2: Geotechnical assessment of existing flood protection**
	PROJECT:**42162267** REV: **A**

Photograph B-7 The Glenorchy-Buckler Burn floodbank is located beneath broom bushes where arrowed. The structure is only about 0.5 m high and heavily overgrown. Photograph taken 14 February 2007 (photo Tim McMorran)

Photograph B-8 View (to the north) along Benmore Place. The Glenorchy-Rees River Floodbank should cross the road in this area. Photograph taken 14 February 2007 (photo Tim McMorran)

PROJECT

Glenorchy Geomorphic and Geo-hazard Assessment

URS New Zealand

Engineering and Environmental Management

Otago Regional Council

Figure B-2: Geotechnical assessment of existing flood protection

PROJECT:**42162267** REV: **A**

Photograph B-9 View to northeast along embankment on Bible Terrace Stream. Note schist boulders on upstream face. Red arrow shows the location of the outlet to the diversion channel. Photograph taken 13 February 2007 (photo Tim McMorran)

Photograph B-10 View to northeast along the diversion channel of Bible Terrace Stream. Photograph taken 13 February 2007 (photo Tim McMorran)

PROJECT

Glenorchy geomorphic and Geo-hazard Assessment

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TITLE

Figure B-2: Geotechnical assessment of existing flood protection

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Photograph B-11 View north along Bible Terrace Stream showing deeply incised channel cut mainly in deltaic sediments. The embankment location is arrowed. Photograph taken 13 February 2007 (photo Tim McMorran)

Photograph B-12 View along the crest of the Bible Terrace Stream embankment showing deltaic sediments dipping to the northeast exposed in the abutment. Photograph taken 13 February 2007 (photo Tim McMorran)

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Figure B-2: Geotechnical assessment of existing flood protection

PROJECT:**42162267** REV: **A**

Photograph B-13 View west along Buckler Burn Groyne showing 5 m wide crest. Buckler Burn floodplain is to the left. Photograph taken 14 February 2007 (photo Tim McMorran)

Photograph B-14 View of upstream face of Buckler Burn Groyne. The Groyne is about 2 m high. Photograph taken 14 February 2007 (photo Tim McMorran)

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Figure B-2: Geotechnical assessment of existing flood protection

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Photograph B-15 Close up of schist blocks armouring Buckler Burn Groyne. Photograph taken 14 February 2007 (photo Tim McMorran)

Photograph B-16 View of rock protection between Buckler Burn and the Glenorchy-Queenstown Road. Photograph taken 14 February 2007 (photo Tim McMorran)

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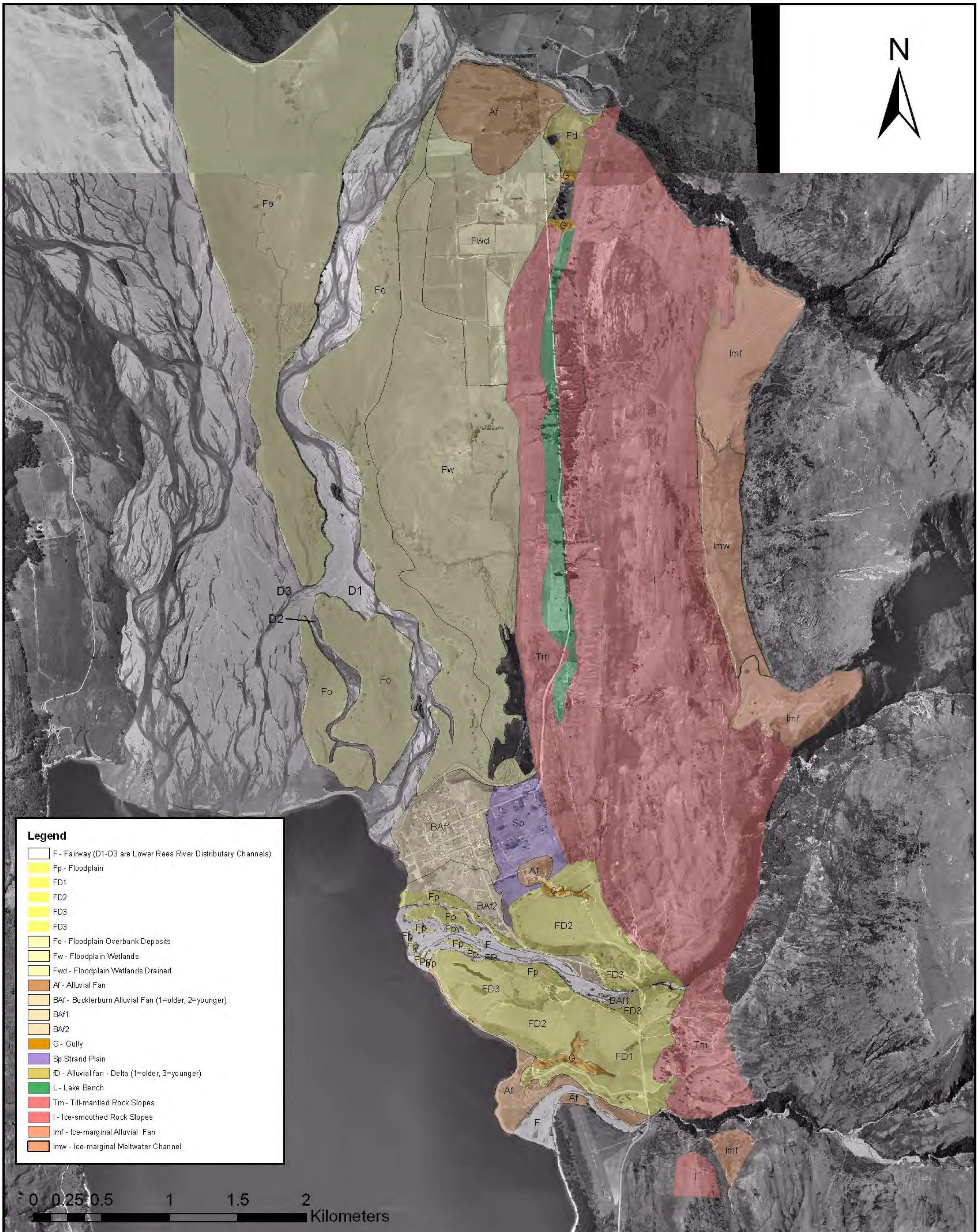
Figure B-2: Geotechnical assessment of existing flood protection

PROJECT:**42162267** REV: **A**



Rev	Description	App	Date

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LANDFORMS OF THE GLENORCHY LOWER REES VALLEY AREA

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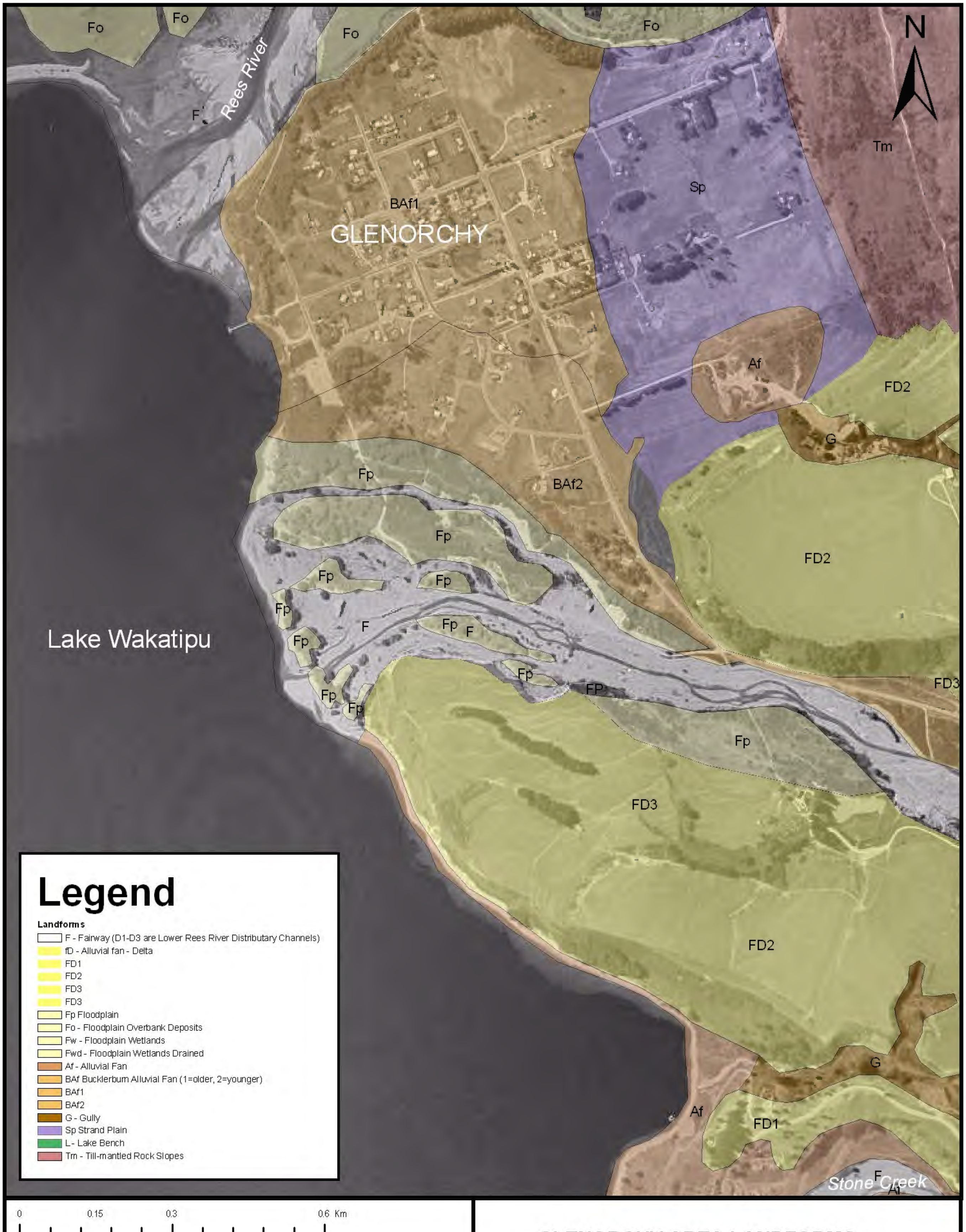
Original Size:	A3	Checked:		Drawing Number	Rev
Date Created:	3 May 2007	Approved:		Figure 4-1	A



GLENORCHY AREA LANDFORMS

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New Zealand

File: 42162267\6000\drawings Glenorchy area landforms	Designed: MM	Status	DRAFT
Scale: 1:10 000	Drawn: STT		
Original Size: A4	Checked:	Figure 4-2	
Date Created: 2 May 2007	Approved:		

Legend

1864 Shoreline	1937 Shoreline
1875 Shoreline	1966 Shoreline
1889 Shoreline	2001 Shoreline
1905 Shoreline	

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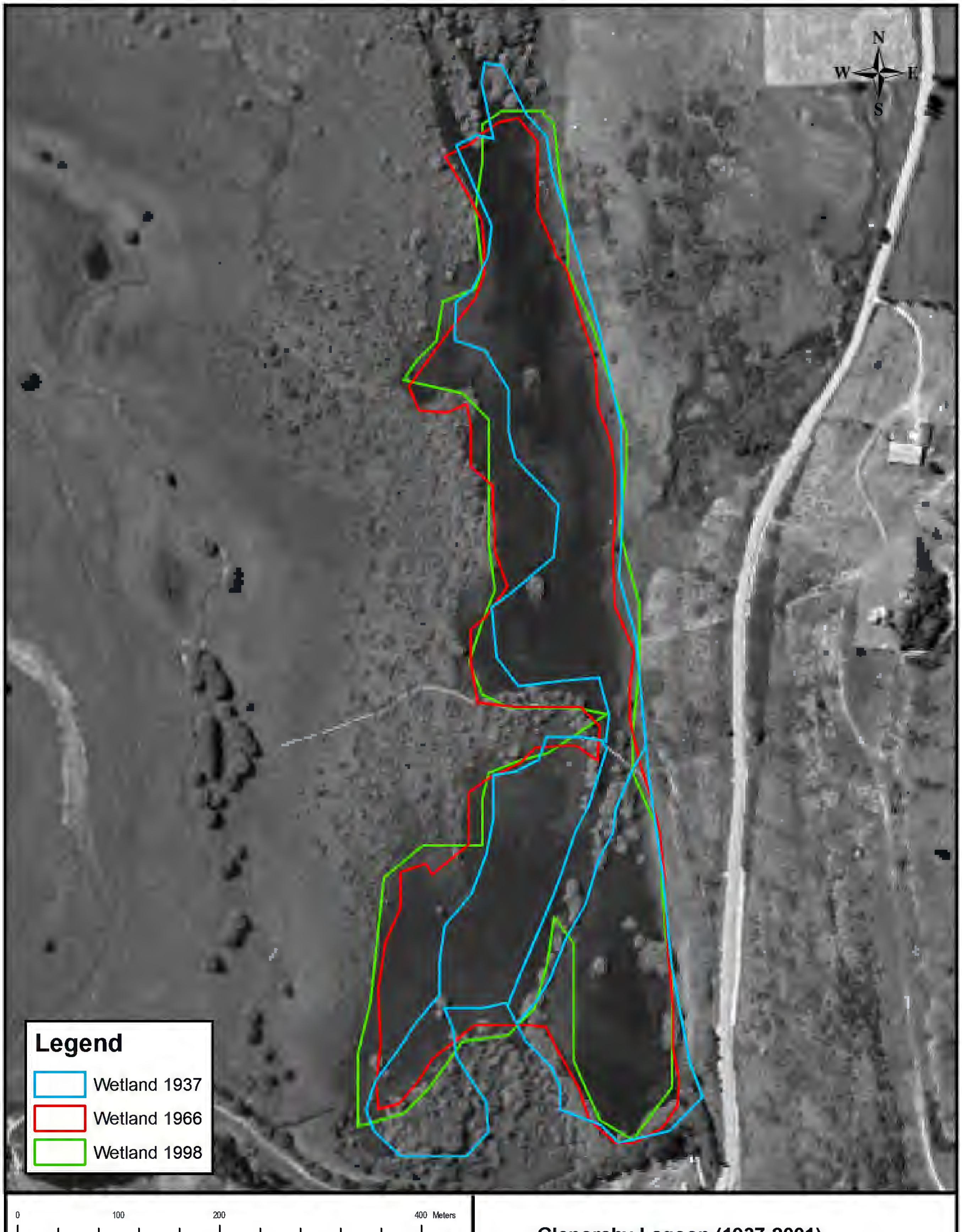
File:	42162267/ Geomorph_aerials	Designed:	WCT	**Shorelines of the Dart, Rees and Buckler Burn Deltas (1864-2001)**	
Scale:	1:15,000	Drawn:	WCT		
Original Size:	A3	Checked:	MM	Status	FINAL
Date Created:	20 April 07	Approved:	MM	Drawing Number: Figure 5-1	Rev: A



Glenorchy Lagoon (1937-2001)

Otago Regional Council	URS New Zealand Engineering and Environmental Management Tel 03 374 8500 Fax 03 377 0655	Level 5 Landsborough House 287 Durham Street Christchurch P.O. Box 4479 Christchurch New Zealand	File: 42162267/Geomorph_aerials_wetland Scale: 1:5000 Original Size: A4 Date Created: 20 April 07	Designed: WCT Drawn: WCT Checked: MM Approved: MM

Status **FINAL**

Figure 6-1

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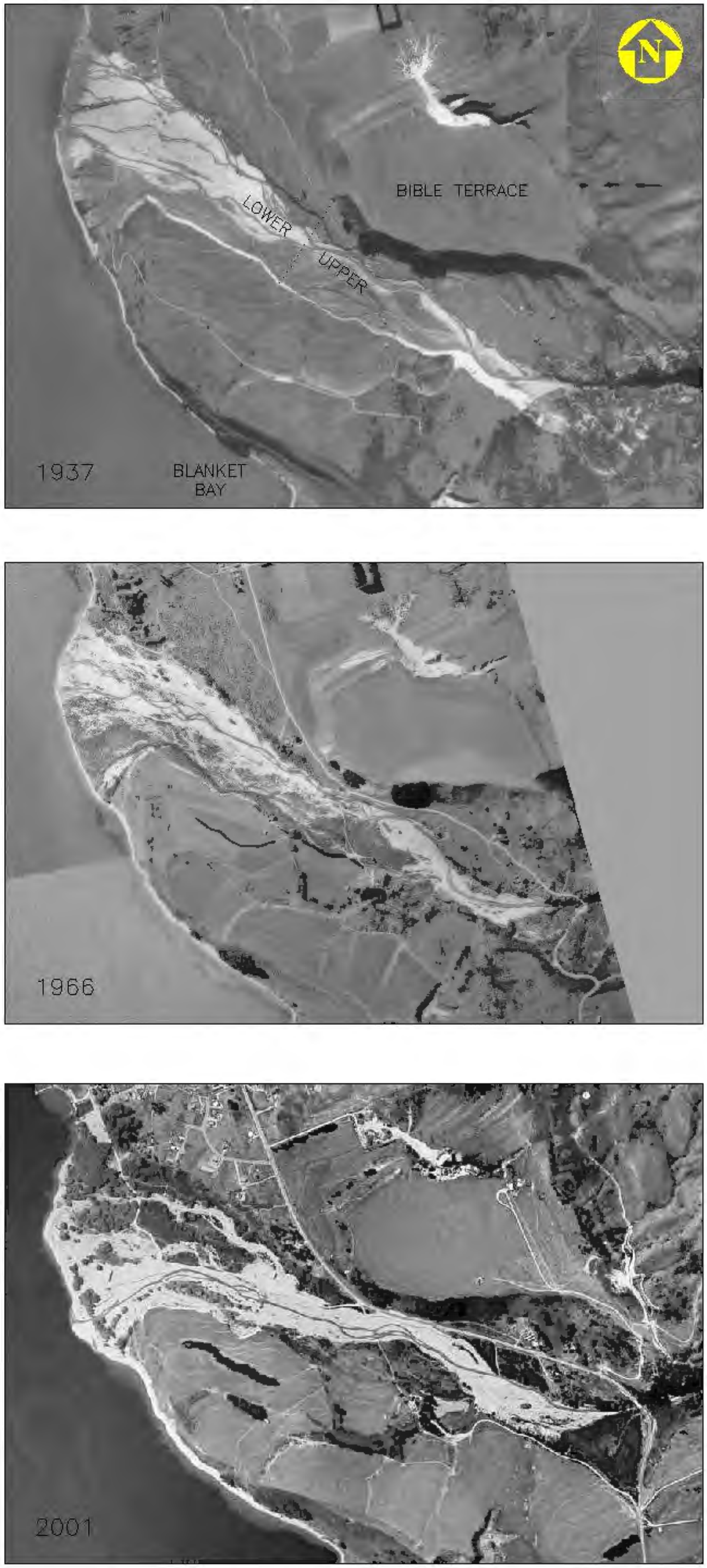
3/6/07 – STT



0 550
APPROX. SCALE (m)

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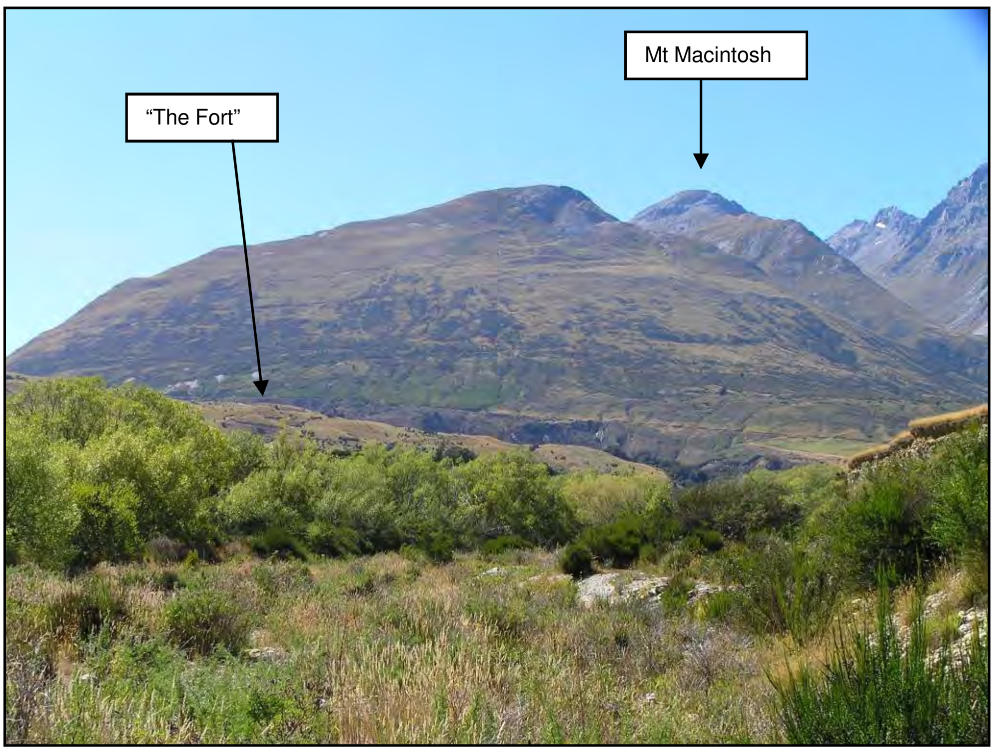
Engineering and Environmental Management

BUCKLERBURN VALLEY

FIGURE 7-1

J:\Jobs\42162267\6000\Drawings\FIG7-1.dwg, 11/06/2007 2:05:52 p.m., Acad-jpg.pc3

Photograph 9-1 View of Mt Larkins across Buckler Burn. Hummocky debris in the centre of the photograph is creeping landslide debris typical of steep schist slopes. Photograph taken 14 February 2007 (photo Tim McMorran)



Photograph 9-2 View of Un-named hill and Mount Macintosh (arrowed). Landslide debris covers this west-facing slope and landslide scarps are visible near the skyline. Glenorchy is protected from any landslide activity by the low ridge visible behind the willows ("The Fort"). Photograph taken 14 February 2007 (photo Tim McMorran)

PROJECT ***Glenorchy Geomorphic and Geo-hazard Assessment***	Otago Regional Council	TITLE **Illustration of creeping landslides near Glenorchy**

			FIGURE
PROJECT: **42162267** REVISION: **A**	DESIGNED: TJM DRAWN: TJM CHECKED: MM	APPROVED: MM DATE: 26 Feb 07 STATUS: Final	**9-1**

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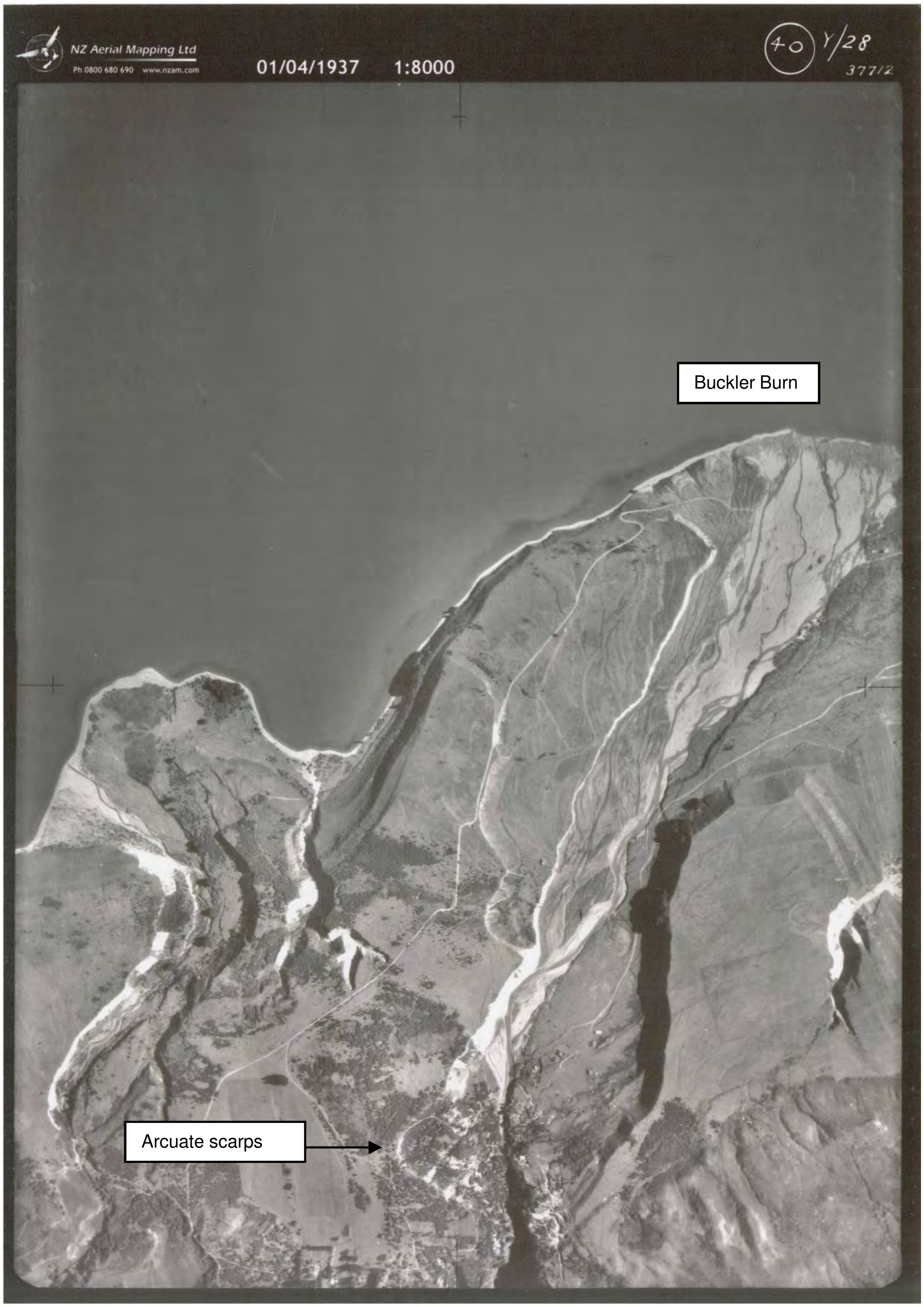
Photographs 9-3 & 9-4 View of West facing slope of “The Fort” above the Glenorchy – Paradise Road.
The steep backscarp is visible with rockfall debris scattered on the slope below.
Photograph taken 14 February 2007 (photo Tim McMorran)

PROJECT ***Glenorchy Geomorphic and Geo-hazard Assessment***	Otago Regional Council	TITLE **Illustration of rock slope failure above Glenorchy – Paradise Road**
PROJECT: **42162267** REVISION: **A**	DESIGNED: TJM DRAWN: TJM CHECKED: MM APPROVED: MM DATE: 26 Feb 07 STATUS: Final	URS New Zealand Engineering and Environmental Management FIGURE **9-1**

Photographs 9-5 & 9-6 Deformation in gravels on the south bank of Buckler Burn. Photograph 5 shows irregular bedding dips in fan gravels (gentle dips toward and away from Lake Wakatipu located to the right of the photograph). Photograph 6 shows bedding in fan gravels deformed by folding and faulting. The fan alluvium is inferred to be underlain by a significant depth of deltaic sediments. Photograph taken 14 February 2007 (Photo Tim McMorran)

PROJECT ***Glenorchy Geomorphology and Geo-hazard Assessment***	Otago Regional Council	TITLE **Illustration of deformation in post glacial deposits adjacent to Buckler Burn**
PROJECT: **42162267** REVISION: **A**	DESIGNED: TJM DRAWN: TJM CHECKED: MM APPROVED: MM DATE: 26 Feb 07 STATUS: Final	URS New Zealand Engineering and Environmental Management
		FIGURE **9-1**



Photograph 9-7 Vertical aerial photograph of lower Buckler Burn showing arcuate scarps that may be natural slope failures. Photograph taken 1937 NZ Aerial Mapping

PROJECT	Otago Regional Council	TITLE
Glenorchy Geomorphology and Geo-hazard Assessment		**Arcuate scarps in the Buckler Burn valley**

PROJECT: **42162267**	DESIGNED: TJM	APPROVED: MM	URS New Zealand Engineering and Environmental Management	FIGURE
REVISION: **A**	DRAWN: TJM	DATE: 26 Feb 07		**9-1**
	CHECKED: MM	STATUS: Final		

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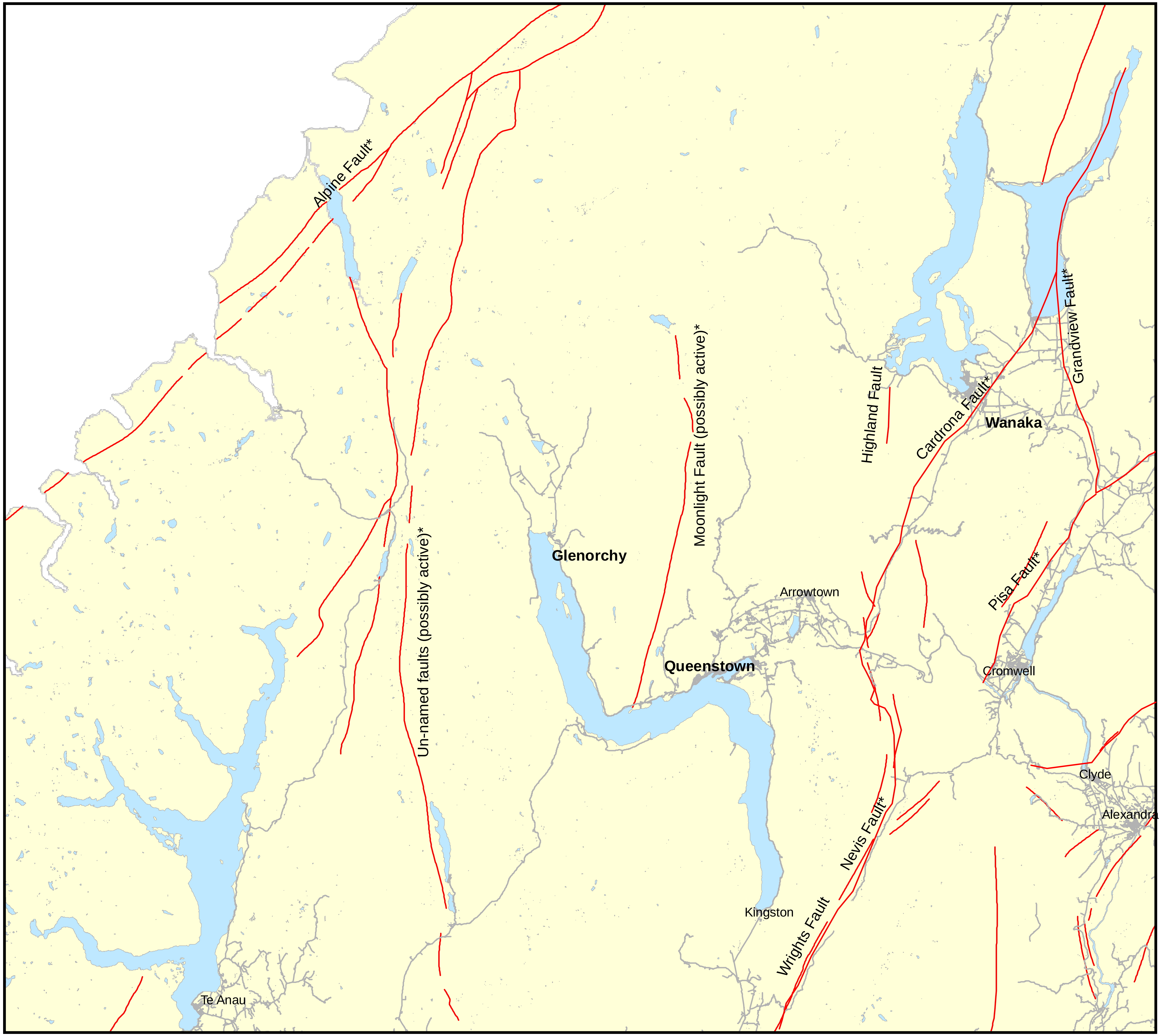

N
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Faults with an asterisk after them are included in Striling et als probalistic seismic hazard model for New Zealand (2002)

0 5 10 15 20 25
Kilometers

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Original Size:	A3	Approved:	MM
Status	DRAFT	Date Created:	Feb 2007

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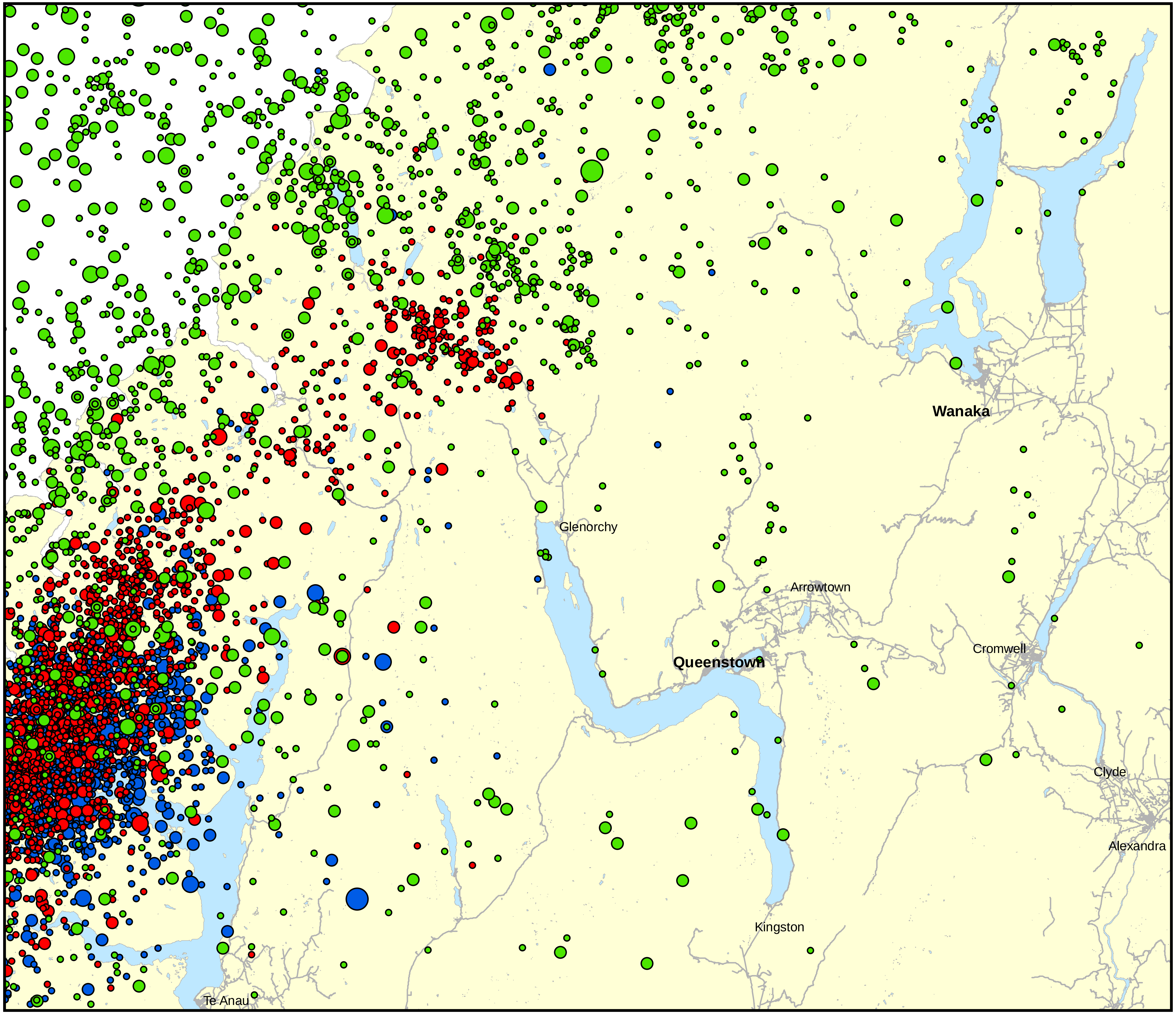
Client
Otago Regional Council

Project
Glenorchy Geomorphic and Geological Hazard Assessment

Title
Surface Fault Rupture Hazard

Drawing Number
Figure 9-2

Rev
Draft



Legend

Depth of Epicentre

- 0 - 40 km
- 41 - 100 km
- > 101

Earthquake Magnitude

- 3.0 - 4.0
- 4.1 - 5.0
- 5.1 - 6.0
- 6.1 - 7.0

0 6 12 18 24 30
Kilometers

File:	J\42162267\6000 Drawings\Maps\ Earthquake mags.mxd	Designed:	RFC
		Drawn:	RFC
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Glenorchy Geomorphic and Geological Hazard Assessment

Title

All recorded earthquakes Magnitude 3 and greater

Drawing Number

Figure 9-3

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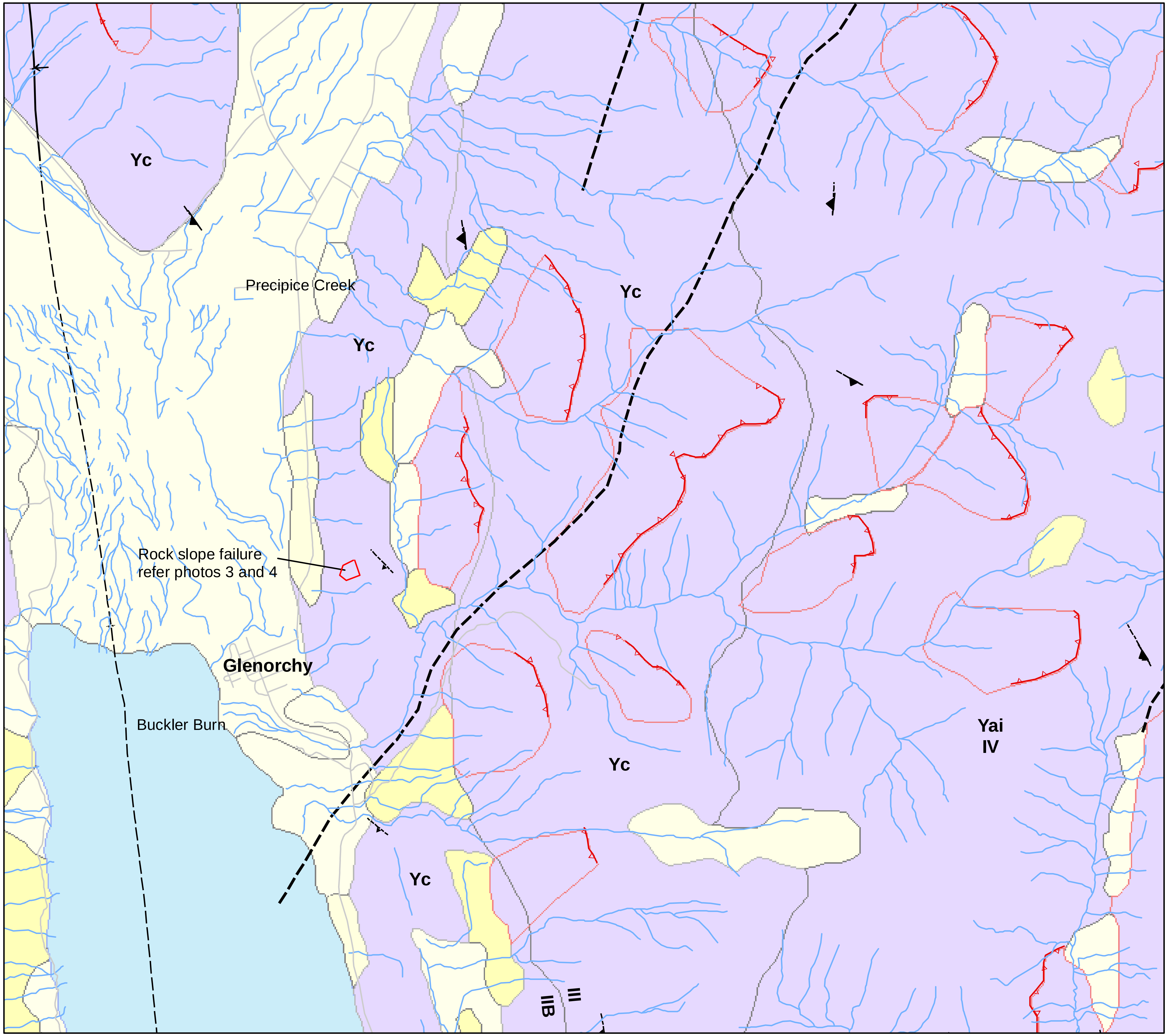

LEGEND

LITHOLOGIES

QUATERNARY

Gravel, sand and mud of modern postglacial flood plains (Q1a), well sorted fine gravel in storm beach ridges (Q1b), Active and inactive scree and slopewash (Q1s), angular bouldery till (Q1t).

Undifferentiated till (Qt2) associated with outwash gravel from valley glaciers.

Undifferentiated Quaternary till (uQt)

HAAST SCHIST

Undifferentiated volcanoclastic sandstone and siltstone (Yc) of the capples terrance. Massive to graded sandstone and black mudsone with conglomerate and volcanic lenses (Ycb)

Schist, variable segregated, veined and foliated (Yai) of the Rakaia terrane.

TEXTURAL ZONATION

IIA Weakly foliated semischist
IIB Foliated semischist
III Well foliated, slightly segregated schist
IV Strongly foliated and segregated schist

GEOLOGICAL SYMBOLS

Landslide/landslide scarp

Fault (approximate)

Syncline

Syncline (inferred)

Foliation/schistosity dipping

0 1 2 3

Kilometers

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		Drawn:	RFC
Scale:	1:50,000	Checked:	MM
Original Size:	A3	Approved:	MM
Status	DRAFT	Date Created:	Feb 2007

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Glenorchy Geomorphic and Geological Hazard Assessment

Title

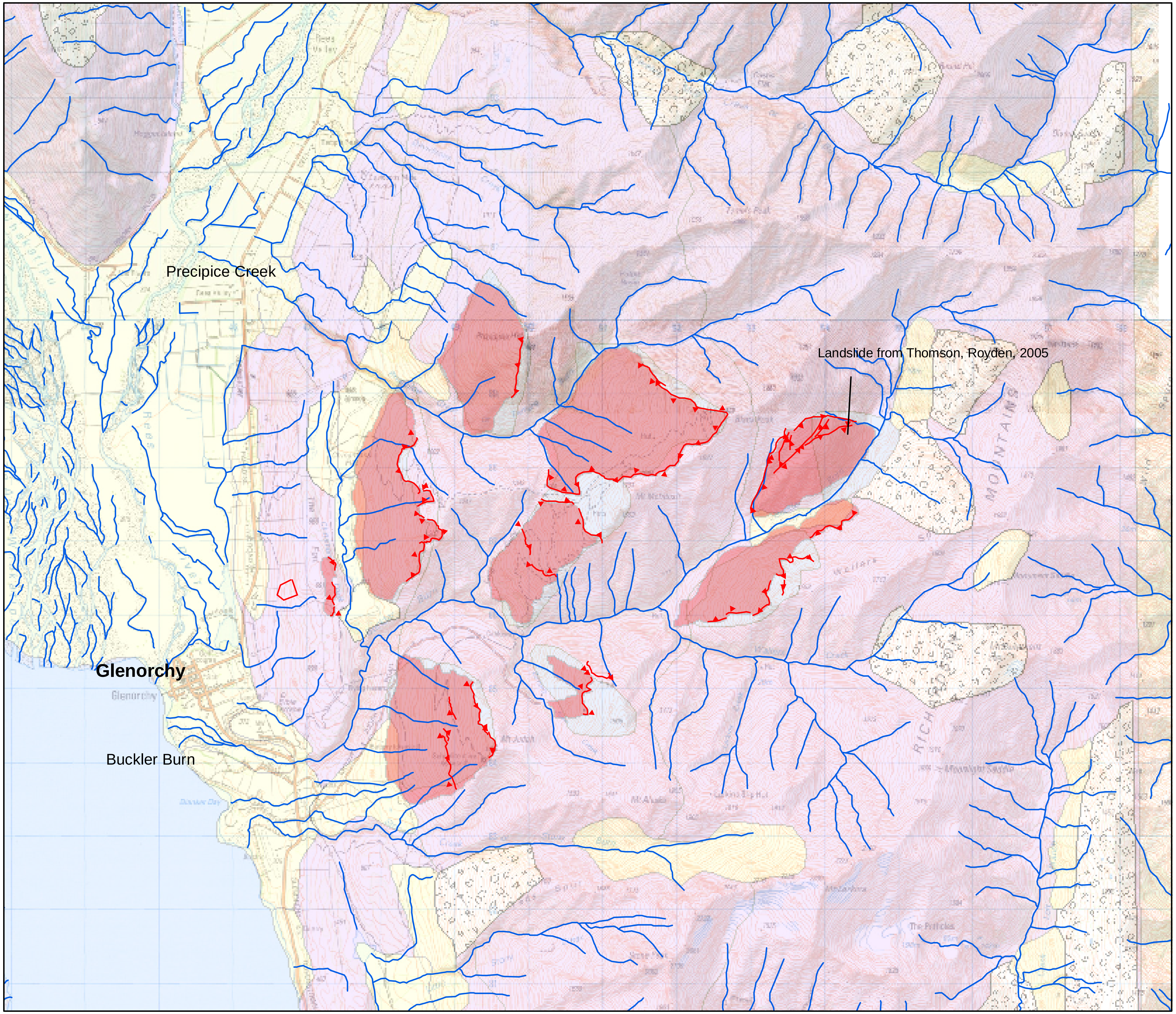
Geological Map

Drawing Number

Figure 9-4

Rev

Draft



N
W E
S

LEGEND

LITHOLOGIES

QUATERNARY
Gravel, sand and mud, scree, slopewash and till.

HAAST SCHIST

GEOMORPHOLOGY

Landslide from geological map

Landslide interpreted from aerial photograph alaysis

Thomson, Royden, Buckler Burn Impoundment: Report on Inspection of the 17 November 2005.

0 0.75 1.5 2.25 3
Kilometers

File: J\42162267\6000 Drawings\Maps\ geomorphology.mxd	Designed: RFC Drawn: RFC
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Title

Geomorphic map of Landslides

Drawing Number

Figure 9-5

Rev

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