Environment Southland
Tsunami and Seiche Study – Stage 2: Evaluation of potential earthquake-induced landslide sites where tsunami waves could be generated on Lake Manapouri and Lake Te Anau

G.T. Hancox

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DISCLAIMER

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EXECUTIVE SUMMARY

This report presents the results of Stage 2 of a seiche and tsunami hazard study of Lake Manapouri and Lake Te Anau being undertaken by GNS Science for Environment Southland. A helicopter reconnaissance survey and aerial photo analysis carried out in the second phase of the study has enabled the earthquake-induced landslide and wave generation potential of specific sites within 31 areas around the shorelines of Lake Manapouri and Lake Te Anau to be evaluated. The steep (≥35-45°) slopes in these areas have high to very high landslide susceptibility, most have active and recent shallow landslides, and some show clear evidence of older (probably prehistoric), large defect-controlled wedge and translational bedrock failures, where previous large collapses into the lakes appear to have occurred.

The main criteria used to identify and evaluate potential sites where landslides could occur during strong earthquake shaking (intensity MM8–MM10) were the scars of active and recently active landslides, rock fall debris on slopes, debris fans, and the absence or variations in vegetation. Landslide size was estimated from the nature, steepness, and height of the possible failure areas, and by comparison to the types and size of landslides triggered by the 2003 and 2009 Fiordland earthquakes. These factors, together with lakeshore location, travel distance, and evidence from historical landslide-generated waves in Fiordland (Deep Cove 1987, Gold Arm 2003) and overseas were used to estimate potential run-up heights of landslide-generated waves on Lake Manapouri and Lake Te Anau in relation to facility sites of interest to Environment Southland.

Evaluations of the potential landslide sites identified in the Stage 2 study have shown that most of the expected earthquake-induced landslides around the shores of Lake Manapouri and Lake Te Anau are likely to be shallow, small to moderate (~10^3–10^4 m^3) rock falls and debris slides, with larger (~10^5–10^6 m^3) bedrock failures possible in some places. No areas were identified where very large (10^7–10^8 m^3) landslides into lakes Manapouri and Te Anau are expected to occur. Although more than 50 very large and giant (≥10^8 m^3) deep seated post glacial landslides are known in Fiordland, there is no evidence to show that earthquake-induced slope failures of that size (10^7–10^8 m^3) are likely to occur in the Manapouri and Te Anau area in the foreseeable future.

The largest (~10^4–10^6 m^3) earthquake-induced landslides that are expected to occur within about 5 km of the facility sites of interest to Environment Southland are at: *Site A1* south of Manapouri powerhouse in West Arm; *Site O1* on the northeast side of Lake Manapouri; *Site L* near Worsley Hut in Worsley Arm of Lake Te Anau; and *Site M* near the Glade Burn wharf and start of the Milford Track at the head of Lake Te Anau. Historical evidence suggests that rapid small to moderate landslides (10^3–10^4 m^3) produce waves with run-up heights of 0.5–1 m within of 1 km of the slide areas. Potentially larger landslides (10^5–10^6 m^3) at Site F1 in Lake Manapouri could generate waves with run-up heights of ~3 to 25 m and affect Manapouri powerhouse, West Arm wharf, and Freeman Burn Hut, which are all about 8 km away.

The facility sites thought to be potentially at greatest risk from waves generated by rapid landslides, rock falls, or debris flows into the lakes are: Manapouri powerhouse and wharf *(Sites A1 and A2)*, Worsley Hut (*Sites L2 and L3*), and the Glade Burn wharf *(Sites M1 and M2)*. Tsunami modelling may be necessary (in Stage 3) to determine the potential wave effects of different size and types of landslides at these three sites. Modelling of generalised large (10^5–10^6 m^3) slope failures at these sites would provide a better indication of the height and distribution of the tsunami waves that could be generated and their potential to cause damage at facility sites. Site specific assessments may also be necessary to assess the direct risk from landslides, debris flows, lateral spreading and delta collapses at these facility sites, and possibly the Freeman Burn Hut and Glaisnock Hut sites.

1.0 INTRODUCTION

In 2011 the Institute of Geological and Nuclear Sciences Limited (GNS Science) prepared a report for Environment Southland (ES) which: (1) identified and characterised the potential seismic sources and possible sites of landslides and delta or lake shore collapses that could cause seiches and/or tsunami[1] on Lake Manapouri and Lake Te Anau; (2) provided a preliminary discussion and estimate of the extent to which key facility sites of priority interest to ES on lakes Manapouri and Te Anau (such as residential and commercial centres, accommodation and tourist facilities, hydro-electric power, and recreation amenities (huts, tracks, wharves) might be threatened by seiches and/or tsunamis (Clark et al. 2011). That report presented the results for Stage 1 of a possible three-stage study.

In Stage 1 of the Lake Manapouri and Lake Te Anau tsunami study GNS Science identified 26 potential areas around the shores of those lakes where strong earthquake shaking (intensity MM8 or greater) could potentially trigger a landslide into the lakes and generate tsunami waves that could affect the sites of priority facilities identified by Environment Southland (Figures 1 and Figure 2). Following a request to GNS Science from Environment Southland Dallas Bradley (Senior Planner, Hazard Mitigation) it was agreed that Stage 2 of the seiche and tsunami study during 2012 would be an evaluation of the earthquake-induced landslide (EIL) tsunami generating potential on Lake Manapouri and Lake Te Anau. This report presents the results of the Stage 2 study, which was undertaken by the author (Graham Hancox) between January and June 2012.

1.1 Scope of Stage 2 Study

The scope of work that was agreed by GNS Science and Environment Southland and undertaken in the Stage 2 study included:

(1) A helicopter reconnaissance survey of the 26 potential earthquake-induced landslide areas around the shorelines of Lake Manapouri and Lake Te Anau that was carried out by the author on 17 and 18 January 2012. Figure 3 shows the approximate helicopter reconnaissance flight paths. The main purpose of the aerial survey was to carry out an inspection of the slopes above the lakes to determine the potential for earthquake-triggered landsliding in the areas identified in stage one, and any other parts of the lakeshore areas with similar EIL potential. Brief ground checks could have been carried out in some places, but given the reconnaissance nature of the survey and total length of the lakeshore inspected (~400 km) no sites were found where this was necessary.

(2) The aerial reconnaissance allowed more than 1000 high resolution oblique aerial photos to be taken of the potential EIL areas, which were then used to assess the characteristics, slope stability, and landslide potential of each area. Some parts of North Fiord in the vicinity of Glaisnock Hut (Figure 2) on the west side of Lake Te Anau were unable to be seen clearly during the aerial inspection because of low cloud and light rain. These areas were assessed using recent (September 2011) Google Earth Pro images. The head of Middle Fiord on Lake Te Anau was not inspected because of cloud and rain, and the absence of potential EIL areas in that more isolated part of the lake.

[1] Seiche, tsunami, landslide, earthquake, and related technical terms are defined in the Stage 1 Report (Clark et al. 2011).

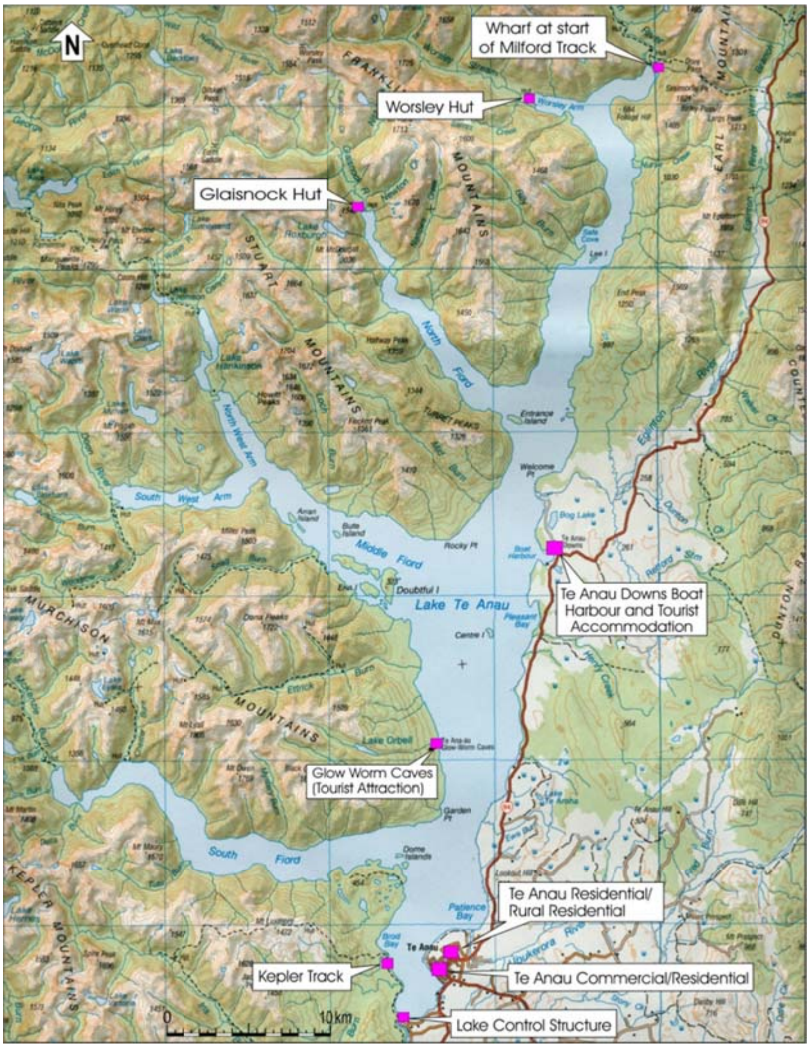

Figure 1. Map of Lake Te Anau showing sites of priority interest to Environment Southland *(information provided by Environment Southland 2011)*.

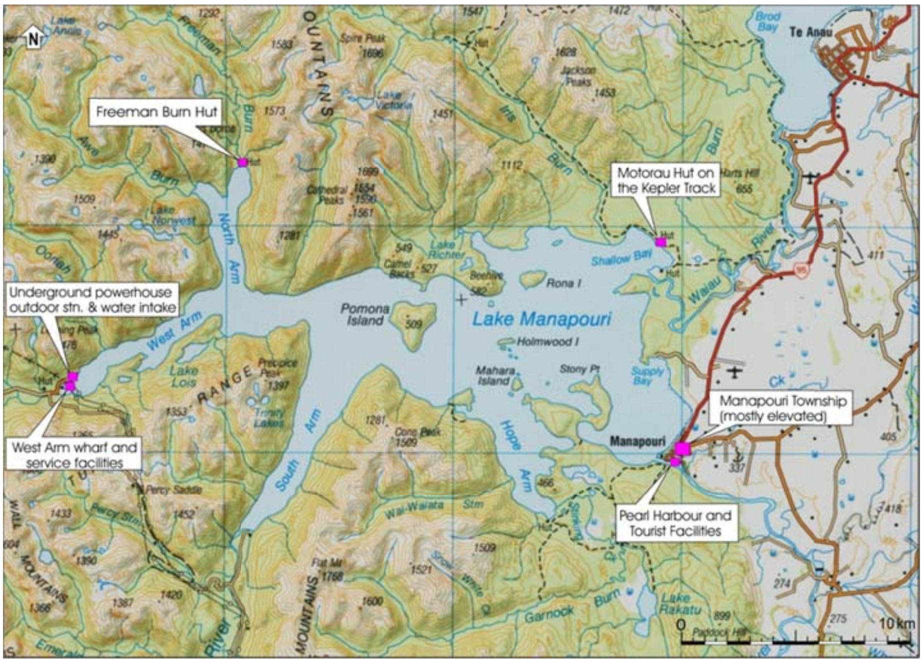

Figure 2. Map of Lake Manapouri showing sites of priority interest to Environment Southland *(information provided by Environment Southland 2011).*

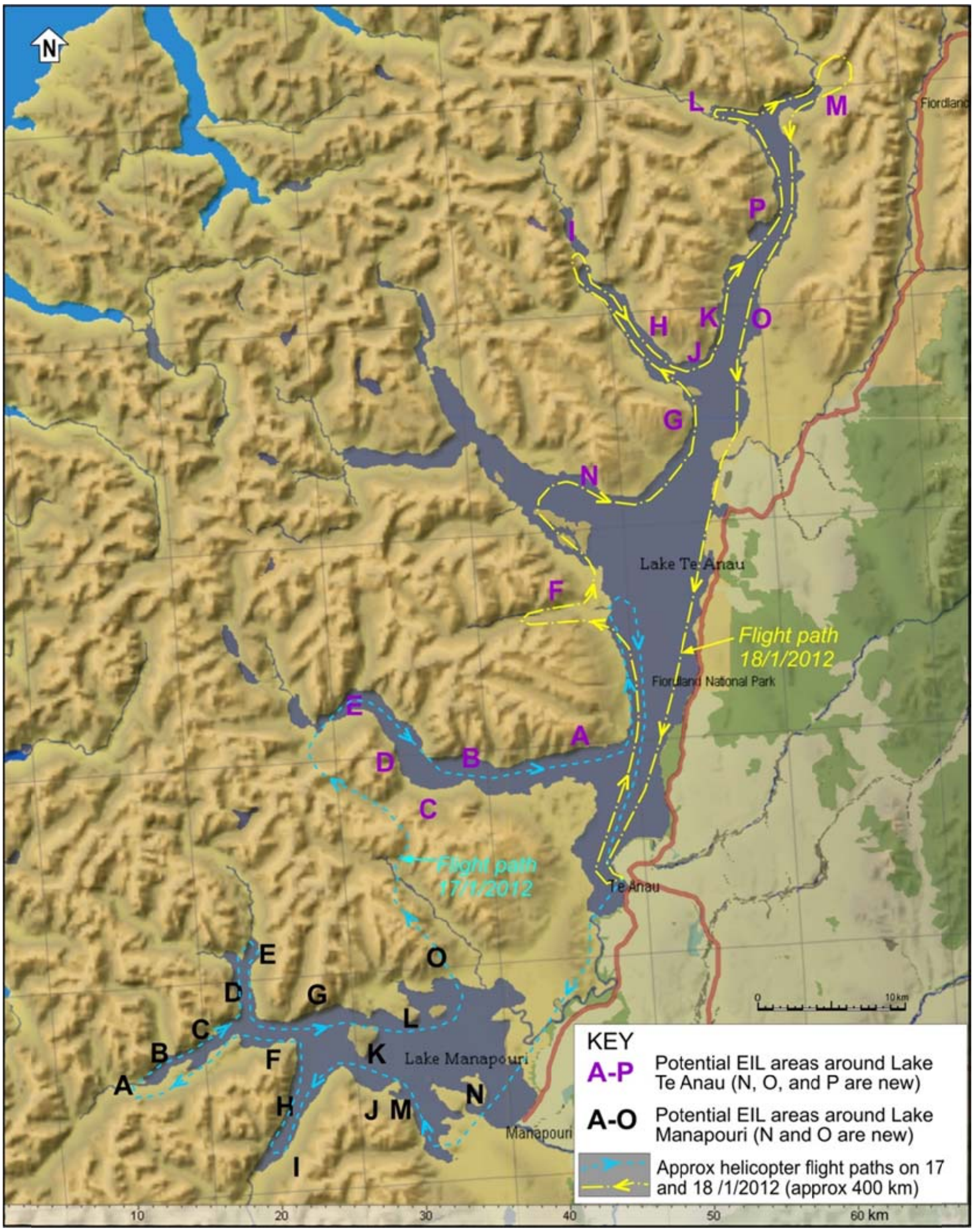

Figure 3. Helicopter flight paths for the 17 and 18 January 2012 aerial reconnaissance of potential earthquake-induced landslide areas around Lake Manapouri and Lake Te Anau.

1.2 Stage 2 Report

This report presents the results of the Stage 2 landslide-induced tsunami study for Lake Manapouri and Lake Te Anau. It has been prepared using observations and photos from the aerial reconnaissance survey in January 2012, Google Earth images, Topo50 topographic maps, and slope angle and landslide susceptibility maps prepared for the Stage 1 report (Clark et al. 2011). These maps were revised during the Stage 2 study (Figures 6 and 8).

General geological information on each of the potential EIL areas was obtained from the GNS Science 1:250 000 geological map of Fiordland (Turnbull 2010). The regional geology of the Lake Manapouri and Lake Te Anau areas are shown in Figure 7 and Figure 9 respectively, along with a summary of the rock types present at potential EIL areas.

2.0 RESULTS OF THE STAGE 2 STUDY

The January 2012 aerial reconnaissance inspection and oblique aerial photos enabled the 26 potential earthquake-induced landslide areas recognised in Stage 1 around the shores of Lake Manapouri and Lake Te Anau to be closely inspected. In addition, five other areas with similar EIL potential (2 in Manapouri, 3 in Te Anau) were identified during the helicopter flight (Figure 3). The locations and slightly revised boundaries of the 31 potential EIL areas are shown on the slope and landslide susceptibility maps (Figures 6 and 8).

During the assessment of the 31 potential EIL areas, specific sites within those areas were identified where landslides are expected during strong earthquake shaking of Modified Mercalli intensity MM8 or greater (see Appendix 1).

The nature and size of expected slope failures and their potential for tsunami generation at the identified sites was then assessed using a combination of geomorphic and geological factors along with historical precedent evidence from landslides triggered by recent large earthquakes in Fiordland (Hancox et al. 2003, 2010). The methodology used for these assessments is described below.

The potential tsunami generation effects at each site are discussed only in general terms, based mainly on the large rock fall in Gold Arm in 2003 (Figure 4) and other landslides that occurred during the 2003 M_w 7.2 Secretary Island earthquake in Fiordland (Hancox et al. 2003, Power et al. 2005), a rock fall-induced wave in Doubtful Sound in 1987, and several well-known overseas landslide-generated tsunamis. These events illustrate the types of wave damage effects that are possible in relatively narrow and confined fiords or arms of large lakes like lakes Manapouri and Te Anau.

Precise estimates of the tsunami-generating potential of the future possible landslides at each site are not included in the report. More detailed assessments and tsunami modelling of future landslides entering the lakes at the potential landslide sites may be undertaken in a Stage 3 study.

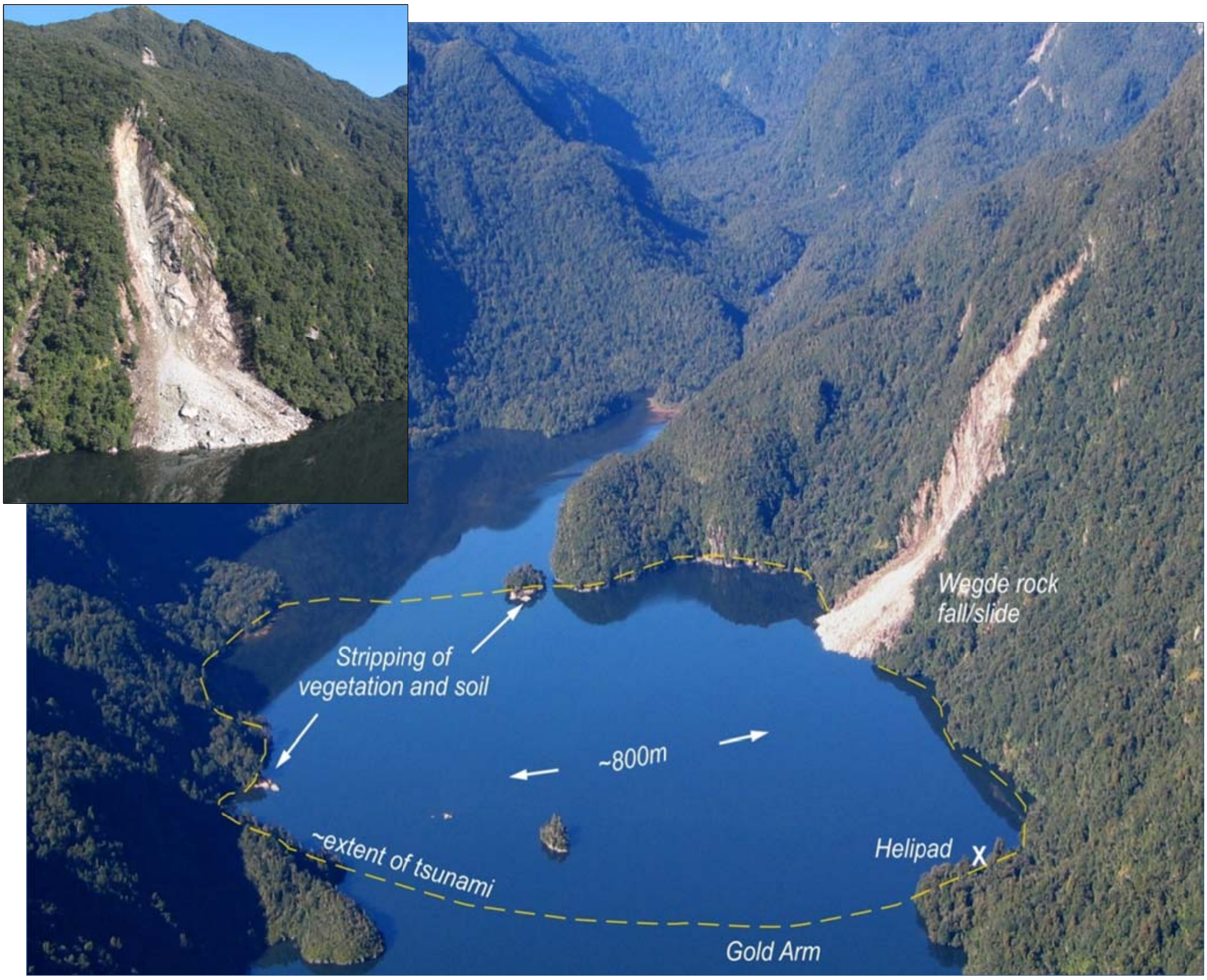

Figure 4. Aerial views of the ~200,000 m^3 rock fall in Gold Arm of Charles Sound which was triggered by the M_w 7.2 Fiordland earthquake in August 2003. The rock fall caused a small tsunami which travelled ~800 m across the sound and stripped vegetation and soil 4–5 m above high tide level, and partially stripped vegetation off a small island (centre). The wave also damaged a helipad (lower right) ~250 m west of the slide *(from Hancox et al. 2003)*.

2.1 EIL assessment methodology

For the 2011 Stage 1 study landslide susceptibility in the Lake Manapouri and Lake Te Anau areas was assessed using a simple slope angle model based mainly on historical earthquake-induced landslide data and relationships determined from recent New Zealand-wide studies of earthquake-induced landslide (Hancox et al. 1997, 2002), and incorporating landslide data from the 2003 and 2009 Fiordland earthquakes (Hancox et al. 2003, 2010).

During the Stage 2 reconnaissance shoreline slopes within and adjacent to each of the potential EIL areas were closely inspected for active landslides, scars of recently active failures, or other evidence of slope instability, such as absence or variations in vegetation, and rock fall or debris fans or accumulations at the foot of slopes. The slope instability evidence was used together with topographic factors (slope steepness, height, and toe support) and geological features (bedding, foliation and joint planes and wedges, and shear zones) to identify specific sites within the EIL areas where landslides could be expected to occur during strong earthquake shaking (MM8–MM10).

Specific sites where earthquake-induced landsliding was most likely to occur within the potential EIL area were identified using the following criteria:

(a) Steep (~25–35°) and very steep (≥35–45°) slopes, particularly cliffs and slopes that are undercut and more than ~200–300 m high.

(b) Slopes scarred by active or recently active rock falls, landslides, debris slides, and gully erosion, especially landslides that were triggered by recent Fiordland earthquakes; areas adjacent to or above old wedge or translational bedrock failure scars.

(c) Other geomorphic or geological indicators such as active erosion areas, thick soils or weaker crushed and sheared rock, rock fall deposits, and debris fans.

The type and size of possible future landslides at each potential EIL site was estimated from the slope characteristics, existing slope failures at the site, and landslides triggered by the 2003 and 2009 Fiordland earthquakes (Hancox et al. 2003, 2010). The tsunami generating potential of future landslides at these sites was estimated based on landslide size, slope height and steepness, location on the lake-shore.

The height of waves that could potentially be generated at different sites was estimated empirically using data from a number of documented landslide-generated tsunamis from New Zealand and overseas, specifically those at: Tafjord, Norway in 1934 (Jorstad 1968), Mt Colonel Foster (Landslide Lake), Canada 1946 (Evans 1989), Lituya Bay, Alaska 1958 (Miller 1960), Deep Cove of Doubtful Sound, New Zealand 1987 (Southland Times, 23/5/87), Gold Arm of Charles Sound, New Zealand 2003 (Hancox et al. 2003), and Chehalis Lake, Canada in 2007 (Roberts 2009). Landslide data and wave heights for those events are summarised in Table 1 and plotted on a log-log graph in Figure 5, along with extrapolated wave heights for hypothetical events with intermediate and smaller landslide volumes. Historical and extrapolated values have been used to estimate possible landslide-generated wave heights for landslides of different sizes at potential landslide sites around the shores of Lake Manapouri and Lake Te Anau (Table 2). The wave heights referred to in this report are in most cases the maximum vertical wave run-up height observed on slopes around the shorelines of lakes and fiords, rather than the vertical height of the waves (top to bottom).

Table 1. Summary of historical landslide-generated tsunami events used to estimate landslide-induced wave heights at potential landslide sites on Lake Manapouri and Lake Te Anau.

Landslide Tsunami Event	Vertical[1] fall (m)	Landslide volume (m^3)	Maximum wave height (m)[2]	References
Tafjord, Norway in 1934 (rock slide/avalanche)	700	3 M m^3	62	Jorstad 1968
Mt Colonel Foster, Canada in 1946 (rock avalanche)	700-1000	0.7 M m^3	29	Evans 1989
Lituya Bay, Alaska in 1958 (rock slide/avalanche)	950	30 M m^3	524	Miller 1960
Deep Cove, Fiordland NZ in 1987 (debris/rock fall)	400	0.1 M m^3	2.5	Southland Times 23/5/87
Gold Arm, Fiordland NZ in 2003 (rock fall)	400	0.2 M m^3	4.5	Hancox et al. 2003, Power et al. 2005
Lake Chehalis, Canada in 2007 (rock slide/avalanche)	600	2.5 M m^3	25	Roberts 2009, Brideau et al. 2011

Notes:
1. The landslides listed are all rapid events (~3-5 m or >/sec), with significant vertical fall (~400 -1000 m).
2. The wave heights listed above (and used in the report) are in most cases the maximum vertical wave run-up height above lake or fiord level observed on slopes around the shoreline, rather than the vertical height of the waves (top to bottom).

Table 2. Estimated tsunami wave heights for landslides into lakes Manapouri and Te Anau.

Potential landslide size	Estimated maximum wave heights
Very small to small landslides (10^2–10^3 m^3)	~< 0.5 m within ~0.5 km of site.
Small to moderate landslides (10^3–10^4 m^3)	~0.5–1 m within 0.5 –1 km of site.
Moderate to large landslides (10^4–10^5 m^3)	~1–3 m, within ~0.5–1 km of site.
Large landslides- a (1–2 x 10^5 m^3)	~3–5 m, within ~0.5–1 km of site.
Large landslides- b (3–5 x 10^5 m^3)	~5–10 m, within ~1–5 km of site.
Large to very large landslides (5 x 10^5–10^6 m^3)	~10–25 m, within ~1–5 km of site.
Very large landslides (1–3 x 10^6 m^3)	~25–60 m, within ~1–5+ km of site.
Notes: 1. These estimates relate to rapid landslides (rock and debris falls, slides, avalanches, with a fall height of ~200-400 m or greater. 2. The wave (run-up) height values, derived from Figure 5, have an estimated error of +/- ~10-20%.	

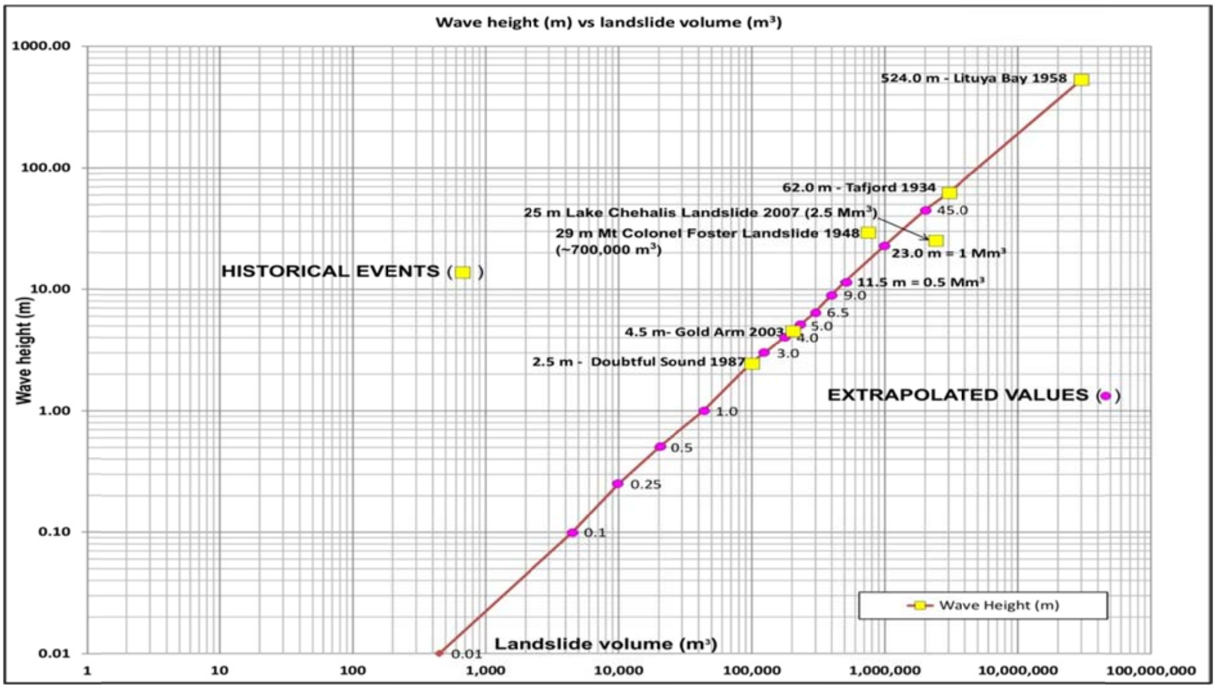

Figure 5. Wave height / landslide volume graph showing historical landslide-generated tsunami events (yellow squares) and extrapolated values (circles) used to estimate possible landslide-induced wave heights at potential landslide sites on Lake Manapouri and Lake Te Anau.

2.2 Potential EIL source areas and failure sites around the shores of Lake Manapouri and Lake Te Anau

Location details, slope morphology, landsliding, and geology of 31 potential EIL source areas around the shores of Lake Manapouri and Lake Te Anau are summarised in Table 3 and Table 4 respectively. The extent of these areas, active and recent landslides, and potential future earthquake-induced landslide sites identified from the reconnaissance inspection and aerial photos are shown on topographic maps of Lake Manapouri (Figures 10a, 10b, 10c and 10d) and Lake Te Anau (Figures 11a, 11b, 11c, and 11d). The earthquake-induced landsliding and tsunami generating potential in the potential EIL source areas and specific sites within them is discussed and evaluated in Section 2.2.1 and 2.2.2. Aerial photos are included to illustrate some potential earthquake-induced landslide sites that are discussed (Figures 12 to 25). The results of site assessments are summarised in Table 5.

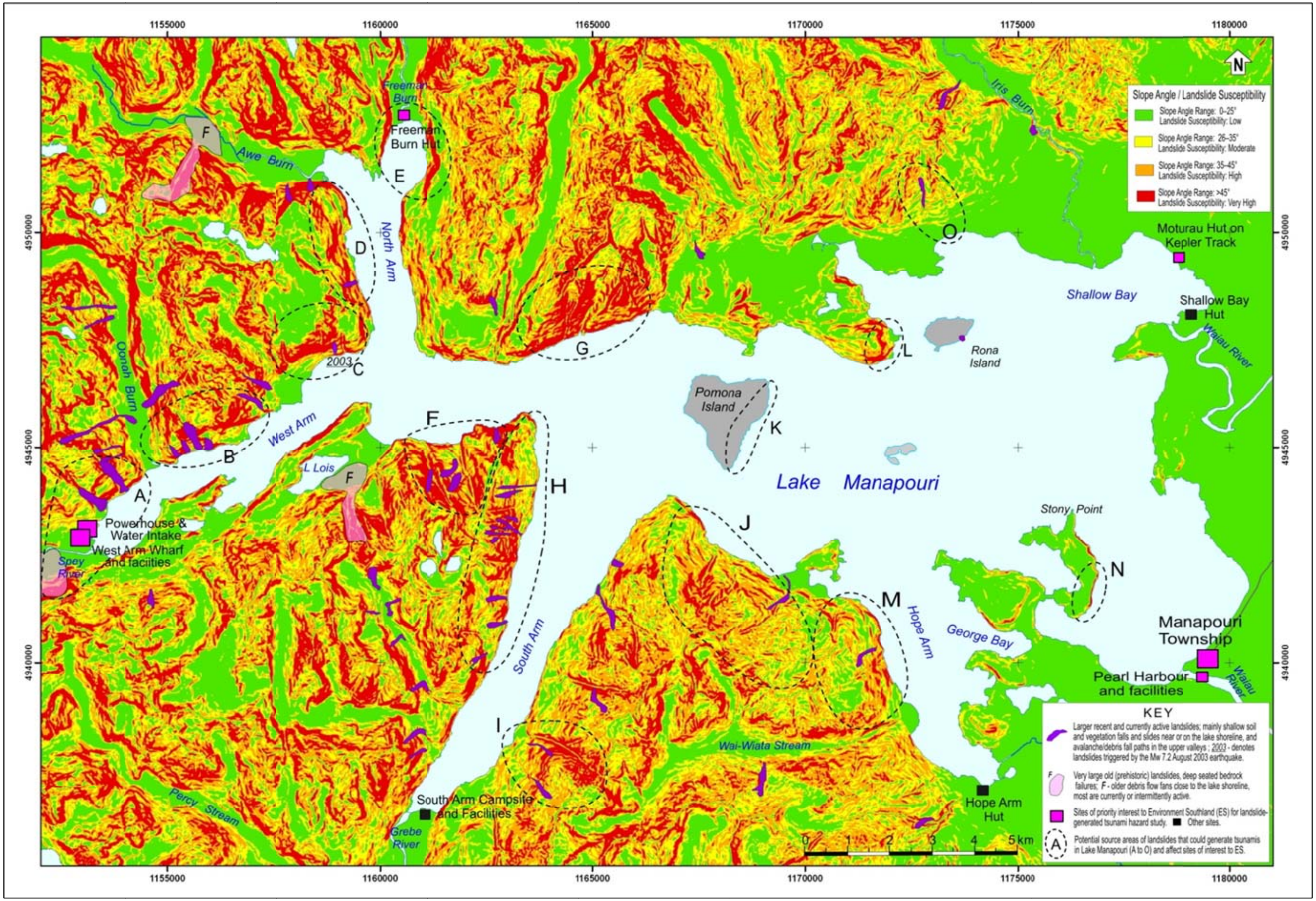

Figure 6. Slope angle landslide susceptibility map of Lake Manapouri showing potential EIL areas (A to O) where landslides into the lake might occur during strong earthquake shaking (MM8-MM10) causing a tsunami that could affect sites of interest to Environment Southland (revised Stage 2).

Figure 7. Regional geological map of the Lake Manapouri area showing the main rock types and structures at the potential EIL source areas (A-O) around the lake shore in relation to facility sites of interest to Environment Southland *(geology from Turnbull et al. 2010)*.

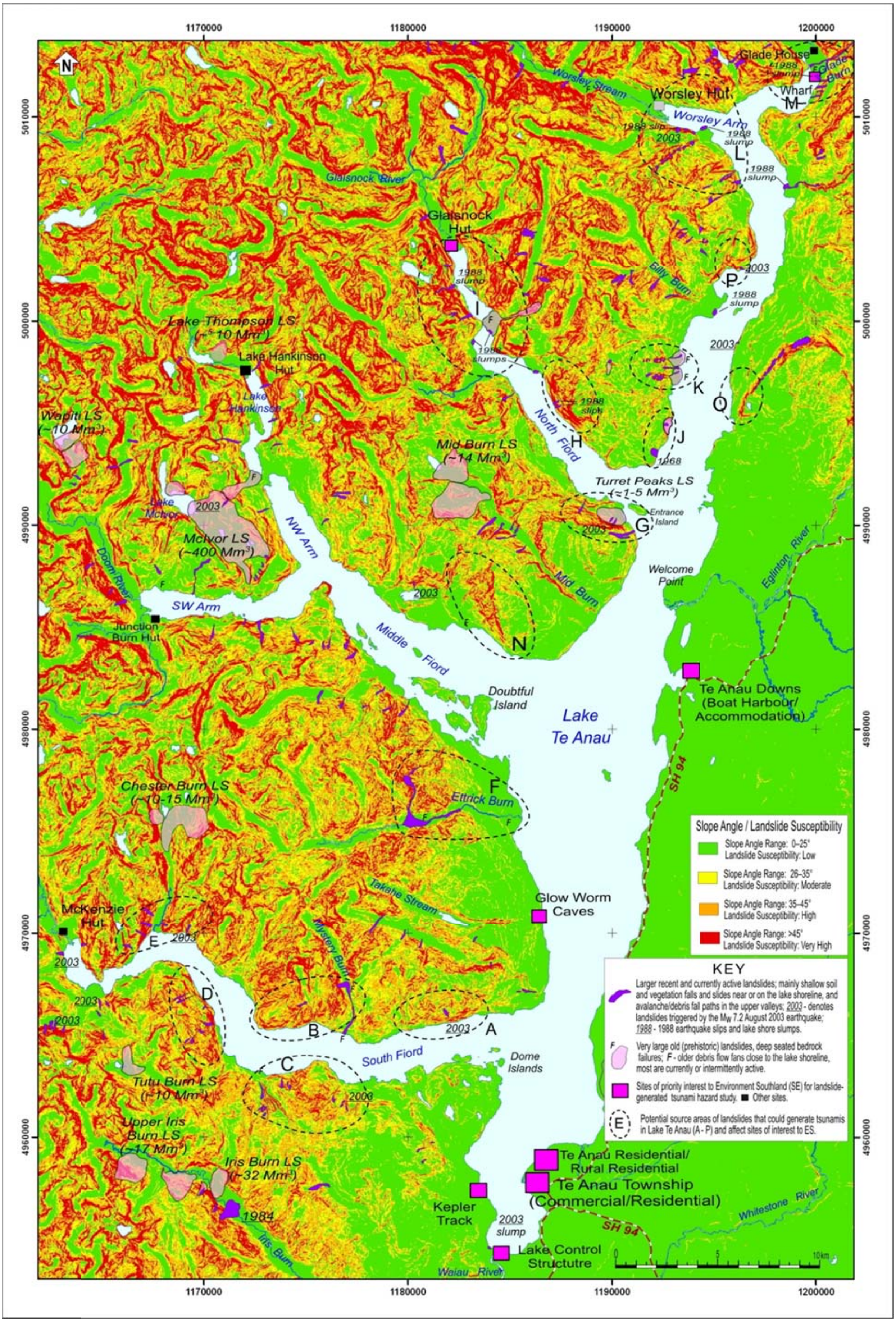

Figure 8. Slope angle and landslide susceptibility map of Lake Te Anau showing potential EIL areas (A to P) where landslides into the lake might occur during strong earthquake shaking (MM8-MM10) causing a tsunami that could affect sites of interest to Environment Southland (revised Stage 2).

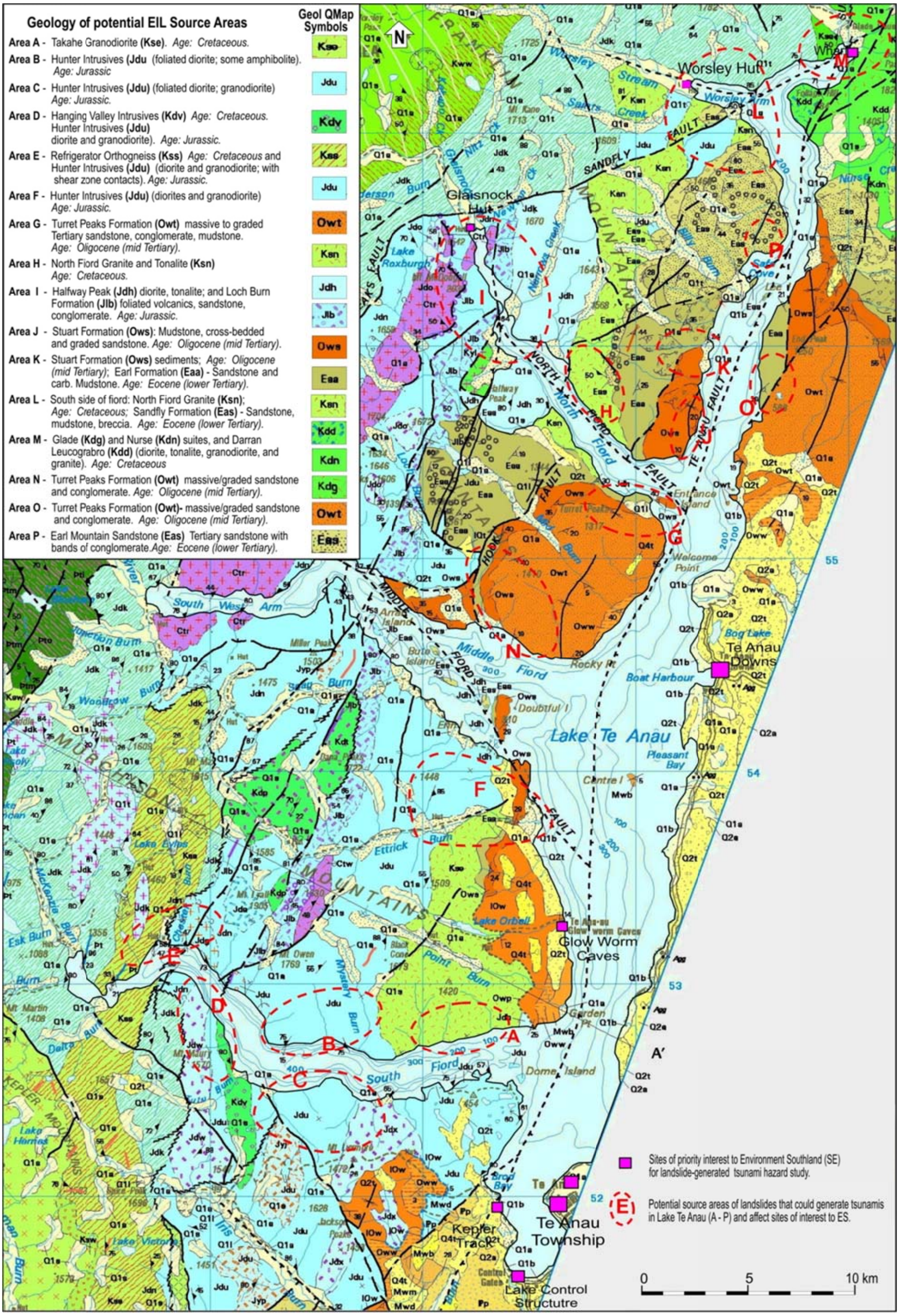

Figure 9. Regional geological map of the Lake Te Anau area showing the main rock types and structures at the potential EIL source areas (A-P) around the **l**ake shore in relation to facility sites of interest to Environment Southland *(geology from Turnbull et al. 2010)*.

Table 3. Locations, slope morphology, landsliding, rock types, and distance from sites of interest to Environment Southland (A–O) of potential source areas of earthquake-induced landslides around the shoreline of Lake Manapouri.

Source[1] Areas	Location[1]	Slope morphology and existing landslides,[2,5]	Minimum distance to nearest sites of interest to ES / Comments[1]	Geology [3]	Aerial Photos[4] (taken 17/1/ 2012)
A	Head of West Arm, N side.	Steep-very steep ~400-600 m high; 2 shallow landslides.	0.5–1 km to Manapouri powerhouse, West Arm wharf (~25 km to Manapouri).	West Arm Leucogranite (Ksw) and meta-sediments (Pt), brecciated along contacts between rock units.	7735a,b; 7749a,b,c; 7755; 7762; 7769; 7774; 7775; 7779; 7782.
B	West Arm, N side.	Steep-very steep ~500 m high; several shallow landslides.	2–3 km to Manapouri powerhouse and West Arm wharf.	West Arm Leucogranite (Ksw).	7762; 7792a, b; 7795.
C	Entrance West Arm, N side.	Area of very steep slopes; one landslide area.	7 km to Manapouri powerhouse and West Arm wharf.	West Arm Leucogranite (Ksw).	7716; 7721; 7801; 7804; 7809.
D	North Arm, W side.	Steep-very steep 200-400 m high slopes; one landslide area.	2–3 km from Freeman Burn hut. Other sites do not appear to be at risk (?).	West Arm Leucogranite (Ksw).	7816; 7820; 7826; 7850; 7853; 7854; 7855.
E	Head of North Arm.	Very steep slopes at head of arm; no known landslides.	200–500 m from Freeman Burn hut. Other sites do not appear to be at risk (?).	West Arm Leucogranite (Ksw).	7830; 7838; 7843; 7846.
F	Opposite North Arm, S side.	Large gullies with very steep slopes; several landslides present.	About 8 km from both Manapouri powerhouse and Freeman Burn hut.	Puteketeke Pluton granite (Ksk).	7687; 7690; 7859a, c; 7697; 7708; 7727; 7864b; 7884.
G	Opposite South Arm, N side.	Extensive face of very steep slopes; 3 known landslides.	12 km to Manapouri powerhouse; 16 km to Manapouri (probably protected).	Refrigerator Orthogneiss (Kss).	876; 7877a, b; 7879; 7882; 7884; 7891.
H	Entrance South Arm, W side.	Area of very steep slopes with several landslides present.	17 km to Moturau Hut; ~19 km to Manapouri (protected by headlands?).	Puteketeke Pluton granite (Ksk).	786b; 7609; 7610; 7667; 7668; 7674.
I	Head of South Arm, E side.	Very steep gully and debris fan; two landslides in the area.	Site remote, no ES sites affected (?); ~3 km to South Arm campsite.	Grebe Mylonite (shear) Zone (Ksz), and Hunter Intrusives – diorite, granite, and granodiorite (Jdu).	7619; 7632. *p. 1/2*

Source[1] Areas	Location[1]	Slope morphology and existing landslides,[2,5]	Minimum distance to nearest sites of interest to ES / Comments[1]	Geology [3]	Aerial Photos[4] (taken 17/1/ 2012)
J	Opposite Pomona Is, S side.	Area of very steep gullies, with two recent landslide areas.	12 km to Moturau and Shallow Bay huts; ~14 km to Manapouri (protected by headlands?).	Hunter Intrusives- Pomona Island Granite (Jyp).	7547; 7551; 7552; 7554; 7581; 7584; 7585; 7595; 7599.
K	East side of Pomona Island.	Steep slopes ~200 m high; old failure on north side of island.	10 km to Moturau and Shallow Bay huts; ~13 km to Manapouri (protected by headlands?)	Hunter Intrusives- Pomona Island Granite (Jyp).	7570.
L	Point west of Rona Island.	Steep slopes ~130 m high; no obvious evidence of instability.	7 km to Moturau Hut and Shallow Bay Hut; about 11 km to Manapouri.	Beehive Diorite (Jdb).	7892; 7911a; 7917; 7918; 7920; 7926.
M	Entrance Hope Arm, on the west side.	Steep-very steep slopes, one recent landslide area.	3 km to Hope Arm Hut; 17 km to Manapouri, which may be protected by ~30 m high neck at head of George Bay (?).	Hunter Intrusives – diorite, granite, and granodiorite (Jdu).	7517; 7531a, b; 7532; 7542; 7544.
N	East side Stony Point ridge about 3 km northwest of Manapouri.	Very steep (~45-70°) ~100m high slopes; one old rock fall scar is evident.	The nearest facility sites are Manapouri township and the Pearl Harbour about 3 km to the southwest.	Hope Arm Formation- Tertiary, coarse conglomerate and sandstone (Owh).	7497; 7504; 7511; 7513.
O	Slope south of 1174 m peak north of Calm Bay on northeast side of lake.	Prominent recent debris slide/ flow in gully head below the 1174 m peak	The nearest facility sites are Maturau Hut ~5 km southwest, and Manapouri township about 12 km to the southeast.	Hope Arm Formation- Tertiary, coarse conglomerate and sandstone (Owh).	7911b; 7932; 7935; 7940; 7961.

Notes:

1. *Locations of potential EIL source areas (A to O) and sites of interest to Environment Southland are shown on Figures 3 and 6. Specific sites and topographic features are shown on Figures 10a, 10b, 10c, and 10d.*
2. *The landslides referred to are mainly recent or currently active shallow landslides, with a few older landslides, which are mainly prehistoric.*
3. *Brief geological descriptions from the Fiordland Geological QMap (Turnbull et al. 2010), see Figure 7.*
4. *The image numbers listed are selected aerial photos which were used to evaluate specific potential EIL sites in each area. Copies of these photos are included on a CD at the back of the report. Some of the potential EIL sites are shown in Figures 12 to 18.*
5. *Terms used in this report to describe landslide size are: Very small (< 10^3 m^3); Small (10^3 –10^4 m^3); Moderate (10^4–10^5 m_3); Large (10^5–10^6 m^3); and Very large (≥10^6 m^3).*

p. 2/2

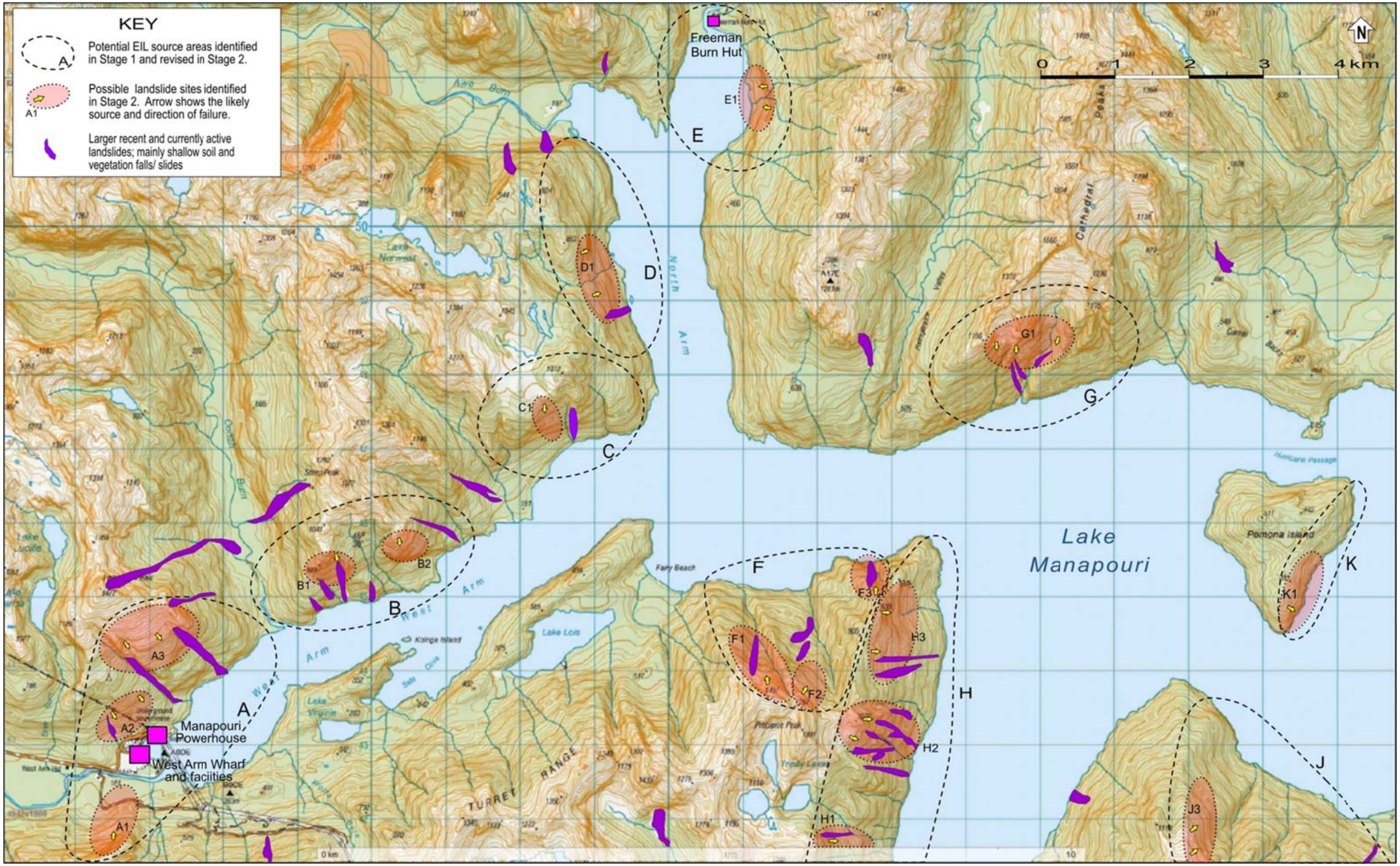

Figure 10a. Topo50 topographic map of the western part of Lake Manapouri showing potential EIL source areas and specific landslide sites in each area.

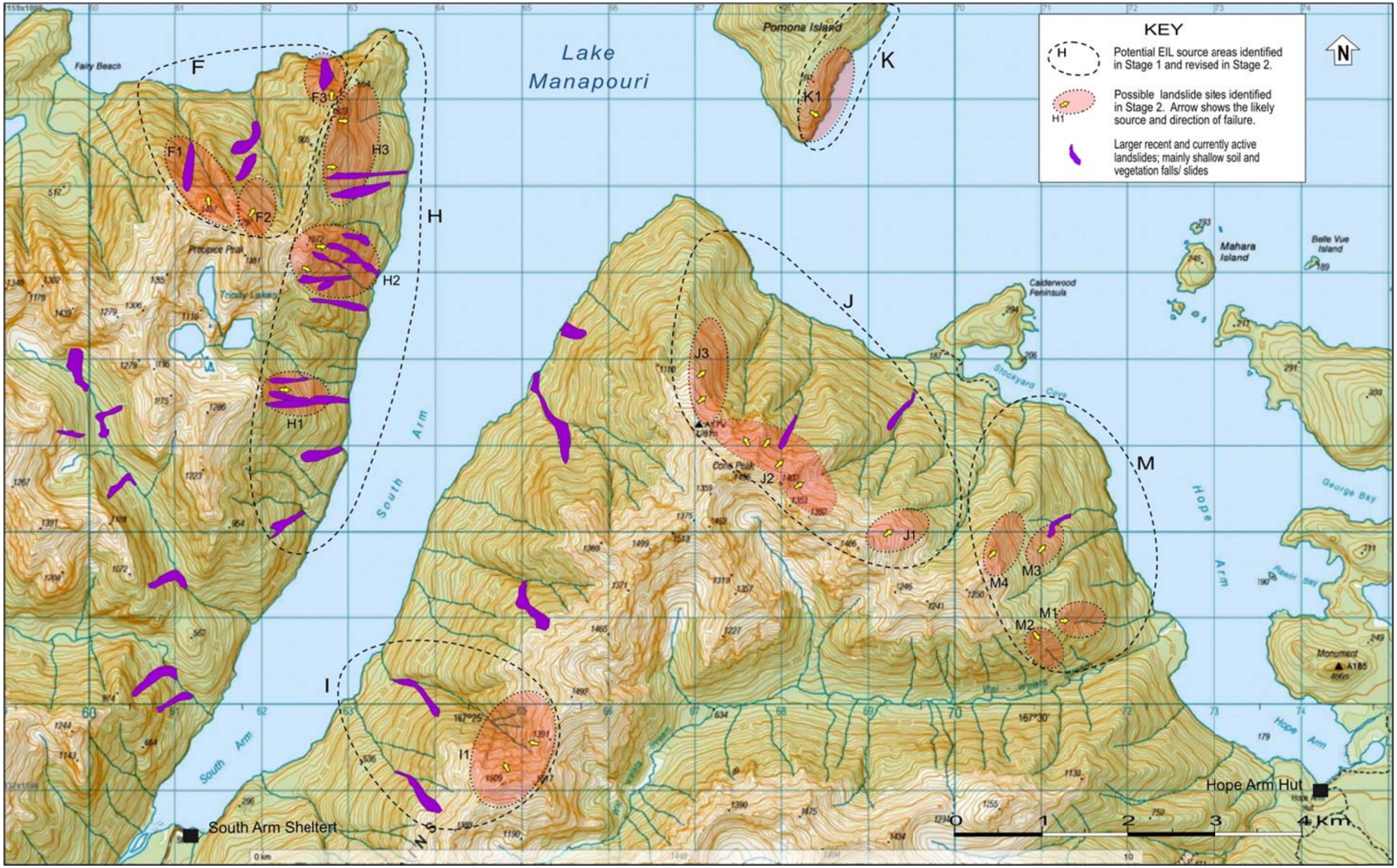

Figure 10b. Topo50 topographic map of the southern part of Lake Manapouri showing potential EIL source areas and specific landslide sites in each area.

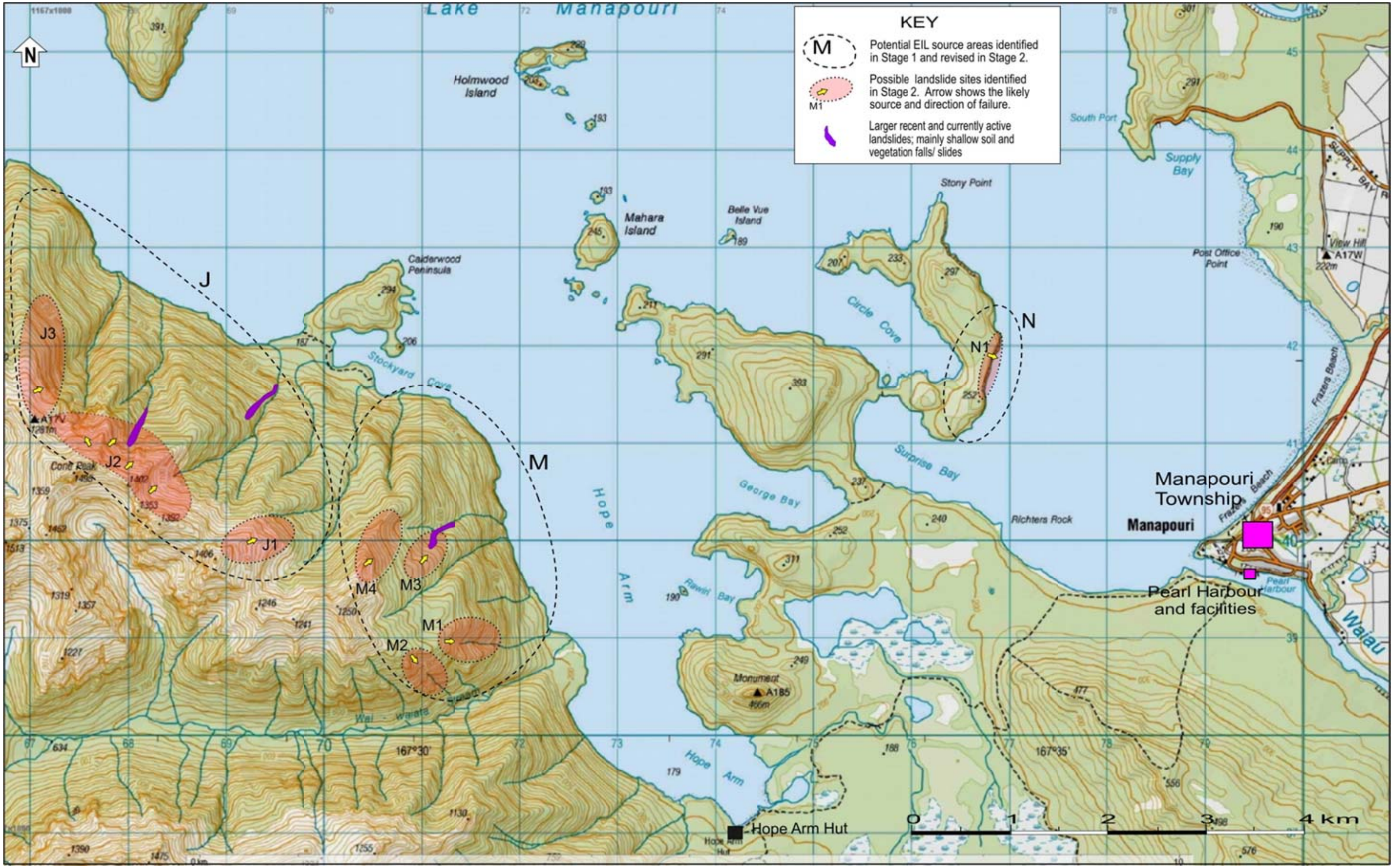

Figure 10c. Topo50 topographic map of the southeast part of Lake Manapouri showing potential EIL source areas and specific landslide sites in each area.

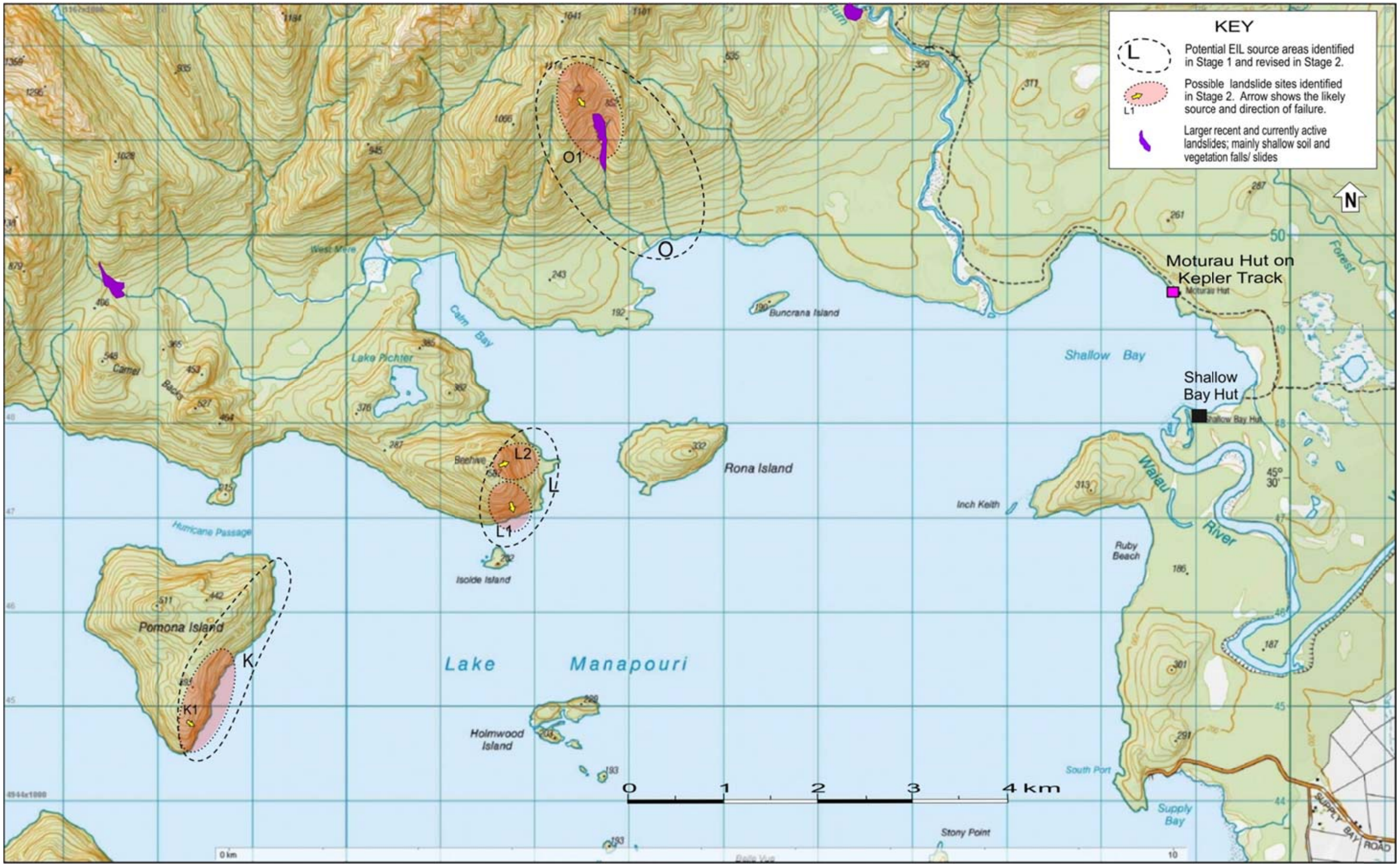

Figure 10d. Topo50 topographic map of the northeast area of Lake Manapouri showing potential EIL source areas and specific landslide sites in each area.

Table 4. Locations, slope morphology, landsliding, rock types, and distance from sites of interest to Environment Southland (A–P) of potential source areas of earthquake-induced landslides around the shoreline of Lake Te Anau.

Source[1] Areas	Location[1]	Slope morphology and existing landslides,[2,5]	Minimum distance to nearest sites of interest to ES / Comments[1]	Geology [3]	Aerial Photos[4] (taken 17-18/1/ 2012)
A	Near the entrance of South Fiord, on the north side.	Mixed moderate to very steep slopes; 2003 landslides.	About 9 km to Te Anau sites, Kepler Track; 10 km to Glow Worm Caves (less exposed).	Takahe Granodiorite (Kse).	8154; 8183; 8283.
B	Middle of South Fiord, on the northern side.	Steep-very steep slopes; large debris slide/fan in Mystery Burn.	About 15 km to Te Anau and Kepler Track; possibly protected by bend at fiord mouth.	Hunter Intrusives (Jdu) – Foliated diorite; some amphibolite.	8077; 8079; 8097; 8100; 8107; 8121.
C	Middle of South Fiord, on the south side.	Steep and very steep slopes and gullies; a few shallow landslides.	About 15 km to Te Anau and Kepler Track; possibly protected by bend at fiord mouth.	Hunter Intrusives (Jdu) – Foliated diorite; granodiorite.	8067; 8074; 8130.
D	Western end of South Fiord, on the west side.	Steep and very steep slopes and gullies; a few shallow landslides.	About 20 km to Te Anau and Kepler Track sites, may be protected by bends in the fiord.	Hanging Valley Intrusives (Kdv) -Hunter Intrusives (Jdu) – diorite and granodiorite.	8061; 8065; 8066; 8139; 8146.
E	Near head of South Fiord, on the north side.	Steep and very steep slopes and gullies; several landslide areas.	At least 25 km to Te Anau and Kepler sites; possibly protected by bends in the fiord.	Refrigerator Orthogneiss (Kss) and Hunter Intrusives (Jdu) – diorite and granodiorite; with a shear zone along contacts.	8036; 8041; 8045; 8046; 8052; 8054; 8058.
F	Ettrick Burn fan west side of lake; Doubtful Islands.	Potential debris flow hazard in stream N side of Ettrick Burn.	About 10 km S to Glow Worm caves; 20 km S to Te Anau; 15 km NE to Te Anau Downs.	Hunter Intrusives (Jdu) – diorites and granodiorite.	8292; 8299; 8309; 8317; 8323; 8325.
G	Entrance of North Fiord on the south side.	Large old rock falls from very steep scarp; 2003 and recent landslides.	About 8 km S to Te Anau Downs; 20 km S to Glow Worm Caves, 30 km S to Te Anau.	Turret Peaks Formation (Owt) – massive to graded Tertiary sandstone, conglomerate, with rare mudstone.	8361; 8368; 8373; 8385.
H	Northeast side of North Fiord.	Extensive steep slope ~1000 m high; a few recent landslides.	About 13 km S to Te Anau Downs; 25 km S to Glow Worm Caves, 35 km S to Te Anau.	North Fiord Granite and Tonalite (Ksn).	8414; 8417; 8422b; 8423.
I	Head of North Fiord on north side.	Extensive steep slopes with recent landslides; large gully and debris fan.	About 1–4 km to Glaisnock Hut; other sites ~20–45 km S, protected by bends in lake.	Halfway Peak (Jdh) diorite, tonalite; Loch Burn Formation (Jlb) –foliated volcanics, sandstone, conglomerate.	8410. *p. 1/2*

Source[1] Areas	Location[1]	Slope morphology and existing landslides,[2,5]	Minimum distance to nearest sites of interest to ES / Comments[1]	Geology [3]	Aerial Photos[4] (taken 17-18/1/ 2012)
J	West side of lake 1–3 km north of North Fiord.	Two landslide areas (old, 1968); future failures possible in area.	About 11km S to Te Anau Downs, 23 km to Glow Worm Caves, 35 km to Te Anau sites.	Stuart Formation (Ows): Tertiary mudstone, cross-bedded /graded sandstone.	8426; 8432; 8435; 8442; 8444; 8447; 8449.
K	West side of lake 5 km north of North Fiord.	Large creeping flow/slides in Tertiary rocks. Debris flows possible on fans.	About 15 km S to Te Anau Downs; 27 km to Glow Worm Caves; 40 km to Te Anau.	Stuart Formation (Ows) sediments; and Earl Formation (Eaa) - Tertiary sandstone and carbonaceous mudstone.	8472; 8476.
L	South and north sides of Worsley Arm.	Steep and very steep areas with several recent landslides.	1–2 km west to Worsley Hut; 7 km NE to Glade Wharf; other sites 25–50 km south.	South side of fiord: North Fiord Granite (Ksn); Sandfly Formation (Eas) - Tertiary sandstone, mudstone, shell beds and breccia. North side of fiord: Indecision Creek Complex (Kai) – plutonic intrusives - diorite, tonalite, orthogneiss.	8508; 8511; 8516; 8517; 8525; 8532; 8533; 8534;8539; 8541; 8543; 8660; 8517.
M	Head of Lake Te Anau - Glade Burn, mouth of Clinton River.	Debris flow hazard in Glade Burn; very steep slopes SE and NW.	Glade Wharf /Milford Track in immediate area; other sites are 30–55 km to the south.	Glade (Kdg) and Nurse (Kdn) suites, and Darran Leucogabbro (Kdd) – plutonic intrusives (diorite, tonalite, granodiorite, and granite).	8550; 8551; 8552; 8568; 8570; 8579; 8586; 8598; 8605; 8642; 8649; 8655.
N	North side of outer Middle Fiord.	Very steep scarp slope; small landslide scars at top of slope.	The closest facility sites are Te Anau Downs Boat Harbour ~10 km to the east, Glow Worm ~14 km south, and Te Anau ~25 km south.	Turret Peaks Formation (Owt) – massive to graded Tertiary sandstone and cong. Scarp slope with bedding dipping ~20° east.	8239; 8321; 8335; 8339; 8342.
O	East side of lake north of Camp Bay/Hourglass Pt.	Very steep scarp slope; small scars on upper slopes of scarp.	The closest facility sites are Te Anau Downs Boat Harbour ~13 km to the south, and Glade wharf ~17 km to the north.	Turret Peaks Formation (Owt)- massive to graded sandstone and conglomerate. Scarp slope southwest of End Peak.	8466; 8980; 8982.
P	North side of Safe Cove on west side of lake.	Very steep slope on south face of Rata Point with old failure and small shallow 2003 landslide.	The closest facility sites are Te Anau Downs Boat Harbour ~20 km to the south, and Glade wharf ~10 km to the north.	Earl Mountain Sandstone (Eas) – Tertiary sandstone with thick conglomerate bands.	8483; 8487; 8492; 8494.

Notes:

1. *The locations of potential EIL source areas (A to O) and sites of interest to Environment Southland shown on Figures 3 and 7. Specific sites and topographic features shown on Figures 11a, 11b, 11c, and 11d.*
2. *The landslides referred to are mainly recent or currently active shallow landslides, with a few older landslides, which are mainly prehistoric.*
3. *Brief geological descriptions from the Fiordland Geological QMap (Turnbull et al. 2010), see Figure 9.*
4. *The image numbers listed are selected aerial photos which were used to evaluate specific potential EIL sites in each area. Copies of these photos are included on a CD at the back of the report. Some of the potential EIL sites are shown in Figures 19 to 25.*
5. *Terms used in this report to describe landslide size are: Very small (< 10^3 m^3); Small (10^3 –10^4 m^3); Moderate (10^4–10^5 m_3); Large (10^5–10^6 m^3); and Very large (≥10^6 m^3)..*

p. 2/2

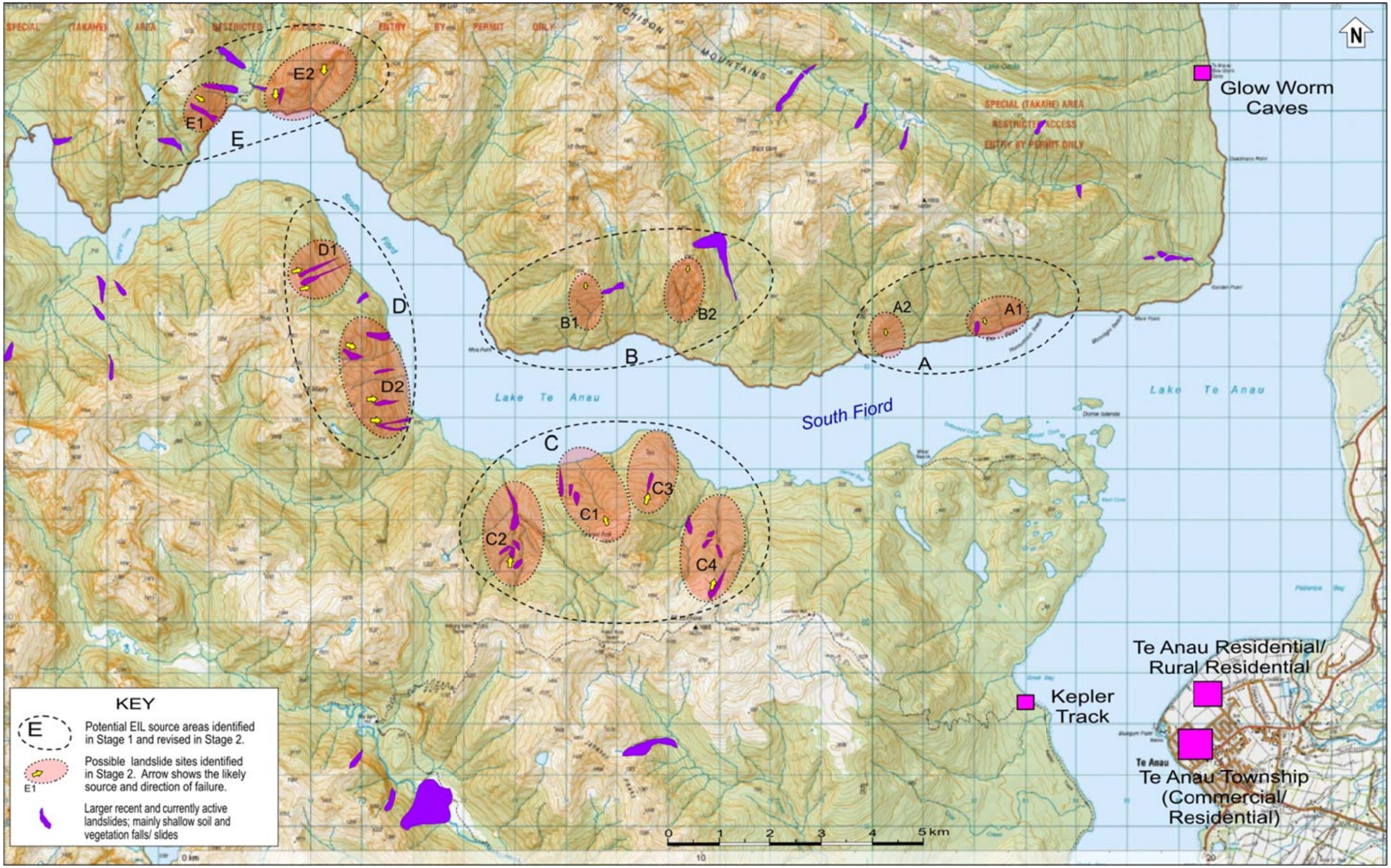

Figure 11a. Topo50 topographic map of the southern part of Lake Te Anau showing potential EIL source areas and specific landslide sites in each area.

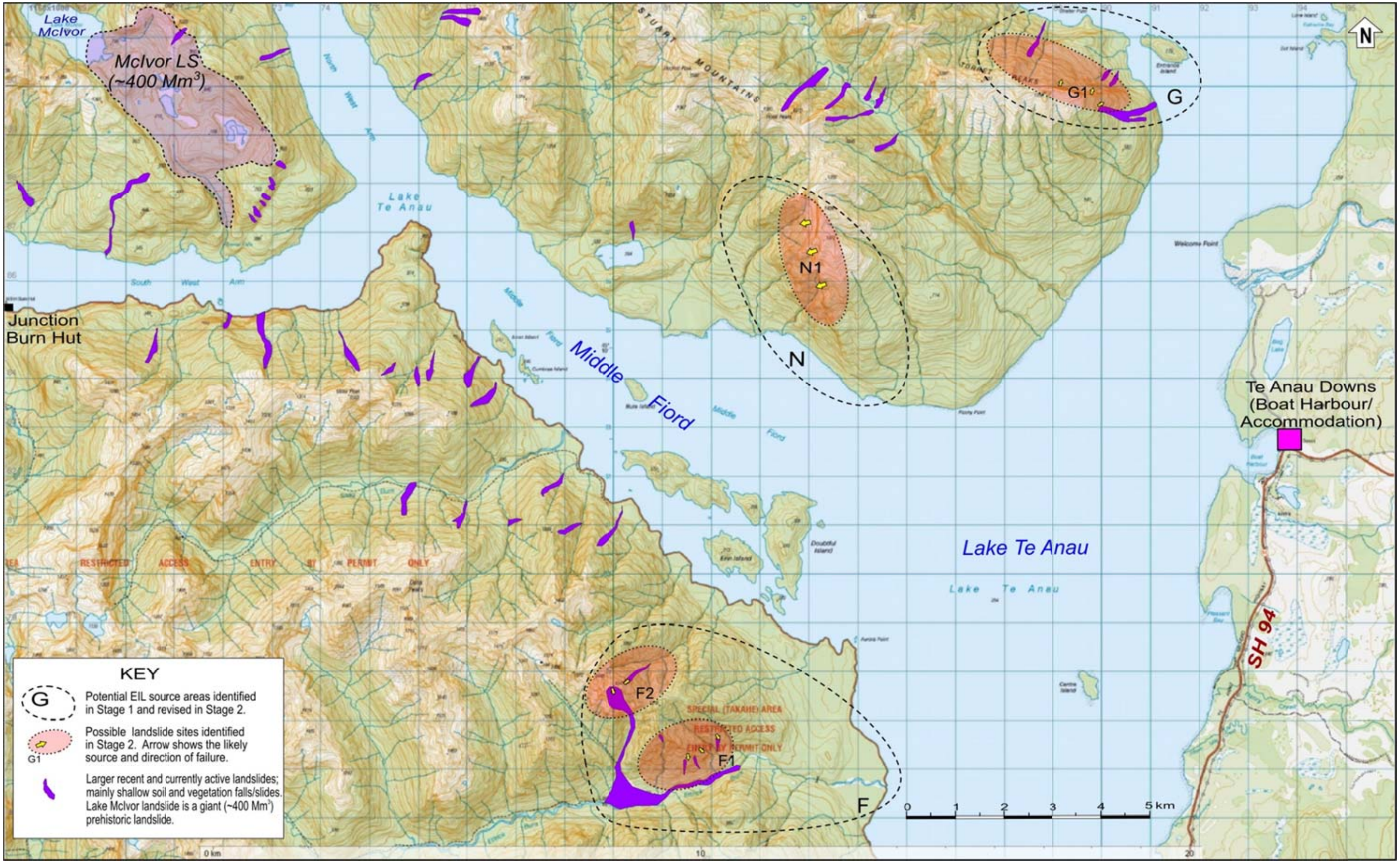

Figure 11b. Topo50 topographic map of the Middle Fiord area of Lake Te Anau showing potential EIL source areas and specific landslide sites in each area.

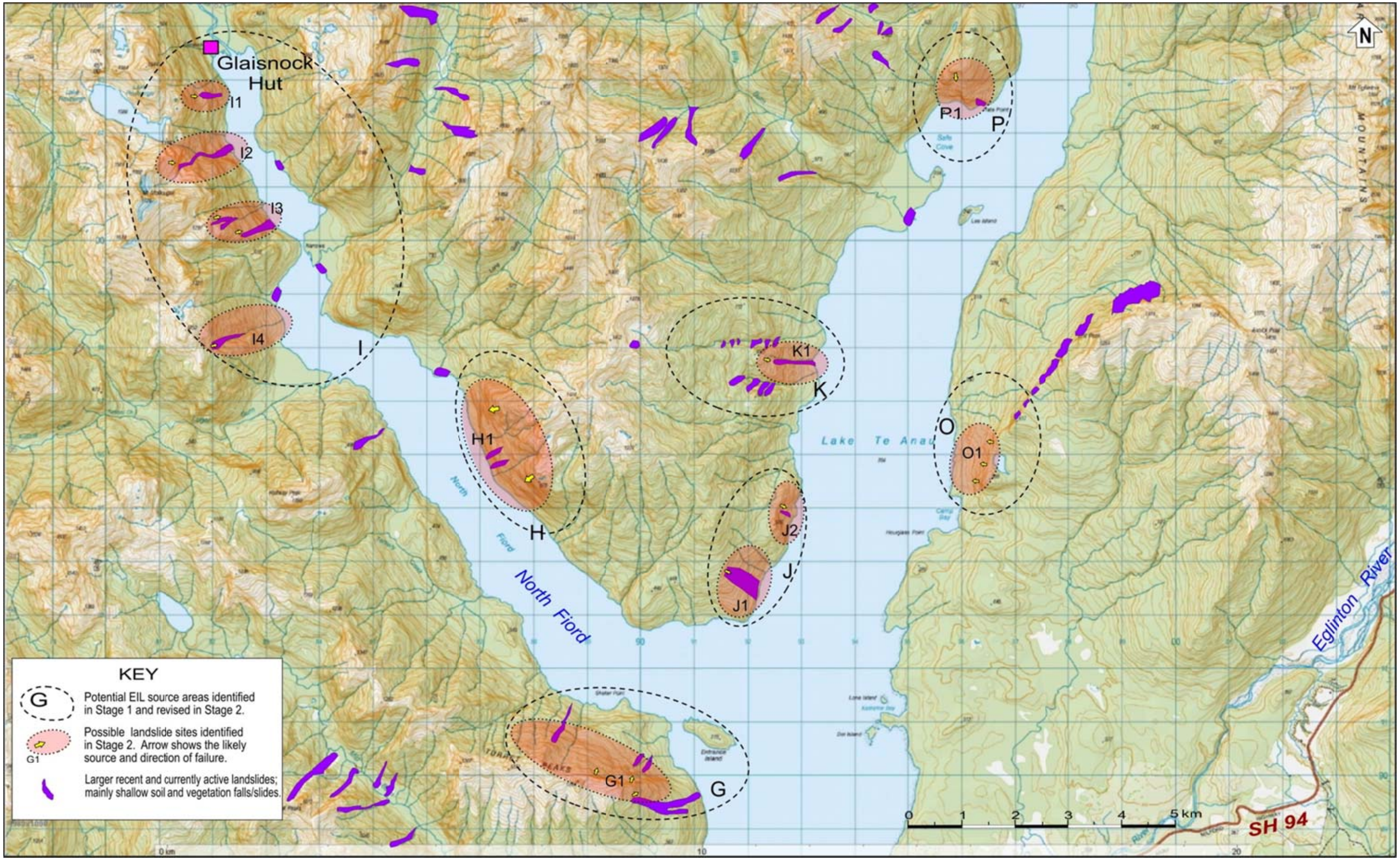

Figure 11c. Topo50 topographic map of the North Fiord area of Lake Te Anau showing potential EIL source areas and specific landslide sites in each area.

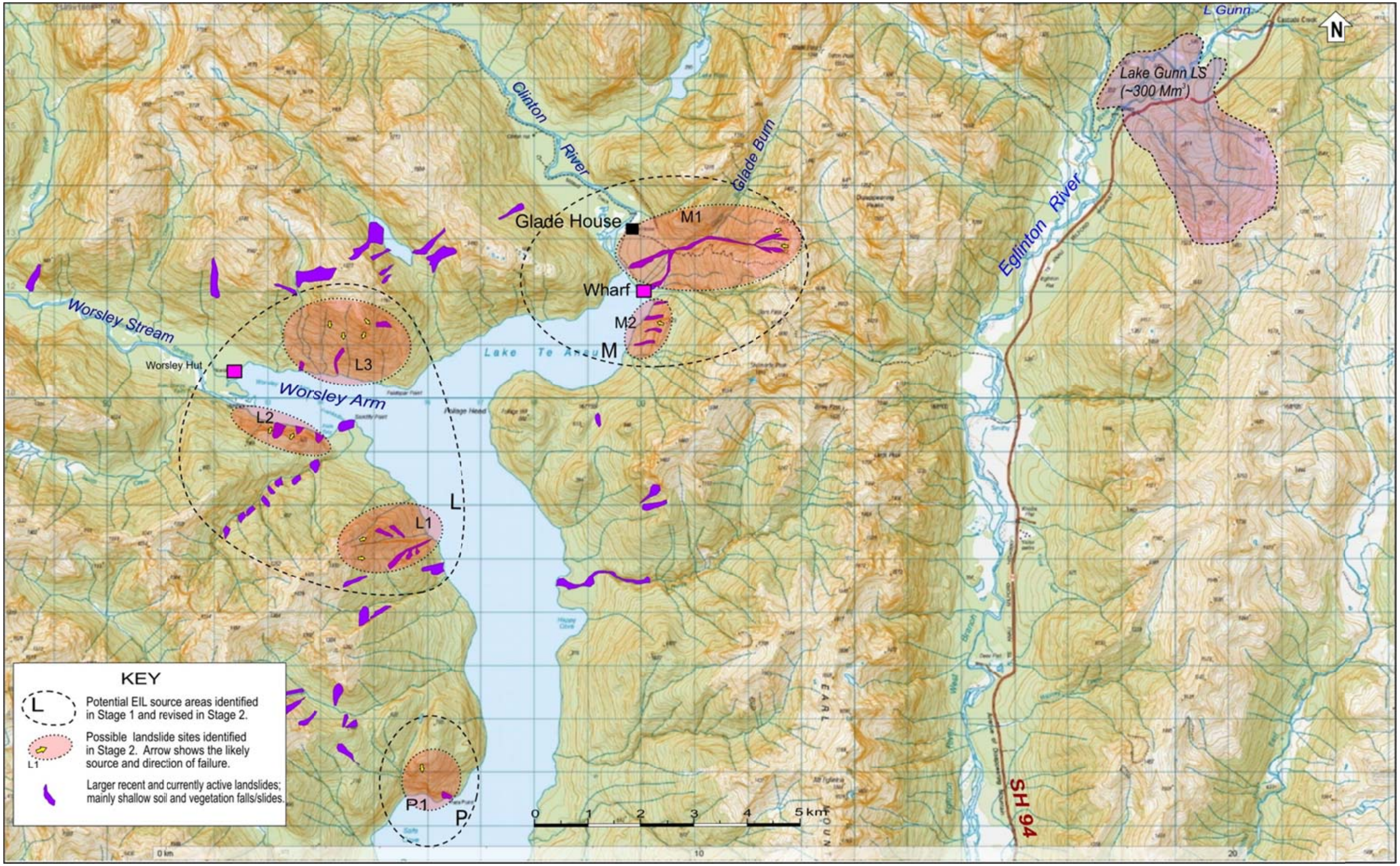

Figure 11d. Topo50 topographic map of the Worsley Arm-Glade area of Lake Te Anau showing potential EIL source areas and specific landslide sites in each area.

2.2.1 Evaluation of potential Lake Manapouri EIL areas

2.2.1.1 Manapouri Area A

Three potential EIL sites (Site A1, A2, and A3) are identified at the head of West Arm within 1– 2 km of the wharf, tourist facilities, and Manapouri Powerhouse. The location of this area is shown on Figure 10a and illustrated by three photos (Figures 12, 13, and 14). Site A1 is located on the very steep (~40-60°) rocky head scarp of a large old (prehistoric) failure on the south side of the Spey River opposite West Arm Hut (Figure 12). Retrogressive reactivation of the source area is likely at this site during MM8-10 earthquake shaking (see Appendix 1), possibly causing a moderate to very large (~10^4–10^6 m^3) rock fall. Slide debris from such a failure is unlikely to reach the lake because of its cross-valley direction of travel, but it could temporarily dam the river and close the Wilmot Pass road. Site A2 is located near an existing shallow landslide scar on the steep (~25-35°) bush-covered slope above the powerhouse, wharf, and tourist facilities (Figure 14). Small to moderate sized (~10^3–10^4 m^3) superficial earthquake-induced landslides at this site are likely to damage these facilities, and debris entering the lake could cause locally damaging waves up to 1 m high (Table 2). Site A3 is located high on the steep rock slope on the north side West Arm about 0.5–1 km north of the powerhouse. Old failure scars on the slope suggests that shallow small to moderate (~10^3–10^4 m^3) EIL failures into the lake are likely at this site, which could cause waves about 0.5–1 m high locally (Table 2). Collapses and lateral spreading of the Spey River delta (Figure 12) are likely to occur during MM8-10 earthquake shaking. Unconsolidated sand and silt from a possible future rapid delta collapse could flow into the Manapouri powerhouse water intake on the north side of West Arm about 200 m north of the delta front. Rock falls and debris slides from the slope at Site A2 could directly affect the outdoor station above the water intake structure (Figure 14). A site-specific evaluation would provide a more accurate assessment the landslide, delta collapse, and tsunami hazard to Manapouri powerhouse and the wharf and tourist facilities at the head of West Arm.

2.2.1.2 Manapouri Area B

Two potential landslide sites (Sites B1 and B2) were identified on the very steep (~40-60°) ~500 m high rock slope on the north side of West Arm about 3 km northeast of the wharf facilities and Manapouri powerhouse (Figure 10a). The scars of several recent shallow debris slides with patchy vegetation on these slopes suggests that MM8-10 earthquake shaking is likely to trigger further shallow small to moderate (~10^3 – 10^4 m^3) debris slides at this site, which are likely to reach the lake. Such failures could cause waves ~0.5– 1 m high locally, say within ~0.5–1 km of the site. The powerhouse and wharf facilities located ~3 km southwest at the head of West Arm are unlikely to be significantly affected by such waves, nor are any other Lake Manapouri facility site of interest to ES.

2.2.1.3 Manapouri Area C

One potential landslide site (Site C1) was identified on the very steep (~40-45°) ~500 m high slope on the north side of the entrance to West Arm ~6.5 km northeast of Manapouri powerhouse (Figure 10a). Scars of shallow debris slides with patchy vegetation on this slope suggests that MM8–10 earthquake shaking is likely to trigger shallow small to moderate (~10^3–10^4 m^3) debris slides into the lake at this site. Such failures could cause waves ~0.5–1 m high within ~0.5–1 km of the site. The powerhouse and wharf at the head of West Arm are unlikely to be affected by such waves, nor is any other facility site of interest to ES.

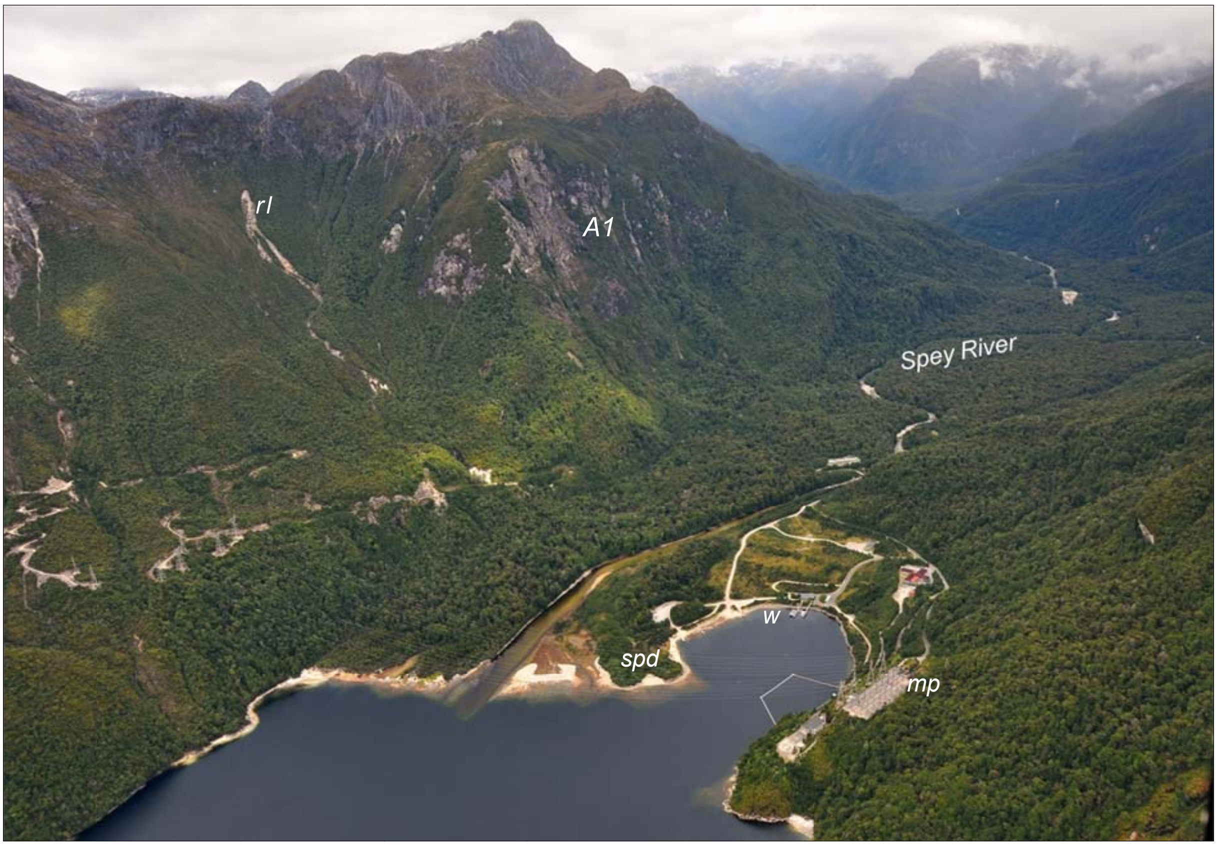

Figure 12. Aerial view of Manapouri power station *(mp)* and wharf *(w)* at the head of West Arm, Lake Manapouri looking up the Spey valley. Potential EIL *Site A1* is on the scarp of a large prehistoric landslide *(A1)* with a recent shallow landslide above the power line access road visible to the left *(rl)*. Collapses and lateral spreading of the Spey River delta *(spd)* could affect the powerhouse intake.

Figure 13. Potential EIL *Sites A1, A2 and A3* above the Manapouri powerhouse *(mp)* and wharf *(w)* at the head of West Arm. Scars of recent landslides *(rl)*, mainly shallow rainfall-induced debris slides, are visible on those slopes. The scarp of the prehistoric landslide above the Spey River can be seen lower right *(pls)*.

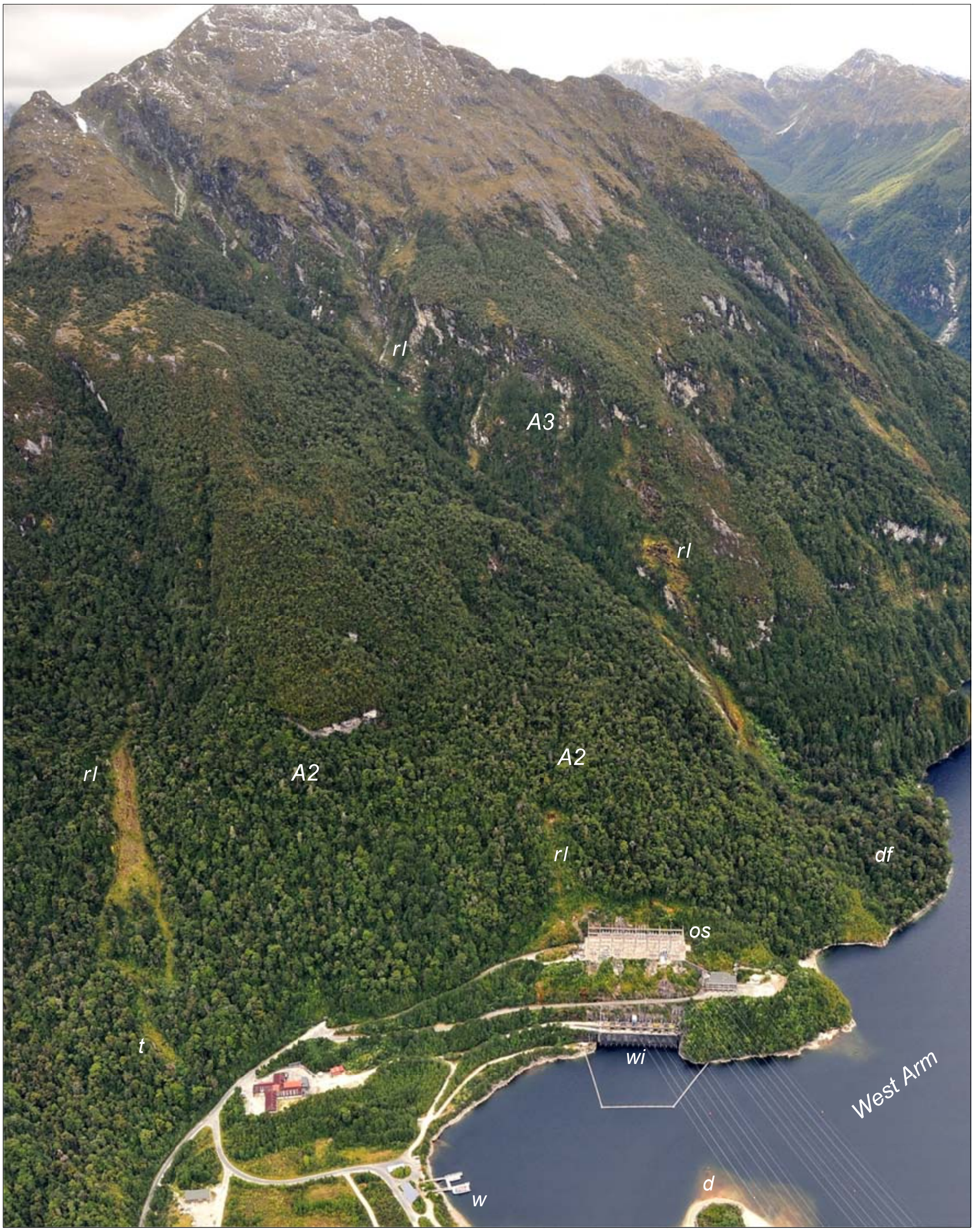

Figure 14. Closer view of sites *A2* and *A3* on the very steep slopes above the Manapouri powerhouse outdoor station *(os),* water intake *(wi),* and wharf *(w)* facilities to the north at the head of West Arm. Scars of typical recent landslides *(rl)*, mainly shallow rainfall-induced debris slides, are visible on these slopes. The toe *(t)* of one recent failure is close to buildings. A large debris fan *(df)* has formed at the mouth of the gully below *Site A3*. Debris flows are expected to occur at that site during rainstorms and strong earthquake shaking. An earthquake-induced collapse of the Spey River delta *(d)* could affect the powerhouse water intake *(wi)*, and rock falls and debris slide could directly affect the outdoor station *(os)* at this site.

2.2.1.4 Manapouri Area D

One potential landslide site (Site D1) was identified on the very steep (~40-60°) ~400 m high rock bluffs on the western side of North Arm (Figure 10a). Patchy vegetation and scars of previous minor rock fall activity on these bluffs suggests that MM8-10 earthquake shaking is likely to trigger further shallow small to moderate (~10^3 – 10^4 m^3) rock falls directly into the lake at this site. Such failures could cause waves ~0.5–1 m high within ~0.5–1 km of the site. Freeman Burn Hut, located ~4 km north at the head of North Arm, is unlikely to be significantly affected by such waves, nor is any other facility sites of interest to ES.

2.2.1.5 Manapouri Area E

One potential landslide site (Site E1) was identified on steep (~30-50°) ~100-200 m high, largely bush covered bluffs on the eastern side of the Freeman Burn arm of North Arm (Figure 10a). Exposed rock bluffs at the site suggest that MM8-10 earthquake shaking could cause small (~≤10^3 m^3) rock falls into the lake at this site. Such failures could cause small waves ~0.5 m high locally (within ~0.5 km) but Freeman Burn Hut, located ~1 km to the north, and is unlikely to be significantly affected by such waves. Because of the isolated location of Site E1, other facility sites on Lake Manapouri that are of interest to ES are unlikely to be affected. However, Freeman Burn Hut could be affected by lateral spreading or a delta collapse wave. A site evaluation would give a more accurate assessment of the hazard.

2.2.1.6 Manapouri Area F

Three potential EIL sites (F1, F2, F3) are identified on very steep slopes (35 – ≥45°) near the bush line ~500-1200m above the lake (Figure 10a). Sites F1 and F2 are on steep broken rock slopes with recent shallow scars adjacent to an extensive old wedge failure below the 1407 m peak on the southern side of the lake opposite North Arm (Figure 15). Site F3 is on a low-level triangular face scarred by shallow landsliding, about 1 km west of the entrance to South Arm. Precedent evidence suggests that MM8-10 earthquake shaking could trigger shallow small to moderate (~10^3–10^4 m^3) rock falls and debris slides at Sites F2 and F3. However, a significantly larger failure, potentially ~5 x 10^5–10^6 m^3, similar to the largest during the 2003 earthquake, is possible at Site F1. A landslide of that size rapidly entering the lake from an elevation of ~500–1000 m above the lake could potentially generate a wave ~10–25 m high within ~1–5 km of the site. Freeman Burn Hut at the head of North Arm ~8 km to the north, and the powerhouse and wharf facilities ~8 km southwest at the head of West Arm could potentially be affected by such a wave, depending on its distribution and rate of attenuation. Tsunami wave modelling would provide a more accurate assessment of the potential landslide-induced wave hazard from this site.

2.2.1.7 Manapouri Area G

Several potential EIL sites were identified within Site G1 in the recently landslide-scarred gully below the 1560 m peak at the south end of Cathedral Peaks on the northern side of the lake opposite South Arm (Figure 10a). Precedent landslide evidence suggests that MM8-10 earthquake shaking could trigger shallow small to large (~10^3 – 10^5 m^3) rock falls and debris slides at Site G1. Any slide debris rapidly entering the lake could generate waves ~0.5–3 m high locally (~0.5 – 1 km), which would spread across to the southern side of the lake and into South Arm. The South Arm Campsite and facilities at the head of South Arm ~12 km to the south are unlikely to be affected by such waves, nor is any other facility site of interest to Environment Southland.

Figure 15. Aerial view of potential landslide sites *F1, F2, and F3* on the south side of Lake Manapouri opposite North Arm. The most notable of these is site *F1* near the ridge crest and 1407 m peak above an old large wedge failure *(wf),* in an area where have been several recent shallow landslides *(rl)*.

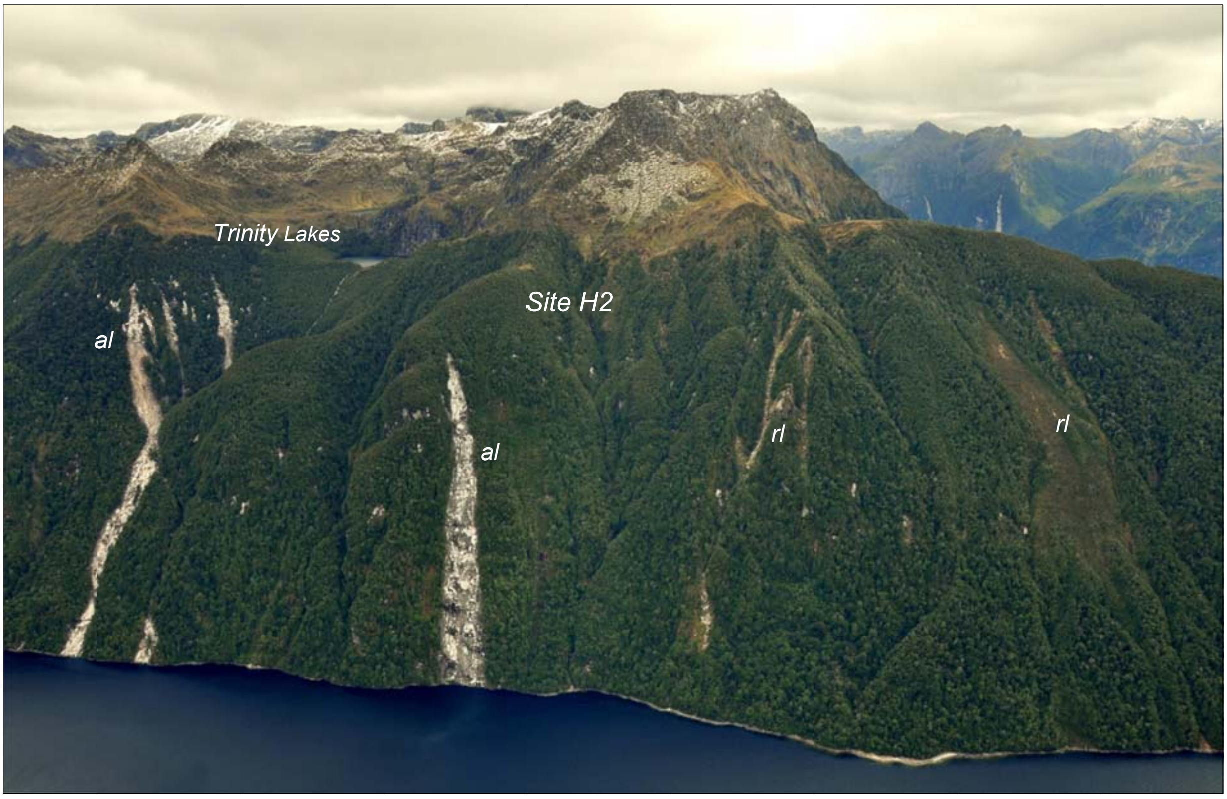

Figure 16. Aerial view of potential landslide *Site H2* in the vicinity of Trinity Lakes on the western side of the entrance to South Arm of Lake Manapouri. Several active shallow landslides *(al)* and recently active slides *(rl)* are present in this area.

2.2.1.8 Manapouri Area H

In this area 3 potential EIL sites (H1, H2, H3) are identified on steep slopes (35 – ≥45°) near the bush line, ~800-1000m above lake level (Figure 10b). The sites are adjacent to several moderate to large active and recent (bare), shallow landslide scars, and older (revegetated) scars (Figure 16). Previous landsliding at these sites suggests that MM8-10 earthquake shaking could trigger shallow moderate to large (~10^4–5 x 10^5 m^3) landslides. Any slide debris rapidly entering the lake could generate waves up to ~5–10 m high locally (~1–5 km), which would probably attenuate substantially as they spread east across the lake, and are unlikely to affect sites of interest to ES, such as Moturau Hut and Manapouri, ~16 km NE and SE respectively, both of which are also protected by islands and headlands.

2.2.1.9 Manapouri Area I

During MM8-10 earthquake shaking there is potential at Site I1 (Figure 10b) for small to moderate or possibly large landslides (~10^3–10^5 m^3) from the steep, broken ridge crest on the east side of South Arm, which could potentially generate ~0.3–3 m high waves locally. Although there are no sites in South Arm that are of specific interest to ES, the South Arm Shelter and camping facilities at the head of South Arm (~3 km southwest) could be affected by a wave generated by very large landslide (≥10^6 m^3) into the lake from this area. There is no evidence that such a failure is likely.

2.2.1.10 Manapouri Area J

Three potential failure sites (Sites J1, J2, and J3) were identified along the very steep (35 –≥45°) rocky bluffs above or just below the bush line near the ridge crest 900–1000 m above the lake shore (Figures 10b and 10c). Two small recent landslides and older shallow gully failures (Site J2) were identified in this area. Small to moderate (~10^3–10^4 m^3) shallow landslides could occur at these three sites during MM8-10 earthquake shaking, possibly involving debris slides or flows down gullies to the lake shore northwest of Calderwood Peninsula. Debris from these failures which rapidly enters the lake could generate a small (~0.5–1 m high) local wave which would spread across the lake towards Pomona and Rona islands, but it is unlikely that sites of interest to ES (~10–12 km east and northeast) would be affected. Larger rapid landslides (~1–2 x 10^5 m^3) into the lake at this site could cause larger (~3–5 m) waves, but these are expected to attenuate across the lake and are unlikely to affect Moturau Hut ~12–14 km to the northeast, or Manapouri township which is protected by headlands 10 km to the southeast.

2.2.1.11 Manapouri Area K

One potential failure site (K1) was identified on the steep bush-covered ~100 m high cliff at the south end of the eastern side of the island, at the site of an old rock fall scar (Figure 10d). Small to moderate (<10^3 to ~10^4 m^3) rock falls directly into the lake are possible at this site under MM8-10 shaking. Such falls may produce small (~0.5–1 m high) waves locally, which are likely to attenuate to perhaps a few 10s of cm at sites of interest to ES, Moturau Hut and Manapouri township ~ 11 km NE and SE respectively, with the latter protected by headlands. There is no evidence that very large (≥10^6 m^3) failures are likely to occur in this area.

2.2.1.12 Manapouri Area L

Two potential failure sites (Sites L1 and L2) identified in old failure scars on the steep (~35 – ≥60°) bush-covered ~330 m high cliff at the eastern end of Beehive Point (Figure 10d and Figure 17). Further very small to moderate (~10^2 to 10^4 m^3) rock falls directly into the lake are possible there during MM8-10 earthquake shaking, especially from the almost sheer rock face at site L1. Such falls may produce small waves up to ~0.5–1 m high locally, which will probably to attenuate to a few cm high at Moturau Hut and Manapouri Township ~7 km to the northeast and ~10 km southeast respectively. There is no evidence that very large (≥10^6 m^3) failures in this area are likely.

2.2.1.13 Manapouri Area M

This area features a steep (35 – ≥45°) bush-covered slope 800-1200 m high with at least one obvious recent small landslide area (Figure 10c). Four potential EIL landslide sites (Sites M1 to M4) are identified on the upper slopes between 500-1000 m: Sites M1 and M2 - Small to moderate (~10^3 – 10^4 m^3) shallow landslides are likely in gully heads, possibly with debris slides and flows reaching the debris fan delta at the mouth of Wai-Waiata Stream near the head of Hope Arm. Sites M3 and M4 – Small to moderate (~10^3 – 10^4 m^3) landslides are possible on the ridge crest (M4) and an existing gully head failure (M3). Slide debris rapidly entering the lake could generate a small (up to ~1 m) wave locally. The Hope Arm Hut is possibly at risk from waves generated by slide debris rapidly entering the lake. Other sites, including Manapouri township (~7 km to the east) are likely to be protected from such waves by land on the east side of Hope Arm. Very large failures (≥10^6 m^3) into the lake could cause larger and potentially hazardous waves, but there is no evidence that such failures are likely.

2.2.1.14 Manapouri Area N

Steep bush-covered and bare cliffs are present in this area, about 40-50 m high and ~400 m long (Figure 10c). At this site very small to moderate sized (<10^2 to ~10^4 m^3) earthquake-induced rock falls directly into the lake are possible during MM8-10 shaking. Such falls could produce waves up to ~1 m high locally, which are likely to attenuate to a barely perceptible height at Manapouri Township and boat harbour. EIL wave hazard estimated to be very low.

2.2.1.15 Manapouri Area O

In this area one potential EIL failure site (Site O1) has been identified adjacent to an existing landslide scar in the steep (~35 – 45°) head of a gully on the 1114 m peak about ~2. 5 km north of Calm Bay on the north side of the lake (Figures 10d, 17 and 18). Further small to possibly large (~10^3 to ~5 x 10^5 m^3) debris slides/flows down the gully and into the lake are possible at this site under MM8-10 shaking. Such flows could produce small to moderate (~1–5 m high) waves locally, which will probably attenuate to less than ~1 m high at Moturau Hut and Manapouri township, about 5 km east and 12 km southeast respectively. There is no evidence that a very large (≥10^6 m^3) failure is likely to occur at this site.

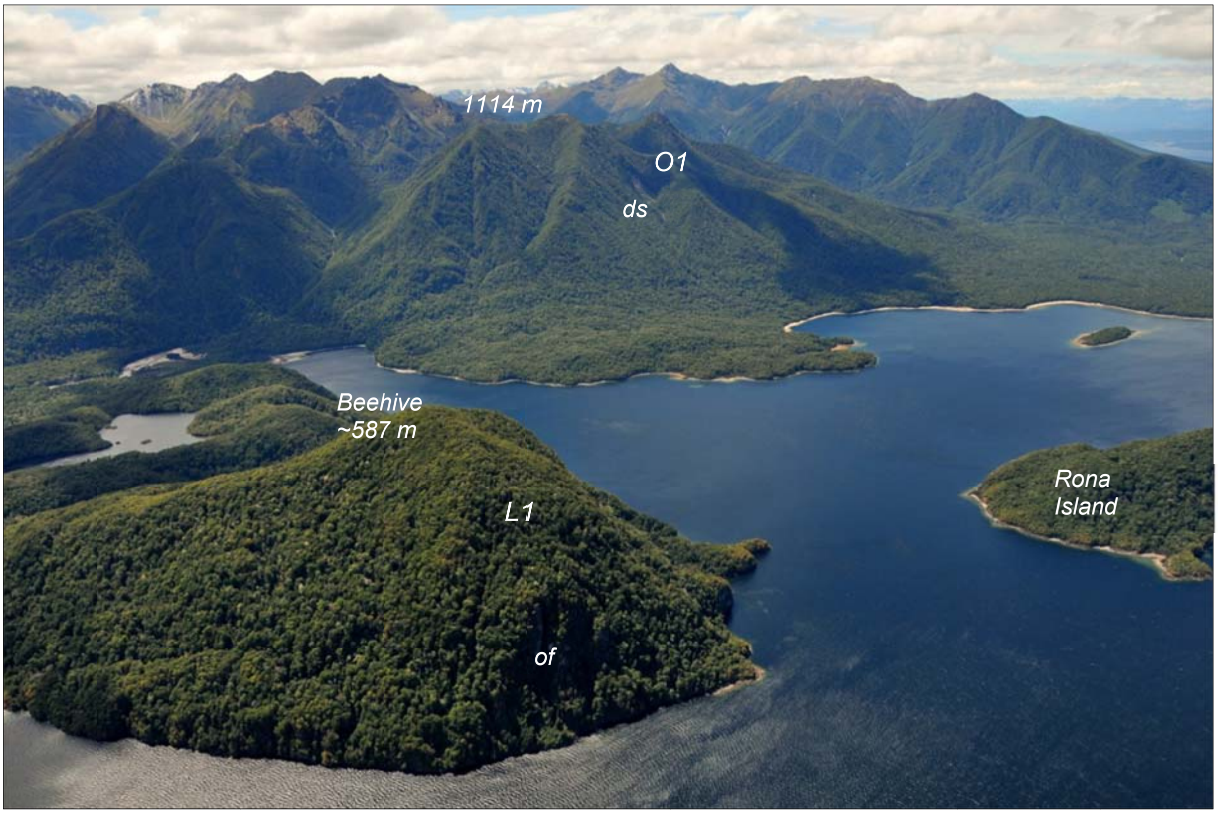

Figure 17. Aerial view of potential EIL areas L and O on the northeast side of Lake Manapouri. An old slope failure *(of)* is visible on the steep face at the end of Beehive point *(Site L1),* and 4 km to the north *(Site O1)* there is a recent debris slide scar *(ds)* in the gully below the 1114 m peak.

Figure 18. Closer view of *Site O1* showing the recent large debris slide scar *(ds)* at the head of a gully below the 1114 m peak about 6 km west of Moturau Hut on the Kepler track.

2.2.2 Evaluation of potential Lake Te Anau EIL areas

2.2.2.1 Te Anau Area A

Two potential failure sites (Sites A1 and A2) have been identified on bush-covered 35-50° slopes on the northern side of South Fiord about 3–5 km west of the main arm of the lake (Figure 11a). A small landslide occurred at Site A1 during the August 2003 earthquake, and there is an old (prehistoric) shallow failure scar at Site A2, about 3 km east of Mystery Burn (Figure 19). During MM8-10 earthquake shaking small to moderate size (~10^3 to 10^4 m^3) debris slides and/or flows could occur at both of these sites and move rapidly into the lake. Such failures could produce small (~0.5–1 m high) waves locally (within ~0.5 km) but they are likely to be barely perceptible (perhaps ~10-20 cm high) by the time they reach the Te Anau Township and residential area about 10 km to the southeast. There is no evidence that large or very large (≥10^5–10^6 m^3) failures are likely at these sites.

2.2.2.2 Te Anau Area B

Two potential failure sites (Sites B1 and B2) are identified on steep bush-covered 30-45° slopes and gullies on the northern side of South Fiord, about 9–11 km west of the main arm of the lake and ~18–20 km from Te Anau (Figure 11a). Recent small shallow landslides in these areas suggest that MM8-10 earthquake shaking would trigger small to moderate size (~10^3 to 10^4 m^3) shallow debris slides at both sites which could reach the lake shore. Such failures could produce small (~0.5–1 m high) waves locally (within ~0.5 km), but because of their dominantly cross-fiord movement waves more than a few 10's of cm high will probably not travel beyond the entrance of South Fiord. Facility sites of interest to Environment Southland around the shoreline of Lake Te Anau are unlikely to be affected. Debris flows caused by future earthquake-induced movements of the large landslide on the west side of Mystery Burn are unlikely to reach the lake shore ~2.5 km to the south.

2.2.2.3 Te Anau Area C

Four potential failure sites (Sites C1, C2, C3, and C4) are identified on the southern side of South Fiord in the heads of moderate to steep (25-40°) gullies where there are a number of recent small to moderate sized shallow landslides ~8–12 km west of the main arm of the lake, and ~17–21 km from Te Anau (Figure 11a and Figure 20). Recent small shallow landslides in these areas, and the scar of a large active landslide on the spur ~700 m northeast of Mt Luxmore, suggest that MM8-10 earthquake shaking would trigger small to large (~10^3 to 10^5 m^3) shallow debris slides at all sites which could reach the lake. Such failures could produce ~1–3 m high waves locally (within ~0.5–1 km), but because of their dominantly cross-fiord movement waves more than a few 10's of cm high will probably not travel beyond the entrance of South Fiord. Facility sites of interest to Environment Southland around the shoreline of Lake Te Anau are unlikely to be affected.

Figure 19. Aerial view of Area A on the north side of South Fiord of Lake Te Anau, about 10 km northwest of Te Anau. An old slope failure scar *(of)* is visible on the bush-covered face at *Site A2.* Site A1 is ~2 km to the east where a small landslide occurred during the 2003 earthquake.

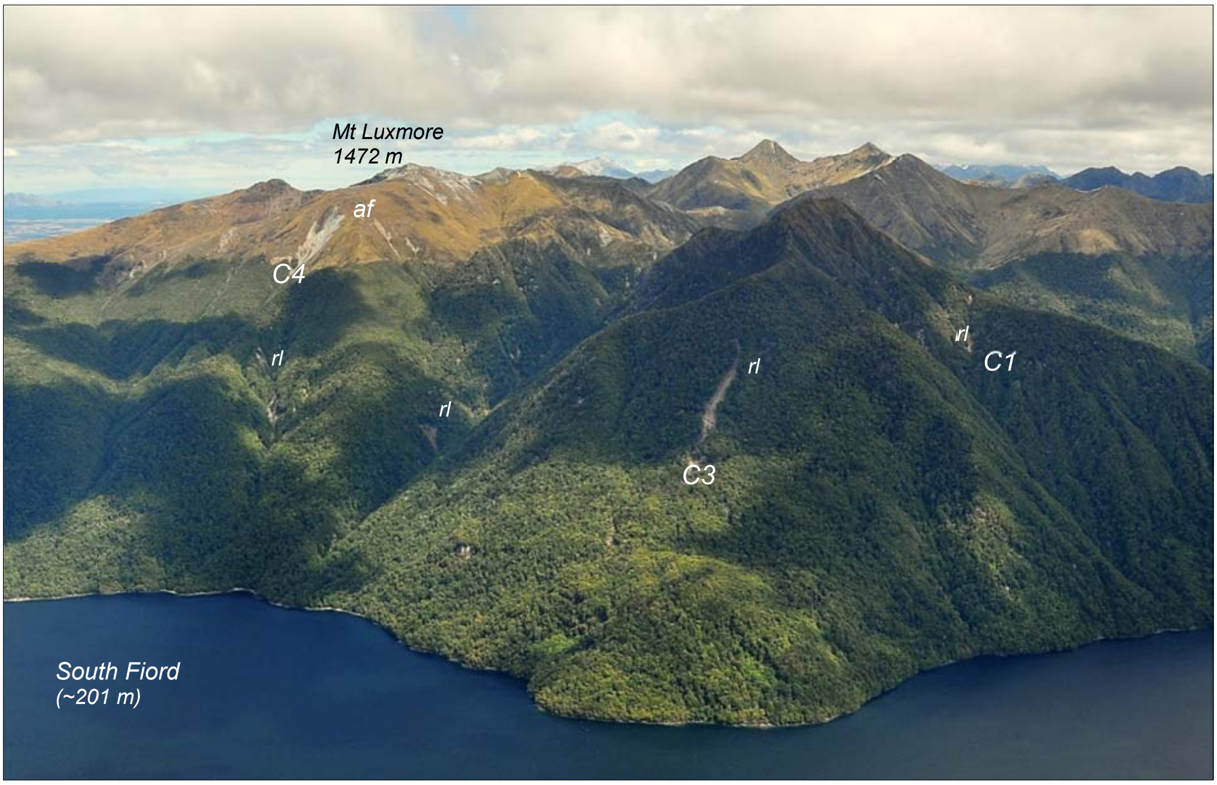

Figure 20. Aerial view of Area C on the south side of South Fiord about 8-12 km west of the main arm of Lake Te Anau. At *Site C4* a large active gully failure *(af)* is visible ~700 m northeast of Mt Luxmore, and there are recent shallow failures (rl) at *sites C1, C3, and C4*.

2.2.2.4 Te Anau Area D

Two potential failure sites (Sites D1 and D2) were identified on very steep (~45-55°) slopes which are scarred by a number of recent, long and narrow shallow debris slides on the southwest side of South Fiord north of Tutu Burn, about 14–18 km west of the main arm of the lake and 20–25 km from Te Anau (Figure 11a). The recent failures in these areas suggest that MM8-10 earthquake shaking is likely to trigger shallow small to large (~10^3 to 10^5 m^3) landslides at several sites, debris from which could reach the lake. Such failures could produce ~1–3 m high waves locally (within ~0.5–1 km), but waves more than a few 10's of cm high are unlikely to travel beyond the entrance of South Fiord. Because of the isolated location of these potential EIL sites, facility sites of interest to ES around the shoreline of Lake Te Anau are most unlikely to be affected.

2.2.2.5 Te Anau Area E

Two potential failure sites (Sites E1 and E2) were identified on steep (~35-45°) slopes scarred by recent shallow debris slides in the vicinity of Chester Burn near the head of South Fiord, about 20–23 km from the main arm of the lake (Figure 11a). Recent shallow failures in these areas suggest that MM8-10 earthquake shaking will trigger shallow small to moderate (~10^3 to 10^4 m^3) debris slides into the lake at several sites. Such failures could produce waves about ~0.5–1 m high locally (< ~0.5 km), but waves more than ~10 cm high are unlikely to travel beyond the entrance of South Fiord. Because of the isolated location of these potential EIL sites, facility sites of interest to ES around the shoreline of Lake Te Anau are most unlikely to be affected.

2.2.2.6 Te Anau Area F

Two sites (Sites F1 and F2) are identified in this area about 8 km north of Te Anau Township. Site 1 is on the north side of Ettrick Burn about 3 km from the western lake shore, and Site F2 is on the steep eroding 1347 m peak ~2 km to the northwest (Figure 11b). Material eroded from that peak has built a large active debris fan across Ettrick Burn valley about 5 km from the lake. Recent and on-going slope failures and gully erosion at these sites suggest that MM8-10 earthquake shaking is likely to trigger shallow small to large (~10^3 to 10^5 m^3) landslides in several places. Debris from either of these sites is unlikely to reach the lake down the Ettrick Burn because of the long travel distance (at least 3–5 km). However, a moderate to large failure on peak 1347 m (Site F2) towards the north could potentially reach the lake behind the Doubtful Islands at the entrance of Middle Fiord, and possibly produce ~1–3 m high waves locally (within ~0.5 km). Such waves are unlikely to travel much beyond the area shielded by the islands, and therefore they are not expected to have any significant affects at Te Anau Downs Boat Harbour ~12 km northeast, or at any of the facility sites of interest to Environment Southland 10–20 km to the south (Glow Worm Caves, Te Anau township, Kepler Track, and Lake Control Structure).

2.2.2.7 Te Anau Area G

One potential failure site (Site G1) was identified on an old (prehistoric) rock fall area on the very steep (~45-75°) northern scarp slope side of Turret Peaks (1317 m) at the entrance of North Fiord, about 9 km north of Te Anau Downs Boat Harbour and ~33 km north of Te Anau (Figure 11c and Figure 21). Previous spasmodic rock fall activity and at the site suggests that MM8-10 earthquake shaking is likely to trigger fresh small to moderate (~10^3 to 10^4 m^3) rock falls and small to large (~10^3 to 10^5 m^3) debris slides from the sheer rock face of the upper scarp on to the bush-covered apron at the base of the scarp (Figure 21). Very large failures appear to be less likely at this site because of the massive nature of the Tertiary rock mass. Some of the rock fall debris (perhaps 50%) might reach the lake and produce smaller (~≤ 1 m) waves locally (< ~0.5 km). Waves of that size are unlikely to have any significant effects at Te Anau Downs Boat Harbour, or at any of the other facility sites of interest to Environment Southland around the shoreline of Lake Te Anau.

2.2.2.8 Te Anau Area H

There are several potential landslide sites on the steep (~45°) failure-scarred, gullied rock face (Site H1) on the northeast side of North Fiord about 5–7 km from the entrance of the fiord (Figure 11c). Evidence of previous shallow landslide activity at this site suggests that MM8-10 earthquake shaking is likely to trigger fresh small to moderate (~10^3 to 10^4 m^3) rock falls and debris slides into the lake. Such failures would probably produce small ~0.5–1 m waves locally (< ~0.5 km), but their direction of travel across the fiord and isolated location suggests they are unlikely to affect any of the facility sites of interest to Environment Southland around the shoreline of Lake Te Anau (the closest site is Glaisnock Hut ~10 km to the northwest at the head of the fiord).

2.2.2.9 Te Anau Area I

Four potential landslide sites (Sites I1, I2, I3, and I4) are identified on very steep (~35–50°) ice scoured slopes on the west side of North Fiord ~1.5 to 6 km south of Glaisnock Hut at the head of the fiord (Figure 11c). There are a number of long, narrow, recent shallow debris slide scars on this face in areas where small to moderate (~10^3 to 10^4 m^3) shallow debris slides into the lake are likely to occur under during MM8-10 earthquake shaking. These failures could produce small ~0.5–1 m waves locally (< ~0.5 km), but their probable direction of travel (across the fiord to the northeast) suggests that Glaisnock Hut (≥ 1.5 km to the northwest) is unlikely to be affected by small waves (perhaps a few 10s of cm high) from any of the potential EIL sites. Other facility sites of interest to Environment Southland around the shoreline of Lake Te Anau are also located too far away to be affected. However, Glaisnock Hut could be affected by lateral spreading or a delta collapse wave. A site-specific evaluation would give a more accurate assessment of the hazard.

Figure 21. Aerial view of Area G on the Turret Peaks scarp at the entrance to North Fiord. At *Site G1* there have been small to moderate prehistoric rock falls on to the bush-covered bench *(b)* above the lake, and small rock and debris falls and slides *(dfs)* occurred during the 2003 earthquake.

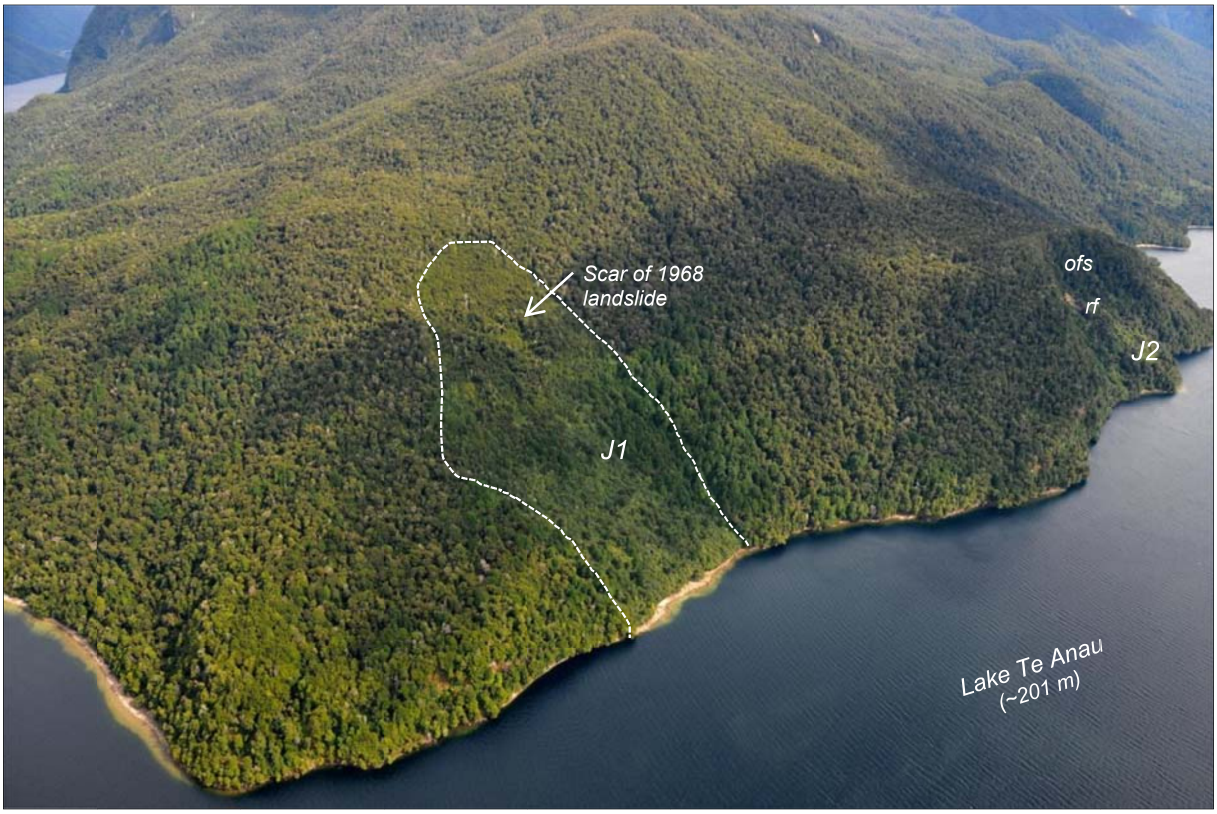

Figure 22. Aerial view of Area J on the west side of Lake Te Anau near the entrance to North Fiord. A large landslide occurred at *Site J1* in 1968 (the scar has now revegetated), and there have been small recent falls *(rf)* on an older failure scar *(ofs)* at *Site J2* about 1.5 km to the north.

2.2.2.10 Te Anau Area J

Two potential failure sites (Site J1 and J2) are identified on a moderately steep (~25–30°) bush covered slope on the west side of the lake ~1 – 2 km north of the entrance of North Fiord (Figures 11c and 22). A large (~700,000 m^3) translational slide occurred at Site J1 during a severe rainstorm in March 1968 (Read 1976). That failure probably moved slowly into the lake as there is no report of a wave. An older failure area with small recent scar is located ~1.5 km to the north at Site J2. The landsliding history at these sites suggests that MM8-10 earthquake could cause rapid small to large (~10^3 to 10^5 m^3) debris slides and falls into the lake, which could produce ~1–3 m waves locally (< ~0.5–1 km). Because of their likely direction of travel across the lake to the east, waves of that size are unlikely to have any significant effects at Te Anau Downs Boat Harbour ~11 km to the south, or at any other facility sites of interest to Environment Southland as they are all more than 20 km away.

2.2.2.11 Te Anau Area K

One potential failure site (Site K1) was identified on a moderately steep (~25–30°) bush covered slope adjacent to two debris fans built at the mouths of shallow gullies on the west side of the lake ~5 km north of North Fiord (Figure 11c). The presence of recent small debris slides at this site suggests that MM8-10 earthquake shaking could trigger shallow, small to moderate (~10^3 to 10^4 m^3) debris slides which could enter the lake. Such failures could produce waves up to ~0.5–1 m high locally (within ~0.5 km), but because of their expected travel direction across the lake to the east, they are unlikely to have significant effects at Te Anau Downs Boat Harbour ~15 km to the south, or at any other facility sites of interest to Environment Southland.

2.2.2.12 Te Anau Area L

Three potential failure sites (Site L1, L2, and L3) were identified in and around Worsley Arm near the head of the lake (Figures 11d). Site L1 is located in very steep (~35–45°) failure-scarred, bush-covered gullies on the southern side of the entrance to Worsley Arm. Site L2 is located on very steep, 300 m high bluffs on the south side of Worsley Arm, about 1 km southeast of Worsley Hut (Figure 23). Small shallow failures occurred at this site during the 2003 earthquake. Site L3 is located on a bush-clad ~25–35° slope on the northern side of Worsley Arm ~1-3 km east of Worsley Hut. The recent small slope failures that have occurred in these areas suggests that MM8-10 earthquake shaking could trigger shallow, small to large (~10^3 to ~2×10^5 m^3) debris slides and/or rock falls into the lake at these sites. At Sites L2 and L3, such failures could produce waves ~1–5 m high waves within 1–2 km of the site and possibly affect Worsley Hut. Similar waves produced by failures at Site L1 near the entrance to Worsley Arm would probably travel east across the lake and are unlikely to threaten any of the facility sites around the shoreline of Lake Te Anau.

Because of the location of Worsley Hut close to the lake shore and the Worsley Stream delta (Figure 23) there is strong possibility the hut could be affected by lateral spreading, or by a wave generated by collapse of the delta during very strong earthquake shaking. A site-specific evaluation would provide a more accurate assessment the landslide, ground deformation, and tsunami hazard at Worsley Hut.

Figure 23. Aerial view of potential landslide Site L2 at the head of Worsley Arm of Lake Te Anau. *Site L2* on the ~300 m high cliffs ~1 km southeast of Worsley Hut. Failures on these cliffs during the 2003 earthquake *(ls)* and more recently *(rl)* indicates their vulnerability to strong earthquake shaking.

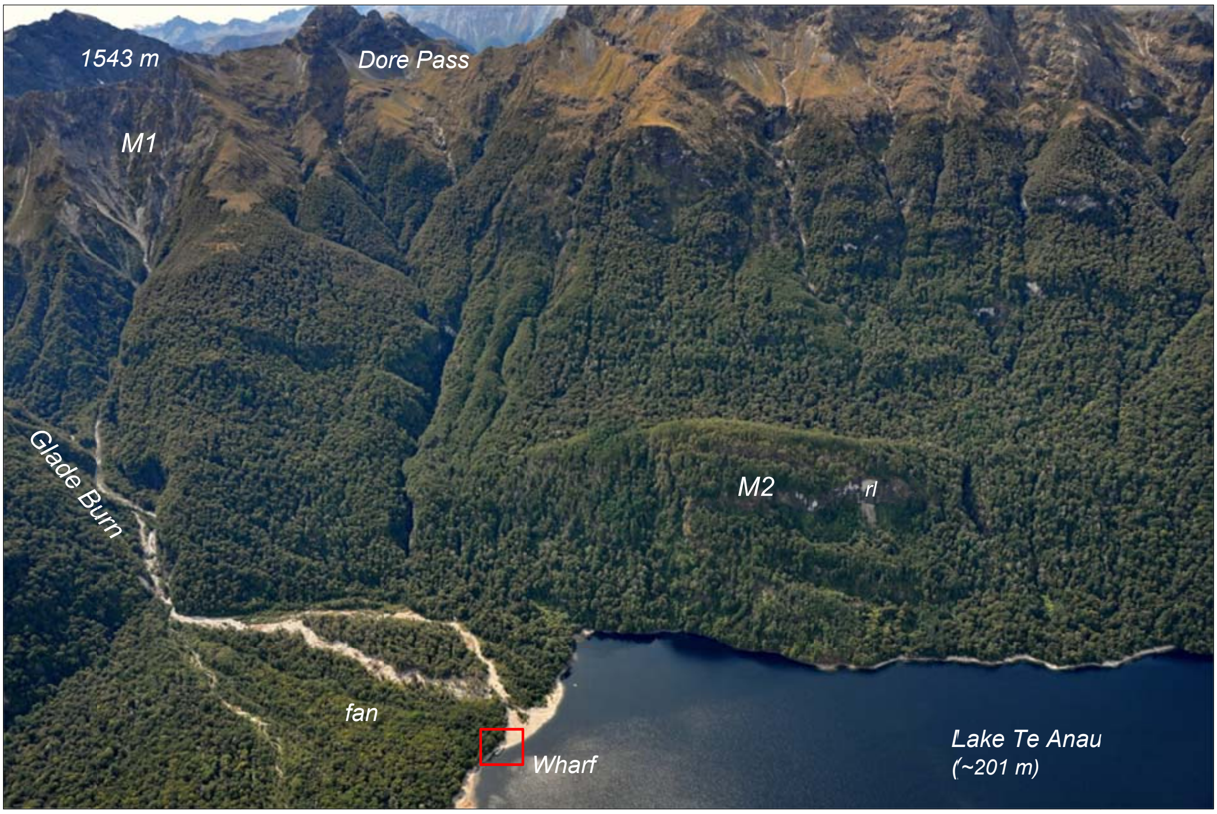

Figure 24. Aerial view of potential landslide Area M at the head of Lake Te Anau. *Site M1* is on an eroding 1543 m peak 1 km north of Dore Pass. Debris slides and flows from this peak onto the Glade Burn fan and into the lake pose a direct damage and wave threat to the Glade wharf facility, as do rock falls on the cliffs at *Site M2*, where there have been small recent failures *(rl)*.

2.2.2.13 Te Anau Area M

Two potential failure sites (Sites M1 and M2) were recognised in the Glade Burn and wharf area at the head of the lake (Figure 11d). Site M1 relates to an extensive area of active gully erosion on the very steep (~45–50°) west face of the 1543 m peak ~1 km north of Dore Pass, debris from which has built the large debris fan at the mouth of Glade Burn (Figure 24). The currently active channels of the Glade Burn fan enter the lake close to (~10-15 m west) the wharf at the start of the Milford Track. Site M2 is located on the east side of the lake about 0.5–1 km south of the wharf on near-vertical 200-300 m cliffs, which are scarred in places by a few small recent rock falls and shallow debris slides. These failures suggest that that at Site M2, very strong (MM8-10) earthquake shaking could trigger shallow, small to moderate (~10^3–10^5 m^3) rock falls and debris slides or rock falls into the lake. Such failures could potentially produce waves ~0.5–3 m high waves locally (~0.5–1 km), which could affect the Glade Burn wharf ~500 m to the north. At Site M1, MM8-10 earthquake shaking could trigger large (~10^5–10^6 m^3) rock falls and slides falls from the highly eroded 1543 m peak, which could transform in the gully or on the fan into a large debris flow, and could possibly reach the lake. The debris flow, or waves caused by it rapidly entering the lake, could potentially damage or destroy the wharf. The wharf could also be affected by lateral spreading, or a wave caused by collapse of the delta during very strong earthquake shaking.

2.2.2.14 Te Anau Area N

One potential failure site (Site N1) was identified on the very steep (~45-75°) west-facing scarp slope at the southern end of the Stuart Mountains on the northern side and near the entrance of Middle Fiord (Figure 11b). As at the Turret Peak (Site G1) about 8 km to the northeast, MM8-10 earthquake shaking could trigger small to moderate (~10^3 to 10^4 m^3) rock falls on the sheer scarp ~1000-1200 m above the lake. Most of the rock fall material will accumulate on the extensive bush-covered platform at the foot of the slope, but some debris could reach the lake and produce small (~≤ 1 m high) waves locally (< ~0.5 km). These waves would probably travel west up Middle Fiord and they are unlikely to have significant effects at Te Anau Downs Boat Harbour site or any other lake shore facility sites of interest to Environment Southland.

2.2.2.15 Te Anau Area O

There are several potential EIL sites on the very steep (~45-75°) west-facing Tertiary sandstone scarp at the southern end of the Earl Mountains just north of Camp Bay on the east side of the lake ~4 km north of North Fiord (Figure 11c). As at Turret Peaks ~8 km to the southwest, MM8-10 earthquake shaking could trigger small to moderate (~10^3 to 10^4 m^3) rock falls on the steep ~400 m above the lake, but only at Site 01 (about ~200 m west of peak 588 m and a small lake) is the debris likely to enter the lake - most of it would fall on the bush-covered apron below the scarp. If rock falls of this sizes enter the lake they could cause small (~≤ 1 m) waves locally (within ~0.5 km), which would probably travel west across the lake and are unlikely to affect the Te Anau Downs Boat Harbour site ~ 13 km to the south, or any other facility sites of interest to Environment Southland.

2.2.2.16 Te Anau Area P

One potential failure site area (Site P1) was identified on the very steep (~40-50°) ~500 m high slope on Rata Point at the north end of Safe Cove on the western side of the lake ~7 km south of Worsley Arm (Figure 11c and Figure 25). The presence of a small recent (2003) shallow failure scar, together with a larger deep seated old failure on the slope, suggests that MM8-10 earthquake shaking could trigger small to large (~10^3 to 10^5 m^3) rock falls into the lake. Such falls could produce ~1–3 m high waves locally (within 0.5–1 km), which would probably travel south down the main arm of the lake. Waves of that size near the head of the lake are unlikely to affect the Te Anau Downs Boat Harbour ~20 km to the south or any other facility sites of interest to Environment Southland.

Figure 25. Aerial view of potential landslide Area P on the north side of Safe Cove on the west side of Lake Te Anau ~7 km south of Worsley Arm. Landslide *Site P1* is on an old failure *(of)* on the steep 500 m south face of Rata Point, where a small landslide *(ls)* occurred during the 2003 earthquake.

Table 5. Summary of landslide volumes and run-up heights of waves generated by potential landslides into lakes Manapouri and Te Anau and geological hazards in relation to facility sites.

Landslide Area (Site)	Estimated[1] Landslide volume (m^3)	Possible max wave run-up height (m)	Closest Facility Site[2] and Distance (km)	Other potential geological hazards at facility sites and explanatory comments[3]
Lake Manapouri				
A (2,3)	10^3–10^4	0.5–1	Powerhouse/wharf (0.5–1)	Landslides, delta col., lat. spread
B (1,2)	10^3–10^4	0.5–1	Powerhouse/wharf (2–3)	
C	10^3–10^4	0.5–1	Powerhouse/wharf (7)	
D	10^3–10^4	0.5–1	Freeman Burn Hut (2–3)	
E	$\leq 10^3$	0.5–1	Freeman Burn Hut (0.2–0.5)	Delta collapse, lateral spreading
F (1)	5×10^5–10^6	10–25	Powerhouse/Freeman B Hut (8)	
G	10^3–10^5	0.5–3	Powerhouse/wharf (12)	
H	10^4–5×10^5	5–10	Moturau Hut (17)	
I	10^3–10^5	0.5–3	NA, area remote	
J	1–2×10^5	3–5	Moturau Hut (12). Man. (14)	
K	10^3–10^4	0.5–1	Moturau Hut (10). Man. (13)	
L	10^2–10^4	0.5–1	Moturau Hut (7). Man. (11)	
M	10^3–10^4	0.5–1	Area remote. Man. (17)	
N	10^2–10^4	0.5–1	Manapouri, P/Harbour (3)	
O	10^3–5×10^5	1–5	Moturau Hut (5). Man. (12)	Failure probably less rapid[1].
Lake Te Anau				
A	10^3–10^4	0.5–1	Te Anau, Kepler Track (9)	
B	10^3–10^4	0.5–1	Te Anau, Kepler Track (15)	
C	10^3–10^5	1–3	Te Anau, Kepler Track (15)	
D	10^3–10^5	1–3	Te Anau, Kepler Track (20)	
E	10^3–10^4	0.5–1	Te Anau, Kepler Track (25)	
F (2)	10^3–10^5	1–3	Glow worm caves (10)	
G	10^3–10^5	0.5–1	Te Anau Downs Harb. (8)	~50% debris likely to reach lake
H	10^3–10^4	0.5–1	Te Anau Downs Harb. (13)	
I	10^3–10^4	0.5–1	Glaisnock Hut (1–4)	Delta collapse, lateral spreading
J	10^3–10^5	1–3	Te Anau Downs Harb. (11)	Failure less rapid (as in 1968)
K	10^3–10^4	0.5–1	Te Anau Downs Harb. (15)	
L	10^3–2×10^5	1–5	Worsley Hut (1–2), Glade Wh. (7)	Delta collapse, lateral spreading
M	10^3–10^6	0.5–3	Glade wharf (<0.1–0.5)	Debris flow, delta col., lat. spread
N	10^3–10^4	0.5–1	Te Anau Downs Harb. (10)	
O	10^3–10^4	0.5–1	Te Anau Downs Harb. (13)	
P	10^3–10^5	1–3	Te Anau Downs Harb. (20)	

Notes:
1. Estimated maximum volumes of possible landslides rapidly entering the lake at potential EIL sites.
2. The most hazardous areas or sites are shaded pink. The Freeman Burn and Glaisnock hut sites are likely to be hazardous because of the potential for lateral spreading and delta collapse waves at those sites.
3. Geological hazards could potentially affect the nearest facility site of interest to ES.

3.0 SUMMARY AND DISCUSSION

The Stage 2 helicopter reconnaissance survey and aerial photo analysis has enabled the earthquake-induced landslide and wave generation potential of specific sites within 31 areas around the shorelines of Lake Manapouri (15 areas) and Lake Manapouri (16 areas) to be evaluated. The very steep (≥35-45°) slopes in these potential EIL areas have high to very high landslide susceptibility, most have active and recent shallow landslides, and some show clear evidence of older (probably prehistoric) defect-controlled wedge and translational bedrock failures, where previous large collapses into the lakes appear to have occurred.

The main criteria used to identify potential sites where landslides could occur during strong earthquake shaking (MM8–MM10) were the scars of active and recent landslides, rock fall debris on slopes, debris fans, and the absence or variations in vegetation. Landslide size was estimated from the nature, steepness, and height of the possible source areas, and by comparison to the types and size of landslides triggered by the 2003 and 2009 Fiordland earthquakes (Hancox et al. 2003, 2010). These factors and precedent evidence (especially the 2003 tsunami in Gold Arm) were also used to estimate the tsunami wave generating potential of landslides into Lake Manapouri and Lake Te Anau. The significance and potential effects of landslide generated waves at facility sites of interest to Environment Southland was estimated based on lakeshore location, direction of travel, and distance to those sites.

The closest distances from the potential earthquake-induced landslide sites to the facility sites are for *Lake Manapouri:* ~500–1000 m to Manapouri powerhouse and West Arm wharf; ~200–500 m to Freeman Burn Hut; and ~ 5 km to Moturau Hut on the Kepler Track; and for *Lake Te Anau*: ~100–500 m to Glade wharf and the start of the Milford Track; ~1–2 km to Worsley Hut; and ~1–2 km to Glaisnock Hut. The Te Anau Downs Boat Harbour, Glow Worm Caves, Kepler Track, Lake Te Anau Control Structure, and the main residential and commercial centres of Te Anau and Manapouri are all about 8–15 km or more from the potential landslide sites.

In assessing the effects of landslides into Lake Manapouri and Lake Te Anau at specific sites the wave generating capability at each site was estimated based on the type and size of landslides that are expected to occur during MM8-10 earthquake shaking, as indicated mainly by the August 2003 M_w 7.2 Fiordland earthquake (Hancox et al. 2003). Although it was larger, the M_w 7.6 earthquake in July 2009 did not produce significant landsliding as its seismic energy release was lower and was mainly directed offshore to the south rather than northwards towards the Fiordland land mass (Fry et al. 2010, Hancox et al. 2010).

Landslides triggered by the 2003 earthquake and earlier studies of earthquake-induced landsliding in New Zealand (Hancox et al. 1997, 2003) suggest that MM 8–9 shaking in the Te Anau–Manapouri area will trigger many shallow small to moderate (~10^3–10^4 m^3) rock and debris slides, and also landslides similar to those which occurred in the epicentral area of the 2003 earthquake. Larger landslides (e.g. 1–2 x 10^5 m^3) which travel rapidly into the lakes with a fall height of ~400 m or greater could cause a tsunami wave ~3–5 m high, similar to those in Deep Cove in 1987 and Gold Arm in 2003 (Tables 1 and 2). However, MM 9 and MM10 intensity earthquake shaking could possibly trigger very large (10^6–10^7 m^3) and giant (≥ 10^8 m^3) deep seated bedrock landslides similar to more than 50 known prehistoric (post glacial) landslides in the Fiordland area (Hancox and Perrin 2009). There are a number of these landslides in the Manapouri – Te Anau area (e.g. Iris Burn, Lake McIvor, Mid Burn, Lake Gunn and others - see Figures 6, 8, and 11d).

Although very large and giant landslides in Fiordland are possible, historically such extreme events are rare in New Zealand. There is no evidence to show that failures like the 30 Mm^3 earthquake-induced rock slide in Alaska, which caused a 524 m high wave in Lituya Bay in 1958 are likely to occur in the Manapouri and Te Anau area. Alaska is particularly susceptible to landslide-induced waves because of its steep topography, high seismicity, and recent glacial retreat which removed slope support – the Lituya Bay area was glaciated up until about 1000 years ago (Miller 1960). However, slopes in the Fiordland area have had at least 10,000 years to adjust to post glacial ice withdrawal, hence it is possible that massive bedrock failures now occur less frequently in that area. GNS Science and others are currently in the process of dating very large landslides in Fiordland to determine their ages and geomorphic histories, and whether or not they can be linked causally to large earthquakes on the Alpine Fault or the Puysegur subduction zone. The latter probably generated the ~M8–8.5 Fiordland earthquake in 1826 which caused widespread landsliding in Fiordland (Downs et al. 2005, Clark et al. 2011).

Evaluations of the potential earthquake induced landslide sites identified in Stage 2 using the information and criteria outlined above has shown that most of the expected landslides are likely to be shallow small to moderate (~10^3–10^4 m^3) rock falls and debris slides, with larger bedrock failures (~10^5–10^6 m^3) possible in a few places (Table 5). All of the potential landslide source areas are near the tops of steep high slopes and ridges which are generally more strongly shaken, possibly by 1 to 2 MM intensity units higher (Hancox et al. 2011). No areas were identified where very large (~10^7–10^8 m^3) landslides are expected to occur.

The largest (~10^4–10^6 m^3) landslides that could occur during MM8-10 earthquake shaking close to (within ~5 km) the facility sites of interest to Environment Southland are at: *Site A1* south of Manapouri powerhouse in West Arm; *Site O1* on the northeast side of Lake Manapouri; *Site L* near Worsley Hut in Worsley Arm of Lake Te Anau; and *Site M* near the Glade Burn wharf at the head of Lake Te Anau. Historical landslide-generated tsunamis in Fiordland (Deep Cove 1987, Gold Arm 2003) and overseas examples with fall heights of ~400-1000 m suggests that rapid small to moderate landslides (~10^3–10^4 m^3) are likely to produce ~0.5–1 m high waves (wave run-up) within of ~0.5 to 1 km of the slide area, while rapid large to very large (~10^5–10^6 m^3) landslides potentially generate waves ~3 to 25 m high and affect areas 1–5 km or more from the failure site *(as at Site F)*. The potential landslides generated waves that and other geological hazards that could possible affect priority facility sites on Lake Manapouri and Lake Te Anau are summarised in Table 5.

Historical precedents suggest that the size of the landslide wave, and hence the potential to cause damage, depends on the volume of landslide debris and displaced water, the fall height, and the velocity with which the slide mass enters the water. It is also clear that waves generally reach their greatest height directly across the fiord or lake from the failure area and diminish in height quickly to the sides (Jorstad 1968). These characteristics have been applied in the landslide wave height estimates presented in the report (Table 5).

The facility sites of interest to Environment Southland that are thought to be potentially at greatest risk from waves generated by large rapid landslides, rock falls, and debris flows are: Manapouri powerhouse and wharf *(Sites A1 and A2)*, Worsley Hut *(Sites L2 and L3),* and Glade Burn wharf *(Sites M1 and M2).* Tsunami modelling may be necessary in Stage 3 to determine potential landslide wave effects at these sites. Modelling of large (10^5–10^6 m^3) slope failures would provide a better indication of the height and distribution of the tsunami waves that could be generated and their potential to damage those facilities. Site-specific evaluations would provide more accurate assessments of the potential hazard and risk from landslides and lateral spreading, as well as landslide and delta collapse waves at these sites.

4.0 CONCLUSIONS

(1) The helicopter reconnaissance survey and aerial photo analysis carried out in Stage 2 of the Environment Southland seiche and tsunami study has enabled the earthquake-induced landslide and wave generation potential of specific sites within 31 areas around the shorelines of Lake Manapouri and Lake Manapouri to be evaluated. The steep (≥35-45°) slopes in these areas have high to very high landslide susceptibility, most have active and recent shallow landslides, and some show clear evidence of older (probably prehistoric) defect-controlled wedge and translational bedrock failures, where previous large collapses into the lakes appear to have occurred.

(2) The main criteria used to identify and evaluate potential sites where landslides could occur during strong earthquake shaking (MM8–MM10) were the scars of active and recent landslides, rock fall debris on slopes, debris fans, and the absence or variations in vegetation. Landslide size was estimated from the nature, steepness, and height of the possible failure areas, and by comparison with the types and size of landslides triggered by the 2003 and 2009 Fiordland earthquakes. These factors, together with lakeshore location, travel distance, and evidence from historical landslide generated waves in Fiordland (Deep Cove 1987, Gold Arm 2003) and overseas were used to estimate potential run-up heights of landslide generated waves on Lake Manapouri and Lake Te Anau in relation to facility sites of interest to Environment Southland.

(3) Evaluations of potential landslide sites identified in this Stage 2 study has shown that most of the expected earthquake-induced landslides around the shores of Lake Manapouri and Lake Te Anau will be shallow small to moderate (~10^3–10^4 m^3) rock falls and debris slides, with larger bedrock failures (~10^5–10^6 m^3) possible in some places. No areas were identified where very large (10^7–10^8 m^3) landslides into lakes Manapouri and Te Anau are expected to occur.

(4) The largest (~10^4–10^6 m^3) earthquake-induced landslides that are expected to occur close to (within ~5 km) the facility sites of interest to Environment Southland are at: *Site A1* south of Manapouri powerhouse in West Arm; *Site O1* on the northeast side of Lake Manapouri; *Site L* near Worsley Hut in Worsley Arm of Lake Te Anau; and *Site M* near the Glade Burn wharf at the head of Lake Te Anau. Historical evidence suggests that rapid small to moderate landslides (10^3–10^4 m^3) produce waves with run-up heights of 0.5–1 m within of 1 km of the slide area. Potentially larger landslides (10^5–10^6 m^3) at Site F1 in Lake Manapouri could generate waves with run-up heights of ~3 to 25 m and possibly affect Manapouri powerhouse and West Arm wharf ~8 km to the west, and Freeman Burn Hut ~8 km to the north at the head of North Arm.

(5) The facility sites that are considered to be potentially at greatest risk from waves generated by large rapid landslides, rock falls, or debris flows are: Manapouri powerhouse and wharf *(Sites A1 and A2)*, Worsley Hut *(Sites L2 and L3),* and the Glade Burn wharf *(Sites M1 and M2).* Tsunami modelling may be necessary (in Stage 3) to determine the potential wave effects of different size and types of landslides at these three sites. Modelling of generalised large (10^5–10^6 m^3) slope failures at these sites would provide a better indication of the height and distribution of the tsunami waves that could be generated and their potential to cause damage at facility sites. Site specific assessments may be necessary to assess the direct risk from landslides, debris flows, lateral spreading and delta collapses at these facility sites, and also possibly the Freeman Burn Hut and Glaisnock Hut sites.

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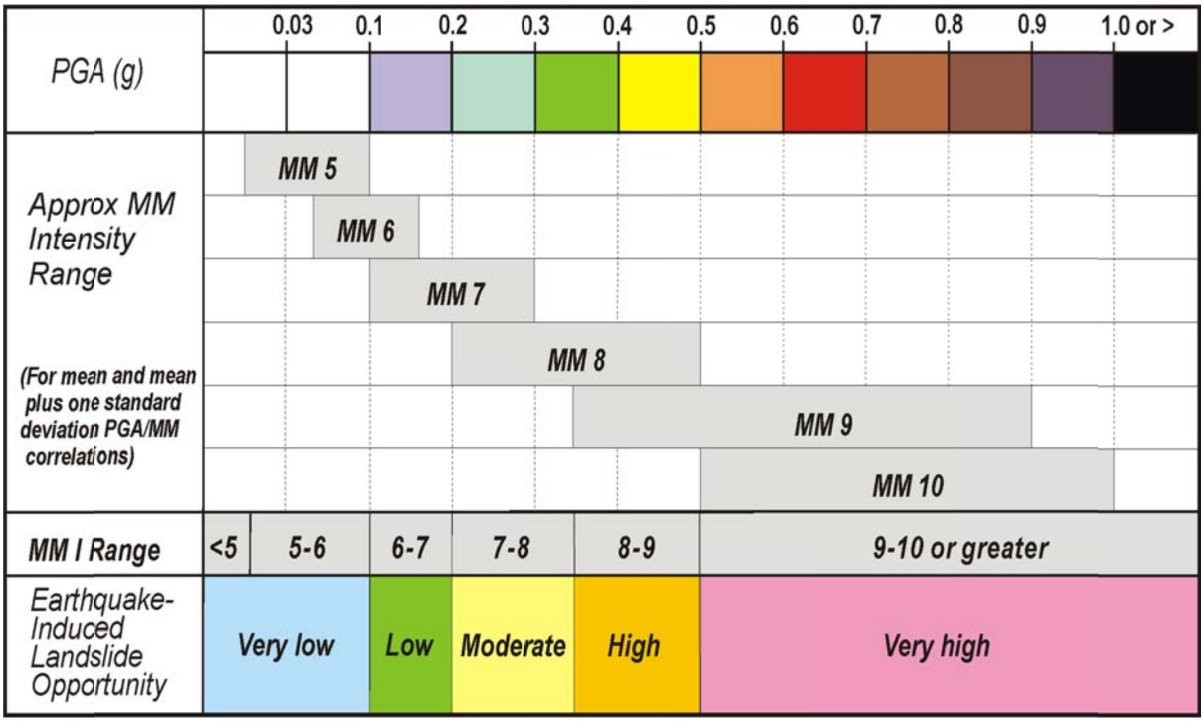
APPENDIX 1. MODIFIED MERCALLI INTENSITY SCALE

A1a Landslide and Environmental Criteria for the Modified Mercalli (MM) Intensity Scale – NZ 2007

MM5	▪ Loose boulders may occasionally be dislodged from steep slopes.
MM6	▪ Trees and bushes shake, or are heard to rustle. ▪ Loose material may be dislodged from sloping ground, e.g. existing slides, talus and scree slopes. ▪ A few very small (≤10^3 m^3) soil and regolith slides and rock falls from steep banks and cuts. ▪ A few minor cases of liquefaction (sand boil) in highly susceptible alluvial and estuarine deposits.
MM7	▪ Water made turbid by stirred up mud. ▪ Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings common. ▪ Instances of settlement of unconsolidated, or wet, or weak soils. ▪ A few instances of liquefaction (i.e. small water and sand ejections). ▪ Very small (≤10^3 m^3) disrupted soil slides and falls of sand and gravel banks, and small rock falls from steep slopes and cuttings are common. ▪ Fine cracking on some slopes and ridge crests. ▪ A few small to moderate landslides (10^3 –10^5 m^3), mainly rock falls on steeper slopes (>30˚) such as gorges, coastal cliffs, road cuts and excavations. ▪ Small discontinuous areas of minor shallow sliding and mobilisation of scree slopes in places. ▪ Minor to widespread small failures in road cuts in more susceptible materials. ▪ A few instances of non-damaging liquefaction (small water and sand ejections) in alluvium.
MM8	▪ Cracks appear on steep slopes and in wet ground. ▪ Significant landsliding likely in susceptible areas. ▪ Small to moderate (10^3-10^5 m^3) slides widespread; many rock and disrupted soil falls on steeper slopes (steep banks, terrace edges, gorges, cliffs, cuts etc.). ▪ Significant areas of shallow regolith landsliding, and some reactivation of scree slopes. ▪ A few large (10^5-10^6 m^3) landslides from coastal cliffs, and possibly large to very large (≥10^6 m^3) rock slides and avalanches from steep mountain slopes. ▪ Larger landslides in narrow valleys may form small temporary landslide-dammed lakes. ▪ Roads damaged and blocked by small to moderate failures of cuts and slumping of road-edge fills. ▪ Evidence of soil liquefaction common, with small sand boils and water ejections in alluvium, and localised lateral spreading (fissuring, sand and water ejections) and settlements along banks of rivers, lakes, and canals etc. ▪ Increased instances of settlement of unconsolidated, or wet, or weak soils.
MM9	▪ Cracking of ground conspicuous. ▪ Landsliding widespread and damaging in susceptible terrain, particularly on slopes steeper than 20˚. ▪ Extensive areas of shallow regolith failures and many rock falls and disrupted rock and soil slides on moderate and steep slopes (20˚-35˚ or greater), cliffs, escarpments, gorges, and man-made cuts. ▪ Many small to large (10^3-10^6 m^3) failures of regolith and bedrock, and some very large landslides (10^6 m^3 or greater) on steep susceptible slopes. ▪ Very large failures on coastal cliffs and low-angle bedding planes in Tertiary rocks. Large rock/debris avalanches on steep mountain slopes in well-jointed greywacke and granitic rocks. Landslide-dammed lakes formed by large landslides in narrow valleys. Damage to road and rail infrastructure widespread with moderate to large failures of road cuts and slumping of road-edge fills. Small to large cut slope failures and rock falls in open mines and quarries. ▪ Liquefaction effects widespread, with numerous sand boils and water ejections on alluvial plains, and extensive, potentially damaging lateral spreading (fissuring and sand ejections) along banks of rivers, lakes, canals etc.). Spreading and settlements of river stop-banks likely.
MM10	▪ Landsliding very widespread in susceptible terrain. ▪ Similar effects to MM9, but more intensive and severe, with very large rock masses displaced on steep mountain slopes and coastal cliffs. Landslide-dammed lakes formed. Many moderate to large failures of road and rail cuts and slumping of road-edge fills and embankments may cause great damage and closure of roads and railway lines. ▪ Liquefaction effects (as for MM9) widespread and severe. Lateral spreading and slumping may cause rents over large areas, causing extensive damage, particularly along river banks, and affecting bridges, wharfs, port facilities, and road and rail embankments on swampy, alluvial or estuarine areas.

Notes: *(1) "Some or 'a few' indicates that threshold for response has just been reached at that intensity. (2) Environmental damage (response criteria) occurs mainly on susceptible slopes and in certain materials, hence the effects described above may not occur in all places, but can be used to reflect the average or predominant level of damage or MM intensity in an area. (3) Environmental criteria not defined for MM11 and 12, as those intensities have not been reported in New Zealand. Earlier versions of the MM intensity scale suggest that environmental effects at MM11-12 are similar to MM9- 10, but are more widespread and severe. (4) This appendix is based on Hancox et al. 1997, 2002, and Dowrick et al., 2008. A summary of the full MM Intensity Scale is given below (A1c).*

A1b Relationship of MM Intensity to Peak Ground Acceleration (PGA) and earthquake-induced landslide opportunity *(after Hancox et al. 2002)***.**



The graph above shows the relationship of MM Intensity to peak ground acceleration (PGA) range based on the mean and mean plus one standard deviation correlations of Murphy and O'Brien (1977) landslide opportunity on New Zealand (from Hancox et al. 2002). The overlap in the PGA values for different MM intensities reflects the considerable scatter in PGA/MM data.

The EIL Opportunity classes define the relative likelihood of earthquake-induced landslides occurring in areas of different shaking (PGA/MM Intensity) based on ground damage effects established for New Zealand. Five classes of relative EIL opportunity are recognised, as follows:

1. Very Low (≤ MM5-6): *Very small rock and soil falls on the most susceptible slopes.*

2. Low (MM6-7): *Small landslides, soil and rock falls may occur on more susceptible slopes (particularly road cuts and other excavations), along with minor liquefaction effects (sand boils) in susceptible soils.*

3. Moderate (MM7-8): *Significant small to moderate landslides are likely, and liquefaction effects (sand boils) expected in susceptible areas. Noticeable damage to roads.*

4. High (MM8-9): *Widespread small-scale landsliding expected, with a few moderate to very large slides, and some small landslide-dammed lakes; many sand boils and localised lateral spreads likely. Severe damage to roads, with many failures of steep high cuts and road-edge fills.*

5. Very high (≥MM9): *Widespread landslide damage expected. Many large to extremely large landslides; sand boils are widespread on alluvium, and lateral spreading common along river banks; landslide-dammed lakes are often formed in susceptible terrain. Extensive very severe damage to roads - failures of steep high cuts and road-edge fills.*

A1c Summary of the Full New Zealand Modified Mercalli Intensity Scale (includes felt effects and damage to buildings and structures, based on information in Downes (1995), Dowrick (2008) and Hancox et al (2002).

The Modified Mercalli intensity scale (MM)

The Modified Mercalli intensity scale (summarised from Downes (1995), Dowrick (1996) and Hancox et al. (2002)) is a descriptive scale used to rank the intensity of an earthquake at a particular location. The intensity of any earthquake will vary from place to place, because of factors such as distance from the epicentre and localised differences in ground conditions (for example, shaking will be much greater on swampy ground than on solid rock).

MM 2 *Felt by people at rest, on upper floors or favourably placed.*

MM 3 *Felt indoors; hanging objects may swing, vibration similar to passing of light trucks.*

MM 4 *Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration like passing of heavy traffic. Doors and windows rattle. Walls and frames of buildings may be heard to creak.*

MM 5 *Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed. Some glassware and crockery may be broken. Open doors may swing.*

MM 6 *Felt by all. People and animals alarmed. Many run outside. Furniture or objects may move on smooth surfaces. Objects fall from shelves. Glassware and crockery broken. Slight damage to some types of buildings. A few cases of chimney damage. Loose material may be dislodged from sloping ground. A few very small (e.g. <1000 m^3) shallow landslides and rockfalls occur.*

MM 7 *General alarm. Furniture and appliances may be shifted and unstable items overturned. Unreinforced stone and brick walls cracked. Some pre-earthquake code buildings damaged. Roof tiles may be dislodged. Many domestic chimneys broken. Small falls of sand and gravel banks. Some fine cracks appear in sloping ground and ridge crests. Rockfalls from steep slopes and cuttings are common. A few small to moderate landslides (e.g. 1 000 to 10 000 m^3) occur on steeper slopes. Some instances of liquefaction at susceptible sites.*

MM 8 *Alarm may approach panic. Steering of cars greatly affected. Some serious damage to pre-earthquake code masonry buildings. Most reinforced domestic chimneys damaged, many brought down. Monuments and elevated tanks twisted or brought down. Some post-1980 brick veneer dwellings damaged. Houses not secured to foundations may move. Cracks may appear on slopes and in wet ground. On slopes in steep or weak ground, numerous small to moderate landslides and some large landslides (e.g. 100 000 m^3). Collapse of roadside cuttings and unsupported excavations. Small sand fountains and other instances of liquefaction.*

MM 9 *Very poor quality unreinforced masonry destroyed. Pre-earthquake code masonry buildings heavily damaged or collapse. Damage or distortion to some pre-1980 buildings and bridges. Houses not secured to foundations shifted off. Brick veneers fall and expose framing. Conspicuous cracking of flat and sloping ground. On steep slopes, many small to large landslides and some very large (>1 000 000 m^3) landslides and rock avalanches that may block narrow valleys and form lakes. Liquefaction effects intensified, with large sand fountains and extensive cracking or settlement of weak ground.*

MM 10 *Most unreinforced masonry structures destroyed. Many pre-earthquake code buildings destroyed. Many pre-1980 buildings and bridges seriously damaged. Many post-1980 buildings and bridges moderately damaged or permanently distorted. Widespread cracking of flat and sloping ground. Widespread and severe landsliding on sloping ground. Very large landslides (>$10^6 m^3$) from steep mountain faces and coastal cliffs. Widespread and severe liquefaction.*

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657