Natural Hazards on the Taieri Plains, Otago

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Cover images
Both cover photos are from the June 1980 floods. The first image is the Taieri River at Outram Bridge, and the second is the Taieri Plain, with the Dunedin Airport in the foreground.

Executive summary

The Taieri Plains is a low-lying alluvium-filled basin, approximately 210km^2 in size. Bound to the north and south by an extensive fault system, it is characterised by gentle sloping topography, which grades from an elevation of about 40m in the east, to below mean sea level in the west. At its lowest point (excluding drains and ditches), it lies about 1.5m below mean sea level, and has three significant watercourses crossing it: the Taieri River, Silver Stream and the Waipori River. Lakes Waipori and Waihola mark the plain's western boundary and have a regulating effect on drainage for the western part of the plains.

The Taieri Plains has a complex natural-hazard setting, influenced by the combination of the natural processes that have helped shape the basin in which the plain rests, and the land uses that have developed since the mid-19th century. The natural setting of the plains exposes the area to flooding, alluvial-fan hazard, landslides, seismic activity and tsunamis. The level of risk that these events present varies greatly across the plains, depending on the nature and scale of the particular hazard and the nature and vulnerability of the features exposed to that hazard.

The area is one of the largest expanses of flat land close to Dunedin city, and is mainly used for agricultural purposes, an activity that was established with the arrival of European settlers to the area in the mid-1800s. A large residential community is located in and around Mosgiel, with a number of smaller communities established at Outram, Allanton and North Taieri. Identified in the early settlement plans of Otago, each of these communities are located beyond the observed-flood extents of the early 19th century, indicating an early awareness of flood hazard on the Taieri Plains.

Flooding has been a fact of life for those living on the Taieri Plains, with a number of significant floods occurring since early European settlement in the mid-1800s. Modification of the flood hazard, through extensive engineering works, has reduced the incidence of flooding; however, a residual flood risk still exists.

Previous assessments of natural hazards on the Taieri Plains have generally focused on the mitigation and subsequent modification of flood risk through the engineering works of the Lower Taieri Flood Protection Scheme and the schemes that it subsumed. This report combines information about residual-flood risks with alluvial-fan, seismic, landslide and tsunami hazard information. A description of the social and environmental settings, which together create the hazardscape of the Taieri Plains, is also provided.

The report also provides a detailed description of how the flood hazard varies across the Taieri Plains. This description is a refinement and extension of that presented in a report prepared jointly with Dunedin City Council in 2006 (report titled '*Mosgiel Flood Event 25/26 April 2006 and Future Action').*

Spatial and temporal changes in extreme rainfall (storm) events have been analysed, using rainfall records from the lower Taieri River catchment. These records show that there is localised variability in extreme rainfall patterns, and that the northern end of the Taieri Plains (including within the Silver Stream catchment) has experienced an increase in the intensity and frequency of extreme rainfall events since the 1960s.

The risk associated with interactions between different types of hazard is explained. In particular, the effect of a fault rupture or severe ground shaking (associated with a high magnitude earthquake) on flood risk is considered. Information about the possible effects of a predicted warmer climate and higher sea level is also presented.

Decisions on land use need to take the complex hazard setting of the Taieri Plains into consideration to ensure that activities are compatible with the hazard exposure and the residual risk across the range of natural hazards. This report is intended to help inform those decisions and other risk-reduction initiatives.

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1. Introduction

The Taieri Plains is a low-lying, relatively flat expanse of land located to the west of Dunedin city (Figure 1.1), covering an area of 21,000 hectares. Used for rural, residential, commercial and industrial activities, the Taieri Plains is home to about 15,000 people, mostly clustered in and around the urban area of Mosgiel. The main land use is agriculture, an activity that was established with the arrival of the first European settlers in the mid-1800s. The land is highly productive, with fertile soils providing ideal conditions for crop and pasture growth. Dunedin International Airport is also nestled at the centre of the plains.

Figure 1.1 The Taieri Plains (looking south from Flagstaff).

A number of small rural and rural-residential communities are located at the edges of the plains (Figure 1.2). The proximity of the plains to Dunedin city and the flat landscape have contributed to the area’s popularity for rural-residential development. Census data (1996 to 2006) show that the population on the northern side of the Silver Stream (North Taieri) has increased from 530 in 1996 to 698 in 2006 (~25% increase). During the same period, Mosgiel experienced a population increase of about 504 (a 5% increase), compared to an increase of about 0.5% in the wider Dunedin City district.

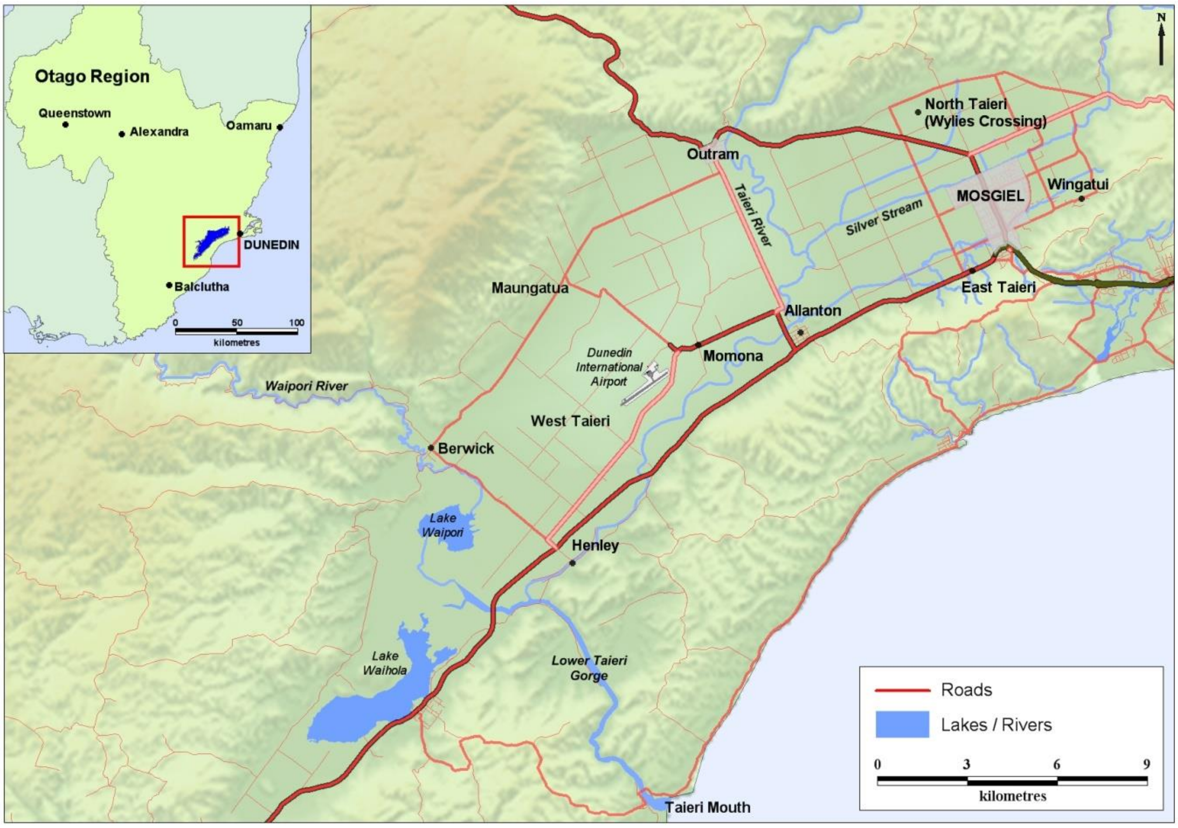

Figure 1.2 Communities on the Taieri Plains.

The alluvium-filled basin that makes up the Taieri Plains is bound by an extensive fault system to the north and south. The gentle topography, which grades from about 40m in the east to below sea level in the west, provides the largest expanse of flat land near Dunedin city. The Taieri River, the second longest river in Otago and fifth longest in New Zealand, meanders across the Taieri Plains before flowing out to sea at Taieri Mouth, via the Lower Taieri Gorge. The Taieri River is tidal at least as far upstream as Allanton, with lakes Waihola and Waipori also influenced by the rise and fall of the tide. Two major tributaries of the Taieri River also cross the Taieri Plains: the Silver Stream, from the north-east, and the Waipori River, from the south-west.

The Taieri Plains and environs have a complex-hazard setting that has shaped it and affects how it is used. Possible hazards include the plain’s exposure to flood inundation from various sources, seismic activity and, to a lesser degree, landslides, alluvial-fan and tsunami hazard. Other weather-related features, such as strong winds and heavy snow (Figure 1.3), also present hazards, although these are not discussed in detail in this report. The level of risk these hazards present varies across the plains, depending on the nature and scale of the hazard and the nature and vulnerability of the features exposed to that hazard. Therefore, decisions on land use need to take these hazards and their variability into account to ensure that human activities are compatible with the hazard exposure. This report is intended to help inform those decisions and other risk-reduction initiatives.

Earlier reports about natural hazards on the Taieri Plains have tended to focus on flood-hazard mitigation and the subsequent modification of flood hazard, usually through engineering works, and often associated with a particular locality or issue. This report combines information about residual-flood risks (the part of the risk that is not managed), and attempts to assess the residual risks of alluvial-fan, seismic, landslide and tsunami on the plain in general.

The following sections describe the social and natural setting of the Taieri Plains and the wider Taieri River catchment, and give an overview of how the flood hazard has been modified (but not eliminated) through engineering works over the past 150 years. The report then goes on to outline the risk of flooding, alluvial-fan, landslide, seismic and tsunami hazards, including their possible effects, based on knowledge of the natural processes of the area.

Figure 1.3 Heavy snow on the Taieri Plain, August 2004 (Source: Otago Daily Times).

2. Social setting

Residential activity is generally clustered around four areas: Mosgiel, Outram, Allanton and North Taieri. An awareness of flood hazard through knowledge of flood history appears to have influenced the placement of these settlements, with all four being largely located beyond the flood extents observed in the late 19th century (Figure 2.1 and Figure 2.2). This awareness of flood history apparently led to an early desire for engineered modifications of the Taieri River, Silver Stream and many other parts of the plains (Figure 2.2), including land-drainage works.

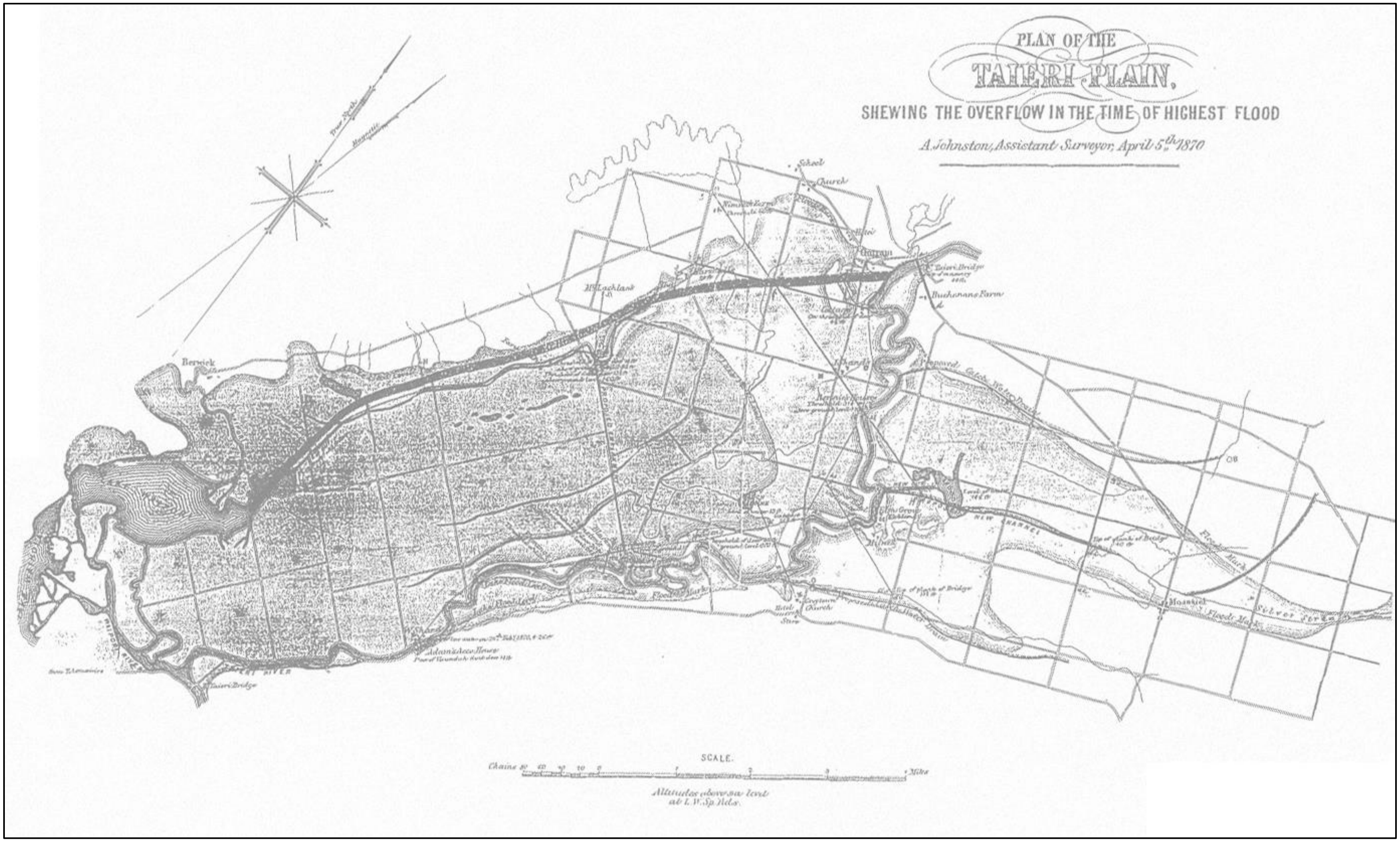

Figure 2.1 Extent of flooding in February 1868, and proposed flood-protection and land-drainage works.

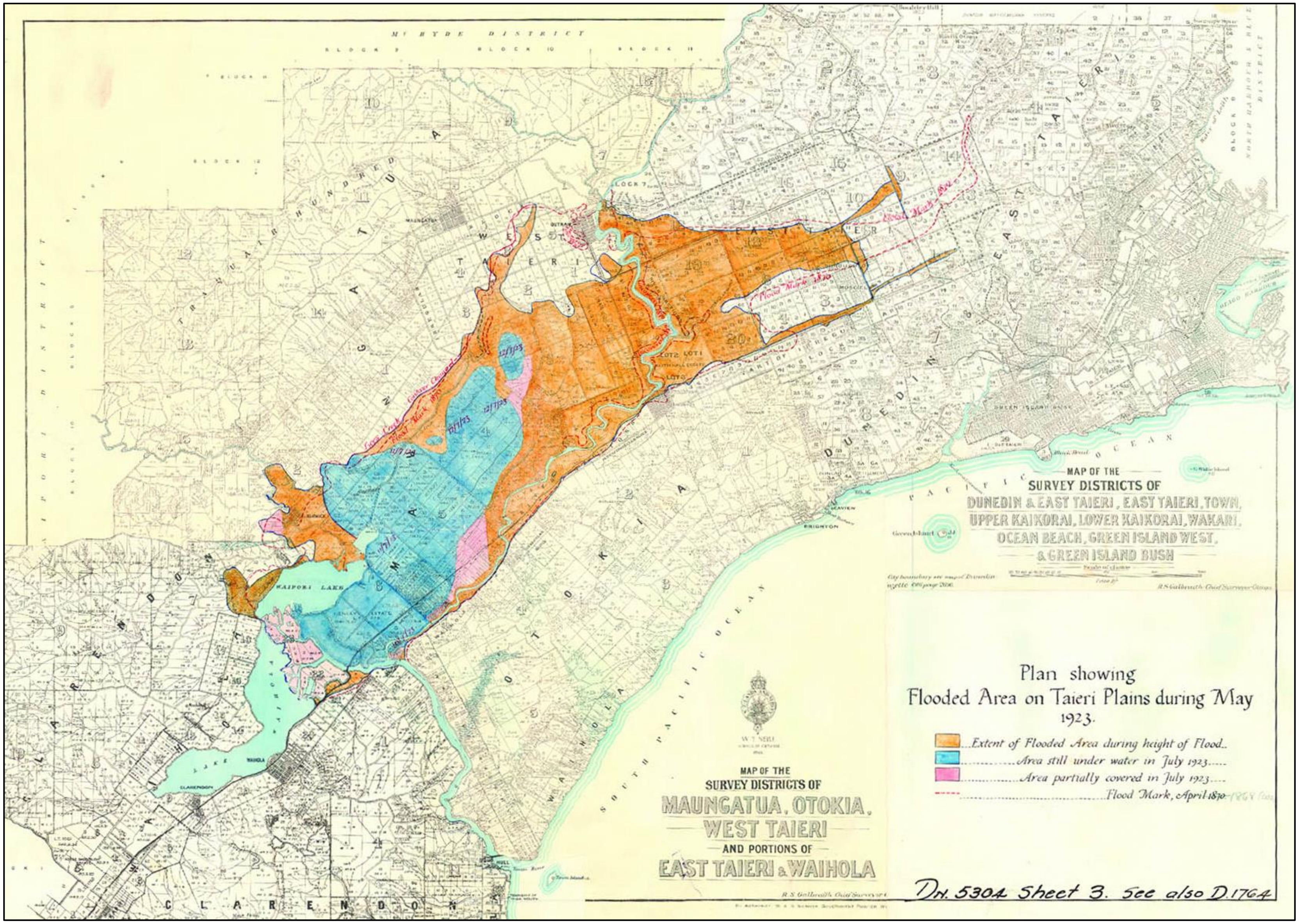

Figure 2.2 Extent of flooding in May 1923, showing the communities of Mosgiel, Allanton and Outram. The map also records the extent of flooding in 1868, from Figure 2.1.

As settlers arrived in Dunedin during the mid-1800s, the search began for expanses of flat land to develop into farms and market gardens. Despite being one of the largest areas of flat land near Dunedin city, the Taieri Plains were not considered suitable at first. During a visit in 1844, with Frederick Tuckett, official surveyor to the New Zealand Company, Dr David Munro, a politician and speaker of the House of Representatives, noted that:

'About the upper third of the Taieri basin is, in my opinion, available but the two lower thirds can hardly be called 'terra firma', being, in fact, an immense grass – tree swamp, through which canals of black sluggish water wind in various direction, and interspersed with stagnant lagoons. And I very much fear that this swamp is not susceptible of being drained, for its level is not above that of the sea' (Houston, 1966).

Dr Munro's observations suggest that, before European settlement and later drainage of the plains, the plain was subject to flooding from even a modest variation in flows of the Taieri River (Houston, 1966). Overland flow from the Maungatua Range, variations in the level of Lake Waipori and tidal influences contributed to the western part of the plains being in a permanent state of swampiness (Figure 2.3).

Figure 2.3 Artist, George O'Brien (1821-1888) impression of the Taieri Plains, 1867. (Source: Hocken Collections, Uare Toaka o Hakena, University of Otago).

However, it was Frederick Tuckett who later realised the value of such an expanse of alluvial lowland so close to a large centre of population (Houston, 1966). The plain was subdivided into 20-25ha sections of land, with wheat, oats, grass and potatoes grown on the upper third. The lower part needed extensive drainage to bring it up to a suitable standard for production. However, the development of refrigerated shipping and the construction of the Burnside Freezing Works saw a movement towards intensification of farming, making the drainage of this land viable (ORC, 1993). This marked the beginning of the modification of the plain's natural-drainage systems, and the ongoing reliance on these changes for land-drainage and flood protection.

The initial construction of flood-protection works began in the late 1800s (1870-1879) with the construction of floodbanks along the western side of the Taieri River, between Outram and the Waipori River (Figure 2.1) (ORC, 1993). The unified approach of settlers on the West Taieri Plain lead to the development of a local drainage board that collectively undertook work in that area, including the construction and ongoing maintenance of the early flood banks, drainage schemes and the West Taieri Contour Channel (Figure 2.4).

Figure 2.4 Early construction of the Contour Channel on the West Taieri Plain (circa 1915).

About the same time, Mosgiel, located on the plain's elevated eastern section, continued to develop as the area's main population centre. The introduction of the rail system and a major woollen mill in the 1870s caused a rapid growth in Mosgiel's population. Today, approximately about 15,000 people live on the Taieri Plains, with most still living in and around Mosgiel (Figure 2.5), which provides the services and amenities of a small satellite town, including a commercial precinct along Gordon Road, the town's main street. Smaller communities include Outram (Figure 2.6), Wingatui, East Taieri, Momona, Henley and Berwick, most of which were also established in the late 19th century (Figure 2.1 and Figure 2.2).

Figure 2.5 Mosgiel, located on the east of the Taieri Plains. The Maungatua Range is on the horizon (Source: NZ Stock Library).

Figure 2.6 The community of Outram is located to the west of the Taieri River, at the foot of the Maungatua Range. In the foreground is the Taieri River, near the Riverside spillway and 'the chute' (refer to Section 4). To the right is the gorge where the Taieri River emerges onto the Plains.

Table 2.1 Population of local communities on the Taieri Plains (2006 Census) and the capacity to expand (from the 2006 Dunedin City Council Residential Capacity Study).

Community	Population (2006)	Population (1996)	Projected population (2031)	Total dwelling capacity (DCC, 2006)
Mosgiel	9144	8640	9820	414
Wingatui	1173	954	1790	512
Outram	642	636	670	46
East Taieri	1383	1281	1910	866
Greater Taieri Plains	2316	2001		288
Wyllies Crossing	288	267	310	

Agriculture, established by the first settlers, is still the plain’s main land use. The highly productive and fertile soils provide ideal conditions for crop and pasture growth. The dominance of this land use is reflected in the Dunedin City District Plan, with about 90% of the plains zoned for ‘Rural’ purposes. Despite the underlying rural zoning, actual land use in some parts of the plain, particularly north of Mosgiel, is rural-residential, as a consequence of landholders subdividing their land.

In the District Plan, about 6km^2 of rural-residential-zoned land, located to the north and east of Mosgiel (Figure 2.7), has been allocated for rural-residential development. One residential unit per 2ha is permitted in rural-residential zones, and one residential unit per 15ha is allowed in rural zones. The rural-residential-zoned land, therefore, has the potential to accommodate a higher density of residential development. Under the current District Plan provisions, the wider Taieri Plains has the potential to absorb a significant amount of residential development (Table 2.1).

The main areas of industry are located to the south-west of Mosgiel (Gladstone Road South), North Taieri (Dukes Road North) and around Dunedin International Airport. The industrial-zoned land to the north of the airport is currently used for agriculture.

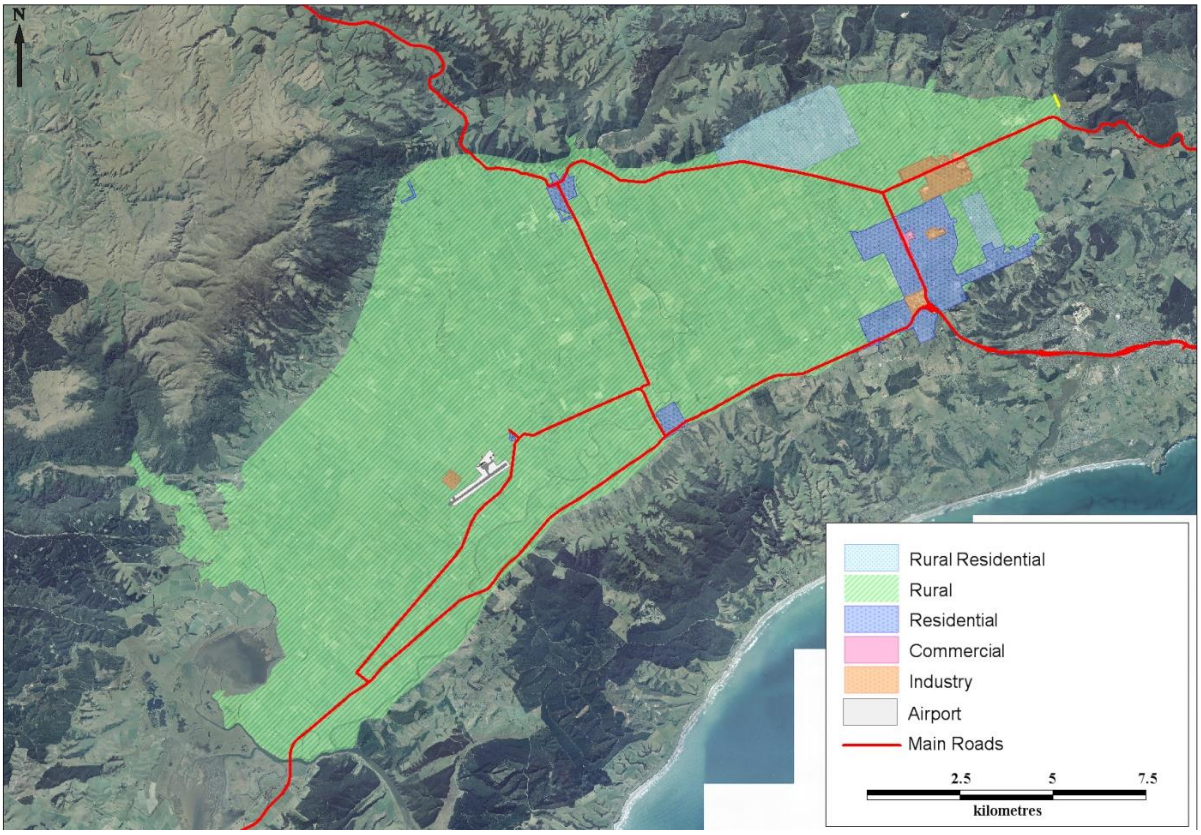

Figure 2.7 Land uses on the Taieri Plains, as defined in the Dunedin City District Plan (DCC, 1999).

Figure 2.8 Dunedin International Airport, following the June 1980 flood. The airport was closed for 53 days.

Dunedin International Airport was established in 1962 near the centre of the Taieri Plains, on land that is approximately one metre above mean sea level (msl) (Figure 2.8). The airport, which carries about 776,000 passengers per year (Dunedin International Airport Ltd, 2011), replaced the Taieri Aerodrome, near Mosgiel, as the main airport for Dunedin city and surrounds.

State highways (SH) 1, 86 and 87 connect Mosgiel with Dunedin city, and regionally connect Dunedin city with Invercargill, Central Otago and the smaller communities on route. Traffic volumes on SH1 average 9,700 vehicles per day near Mosgiel, reducing to 6,168 vehicles just south of Allanton (NZTA, 2010). SH87 provides one of three routes from Dunedin to Central Otago. Through Mosgiel, this network carries about 13,400 vehicles per day, reducing significantly to 2,700 vehicle movements at Outram (NZTA, 2010). SH86, which carries about 3,500 vehicles per day (NZTA, 2010), mainly serves as a link between SH1 and Dunedin International Airport.

Between Otokia and the Waipori River Bridge, SH1 is colloquially referred to as the 'flood-free highway'. Although not part of the flood-protection scheme, the elevated highway embankment prevents flood flows from the Taieri River entering onto the western plain. During the June 1980 flood, this section of highway was one of the few areas to remain free of flooding on the West Taieri plain. During the same flood event, the SH87 bridge over the

Taieri River, near Outram, suffered significant damage. The central bridge piers and bridge deck were completely demolished by flood flows in the Taieri River (Figure 2.9).

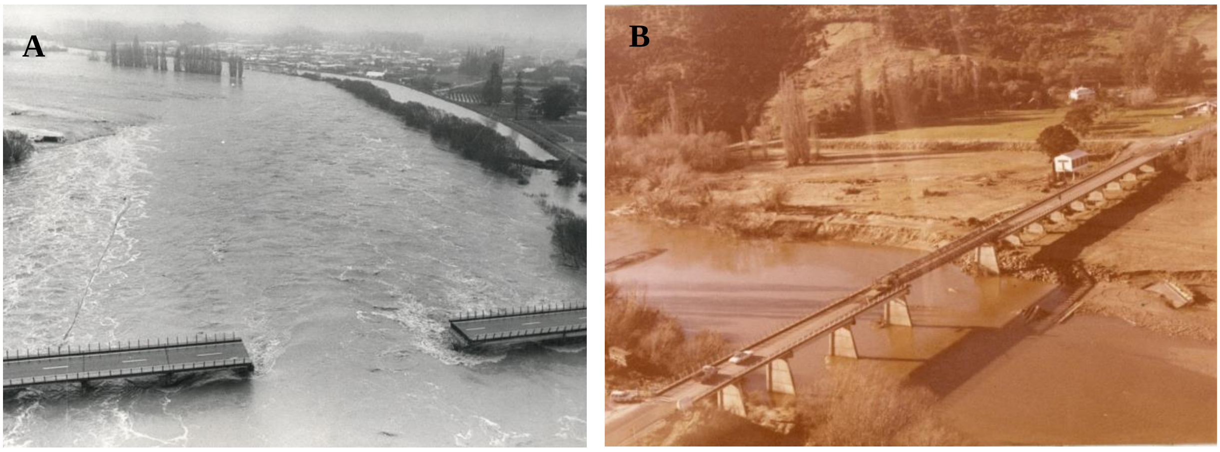

Figure 2.9 A. Outram Bridge during the June 1980 flood (6 June at 3pm); B. Outram Bridge, with temporary Bailey bridge constructed post-event.

The South Island Main Trunk Railway crosses the southern part of the Taieri Plains and, for the most part, runs close to and parallel with SH1. The railway is built on an embankment elevated above the plain, but can be overtopped by floodwater at several locations (Figure 2.10), disrupting train operations.

A second railway line deviates from the main trunk near Wingatui, providing a rail connection between Dunedin and Middlemarch, used mainly by the Taieri Gorge excursion train. A siding provides access to the industrial precinct in North Taieri.

Figure 2.10 South Island Main Trunk Railway, after the April 2006 flood on the Taieri Plains. The south-bound train was forced to stop and wait.

3. Environmental setting

Tectonic, climatic and sea-level changes have influenced the landscape of the Taieri Plains, creating a complex environmental setting, which engineering and land drainage works have further modified. The environmental setting gives rise to the plain's natural hazards, such as flooding and liquefaction; however, its positive attributes, such as its fertile land and reliable rainfall, both of which allow the land to be intensively developed and occupied, have also increased the risks of these hazards.

The topography of the Taieri Plains is largely determined by its geology and that of the wider Taieri River catchment within which it lies; its climate is influenced by its topography and setting. Climate and topography affect surface-water hydrology and are determined in part by the plain's elevation and catchment, relative to sea level. Groundwater is also influenced by elevation relative to sea level and geology. These aspects of the plain's setting are discussed next, in the context of natural hazards. Each natural hazard is discussed in more detail in subsequent sections.

3.1 Geology and topography

The Taieri Plains are part of the wider Taieri River catchment, which covers an area of approximately 5,700km between Central Otago and the Pacific Ocean coastline. The Taieri River catchment is dominated by schist-block mountains and fault-controlled basins (OCB, 1983). Between 99 and 2.6 million years ago[1], the schists were uplifted by tectonic processes. Over time, these have eroded to form the Otago peneplain surface, on which sediments have subsequently been deposited (Norris and Nicholls, 2004). Throughout the catchment, the peneplain surface is broken by numerous post-peneplanation faults, of which those associated with the Taieri-Tokomairiro depression are the most significant (Bishop and Turnbull, 1996). The Taieri Plain and the Tokomairiro Plain, to the south, formed within this depression. The peneplain is also obscured beneath distinct landforms, such as the Dunedin Volcano Complex to the north-east.

The Taieri-end of the depression rests between the Maungatua and North Taieri faults to the north-west and the Titri Fault to the south-east. Movement along these faults has resulted in the north-west (Maungatua) and south-east (coastal) mountain blocks being up-thrust relative to the basin floor (ORC, 2010b) (Section 7). Continued movement along these faults (over long geological timeframes) has also resulted in subsidence of the basin floor. It is not known whether the basin floor is still subsiding (Irricon, 1994). Any further subsidence would have implications for hazards on the Taieri Plains that are influenced by the difference between ground level and sea level.

As with the wider Taieri River catchment, Otago Schist forms the basement rock beneath the Taieri Plains. The depth to the schist basement is estimated to be between 150 to 300m in places (Bishop and Turnbull, 1996; Irricon, 1994).

The Quaternary[2] geology of the area reflects the depositional and tectonic processes of the past 2 million years. The underlying depression is largely filled with Quaternary silts, sands

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[1] The geological time period between 99 to 65 million years before present is also known as the 'Late Cretaceous' period. The 'Early Tertiary' period refers to a geological time period about 65 to 2.6 million years before present. Refer to Appendix 1 for a geological timeline.

[2] See the Glossary for a definition of this and other geological terms. See Appendix 1 for a geological timeline.

and gravels derived from the Otago schists (Tonkin & Taylor, 2005). On the West Taieri Plain, the Taieri and Waipori rivers have built extensive alluvial surfaces (Barrell *et al*., 1999). Young alluvial fans grade into these surfaces, most notably along the margins of the Maungatua Range. On the East Taieri Plain, an extensive alluvial surface has established from the Silver Stream and the merging of the lower portions of alluvial-fan features from the surrounding hill catchments.

Sea-level change has also had an influence on the topography of the Taieri Plains area, and the composition of the stratigraphy which underlies them (as discussed in Section 3.4). Much of this area was rapidly inundated by the sea and estuary waters between 8,000 and 4,000 years ago. The toes of many intermediate and old alluvial fans and the distribution and morphology of cliff and gully features suggest that they were formed by wave action at the margins of an extensive body of standing water (lake or marine inlet) during the Holocene period (Barrell *et al*., 1999).

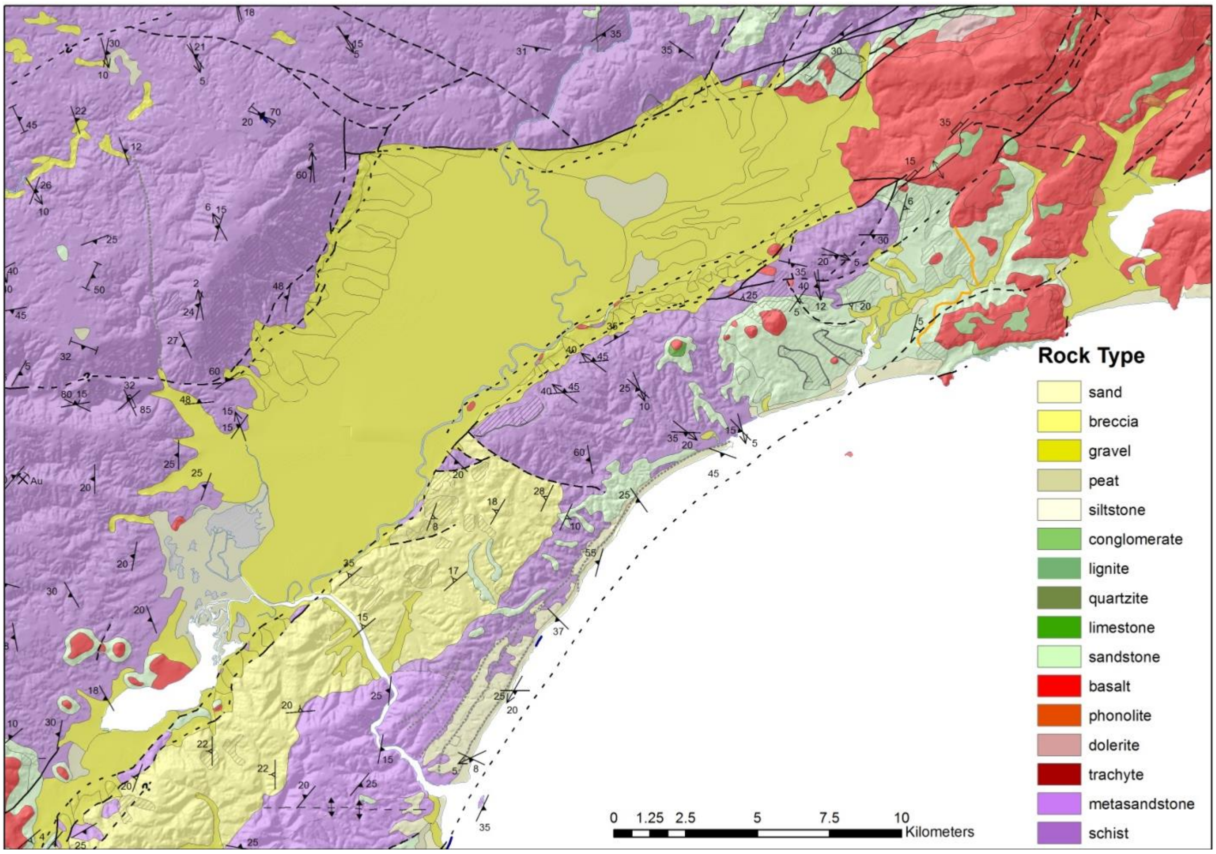

Figure 3.1 Geology of Taieri Basin (adapted from Bishop and Turnbull, 1996).

The Taieri Plains have formed in a basin, about 30km long, and orientated northeast-southwest at the southern end of the Taieri River catchment (Figure 3.2). The plains are bound to the north by the Maungatua Range (865m), to the east by the flanks of Flagstaff (668m), to the west by lakes Waipori and Waihola, and to the south by the lower coastal hills (Chain Hills, Saddle Hill, Scroggs Hill, Otokia Hill) (Figure 3.3). They are connected to the coast by the narrow, 10km long Lower Taieri Gorge.

The Taieri Basin is characterised by flat, gently sloping land, and dissected by the meandering Taieri River, which creates two distinctly separate areas, locally referred to as ‘East Taieri’ and ‘West Taieri’. Elevated about 40m above msl at its northern end, the land grades down to within a couple of metres of sea level to the south-west (ORC, 2010b). The lowest parts of the plains (excluding drains and ditches) lie about 1.5m below msl (Figure 3.7).

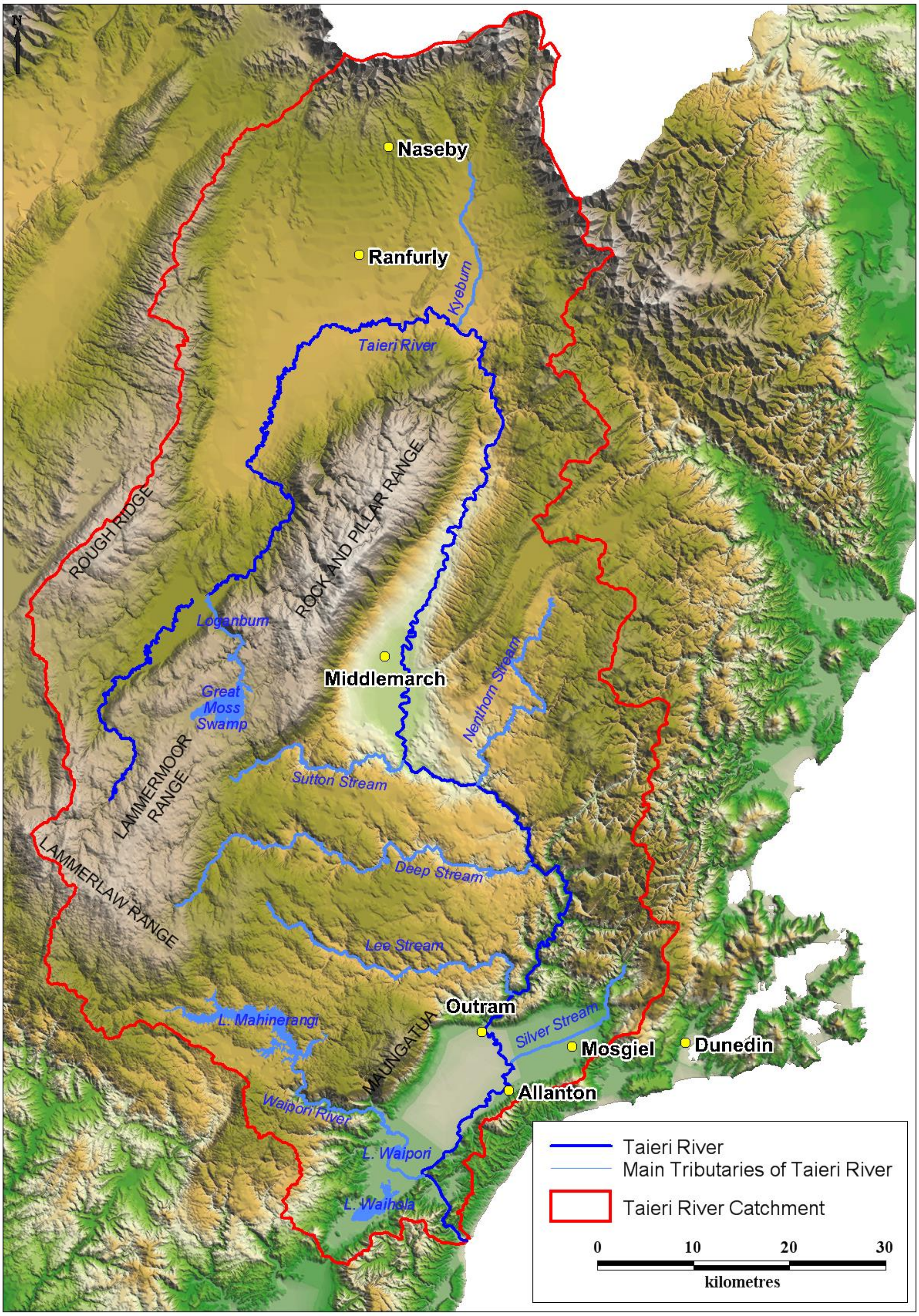

Figure 3.2 Topography of the Taieri River catchment.

Figure 3.3 Digital Elevation Model of the Taieri Plains. Oblique image, looking north-east, up the Taieri Basin.

3.2 Precipitation

The frequency and magnitude of hazards such as flooding, landslides and alluvial fans are closely related to the rainfall events from which they are derived. Antecedent conditions (driven by longer-term weather patterns) within the catchment can also have a direct influence, by affecting groundwater and soil-moisture levels, for example.

The coastal sector of the Taieri River catchment is characterised by a cool, temperate, sub-humid maritime climate (Glassey *et al*., 2001). Mean annual rainfall is generally between 650-750mm/year in the Taieri Basin (Table 3.1), and up to 1,300mm/year in the Maungatua Range to the west and Silver Peaks to the north. Further inland, the upper Taieri River catchment includes some of the driest areas in New Zealand, with less than 500mm of rain per year in some places. The upper to central catchment area is characterised by a semi-arid, semi-continental climate, with hot summers and cold frosty winters.

Table 3.1 Rainfall characteristics of the Taieri Plains and the hills to the north, as at December 2011. The location of the measurements is shown on Figure 3.4.

Site and length of record	Altitude (m)	Mean annual rainfall (mm)	Maximum annual rainfall (mm)	Minimum annual rainfall (mm)	Maximum daily rainfall (mm)
Silver Stream at Riccarton Road (1989-2011)	15	654	1024.5 (2000)	416 (1990)	164.5 (26 Apr 2006)
Mosgiel (1952-2011)	8	684	1023.8 (2000)	415 (1985)	147.2 (26 Apr 2006)
Maungatua (1971-2011)	25	787	1060 (1994)	448 (1985)	122 (26 Apr 2006)
Dunedin Airport (1963-2011)	1	654	904.6 (1983)	412 (1985)	134.8 (26 Apr 2006)
Deep Stream at SH87 (1994-2011)	369	556.66	737.88 (1994)	381 (2003)	85.5 (26 April 2006)
Three O’clock Stream at Lamb Hill (Aug 2010-2011)	160	N/A	N/A	N/A	95.2 (18 Oct 2011)
Silver Stream at Swampy Spur (2008-2011)	630	1325	1429 (2010)	1220 (2008)	164 (25 May 2010)

The more elevated parts of the upper catchment (i.e. Rock and Pillar Range, Rough Ridge and the Lammerlaw Range) (Figure 3.2) experience a colder, wetter climate, typical of more mountainous areas. Annual precipitation across the peaks of the ranges exceeds 1,200mm, with much of this falling as snow during the winter.

A number of perceptible trends in annual rainfall were evident across the lower South Island during the latter part of the 20th century, including an increase in rainfall in the west and in south Otago, and a trend towards drier conditions in the east (Mojzisek, 2005). No obvious trends were evident at rainfall sites on the Taieri Plain during this period, although these sites generally have relatively short records, or extensive periods of missing record.[3]

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[3] ORC has provided additional information about the spatial distribution of average (annual and seasonal) rainfall on the Taieri Plain and surrounding area through growOTAGO (http://growotago.orc.govt.nz).

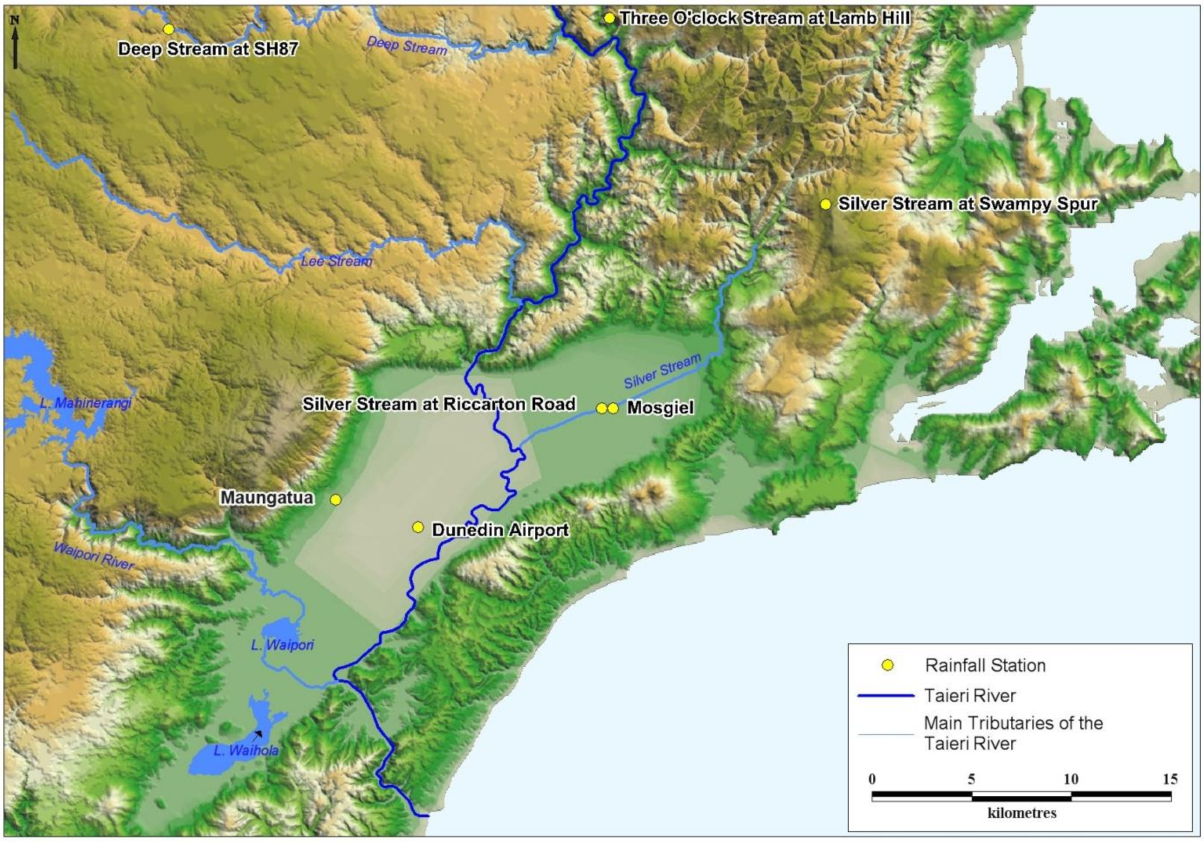

Figure 3.4 Locations of the rainfall measurements presented in Table 3.1.

Of more importance to weather-related natural hazards (such as flooding) are the characteristics of extreme rainfall events (i.e. storms). Precipitation extremes in the east of the South Island generally became less frequent and less intense between 1951 and 2003 (Mojzisek, 2005). Stations with long-term records nearest to the Taieri Plains (Musselburgh and Ross Creek) showed a similar trend, with decreases in rainfall intensity and very wet days[4] occurring during that period.

Rainfall stations on the Taieri Plains generally have a shorter record than those used by Mojzisek, or are missing data from the early part of their record. Figure 3.5 gives an updated analysis (using Mojzisek's methodology) of the full length of continuous record up to December 2011 at stations within the lower Taieri catchment. The figure shows changes over time (since records began) for the following parameters: (a) the highest 5-day precipitation amount (b) total annual precipitation (c) the number of wet days[5] (d) the average intensity of rainfall (e) the number of very wet days and (f) the percentage of annual rainfall falling on very wet days.

Figure 3.5 shows that the trends identified by Mojzisek (i.e. a reduction in the number and intensity of heavy rainfall events) are also evident at Dunedin Airport between 1963 and 2011. However, at the northern end of the plain, the Mosgiel station shows a statistically

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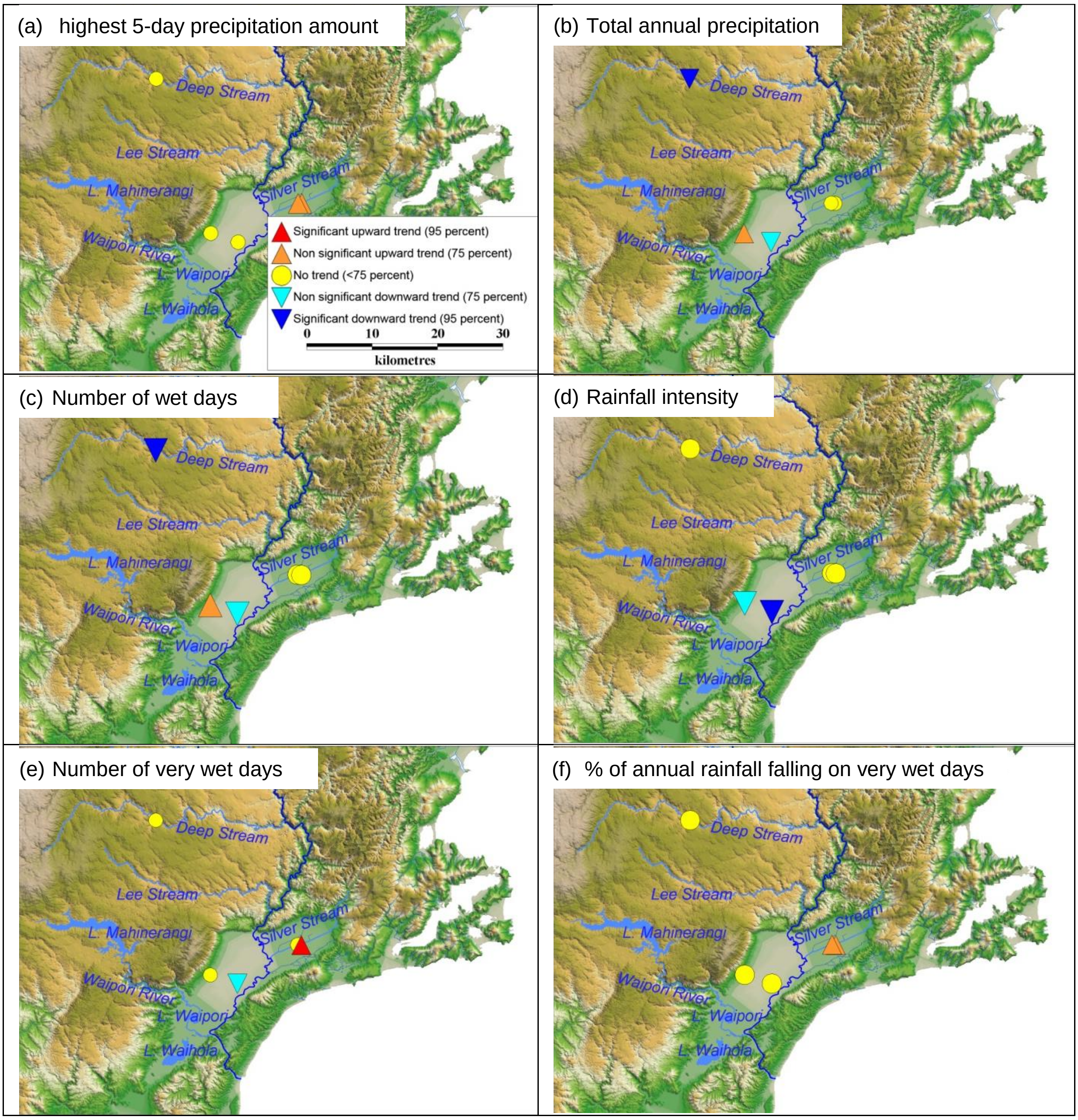
[4] Mojzisek used the number of very wet days as an indicator of extreme precipitation frequency. It refers to the number of days with rainfall totals in the top 5% of those recorded at a particular site.

[5] Wet days are those where daily precipitation exceeds 1.0mm.

significant[6] increase in the number of very wet days (Figure 3.5e). Both Mosgiel and the nearby Riccarton Road station also show a general increasing trend[7] in the percentage of rainfall which falls on very wet days (Figure 3.5f) and the highest 5-day precipitation amounts (Figure 3.5a). Figure 3.5 shows that there is localised variability in extreme rainfall patterns, and that the northern end of the Taieri Plain (including the Silver Stream catchment) has experienced an increase in both the intensity and frequency of extreme rainfall events.


(a) highest 5-day precipitation amount

(b) Total annual precipitation

(c) Number of wet days

(d) Rainfall intensity

(e) Number of very wet days

(f) % of annual rainfall falling on very wet days

Figure 3.5 Spatial variability of extreme precipitation trends on the Taieri Plains and the hill catchments to the north. The trends shown are for the full length of record, until the end of 2011.

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[6] 'Statistical significance' means that something is probably true (i.e. not due to chance). The most common level of significance, used to mean something is good enough to be believed, is 95%. This means that the finding has a 95% chance of actually having occurred, rather than just being a random event.

[7] at the 75% level of significance.

During the 20th century, climate stations near the Taieri Plains showed an overall warming trend (Brown, 2006; Salinger and Griffiths, 2001). In Dunedin city (which is nearby and experiences similar climatic conditions to the Taieri Plains), climate stations also showed an increase in temperature of between 0.5 to 0.8ºC over the past century. Furthermore, records show that, between 1940 and 1970, both the maximum and minimum temperature extremes for the area have warmed, suggesting cold extremes are becoming less frequent, and warmer extremes becoming more frequent. Since the 1970s, the warming trend has continued, but only for the colder values (Brown, 2006).

Average temperature is predicted to increase by another 2ºC by 2100. Given that a warmer atmosphere can hold more moisture, there is potential for storm events to bring heavier (or more intense) rainfall, and to occur more frequently than has previously been observed (MfE, 2008). Heavy rain events, resulting from subtropical depressions drifting southward over New Zealand, are likely to become more common. This type of event has the potential to produce daily rainfall totals well in excess of the maximum daily rainfall totals observed to date (Table 3.1).

However, a number of factors may influence regional trends in heavy rainfall patterns, including the rugged topography of the hills surrounding the plains, the susceptibility of the lower catchment to heavy rainfall events approaching from the east, and that the Taieri River catchment’s location on the east coast of South Island is in the lee of the prevailing westerly airflow. It is difficult to assess whether local topography and location will intensify or moderate the effects of a warmer climate on extreme rainfall patterns in the Taieri River catchment and on the Taieri Plains themselves. Previous trends (as discussed above) indicate that changes in the intensity and frequency of heavy rainfall events has varied across the plains, and this spatial variation may also continue under a warmer climate.

3.3 Surface water

Rising in the Lammerlaw and Lammermoor ranges, the Taieri River flows from the headwaters for about 318km, before crossing the Taieri Plains and entering the Pacific Ocean 30km south-west of Dunedin (Figure 3.2). The river has eight main tributaries: the Loganburn and Kyeburn in its upper reaches; the Sutton, Nenthorn, Deep and Lee Streams in its central reaches; and the Silver Stream and Waipori River on its lower reaches. Other hydrologic features include lakes Mahinerangi, Waipori and Waihola, and the Great Moss Swamp, near the headwaters of the catchment.

The three main water courses on the Taieri Plains are the Taieri River, the Silver Stream and the Waipori River. However, many other, smaller watercourses, drains and ephemeral swales are associated with flood hazard (Figure 3.6 and Figure 4.3).

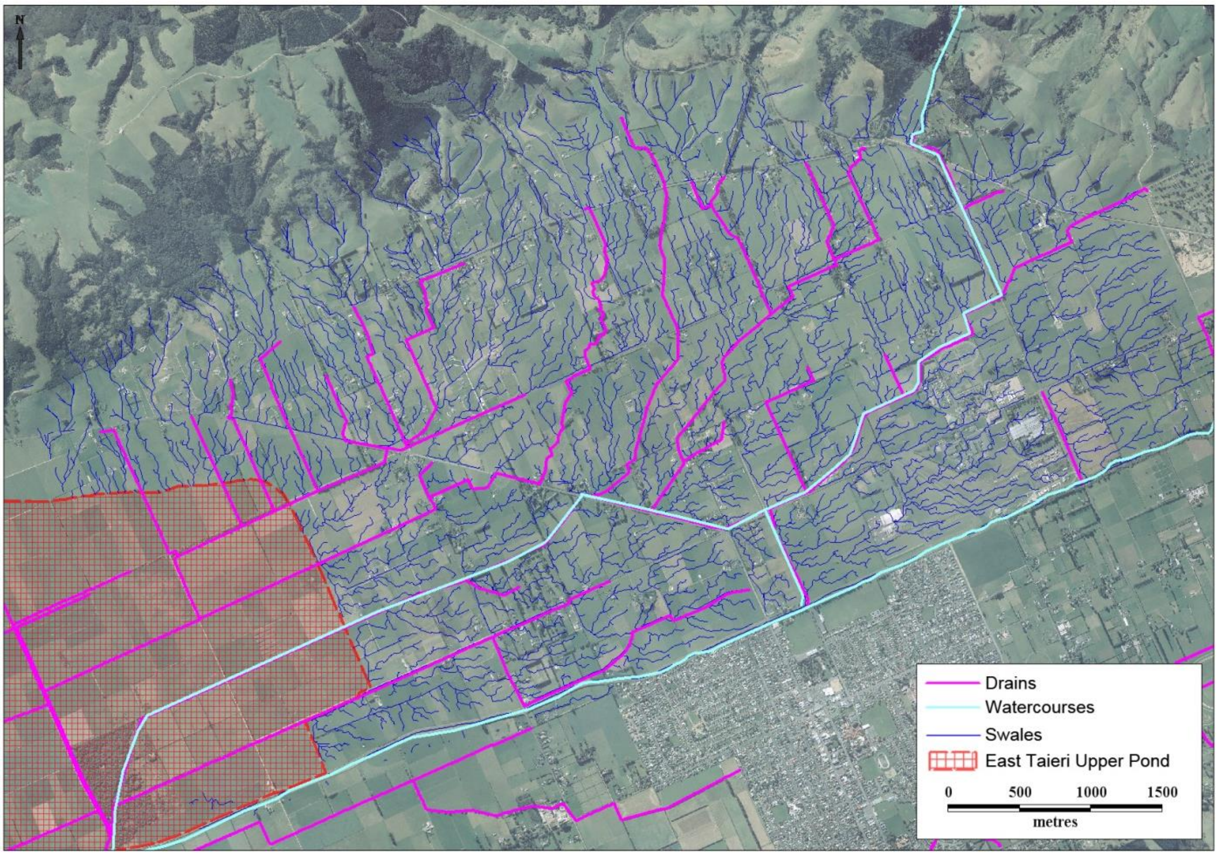

Figure 3.6 Watercourses, drains and swales on the East Taieri Plain. Swales also cross the plain on the south side of the Silver Stream (including through parts of Mosgiel), although these features are not shown.

The Silver Stream originates in the Silver Peaks and emerges from the north-eastern corner of the Taieri Plains. Initially flowing in a southerly direction, the Silver Stream follows a highly modified channel through the centre of the eastern part of the Taieri Plains, joining the Taieri River mid-way across the basin, about 4km upstream of Allanton. In the late 1800s, the Silver Stream, below Puddle Alley, was diverted from its natural watercourse into its present position, which flows straight to the Taieri River (Figure 2.1).

Flows from the Waipori River are semi-controlled by the Waipori hydro-electric scheme and Lake Mahinerangi, entering the Taieri Plains at the south-western corner near Berwick. The Waipori River is joined by the Contour Channel soon after emerging onto the plains, and discharges into Lake Waipori before joining the Taieri River at Henley Ferry.

The Taieri River emerges from its schist-rock gorge near Outram and meanders across the basin in a southerly direction before turning south-west at the foot of the coastal hills near Allanton. Following the foot of the hills, the Taieri River joins the Waipori River at Henley Ferry before exiting the basin through the Lower Taieri Gorge.

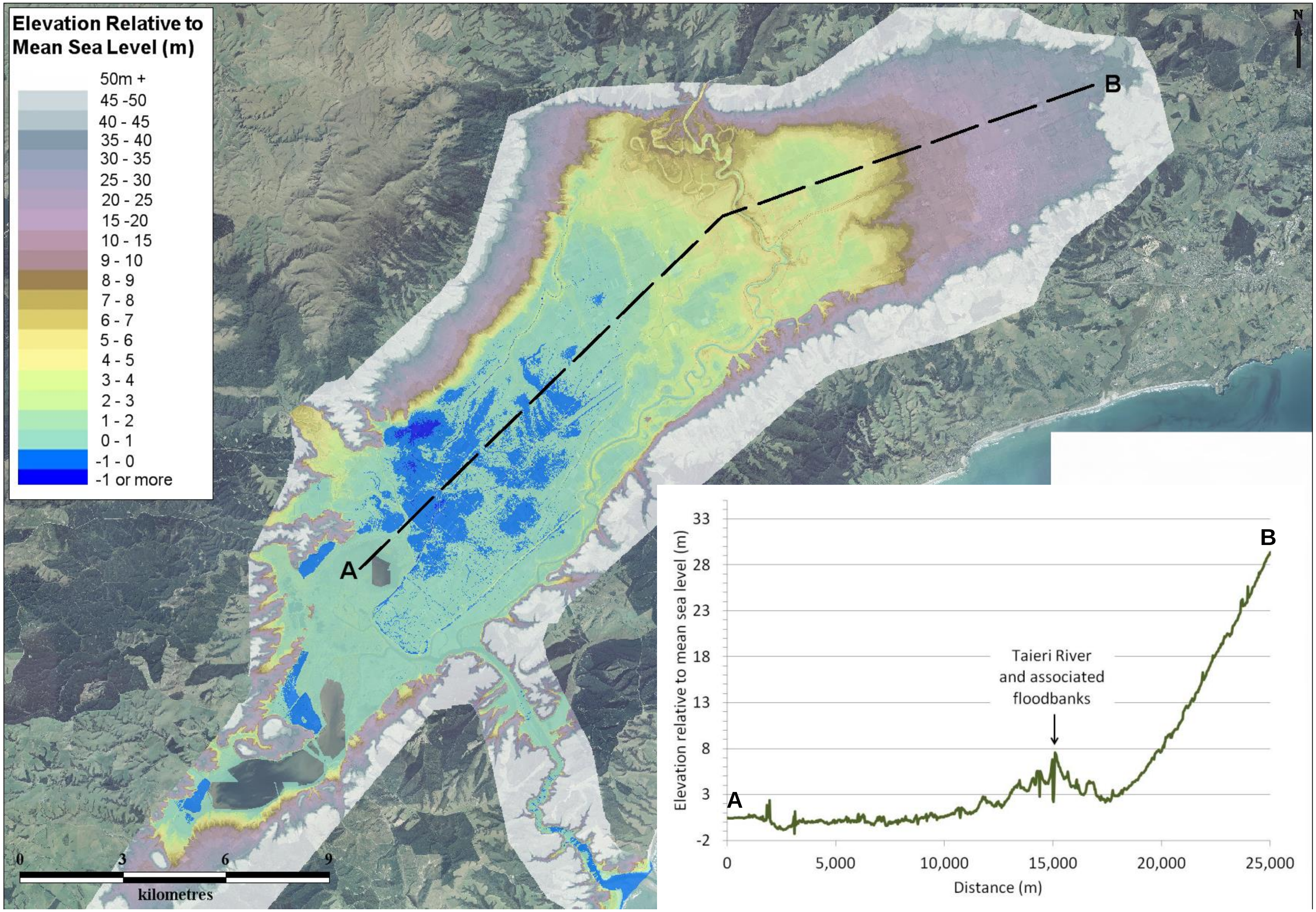

Figure 3.7 Elevation of the Taieri Plains (main image) and cross section A-B from south-west to north-east (inset). Land elevation is in metres, relative to msl.

Most of the flood-producing storms on the Taieri Plains are easterly or southerly in origin and are associated with depressions that slow or stall over Otago. Cold fronts, advancing from the south, bring heavy falls over the central Taieri River catchment, moderately heavy falls over the eastern areas and lighter falls in the northern regions (Houston, 1966; ORC, 2001). Unless coupled with pre-existing high flows (as observed during the May 2010 flood (Figure 3.8)), southerly fronts generally move swiftly across the catchment and are less conducive to widespread flooding.

Cold fronts from the west tend to bring relatively heavy falls to the north-western edge of the Taieri River catchment (including the Maniototo Plain). Heavy rainfall in the upper catchment and any subsequent higher flows in the upper reaches of the Taieri River tend to be moderated by the presence of the Taieri Scroll Plain (ORC, 2007b). Heavy falls in the upper catchment do contribute to higher flows in the Taieri River at Outram and extend the duration of flooding; however, by themselves, these events tend not to produce large floods on the Taieri Plains.

Conversely, flood-producing storms approaching from the east bring heavy rainfall to the eastern coastal regions, but produce little rain in areas west of the Rock and Pillar Range (i.e. the upper catchment) (ORC, 2007b). On many occasions, the persistent easterly fronts have brought the smaller tributaries of the Taieri Plains - the Silver Stream, Owhiro Stream, Quarry Creek and Mill Creek - into flood. If the event is sufficiently confined and isolated, easterly events can inundate parts of the East Taieri Plain adjacent to these watercourses, but cause no appreciable rise of the Taieri River. More widespread easterly events, reaching into Nenthorn, Sutton, Deep and Lee streams, can cause large flows in the Taieri River at Outram.

Due to the ‘horse-shoe’ shape of the upper Taieri River and the combination of plains, wetlands and narrow gorges through which it passes (Figure 3.2), the pattern of flows in the river can vary considerably along its length. High flows originating in the upper catchment take several days to reach the plain, while high flows originating from tributaries closer to the coast (e.g. Three O’clock Stream, Deep Stream and Silver Stream) can reach the plain in a matter of hours. In addition, the watercourses that traverse the plain (including the Taieri River, Silver Stream, Waipori River, Owhiro Stream, Quarry Creek and Mill Creek) will all respond differently during a flood event, depending on the distribution and intensity of rainfall across the catchment. As a result, the timing, magnitude and duration of the flood peaks in these tributaries and in the main stem of the Taieri River will vary across the plains.

From its headwaters, the Taieri River flows through four main basins: the Styx and Maniototo, in the upper catchment; the Strath Taieri, in the centre of the catchment; and the Taieri, near the outlet to the ocean. Each basin is connected by confined river gorges. Because of the essentially independent but hydrologically related basins, heavy rainfall events that cover the whole catchment can result in multiple-flood peaks in the Taieri River where it emerges onto the Taieri Plains at Outram (ORC, 1993) (Figure 3.8).

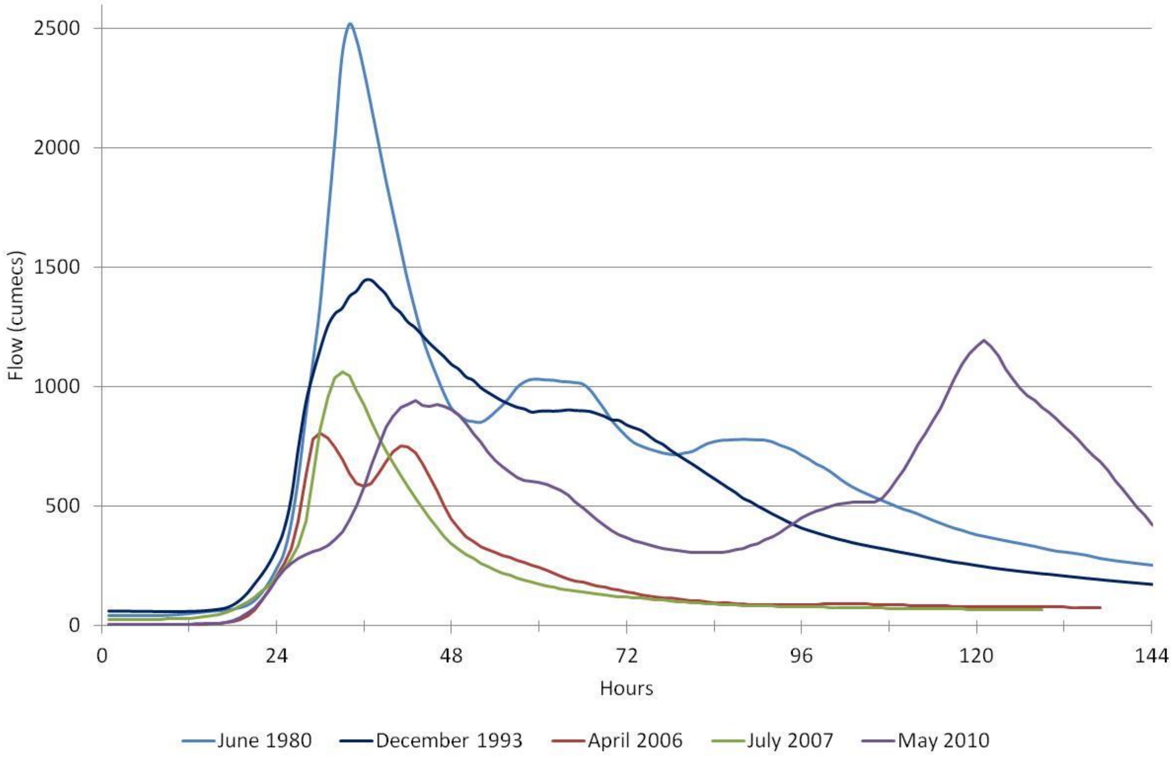

Figure 3.8 Changes in flow in the Taieri River at Outram during flood events in 1980, 1993, 2006, 2007 and 2010.

The first peak is generally the result of runoff from the catchment downstream of Sutton, including the major tributaries of Deep, Lee, Nenthorn and Three O'clock streams (Figure 3.2). The second peak is the result of runoff from heavy rainfall further up the catchment, with the moderating effect of the upper catchment (as described above) usually producing flow magnitudes lower than the first peak. Figure 3.8 shows that a second peak in flow can occur, for example, 12 (e.g. April 2006) or 26 hours (e.g. December 1993 and June 1980) after the first peak. During the May 2010 event, the second flood peak, observed three days after the first, resulted, in part, from a second, independent band of heavy rainfall crossing the catchment.

Downstream of Outram, flood flows from the upper catchment join with those from the Silver Stream. The Silver Stream can also have more than one peak, depending on rainfall patterns in its upper catchment. Peak flow in this tributary tends to be much smaller than in the main stem of the Taieri River, and typically only lasts a few hours. The Silver Stream normally peaks before the Taieri River at Outram, although peaks do occasionally occur at the same time (Figure 3.9) (Opus, 2010).

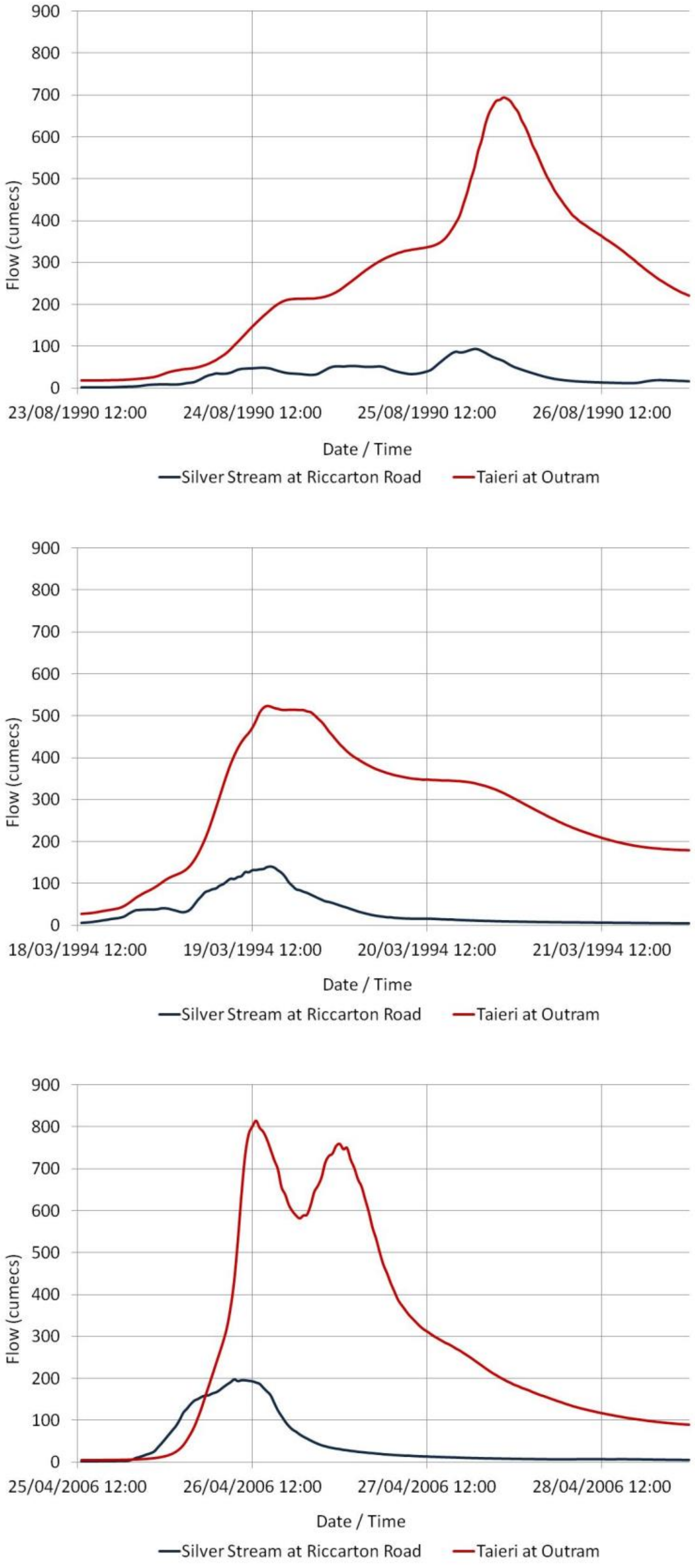

Figure 3.9 Examples of the Taieri River and Silver Stream flood hydrographs from events in August 1990, March 1994 and April 2006.

During flood events, the river level in the lower reaches of the Taieri River rises well above the level of the adjacent land on the West Taieri Plain. Figure 3.10 shows the maximum water level in the Taieri River at Henley, during the period October 2002 (when records began) to April 2012, in relation to the adjacent land.

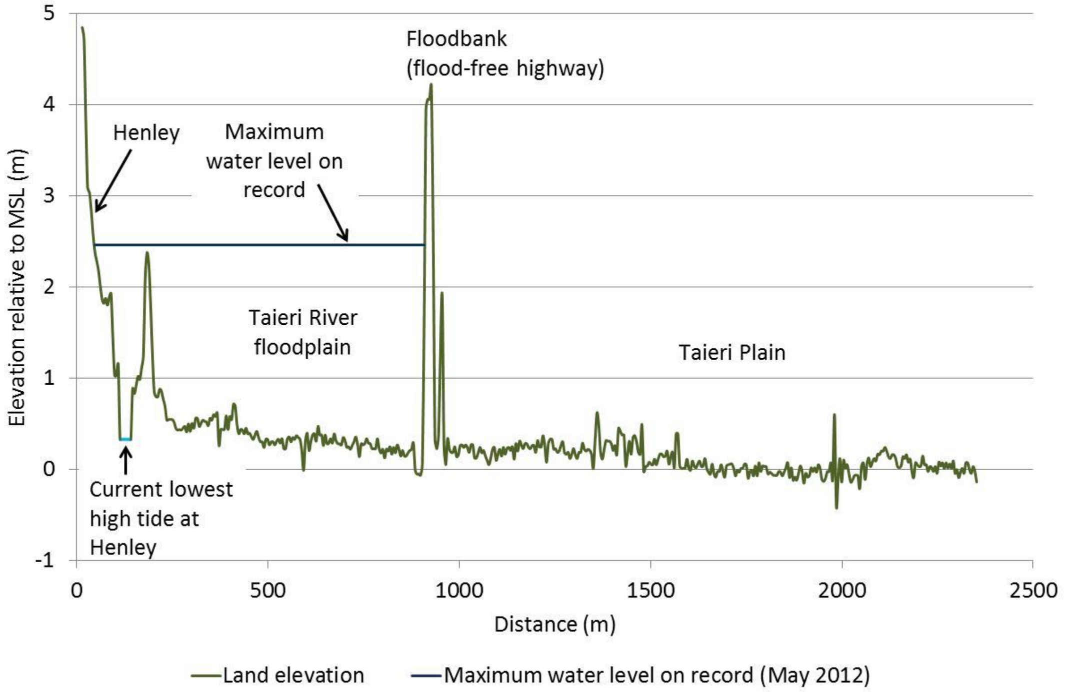

Figure 3.10 Cross section from Henley to West Taieri Plain (as shown in Figure 3.11), showing the maximum water level observed between October 2002 and April 2012. The water level in the Taieri River at Henley is shown as the current lowest high tide (Figure 3.15).

Figure 3.11 Location of the cross section shown in Figure 3.10.

There is also a significant tidal component to water level in the lower reaches of the Taieri and Waipori rivers. During low-flow conditions, the river level at Henley can rise and fall up to 0.7m due to the influence of the tide, and can reach 1 metre above msl (Figure 3.12 (bottom)). Therefore, flood water can pond for some time within the lower reaches of the Taieri River before it is able to drain out to sea. For example, during the May 2010 flood, the water level at Henley remained 2m or more above msl for about 4½ days (Figure 3.12 (top)). If sea level was significantly higher than at present,[8] the river level during flood events would be likely to peak at higher levels than under current conditions and remain at a higher level for a longer period.

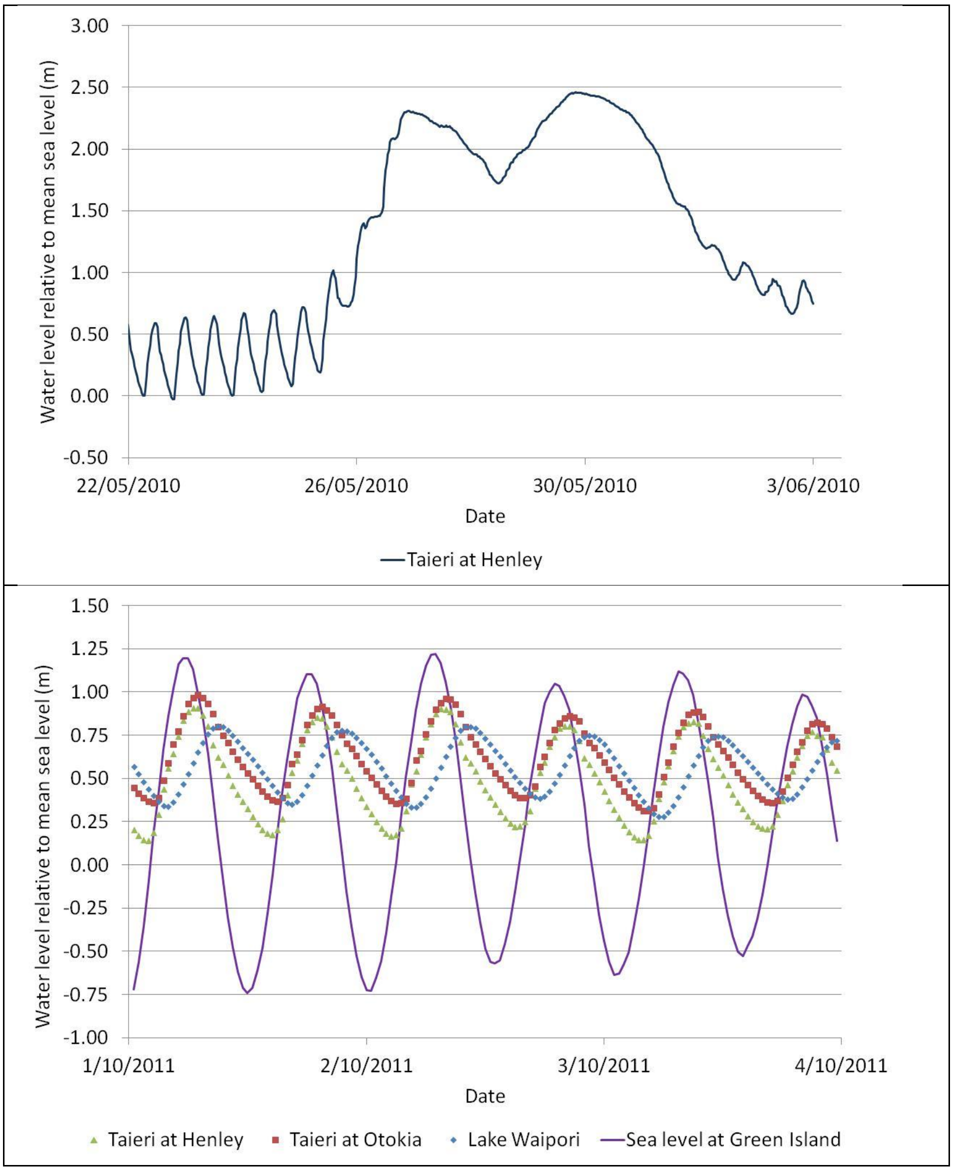

Figure 3.12 Water level in the Taieri River at Henley during the May 2010 flood (top). Fluctuations in water level on the lower Taieri and Waipori rivers under normal, low flows and in the Pacific Ocean at Green Island (bottom).

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[8] The Ministry for the Environment recommends that decision makers should regard a rise in sea level of 0.3m by 2040 and 0.6m by 2090 as a baseline for future considerations. These estimates are based on projections released by the IPCC in their 2007 Assessment Report. However, further research since the release of this report suggests that melting of the polar ice sheets before the end of the century could contribute to as much as a 0.7m to 1.6m rise in sea level by 2090 (Fitzharris, 2010).

As most of the West Taieri Plain lies at or below current msl, it relies on the Waipori pumping station (Figure 3.13), even during normal low-flow conditions, to prevent it from transforming back to its former swamp-like state (Section 2). Water levels in Lake Waipori, to the west of this area, are generally elevated above the land on the eastern side of the flood bank (Figure 3.14), making the pump station and flood banks critical to the occupation and use of the land (ORC, 2007a; ORC, 2010d). This characteristic also has implications for seismic risk, as discussed later.

Figure 3.13 Waipori Pump Station and the inlet channel to the station (Main Drain). The underground chamber (installed in 1989) housing the two 'D' pumps is on the left, and the building housing the three 'F' pumps installed in 1929 is on the right. The three 'F' pumps are being replaced with two new submersible pumps in 2012/2013.

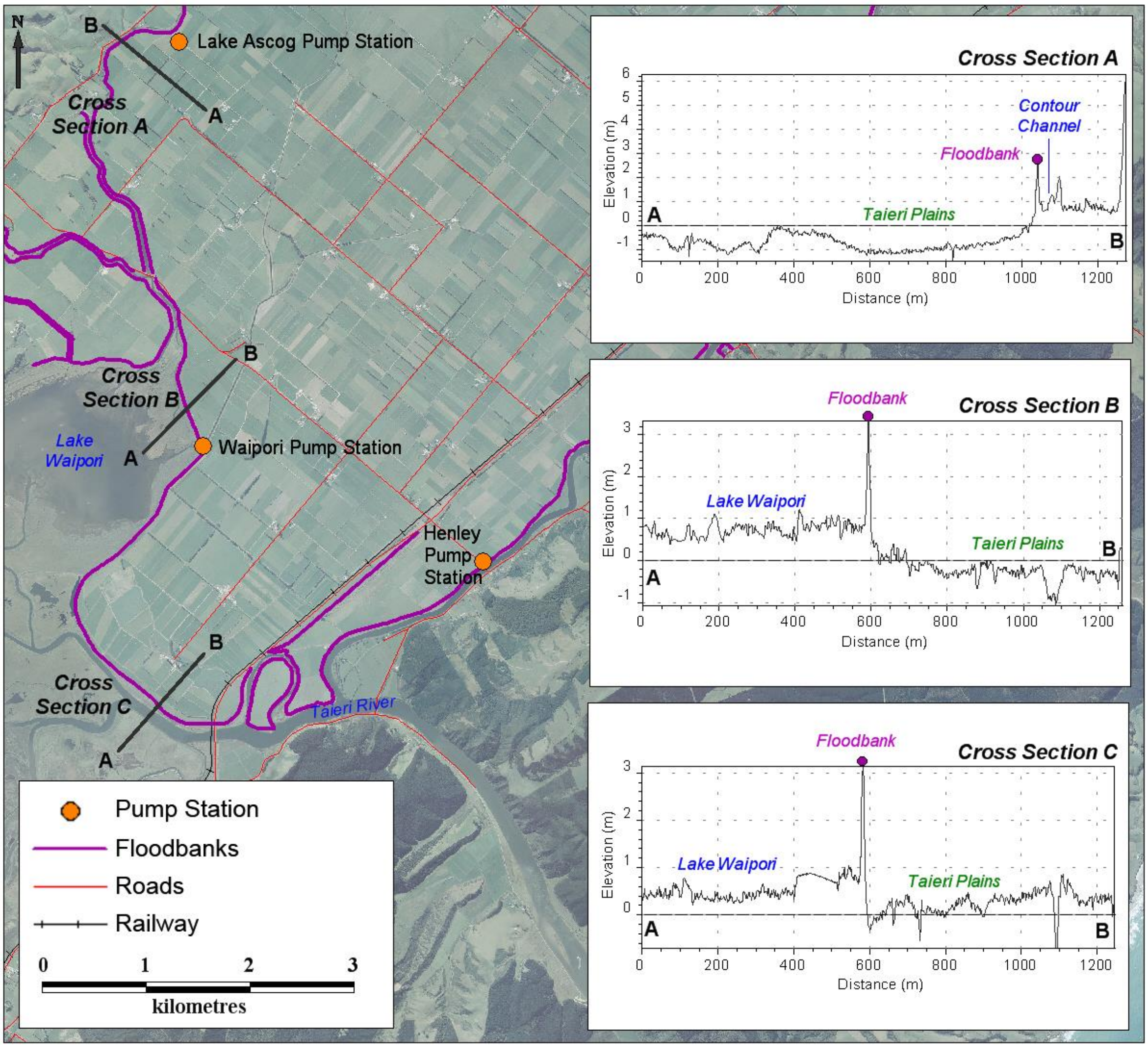

Figure 3.14 Cross section of three areas on the West Taieri Plain.

Figure 3.15 shows the vulnerability of the West Taieri Plain to sea level. Specifically, the figure shows the extent of inundation that would occur if the Lower Taieri Flood Protection Scheme flood banks next to Lake Waipori did not exist or were ineffective (for example, if they failed after a major fault rupture or significant ground shaking caused by a major earthquake). The scenarios shown are:

1. the extent of inundation if the water level on the West Taieri Plain was 0.33m above msl (i.e. the water level in the Taieri River at Henley at the current lowest high tide) (pink)
2. the extent of inundation if the water level on the West Taieri Plain was 0.83m above msl (as for 1, but with 0.5m sea level rise) (yellow)
3. the extent of inundation if the water level on the West Taieri Plain was 1.13m above msl (as for 1, but with 0.8m sea level rise) (green).

Seismic performance and foundation piping[9] risks for the flood banks on the Taieri Plains are discussed in later sections.

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[9] See the Glossary for further explanation of these and other terms used in this report.

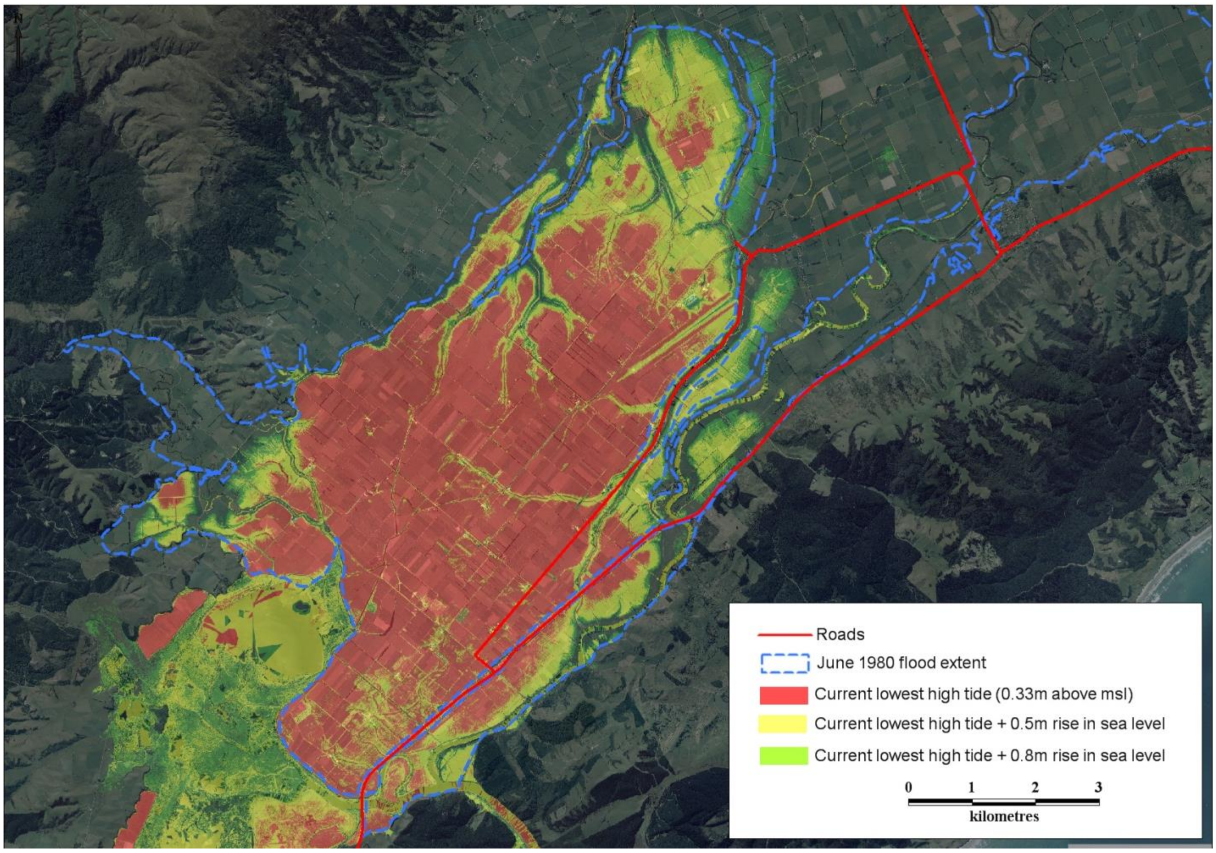

Figure 3.15 Potential landward extent of inundation during a 'flood banks down' scenario on the West Taieri Plain. Note the correlation with the June 1980 flood (Figure 4.1), where numerous breaches in the flood banks occurred along the Waipori River and Contour Channel.

3.4 Groundwater

The lower Taieri Basin is a tectonic depression resting between two major faults. Deposits of sand, gravel, silt, clay and peat have built up within the basin, and are thought to extend to depths of over 200m below the surface (ORC, 2010b). In the Mosgiel area, the mixtures of these different sediments are highly variable and thinly layered. By contrast, western parts of the Taieri Plain (from Henley to Riccarton Road) are more consistently layered. The groundwater aquifer is located within loosely sorted gravels, and, at the plain's western end, is overtopped by a 20-25m thick layer of fine-grained deposits with low permeability. This layer of silt and clay was formed over the underlying gravels when the Taieri Basin was inundated by the sea and estuary waters, following the post-glacial rise in global sea levels, about 4,000-8,000 years before present. This denser layer of silt and clay tends to confine and pressurise the underlying gravel layers to produce confined aquifers (Figure 3.16).

Accumulated or heavy rainfall, or high flow in the Taieri River and its tributaries, acts to recharge the aquifers beneath the Taieri Plain. However, the overlying silt and clay layer limits the ability of groundwater to surcharge out onto the surface due to their low permeability. As a result, flood events tend not to result in significant surface ponding due to groundwater, despite the fact that much of the surface of the western Taieri Plain is lower than the surrounding waterways (Figure 3.16) and the groundwater-pressure surface.[10] Ponding on the Taieri Plain during flood events is instead dominated by surface water runoff.

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[10] The groundwater pressure surface is the equivalent level that groundwater would rise to in a bore.

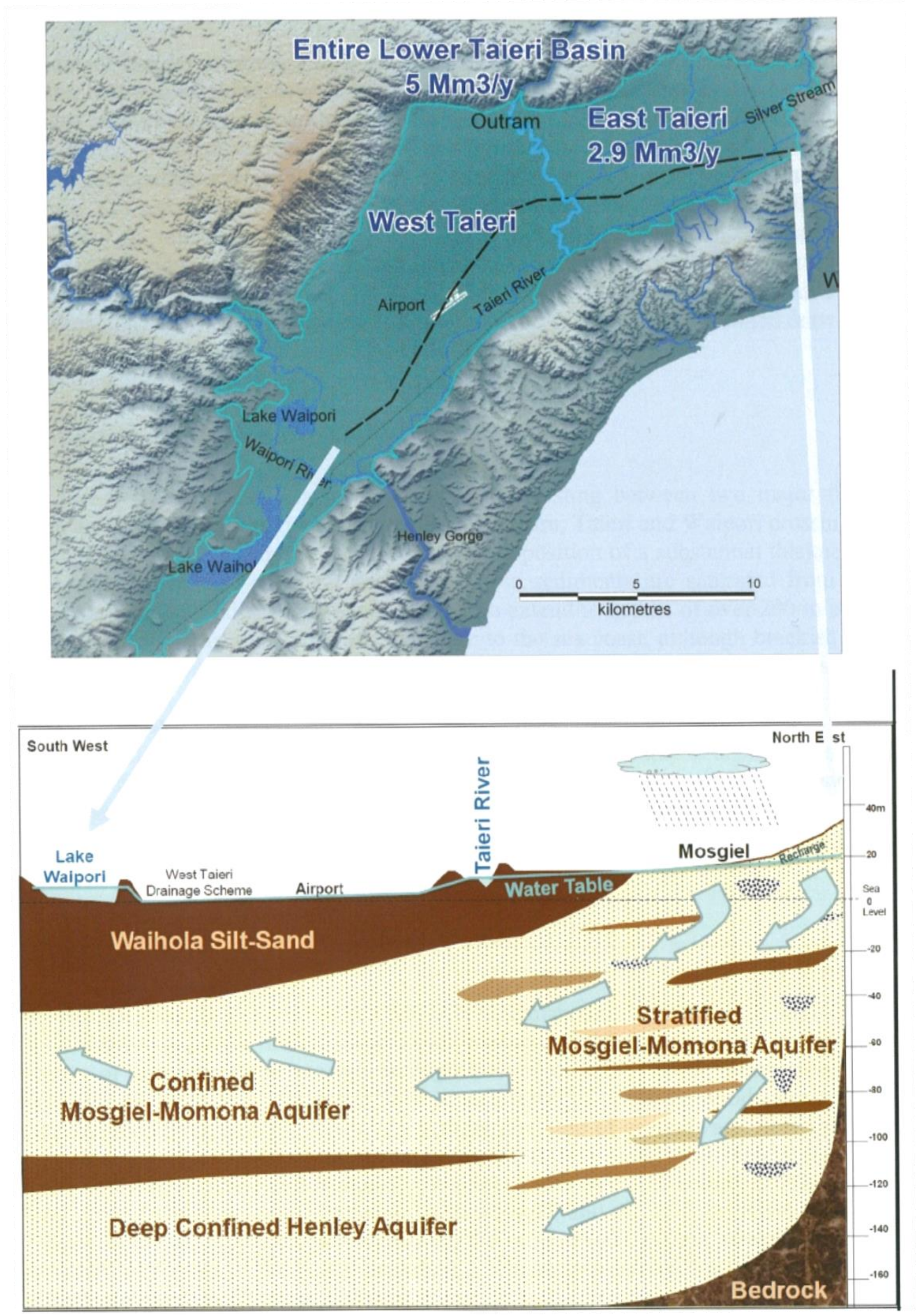

Figure 3.16 **Map view of Lower Taieri Basin, with schematic cross section from Wingatui to Lake Waipori, showing groundwater-flow directions as arrows (ORC, 2010b).**

4. Flood hazard

Flooding has been a fact of life for residents on the Taieri Plains for over a century, with a number of significant floods occurring since European settlement in the mid-1800s. Reconstructed maps of the February 1868 and May 1923 floods show that most (approximately 120km^2) of the Taieri Plains was inundated during these events (Figure 2.1 and Figure 2.2). The significance of these two events, being just two of many floods on record, is that they occurred prior to the construction of any major, coordinated flood-protection works and therefore reflect the underlying flood hazard of the Taieri Plains.

The Lower Taieri Flood Protection Scheme, and earlier schemes such as the Waipori Catchment Control Scheme (OCB, 1981) and elements of the East Taieri Internal Flood Control and Drainage Scheme (OCB, 1974), has significantly modified the flood hazard of parts of the Taieri Plain. The Taieri River, Silver Stream, Waipori River, Owhiro Stream, Mill Creek, Meggatburn and Quarry Creek have all been modified in some way by engineering works. Despite the scheme works, residual risk remains for the parts of the Taieri Plains that rely on them for some degree of protection. For example, the possibility of flood banks being overtopped or breached can never be totally eliminated, including during floods that are smaller than the ‘design’ flood.

In this section, characteristics of the flood-hazard of the Taieri Plains are outlined, with reference to past flood events and the engineering works that have modified it. The interaction between different parts of the floodplain is explained, based on the intended operation of the Lower Taieri Flood Protection Scheme, and current understanding of actual and expected operation, based on modelling and observations of performance. The variation in flood hazard is then described for specific parts of the plains.

This report does not present a complete record of the flood history for the Taieri Plains, but does refer to historical events to illustrate the flood-hazard characteristics. The mapping is incomplete because not all floods are comprehensively mapped, and some are only mapped in certain areas. For example, the mapping of the April 2006 event focussed exclusively on the area north of the Silver Stream, even though flooding occurred elsewhere too. The absence of mapping does not mean that an area is flood free or affected less than areas that have been mapped.

Flood hazard is determined in part by the capacity of watercourses and their ability to contain and convey floodwater along assured pathways, sometimes augmented by flood banks. That capacity is reduced by sediment and debris deposited by landslides, and by bed and bank erosion being transported across alluvial fans, and by lateral spreading and settlement of flood banks as the result of seismic-induced ground shaking. The consequential effects of these hazards must be taken into consideration when assessing the potential flood hazard of the Taieri Plains. Information on these other natural hazards is presented in later sections of this report.

4.1 Repeat flood events

The flood of June 1980 is the largest event to have occurred on the Taieri River since records began in the late 19th century, with flows reaching approximately 2,500m^3/s at Outram (Table 4.1). An event with this peak flow (but not flood volume) has an assessed-return period of about 110 years (Appendix 2). Major flood-bank breaches occurred in a number of locations, including two on the left bank of the Taieri River between Outram and Allanton, three on the Silver Stream, one on the Contour Channel and 11 on the Waipori River (ORC, 1993). The Waipori flood banks incurred significant damage, including the complete removal of a 175m-long section. This breach contributed to the inundation of approximately two thirds (48km^2) of the West Taieri (Figure 4.1). Four weeks after the flood peak, approximately 28km^2 was still underwater (ORC, 1993), including Dunedin International Airport, which was closed for 53 days (Orchiston, 1982).

Table 4.1 Flows on the lower Taieri River in excess of 1,050m^3/s at Outram. Flood extents in bold are shown in Figure 4.1.

Year	Month	Estimated peak flow (m^3/s)
1868	***February***	***2,200***
1877	February	1,650
1908	July	1,400
1913	August	1,250
1917	May	1,600
1919	January	1,150
1923	***May***	***1,150***
1940	May	1,800
1944	May	1,750
1945	February	1,300
1957	May	2,000
1961	May	1,250
1978	August	1,150
1980	***June***	***2,526***
1993	December	1,470
1994	July	1,065
2007	July	1,070
2010	May	1,200

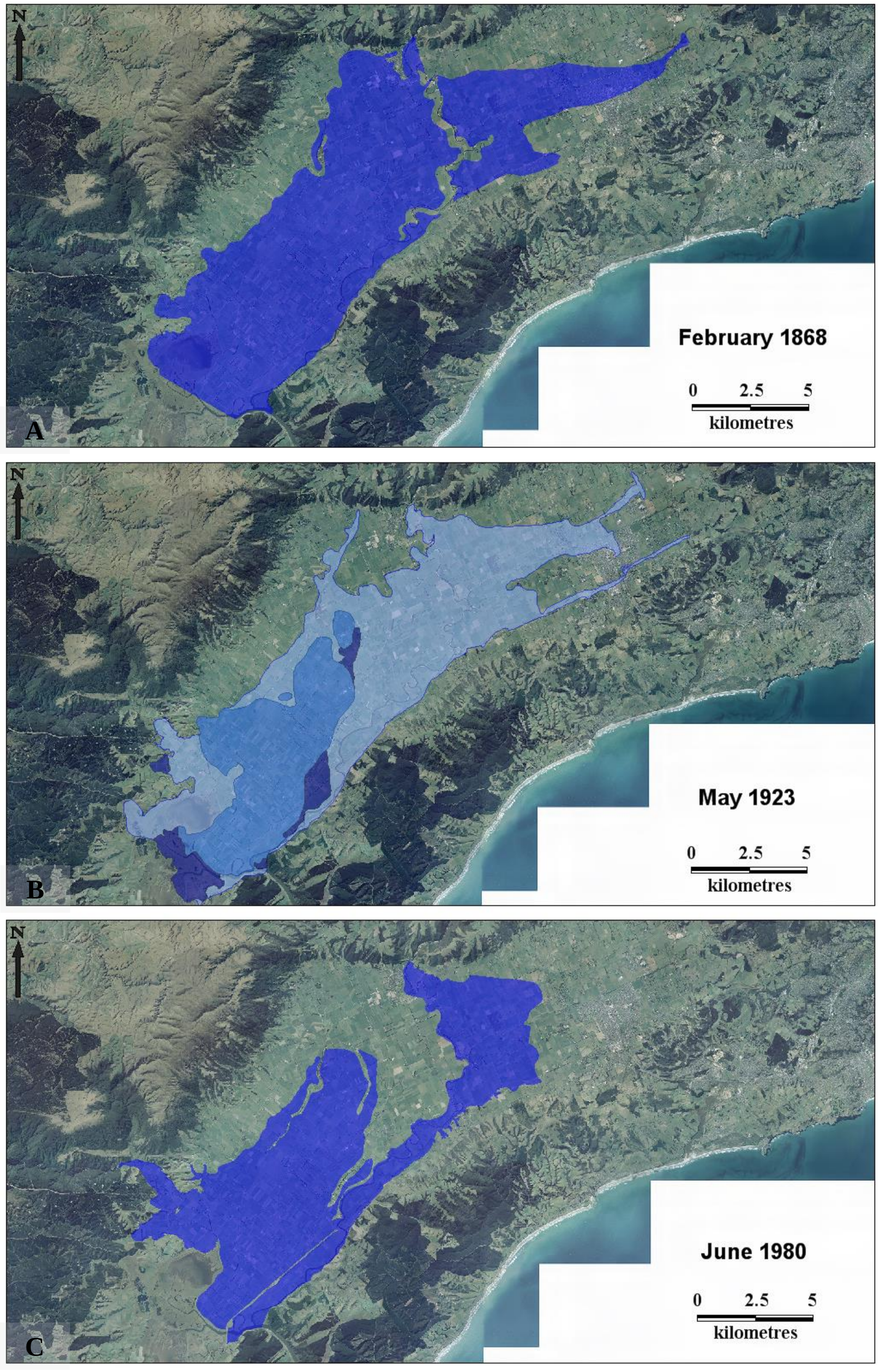

Figure 4.1 Mapped inundation extents during the February 1868, May 1923 and June 1980 floods.

There is less data on the flood history and repeat floods of the Silver Stream, despite the hazard maps of the 1868 and 1923 events showing inundation associated with it. Table 4.2 shows the ten largest recorded flows since continuous measurement began in 1970. The April 2006 flood is the largest measured event on record, with water overtopping the Gordon Road spillway, causing extensive ponding on the northern side of the East Taieri floodplain (Figure 4.2) (ORC, 2010c).

Spill also occurred, to a lesser extent, in the June 2007 event, and was imminent in May 2010. Notably, the flood flow in 2006 is the largest in the Silver Stream since 1980, and over that 27-year period, the flows were less than the threshold for overflow at the Gordon Road spillway (about 170m^3/s, with an assessed-return period of about 20 years). The occurrence of a number of events with high (but not extreme) flows that were apparently contained within the Silver Stream channel may have created the impression within the community that the residual risk associated with flooding is less than it actually is. Furthermore, most of the changes in land use north of the Silver Stream (from rural to rural-residential, as described in Section 2) have occurred during that period.

Table 4.2 Ten highest flows on the Silver Stream (since records began in 1970) (ORC, 2010c).

Year	Month	Estimated peak flow (m^3/s)
2006	April	264
1980	June	194
2007	July	159
1994	March	143
2010	May	131
1971	November	123
2010	May	113
1984	March	110
1978	August	109
1982	October	108

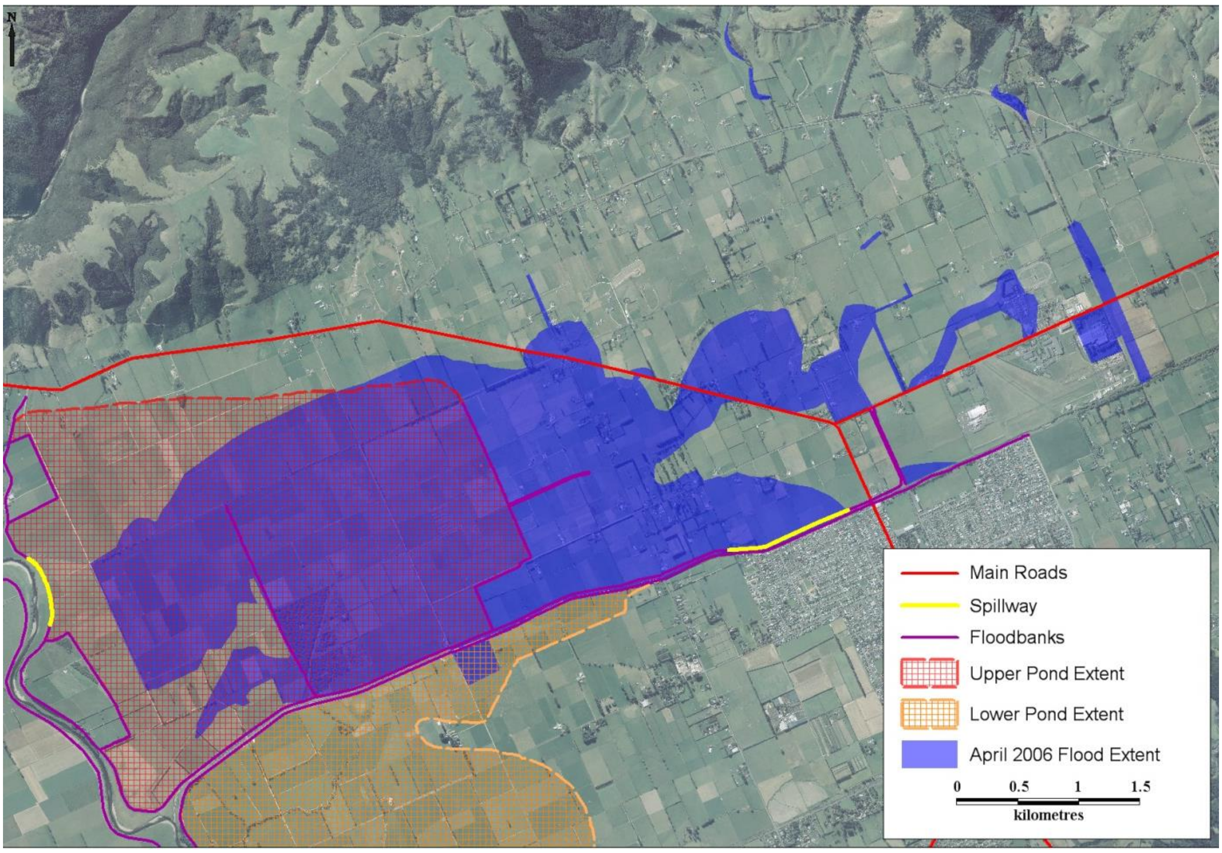

Figure 4.2 Extent of ponding in April 2006 flood (north side of Silver Stream mapped only).

4.2 Modification of the flood hazard

The Lower Taieri Flood Protection Scheme consists of a series of flood banks, spillways and ponding areas (Figure 4.3) that assist the orderly passage of flood water across the Taieri Plains to the Lower Taieri Gorge (OCB, 1985). Flooding is avoided or mitigated in places ‘protected’ by flood banks whenever water levels in the adjacent watercourse exceed the pre-existing natural-bank level (Figure 3.14). A residual risk arises from dependency on that protection (Figure 3.15).

The scheme relies on temporary ponding at defined locations for its most effective operation. During large-flow events, the East Taieri Upper Pond, East Taieri Lower Pond, and lakes Waipori and Waihola are critical to the operation of the scheme because of the limited fall across the plains and the tidal influence and limited capacity of the Lower Taieri Gorge. The two lakes, and the upper and lower ponding areas have the effect of attenuating the peak flow in the Taieri River and reducing the flood hazard for parts of the Taieri Plains, particularly on the West Taieri.

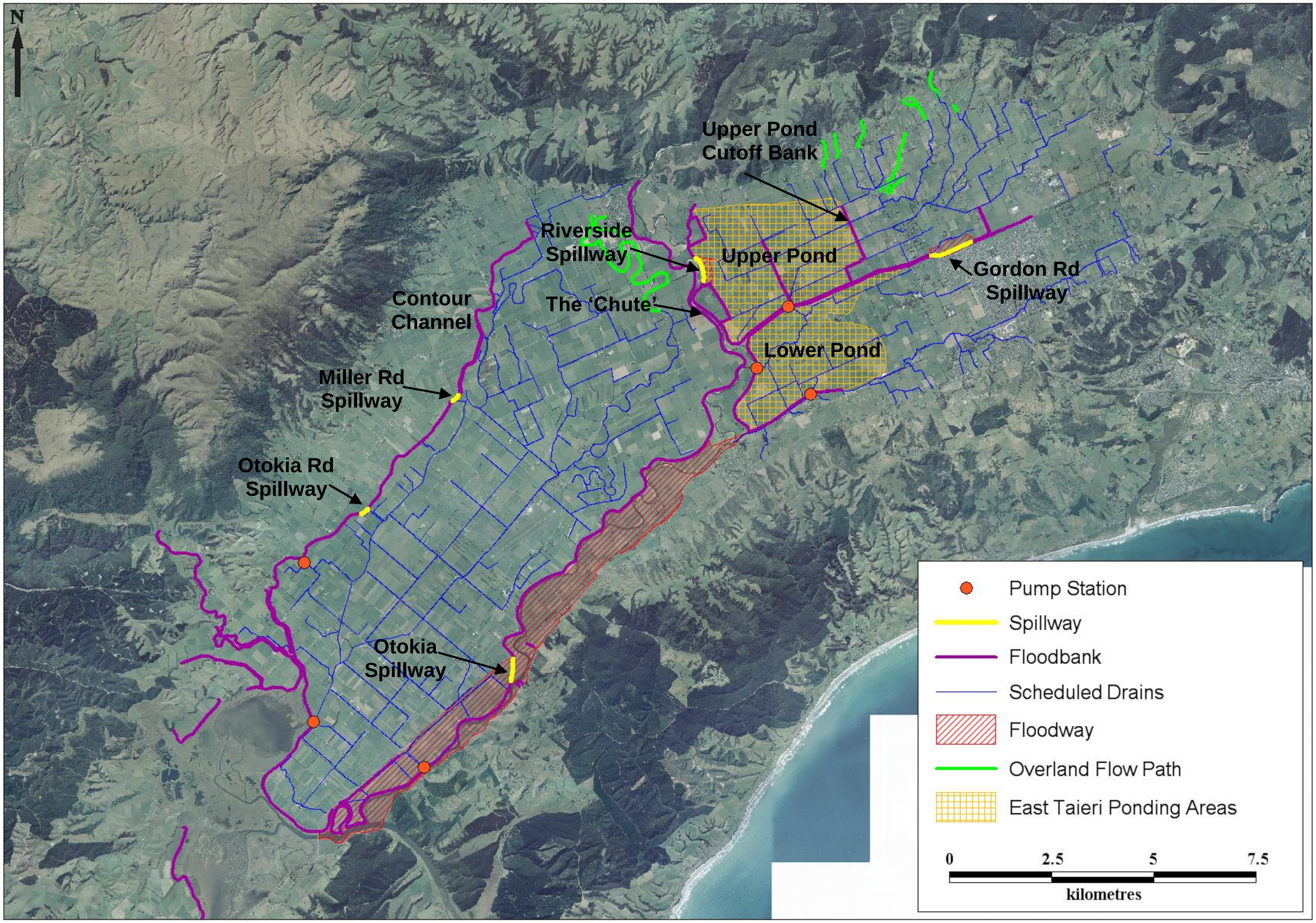

Figure 4.3 **Engineered features of the Taieri Plains that modify the flood hazard.**

Figure 4.4 East Taieri ponding areas flooded on 8 June 1980.

The development of flood-protection works in East Taieri in the 1970s (East Taieri Internal Flood Control and Drainage Scheme) sought to improve the standard of protection of this area, without compromising the flood hazard for West Taieri (OCB, 1974). This requirement of not doing anything that would impact on the flood hazard of West Taieri is set out in the Taieri River Improvement Act 1920. Those provisions are still operative.

The works undertaken as part of the Lower Taieri Flood Protection Scheme in the late 1980s and the 1990s formalised the two ponding areas as features expressly intended to attenuate flows within the Taieri River. These works, which involved construction of the Riverside spillway in the early 1990s and then reconstruction of the spillway in its current, modified form after failure of the first spillway before commissioning (Figure 4.5A), enhanced the naturally occurring detention characteristics of the ponds, while further increasing the standard of flood protection of the land within them (Figure 4.4). Regardless of their use as detention areas, the East Taieri Upper Pond and Lower Pond have higher standards of flood protection than if there were no flood protection scheme.

Water from the Taieri River enters the Upper Pond via the Riverside spillway whenever flows at Outram exceed approximately 800m^3/s (Figure 4.5B and C)[11], an event which has an assessed-return period of about 10 years (Appendix 2). The Upper Pond can store about 34 million cubic metres of water before it begins to overtop the surrounding flood banks (ORC, 2010c) and/or pond behind the cut-off bank. The cut-off bank was constructed in the 1990s and limits the eastern extent of the ponded area, provided the bank does not fail.

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[11] Based on flows measured in April 2006, July 2007 and May 2010. This threshold is lower than the design assumptions of initially 1,300m^3/s (OCB, 1985) and then 1,050m^3/s.

The detention characteristics of the Upper Pond are optimal for a flood with the particular characteristics of the June 1980 flood, which had a very rapid rate of rise (the flow increasing by approximately 300m^3/s per hour), sharp peak and rapid recession (Figure 3.8). The Upper Pond will be less effective for floods that have a slower rate of rise or a flatter peak or a longer duration, like that which occurred in May 2010 (Appendix 2).

Drainage of the Upper Pond is via the Silver Stream pump station and gravity outlets, which discharge into the lower Silver Stream.

Figure 4.5 Destruction of the Riverside spillway into the Upper Pond after the December 1993 flood (A) Taieri River flows spilling into the Upper Pond on 26 May 2010 (B) and 29 May 2010 (C) over the current spillway. Photos (B) and (C) courtesy of Otago Daily Times.

Figure 4.6 Looking downstream towards the chute. The photograph was taken on 31 July 2007, the day after the river peaked at 1,067 m^3/s at Outram.

The Lower Pond is located to the east of the Taieri River, immediately downstream of, and next to, the confluence with the Silver Stream. In the past, the Silver Stream and Mill Creek flowed through what is now referred to as the ‘Lower Pond’ (Figure 4.3) and were diverted in the late 19th century. Unlike the Upper Pond, the area where spill occurs into the Lower Pond is not well defined. The crest of the Lower Pond flood bank is instead designed to be lower than that of the flood bank on the west of the Taieri River, causing flows to preferentially spill into the Lower Pond. Overland flow and stormwater from part of Mosgiel, as well as overbank spill from the Owhiro Stream, can pond in this area, although generally not in large quantities.

Like the Upper Pond, the Lower Pond is a critical part of the Lower Taieri Flood Protection Scheme and is intended to work in conjunction with the Upper Pond, by reducing peak-flood flows in the Taieri River further once the Upper Pond is full. The threshold for spill into this area is higher than for the Upper Pond, with the scheme’s design assuming that water from the Taieri River would enter the pond when the Upper Pond was full and flows in the Taieri River (at Outram) exceeded approximately 2,500 m^3/s. Flows in the Taieri River after the scheme upgrade in the 1990s have never been large enough to test this assumption.

The combination of flood banks and the two ponding areas is intended to protect the whole West Taieri area to about a 1:100-year standard or 2,500m^3/s (at Outram). The flood banks narrow as they move southward across the Plain, creating a confined channel known as ‘the chute’ (Figure 4.6). The reduced capacity of the chute assists spilling of flood flows into the Upper Pond and hence the attenuation of flows in the Taieri River. Recent analysis has shown that spill will probably occur into West Taieri immediately upstream of the chute when the flows at that location are in the range 1,200 to 1,400 m^3/s and that overtopping into West Taieri would probably occur before the Lower Pond ever comes into operation. For a flood with the same hydrological characteristics as that of the June 1980 event, there will be no freeboard on the West Taieri flood bank upstream of the chute when flows at Outram exceed about 2,500m^3/s. Options to ensure the operation of the Lower Pond and to restore a satisfactory design freeboard on the West Taieri flood bank are to be investigated (ORC, 2012c).

Downstream of the Lower Pond, the Taieri River floodway is approximately 12km long and 600m wide and has the capacity to carry and store a significant volume of water. These characteristics are crucial during floods. The floodway is also subject to tidal influences (Section 3).

The Contour Channel intercepts run off from the Maungatua Range and diverts it into the Waipori River, thereby reducing the amount of water that must be pumped from the West Taieri drainage area by the Waipori pump station (Figure 3.13). A flood bank on the southern (down-slope) side of the Contour Channel, constructed in the 1900s, augments the capacity of the channel (Figure 2.4). The concept of this flood bank was identified in the late 19th century (Figure 2.1). The bank is being reconstructed in sections to improve its profile and structural integrity, using techniques and knowledge of performance that were not available when construction first began (ORC, 2012c).

The capacity of the Contour Channel varies along its length due to the change in catchment area. The magnitude of flows within the Contour Channel is dependent in part on the spatial variability in rainfall along the Maungatua Range, and so it is difficult to assign a probability or return period to channel capacity and observed or expected flood flows. The limited capacity of the Contour Channel is managed by allowing spill to occur at the Miller Road and Otokia Road spillways during reasonably small (and frequent) events (Figure 4.7).

Figure 4.7 Flow over the Otokia Road (left) and Miller Road (right) Contour-Channel spillways in April 2006.

High-sediment loads from the Maungatua Range can reduce the capacity of the Contour Channel, requiring ongoing maintenance to remove excess sediment. Despite the two engineered spillways, overflow occurs into West Taieri at numerous locations along the channel during high flows.

A number of flood banks are located to the north and west of lakes Waipori and Waihola and next to the Waipori River and the Meggatburn. These flood banks offer a low level of protection to farmland and the settlement of Berwick.

Flood banks are located along the length of the Silver Stream, which contains flows of 260m^3/s (the assessed peak flow of the April 2006 event) or more on the Mosgiel (southern) side. Flow over the Gordon Road spillway on the true-right (northern) bank of the Silver Stream, downstream of Gordon Road, occurs when flows exceed about 170m^3/s (the assessed threshold flow for the April 2006 event (ORC,2010a)) (Figure 4.8). Due to the lack of any defined flow path, these flows tend to spread out over a wide area on route to the Upper Pond cut-off bank, combining with flows from Mill Creek and the hill catchments to the north of the plains (Figure 4.2).

Figure 4.8 Silver Stream flows spilling over the Gordon Road Spillway, 26 April 2006 (A), and Silver Stream looking south (downstream) near Gordon Road on 28 April 2006, with the spillway on the true-right bank (B). Floodwater within the Upper Pond can be seen in the distance.

Mill Creek, north of the Silver Stream, collects flows from the northern hill catchments and directs them into the Silver Stream via the Mill Creek diversion. Flows from Mill Creek can also continue along their natural-drainage path, into the Upper Pond.

The ability of the Lower Taieri Flood Protection Scheme flood banks to contain and convey flows across the plains depends on their having the necessary structural and foundation integrity throughout the duration of the flood and any successive floods. The risks of a foundation-piping failure are greater in some places than others, particularly near Otokia (Figure 4.9). This risk is managed through engineering remedial works, detailed investigations, targeted monitoring during floods and land-use controls in defined ‘excavation sensitive areas’ (ORC 2012b). The expected seismic performance of the scheme flood banks is discussed in Section 7.

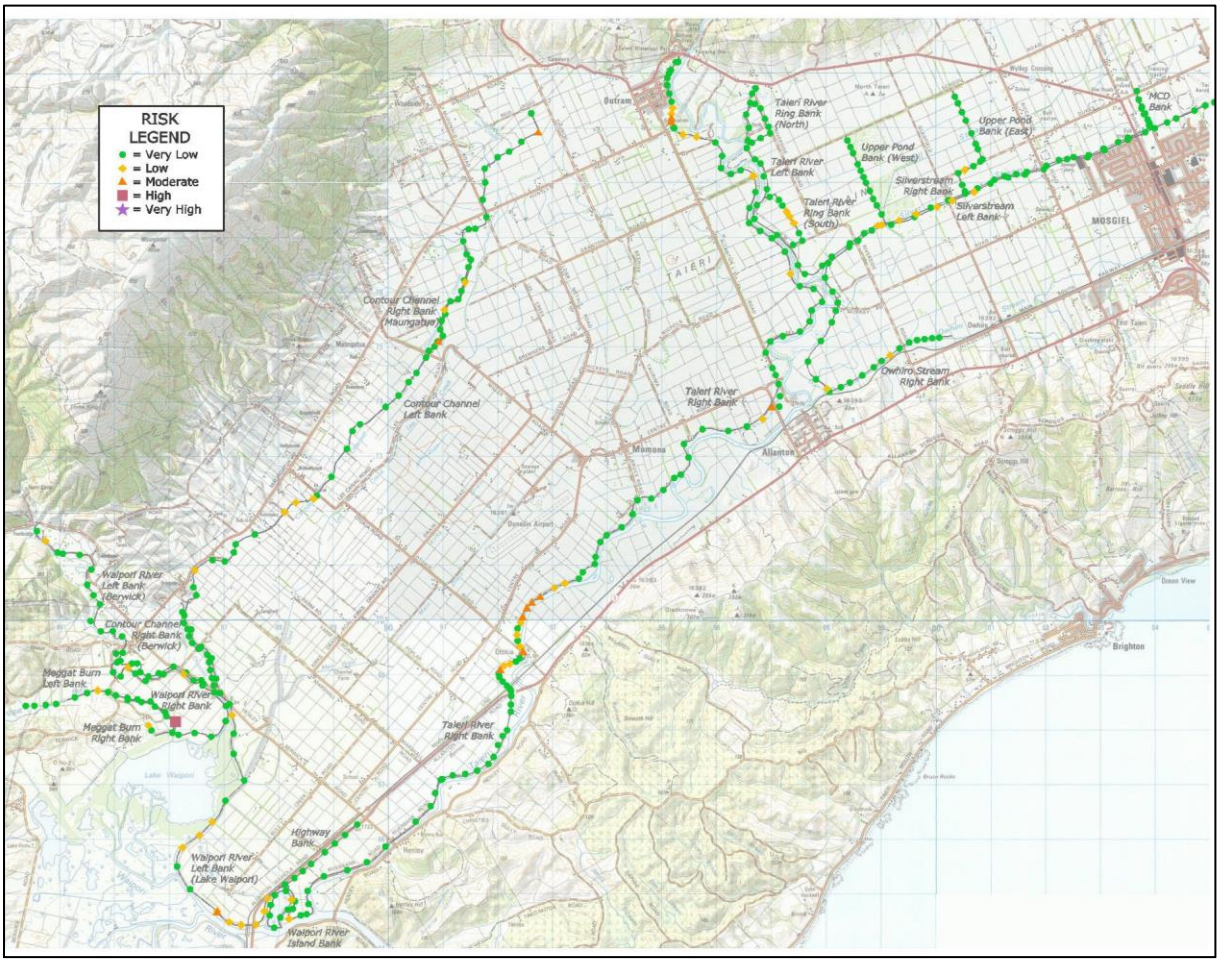

Figure 4.9 Assessed risk of piping failure of the Lower Taieri Flood Protection Scheme flood-bank foundations when the river level is at flood-bank crest for an extended period (Tonkin & Taylor Ltd, 2005).

4.3 Variation in flood hazard by location

The nature and severity of the flood hazard varies across the Taieri Plains due to topography, variations in proximity of watercourses, the hydrological characteristics of those watercourses and the presence or absence of elements of the Lower Taieri Flood Protection Scheme. For the purposes of this report, the plains have been divided into 22 geographical areas, based on flood-hazard characteristics (Figure 4.10). This approach is a refinement of that reported in ‘*Mosgiel Flood Event 25/26 April 2006 and future action’* (DCC and ORC, 2006). The colour-coding and labeling of the areas is a way of defining and describing flood hazard across the Taieri Plains and does not represent the significance of the hazard.

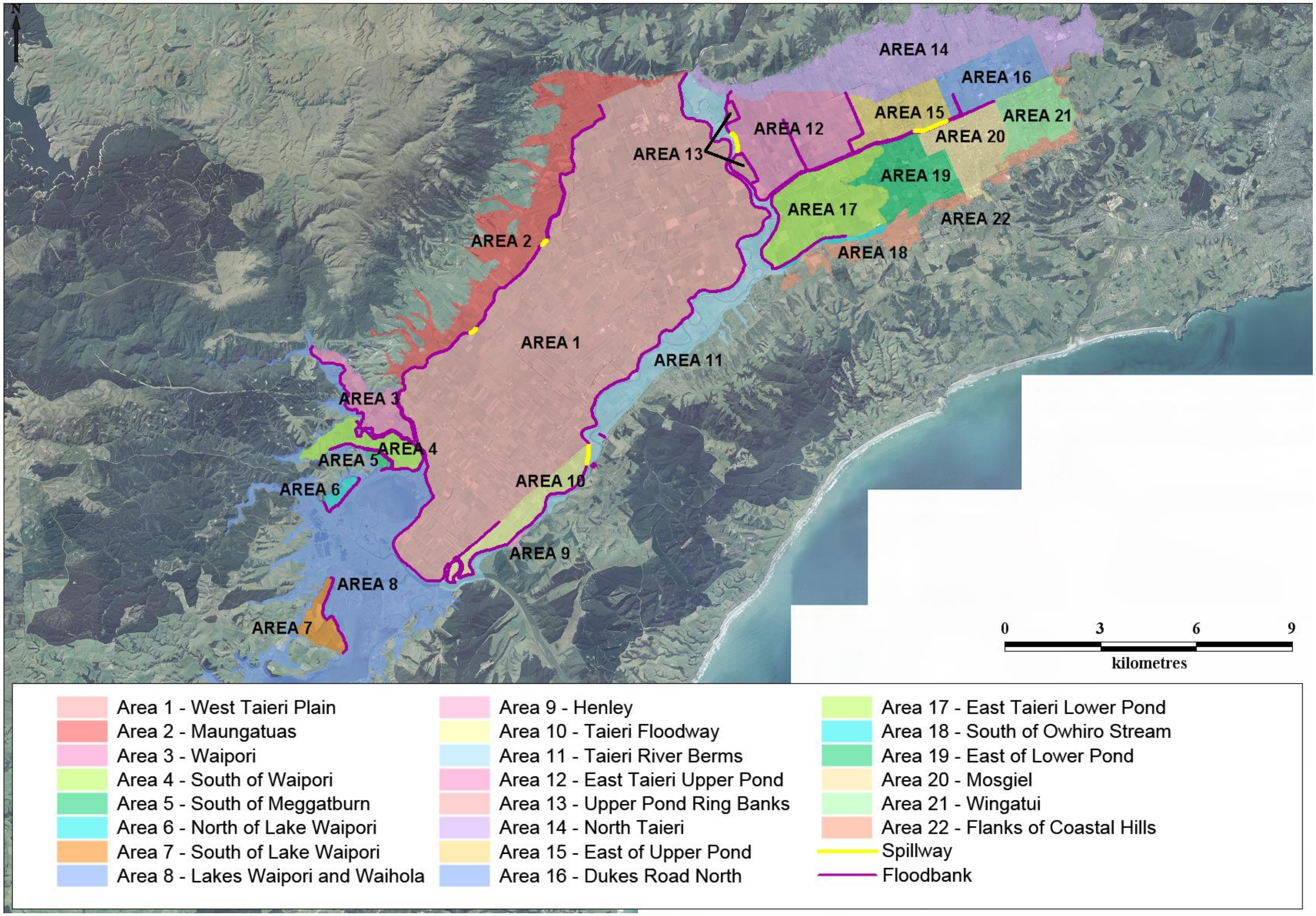

Figure 4.10 Flood-hazard areas on the Taieri Plains. Note that the flood hazard within each area is not uniform. Localised topographical features will influence the flood hazard within each area.

While each area has similar flood-hazard characteristics, it does not necessarily mean that all the land is flood prone or has the same flood risk in that area. The hazard is influenced by localised topographical features, overland flow paths and proximity to constructed or artificial features, such as fences, shelterbelts and buildings. During a flood, some portions of a defined area may remain ‘flood free’, while others will be completely inundated. As noted above, this report does not present a complete record of the flood history for the Taieri Plains, but does refer to historical events to illustrate the flood-hazard characteristics of the plains.

The flood-hazard characteristics of each area are listed below.

Area 1: West Taieri Plain

Most of this area is close to or below current msl (Figure 3.7) and relies on the West Taieri Drainage Scheme for drainage. The area is exposed to flood hazard from the Taieri River, streams along the Maungatua Range and (for the western part of this area), the Waipori River and Lake Waipori.

Tidal effects occur around Lake Waipori and the Taieri River as far upstream as Allanton (Figure 3.12). The tide has little effect on river levels upstream of Henley during large floods. Tidal effects are, however, predicted to become more pronounced due to sea-level rise.

The western part of the area used to be a wetland complex associated with Lake Waipori and relies on the flood bank along the current lakeshore for protection from inundation (Figure 3.14). That flood bank is susceptible to lateral spreading and settlement or damage due to seismic-induced shaking as it is founded on soft soils and is near the banks of the lake (Section 7). The partial embedment of the Waipori pump station (Figure 3.13) within the flood bank increases the likelihood of damage during a seismic event due to differential movement of the station and the flood bank. The amount and rate of inundation of West Taieri due to inflow from Lake Waipori would depend on the amount of damage to the flood bank and pump station and the state of the tide (Figure 3.12). This issue is to be further investigated (ORC, 2012c).

The Contour Channel (to the north) intercepts run off from the Maungatua Range, which is discharged into the Waipori River. Flows that exceed the capacity of the Contour Channel spill into this area via engineered spillways located near Miller Road and Otokia Road (Figure 4.3 and Figure 4.7). During high flows, spilling occurs into this area at many locations along the Contour Channel.

The Maungatua streams carry large amounts of sand and gravel that settle out where they join with the Contour Channel. This matter is discussed further in Section 5. A number of landslides are located on the flanks of the Maungatua Range (Figure 6.1). Intense rainfall in the upper catchment and/or a large seismic event could reactivate these features or trigger new ground movement. Such activity might provide additional sediment loads for alluvial-fan activity, which could reduce the capacity of the Contour Channel and the tributaries themselves, thereby increasing the likelihood of spill into West Taieri.

In the absence of the flood banks, overland flow from the Taieri River would naturally be concentrated to West Taieri, as demonstrated in the February 1868 and May 1923 flood events (Figure 4.1A and B, and Figure 4.11).[12] During the June 1980 flood event, numerous flood-bank failures along the length of the scheme caused inundation of about 48km^2 or two thirds of the West Taieri (Figure 4.1C and Figure 4.12) (ORC, 1993).

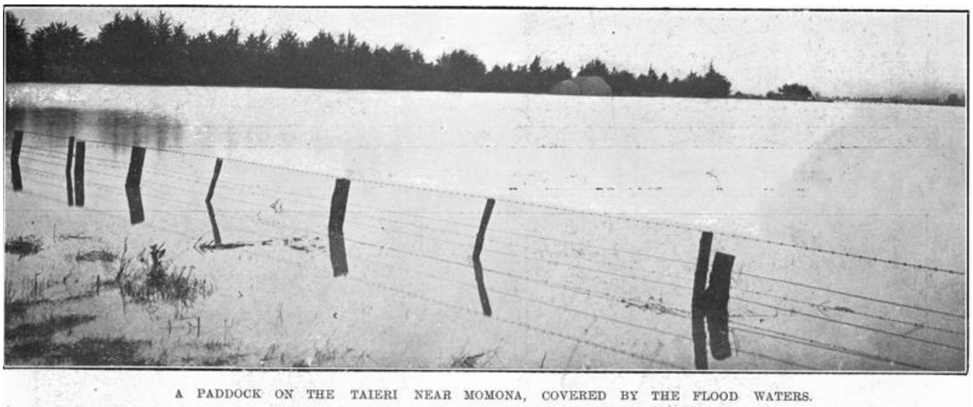

Figure 4.11 Ponding on the West Taieri Plain, near Momona, after the May 1923 flood.

Figure 4.12 Aerial view of inundation on the West Taieri Plain, after the June 1980 flood.

The flood banks near Outram are capable of containing flows of up to 2,500m^3/s in the Taieri River, a similar flow to that of the 1980 flood (Figure 4.13). Even so, seepage under the flood banks can still occur, especially during large, long-duration flood events. Overland flow also

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[12] The February 1868 and May 1923 flood events occurred before the construction of the current flood protection scheme.

ponds in low-lying areas, with local topographical depressions visible in the LiDAR[13] image of the area (Figure 4.14).

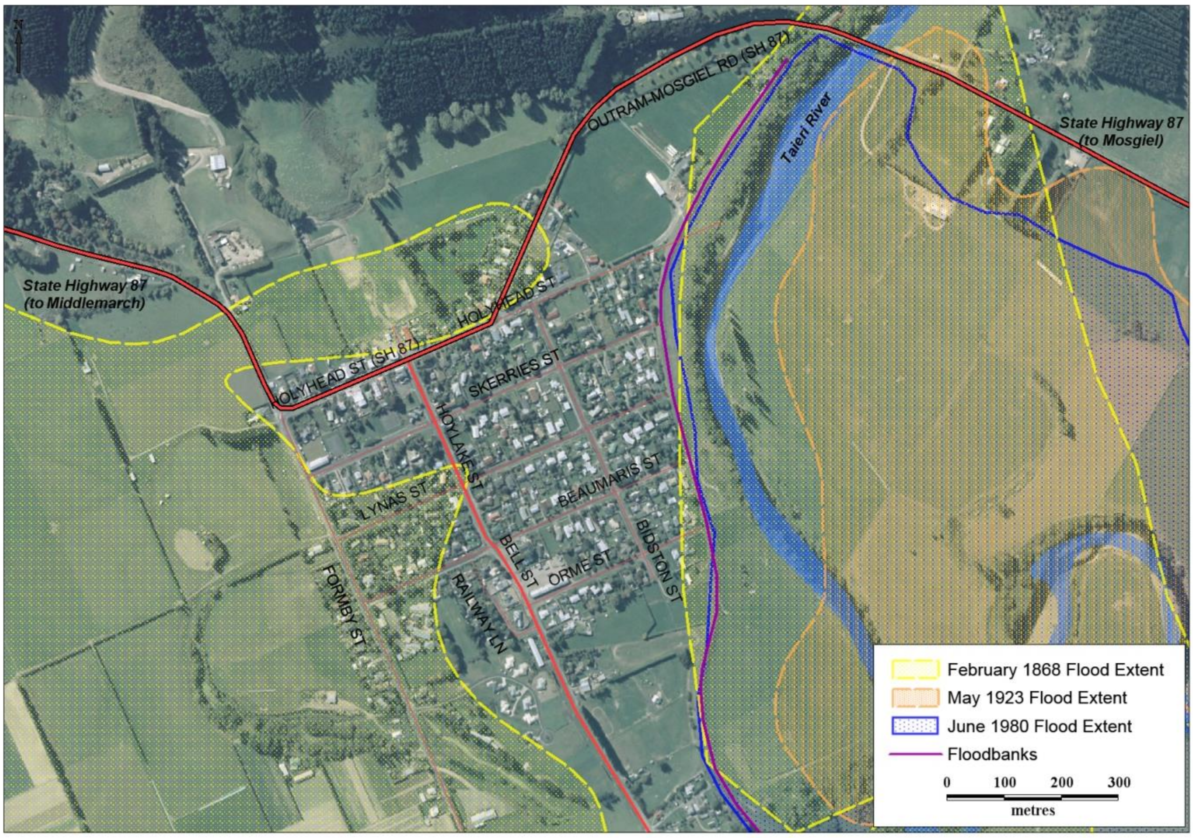

Figure 4.13 Extent of February 1868, May 1923 and June 1980 flood events at Outram. The boundaries of the February 1868 and May 1923 extents are indicative only and are based on survey plans prepared after these events.

A breach of the flood bank in this location could result in much of Outram being inundated as it generally lies lower than the land on which the flood bank is located (Figure 4.14). In the absence of the flood banks, inundation would probably begin to occur at flows as low as 270m^3/s.[14] A section of the crest of the flood bank immediately upstream of Outram is at a slightly lower elevation than the rest and is apparently intended to act as a super-design spillway. The possibility of relocating this spillway to a location where overflows would have less impact is to be investigated (ORC, 2012c).

As noted above, recent analysis shows that spill will probably occur into West Taieri immediately upstream of the chute when the flows at that location are in the range of 1,200 to 1,400 m^3/s and that overtopping into West Taieri would probably occur before the Lower Pond ever comes into operation. For a flood with the same hydrological characteristics as the June 1980 event, there will be no freeboard on the West Taieri flood bank upstream of the chute when flows at Outram exceed about 2,500m^3/s. Options to ensure the operation of the Lower Pond and to restore a satisfactory design freeboard on the West Taieri flood bank are to be investigated (ORC, 2012c).

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[13] **Li**ght **D**etection **a**nd **R**anging – see the Glossary for a definition of this and other terms used in this report.

[14] Assuming an average ground elevation across Outram of 8m above msl.

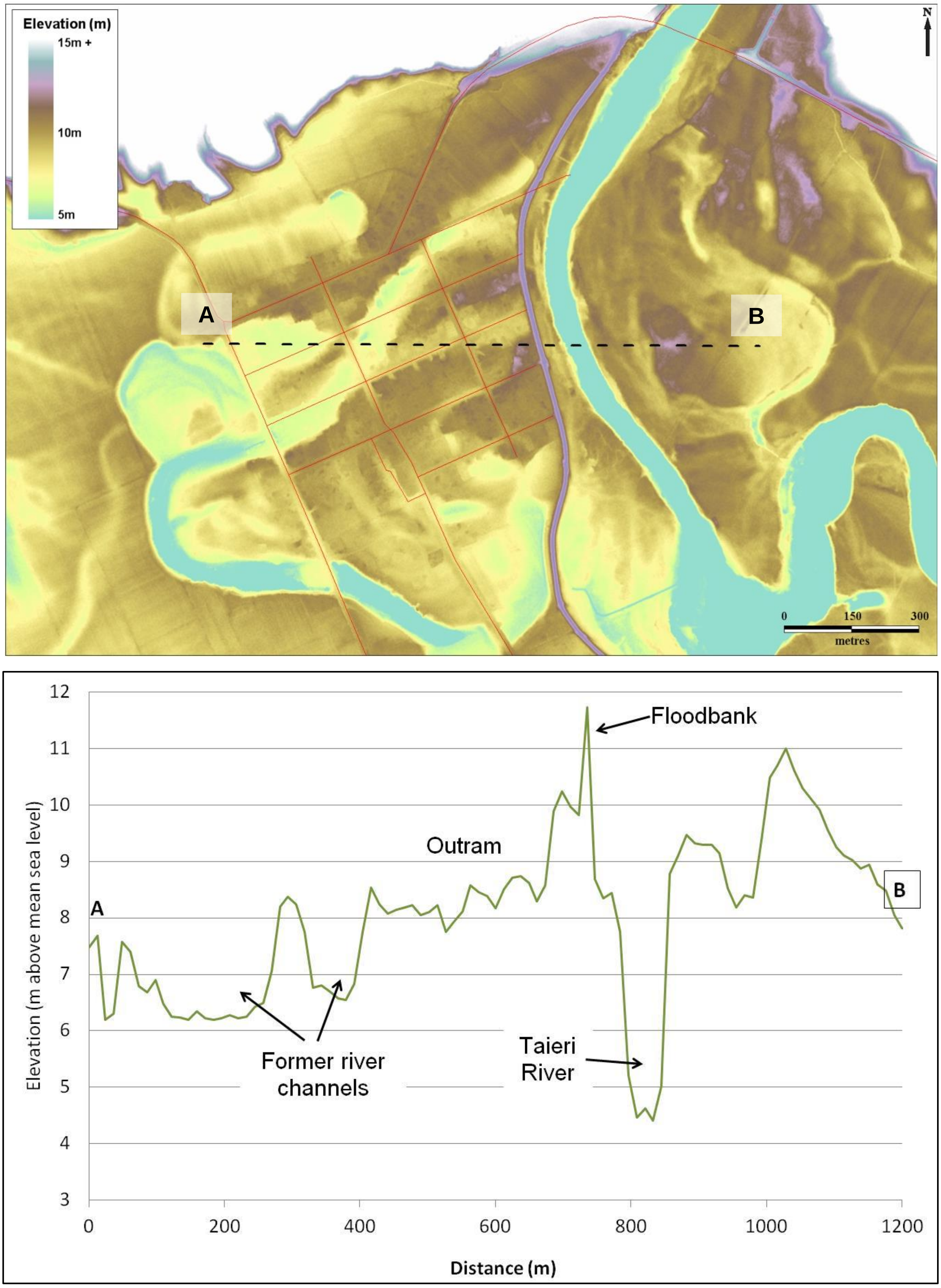

Figure 4.14 LiDAR image showing elevation of Outram (top) and cross-section profile, as indicated on the LiDAR image (bottom).

Area 2: Maungatua foothills

The flanks of the Maungatua Range are exposed to flood hazard from overland flow of the streams in the hill catchments, and the presence of floodwater-dominant alluvial fans. The fans include both active and recently abandoned alluvial-fan floodplains (Barrell *et al.*, 1998), as described in Section 5. The hazard associated with these sometimes ephemeral streams often goes unnoticed until a large rainfall event occurs.

The streams incised into these fans carry large amounts of sand and gravel from the Maungatua Range, depositing the sediments in the Contour Channel (Figure 4.15 and Figure 4.16). During significantly large flood events, such as in June 1980, the areas immediately next to the Contour Channel have been inundated.

The elevation of this area is such that it is not exposed to flood hazard from the Taieri River.

Figure 4.15 Deposition of gravel in the Contour Channel from a tributary hill stream.

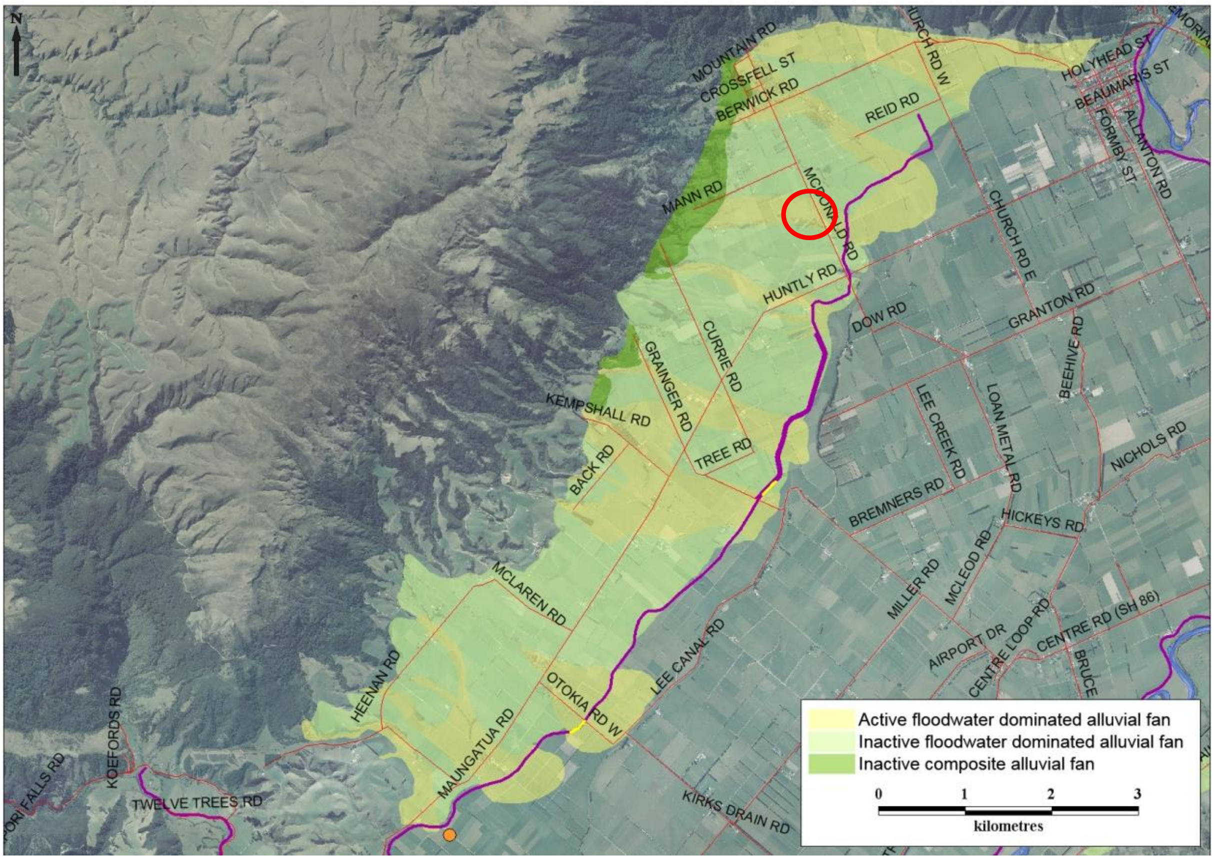

Figure 4.16 Alluvial-fan hazard near the Maungatua Range and Contour Channel. The red circle indicates the approximate location of the alluvial fan shown in Figure 5.2.

Area 3: Waipori; Area 4: South of Waipori River; Area 5: South of Meggatburn

A significant part of each of these areas lies below current msl (Figure 3.7). They were extensively inundated in the floods of 1868, 1923 and 1980 (Figure 4.1), and possibly during other undocumented events.

These areas are exposed to flood hazard from one or more of the Waipori River, the streams along the Maungatua Range (via the Contour Channel), Lake Waipori and Meggatburn.

The Contour Channel intercepts run off from the Maungatua Range and discharges these flows into the Waipori River.

The settlement of Berwick lies within Area 3.

Flood banks that are part of the Lower Taieri Flood Protection Scheme provide a low level of protection to a rural standard (OCB, 1981). The southern part of Area 3 lies within the West Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Area 6: North of Lake Waipori; Area 7: South of Lake Waipori; Area 8: Lakes Waipori and Waihola

These areas are below current msl and are exposed to flood hazard from surrounding hill catchments and lakes Waipori or Waihola.

Flood banks that are part of the Lower Taieri Flood Protection Scheme provide a low level of protection to a rural standard.

Area 9: Henley

Henley is a low-lying community, with much of the land being less than 0.5m above current msl (Figure 4.17). The area is exposed to flood hazard from the Taieri River and run off from the coastal hill range to the south. The area was flooded in 1868, 1923 and 1980 (Figure 4.19), and possibly during other undocumented events. A low flood bank, constructed in the 1990s near the township, is part of the Lower Taieri Flood Protection Scheme and provides protection from small to medium events on the Taieri River. Despite the flood bank, flooding of parts of this area typically occurs every few years, most recently in April 2006, July 2007 and May 2010 (Figure 4.18B). An isolated ring bank provides some protection to a single house located within the floodway towards the northern end of this area.

This part of the Taieri River is subject to tidal influences (Figure 3.12). However, tidal effects are largely drowned out during large flood events.

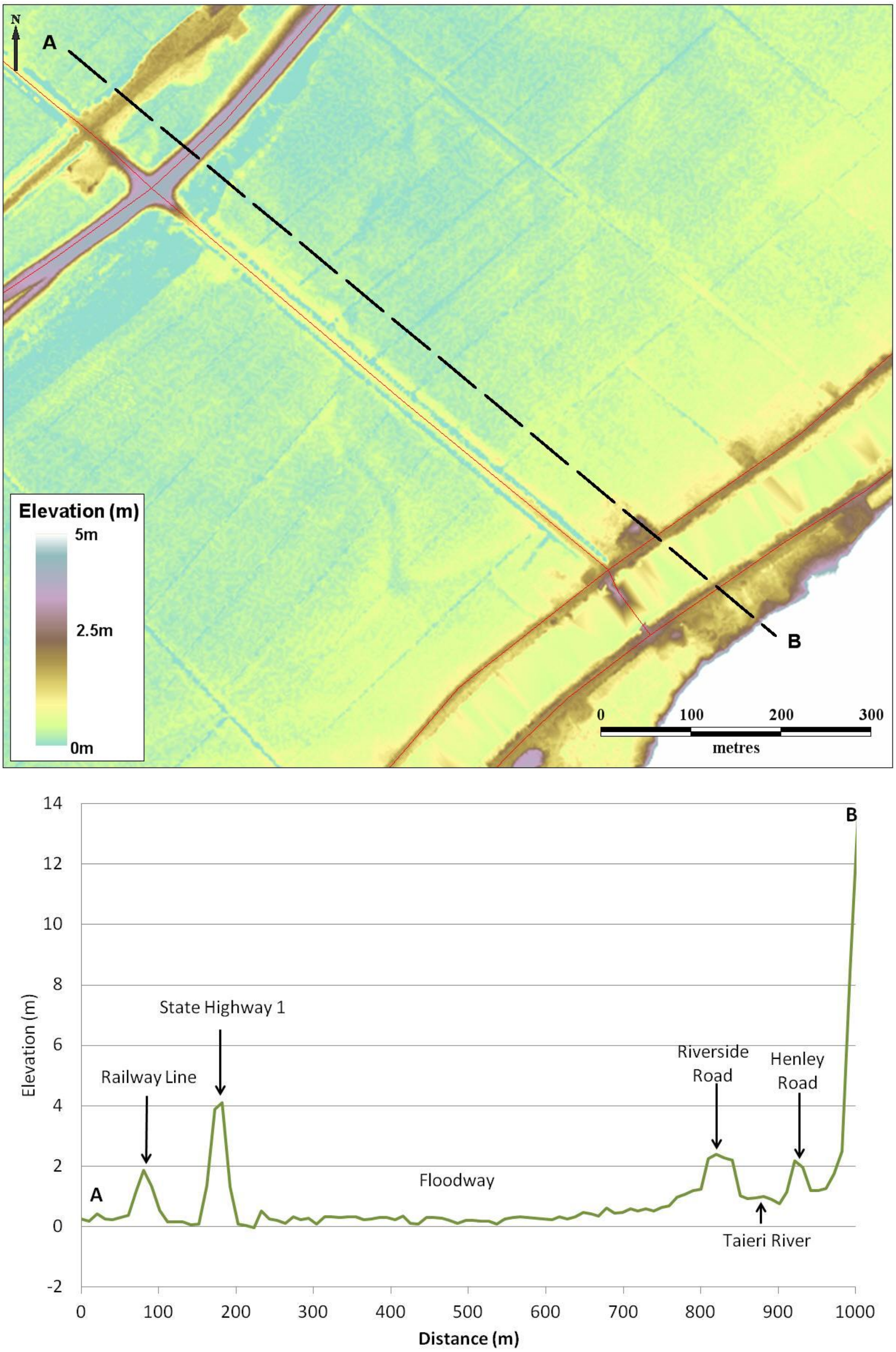

Figure 4.17 LiDAR image showing elevation of Henley (top) and cross-section profile AB, as indicated on the LiDAR image (bottom).

Figure 4.18 Cars parked on the Taieri River bridge at Henley on 5 June 1980 (A); Henley on 29 May, 2010 (B). (Source: Otago Daily Times)

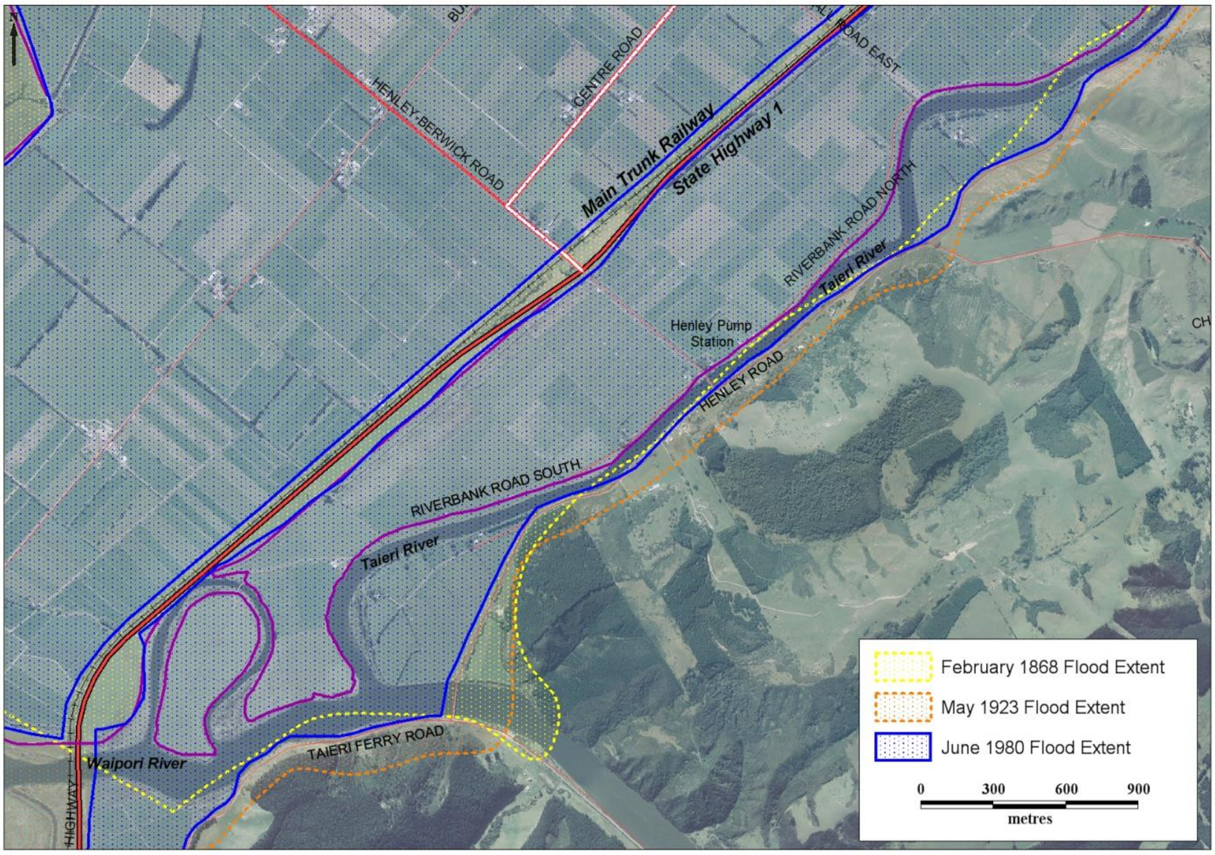

Figure 4.19 Extent of February 1868, May 1923 and June 1980 flood events at Henley. The boundaries of the February 1868 and May 1923 extents are indicative only and are based on survey plans prepared after these events.

Area 10: Lower Taieri Floodway

All of Area 10 is at or slightly above current msl and exposed to flood hazard from the Taieri River (Figure 4.19 and Figure 4.20). The highway embankment to the north separates the floodway from the rest of the West Taieri Plain (Figure 3.10).

A low flood bank provides very limited protection from the Taieri River, and overflow into this area occurs first at a low spillway, near the upstream end of the flood bank (Figure 4.3). Flooding typically occurs every few years, most recently in April 2006, July 2007, May 2010 and August 2012.

Tidal effects are observed as far upstream as Allanton, under low-flow conditions (Figure 3.12). Tidal influences are largely drowned out and have little effect on river levels during floods. The area has some ability to drain by gravity, but drainage depends, in part, on the Henley pumping station, which is part of the West Taieri Drainage Scheme (Figure 3.14).

Figure 4.20 Lower Taieri Floodway, looking downstream to Henley, 31 July 2007.

Area 11: Taieri River Berms

This area consists of the berms between the Taieri River flood banks and is exposed to flooding from the Taieri River and, to a lesser degree, the Silver Stream and Owhiro Stream. The area lies within the Lower Taieri Flood Protection Scheme and plays a crucial role in the conveyance of floodwater and hence the mitigation of flood hazard for other parts of the Taieri Plains (Figure 4.21).

Figure 4.21 Taieri River, looking south-west during flood on 23 February 1945. Allanton is on the left in the middle distance.

The area is typically flooded annually. Tidal influences are felt in the lower reaches, downstream of Allanton (Figure 3.12). During floods, tidal influence has little effect on river levels in this area. As the sea level rises in the future, the tidal effects in the Taieri River are likely to become more pronounced.

The settlement of Allanton is situated on an old, highly dissected alluvial-fan remnant at the eastern edge of this area (Section 5). The slightly higher elevation of most parts of Allanton, relative to the surrounding plains means that most of the land on which there are currently residential dwellings is not exposed to Taieri River flood hazard. The lower-lying areas, however, were flooded in 1980 (Figure 4.22) and 2006.

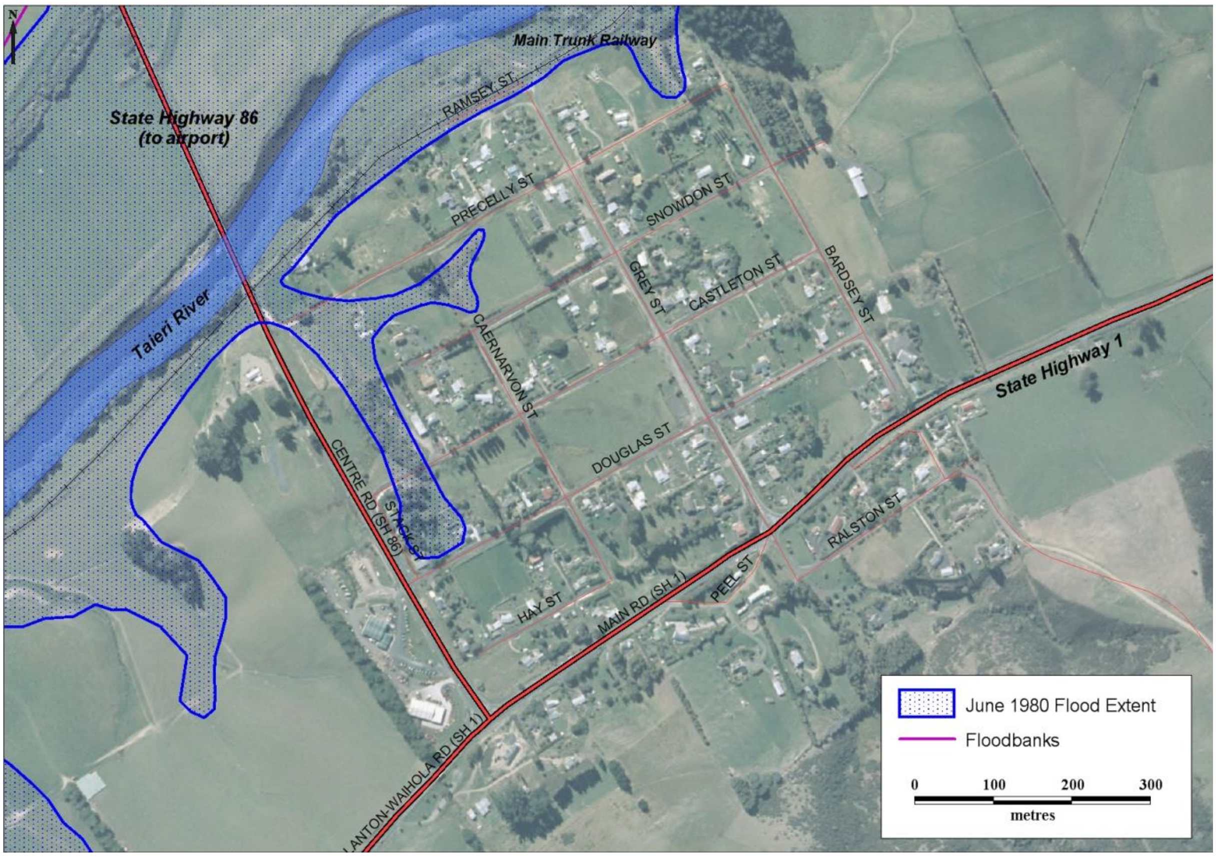

Figure 4.22 1980 flood extent near Allanton.

Area 12: East Taieri Upper Pond

The perimeter of this area is the possible extent of ponding within the East Taieri Upper Pond. As noted above, the Upper Pond is a critical part of the Lower Taieri Flood Protection Scheme because it attenuates flood flows in the Taieri River and reduces the flood hazard elsewhere. The eastern boundary of the area is defined by the upper pond cut-off bank (Figure 4.3). Without the cut-off bank, the pond would extend further east, into the western part of Area 15.

Historically, this area flooded frequently (typically, annually) (OCB, 1974) for long periods because it is naturally low lying. Flood hazard mainly relates to the Taieri River, but also to the Silver Stream, Mill Creek and the hill catchments to the north. Flooding can occur from any one of these sources or in combination. The area lies within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Water from the Taieri River enters this area over the Riverside spillway whenever flows at Outram equal or exceed about 800 m^3/s (Figure 4.5). This occurrence has an assessed-return period of 10 years. The depth and duration of ponding depends on both the duration and the magnitude of flows exceeding this threshold (Appendix 2). For that reason, the frequency distribution of water depths in the Upper Pond differs from the frequency distribution of peak flows in the Taieri River. The ponding can reach depths of three metres (the depth at which spill over the cut-off bank first occurs) and can last for several weeks. The extent of flooding during two recent floods is shown in Figure 4.23.

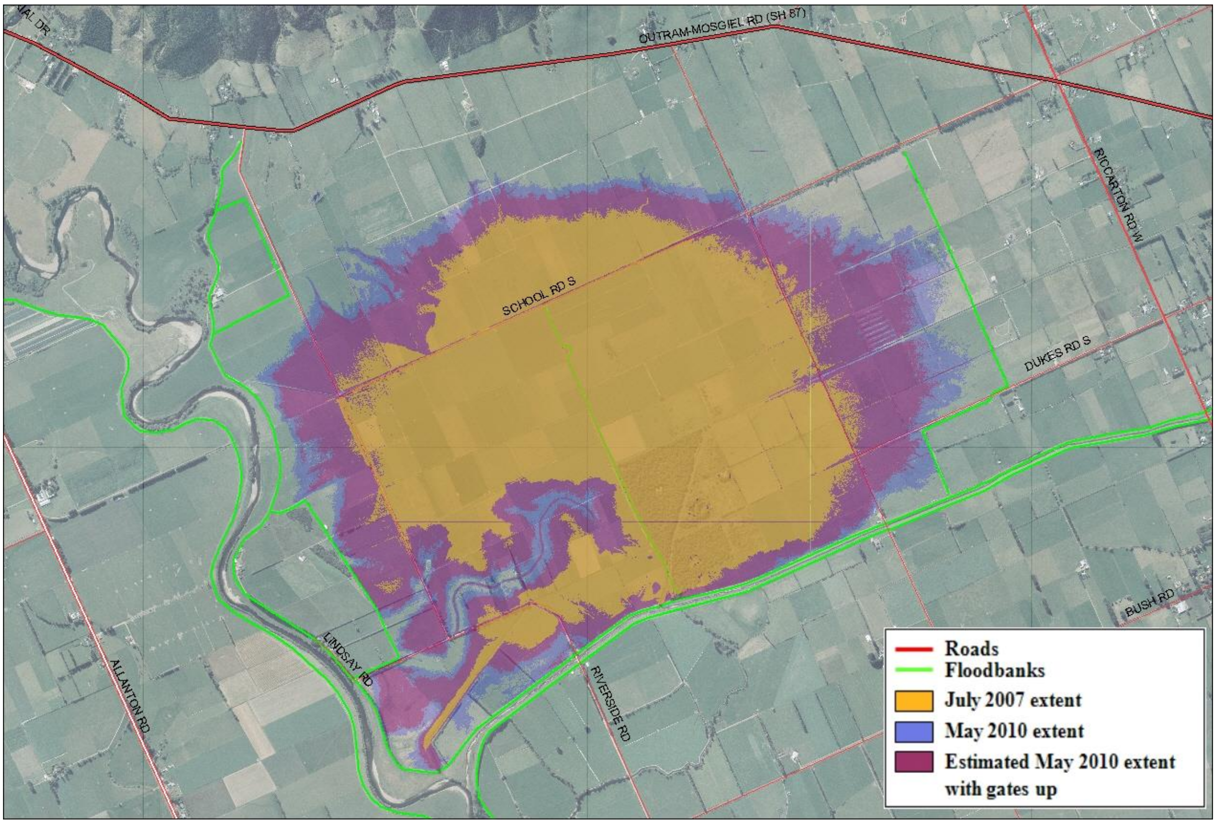

Figure 4.23 Maximum extent of ponding within East Taieri Upper Pond in July 2007 and May 2010.

Improvements are being made to the integrity of the Riverside spillway to reduce the likelihood of it failing while in operation and causing rapid uncontrolled release of water from the Taieri River into the Upper Pond (ORC, 2012c).

Flows from the Silver Stream (whenever the flow is greater than 170m^3/s), Mill Creek and the hill catchments to the north enter the ponding area via culverts located within the cut-off bank (Figure 3.6).

Area 13: Upper Pond Ring Banks

Flood hazard in this area is mainly associated with flows from the Taieri River and water ponded in the Upper Pond (Area 12) and, to a lesser degree, the Silver Stream, Mill Creek and the hill catchments to the north of the Taieri Plains. These areas flooded in the 1868, 1923 and 1980 events (Figure 4.1). They are, in effect, former parts of the East Taieri Upper Pond that have been isolated and provided with a higher standard of protection. The ring banks around these two areas supplement rather than replace the primary flood banks on the Taieri River and Silver Stream. The ring banks are part of the Lower Taieri Flood Protection Scheme and were constructed in the 1990s.

Both ring-banked areas lie within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Area 14: North Taieri

The alluvial fans located on the northern margins of this area grade into an extensive alluvial plain, which descends from about 40m in elevation in the north-east, to less than 10m near the Taieri River (Figure 4.25). A number of active floodwater-dominant alluvial fans are located near the east of the area, the two largest following the Silver Stream and Mill Creek. These two watercourses are well incised at that location, reducing the likelihood of avulsion without large inputs of sediment into the system.

Flood hazard is derived from Mill Creek and the tributaries from the surrounding hill catchments. Although the area is located outside the influence of the Taieri River, it was probably flooded in 1868 and 1923, even though it is not obvious from the maps of those events (Figure 4.1). As a consequence of the alluvial fans emerging from the hill catchments to the north, the area comprises a significant number of paleochannels and ephemeral swales (Figure 3.6) (Section 5). Because of the subtle topography, flooding is also influenced by local features such as fences, shelterbelts and buildings, which impede natural downslope drainage. Such features can also divert water into areas that would not have otherwise been affected by flooding.

Significant overland flow and ponding occurred in parts of this area during the April 2006 and July 2007 floods (Figure 4.2 and Figure 4.24). Options for managing the overland flow in the vicinity of Wyllies Crossing have been investigated (ORC, 2009).

Most of the area lies within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Figure 4.24 Flooding at Wyllies Crossing in April 2006 (left) and July 2007 (right).

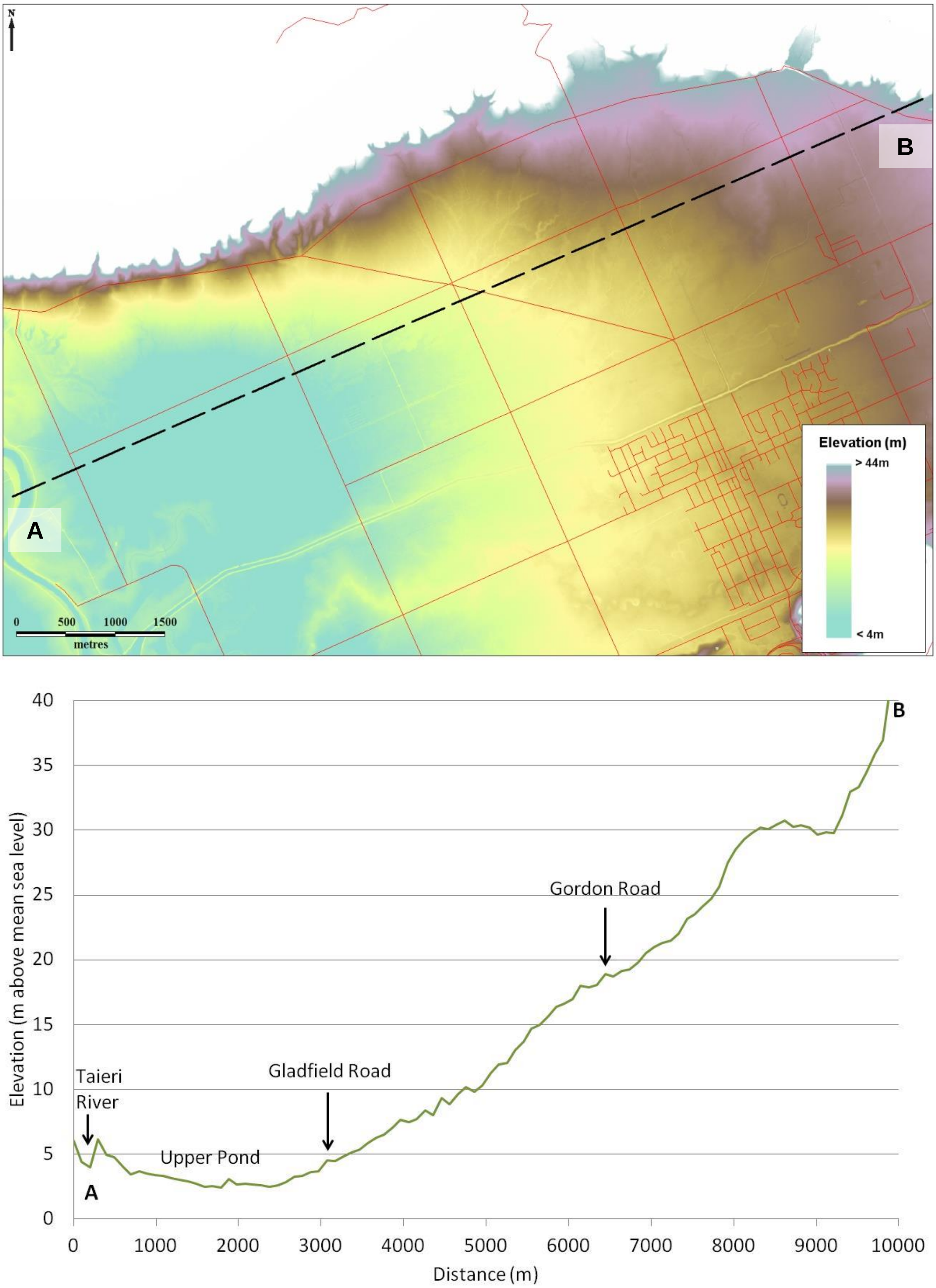

Figure 4.25 LiDAR image showing elevation of the North Taieri area (top) and cross-section profile AB, as indicated on the LiDAR image (bottom).

Area 15: East of the Upper Pond

The land within this area is generally lower than that on the southern side of the Silver Stream (Figure 4.26) and is therefore more susceptible to flooding from the stream. The area is also exposed to flood hazard from Mill Creek (Figure 4.27) and the hill catchments to the north (Figure 3.6).

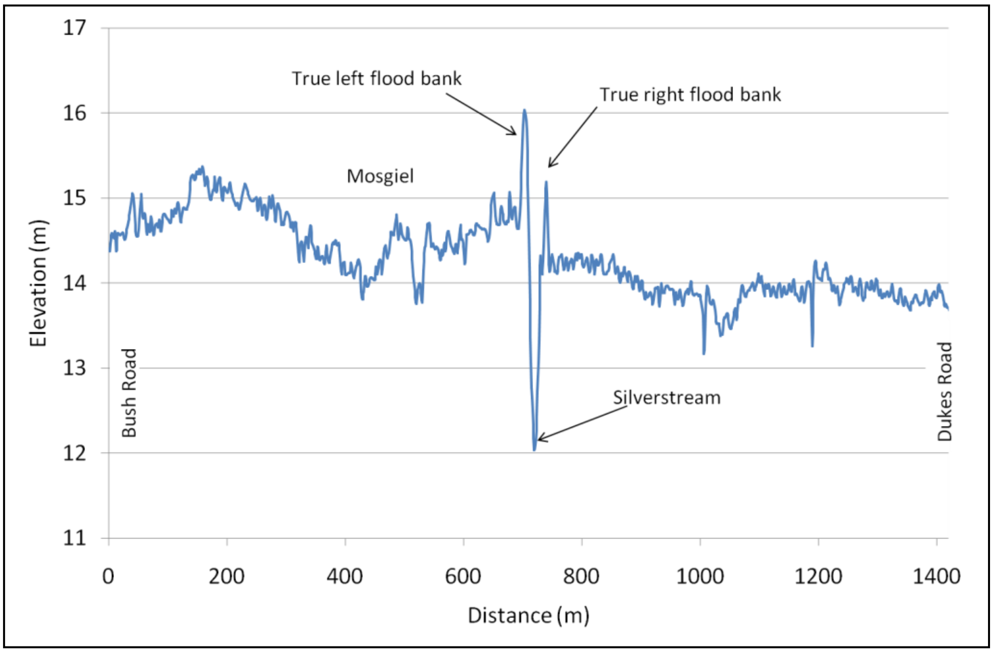

Figure 4.26 Cross section through the Silver Stream (from Bush Road in the east to Dukes Road in the west), looking downstream (top). The approximate location of the cross section just downstream of Gordon Road during the April 2006 flood is shown in the lower image (Source: TVNZ).

Water from the Taieri River is generally prevented from entering the western part of this area by the East Taieri Upper Pond Cut-off Bank, which defines the western boundary of this area. The western part relies on the cut-off bank safely containing surface water within the Upper Pond (Area 12) at depths of up to three metres and for up to several weeks at a time. Floodwater within the Upper Pond (originating from the Taieri River via Riverside spillway) has not reached the cut-off bank since the bank was constructed in the 1990s; therefore, the integrity of the bank and its foundations have never been tested in a flood.

Water from the Silver Stream enters this area from the south-east whenever flows exceed approximately 170 m^3/s at the Gordon Road Spillway (Figure 4.8). This threshold has an assessed-return period of 20 years. The water then drains into the Upper Pond through culverts in the cut-off bank. During the April 2006 flood, spilling from the Silver Stream, Mill Creek and the hill catchments to the north ponded behind the cut-off bank (i.e. east of the cut-off bank), inundating the area for several days (Figure 4.2). Water also started to enter the area from the Silver Stream in July 2007 and May 2010. The rate at which floodwater is drained depends in part on the level of the floodwater within the Upper Pond. The capacity of several culverts in the cut-off bank was improved after the April 2006 flood; however, ponding to the east of the cut-off bank will still occur.

Flooding is also influenced by local features, such as fences, shelterbelts and buildings and the effects they have on ephemeral swales and paleochannels (Figure 4.28). Options for managing the overland flow have been investigated (ORC, 2010a; ORC, 2012c).

The area lies within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Figure 4.27 Water ponding on the north side of Mill Creek, upstream of Riccarton Road after a flood event in November 1971.

Figure 4.28 Evidence of overland flow and ponding behind hedges, fences and buildings after the April 2006 flood. The red lines indicate the location of fences and hedgerows; the blue arrows indicate the direction of flow.

Area 16: Dukes Road North

North Taieri is the highest-elevated location on the Taieri Plains with the land gradually grading downslope to the south-west and containing a number of ephemeral swales and paleochannels (Figure 3.6). This area is exposed to flood hazard from the Silver Stream; however, the channel is well incised. During the April 2006 flood, the Mill Creek diversion captured some of the flow from the Silver Stream and conveyed it in a northerly (reverse) direction, adding to the flows from the hill catchments (Figure 4.2). Despite that, Mill Creek itself generally poses a more significant flood hazard, particularly where stream and overland flow is concentrated by the Otago Central Railway (Figure 4.29). This occurred during the April 2006 and the 1923 events (Figure 4.1), along with localised ponding. Figure 4.30 shows ponding near Hazlett and Saunders Roads during the April 2006 flood.

The area lies within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Figure 4.29 Water ponding behind the Taieri Gorge Railway during the April 2006 flood event.

Figure 4.30 Aerial view looking south along Hazlett Road, north of the Silver Stream, during the April 2006 flood.

Area 17: East Taieri Lower Pond

Flood hazard in this area mainly relates to the Taieri River, but also to the Silver Stream and Owhiro Stream. Flooding can occur from any one of these sources or in combination. The area was flooded in 1868, 1923 and 1980 (Figure 4.1).

The area's perimeter is the likely maximum extent of ponding because of flows from the Taieri River. Historically, the area flooded frequently (typically annually) for long periods because it is naturally low lying (OCB, 1974). The flood banks located next to the Taieri River, Silver Stream and Owhiro Stream have reduced the frequency of flooding. Unlike the Upper Pond, the eastern boundary of the ponding area is not confined by any sort of cut-off bank (Figure 4.3). The extent, depth and duration of ponding during each flood depend on the flood's duration and size.

The Lower Pond is a critical part of the Lower Taieri Flood Protection Scheme and is intended to work in conjunction with the Upper Pond, once the Upper Pond is full, to further reduce peak flood flows in the Taieri River. The threshold for spill is higher than for the Upper Pond, with the scheme's design assuming that water from the Taieri River would enter the Lower Pond once the Upper Pond was full and flows in the Taieri River (at Outram) exceeded approximately 2,500 m^3/s. Flows in the Taieri River after the scheme upgrade in the 1990s have never been large enough to test that assumption. As noted above, recent analysis shows that spill will probably occur into West Taieri (Area 1) before the Lower Pond ever comes into operation.

By design, the crest of the flood bank next to the Owhiro Stream is lower than that of the flood bank which separates the Taieri River from the Lower Pond. Depending on the magnitude and duration of high flows within the Owhiro Stream and Taieri River, water ponding behind the flood bank can overtop the flood bank and spill into Area 17, as occurred in April 2006 and August 2012 (Figure 4.31). The area lies within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Figure 4.31 Overtopping of the Owhiro Stream into the East Taieri Lower Pond on 15 August, 2012.

Area 18: South of Owhiro Stream

Flood hazard in this area, immediately south of the Owhiro Stream near the confluence of the Taieri River, is associated with the Taieri River, the Owhiro Stream and the hill tributaries to the south. Part of the area lies within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Flood banks that are part of the Lower Taieri Flood Protection Scheme are located next to the Taieri River and along the southern boundary of the East Taieri Lower Pond (Area 17) (OCB, 1974). The Owhiro Stream Gated Outfall Structure prevents flow from the Taieri River entering this area, while providing the capability for the Owhiro Stream to discharge by gravity into the Taieri River whenever water levels in the river are lower than those in the Owhiro Stream. Ponding occurs behind (to the east of) the flood gate during high-flow events but is less than it would be without the structure.

The railway embankment continues on from the flood bank in an easterly direction along the edge of the Lower Pond; however, culverts in the railway embankment allow backflow from the Lower Pond into this area. The railway embankment, therefore, does not act as a flood barrier for this area.

Area 19: East of the Lower Pond

This area east of the East Taieri Lower Pond is exposed to flood hazard from the Silver Stream, Owhiro Stream, the hill catchments to the south and from internal run off. Because of its elevation, it is not affected by the flood hazard of the Taieri River. The area lies within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

The flood banks along the southern side of the Silver Stream contain flows of 260m^3/s (the assessed peak flow of the April 2006 event) or more. There are no flood banks next to this part of the Owhiro Stream, but the stream channel has been modified in the past to increase its capacity. Even so, extensive flooding of Gladstone Road South occurred in the April 2006 flood, making the road impassable to vehicles and pedestrians.

Area 20: Mosgiel

Mosgiel has limited exposure to flood hazard from the Silver Stream, Owhiro Stream, Quarry Creek and from internal ponding. Because of its elevation, Mosgiel is not affected by the flood hazard of the Taieri River or the operation (or in-operation) of the Upper and Lower Ponds or by sea level. Part of the area was flooded in 1868 and 1923 (Figure 4.1).

Flood banks are located along the length of the Silver Stream, containing flows of 260m^3/s (the assessed peak flow of the April 2006 event) or more on the Mosgiel (southern) side. As noted above, flow over the true-right (northern) bank of the Silver Stream, downstream of Gordon Road, into Area 15 (thence Area 12), occurs when flows exceed about 170m^3/s (the assessed threshold flow for the April 2006 event) (Figure 4.26).

Surface flooding and run off from the eastern hills can cause localised ponding, as occurred in April 2006, especially in the industrial, southern part of the urban area, near Quarry Creek. Quarry Creek has a history of flooding (OCB, 1974). The extent of localised ponding within urban Mosgiel is determined in part by the stormwater network, which is designed to provide primary drainage to an urban standard.

Part of the area is located within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Area 21: Wingatui

Parts of this area are exposed to flood hazard from the Owhiro Stream and, to a lesser extent, Silver Stream and the hill catchments to the east. The Silver Stream is deeply incised at this location. The area lies within the East Taieri Drainage Scheme, which provides land drainage to a rural standard (ORC, 2012c).

Area 22: Flanks of coastal ranges

The flood hazards in this area are derived from the Owhiro Stream and the hill tributaries on its southern side. Flood hazard is mainly associated with overland flow and, in some places, the presence of an active, floodwater-dominant alluvial fan (Section 5). This area is sufficiently elevated not to be affected by the Taieri River or the Silver Stream.

5. Alluvial-fan hazard

An alluvial fan is an accumulation of river or stream (alluvial) sediments that form a sloping landform, shaped like an open fan or segment of a cone (Figure 5.1). They form where rivers or streams exit a valley, allowing sediment-laden flows to spread over a broad area. As these flows exit the confines of the valley, they lose energy, and their ability to carry sediment decreases. This results in the deposition of layer upon layer of sediment along the boundary of the hill slopes and valley floors. Figure 5.2 shows an example of an alluvial-fan feature on the Taieri Plains.

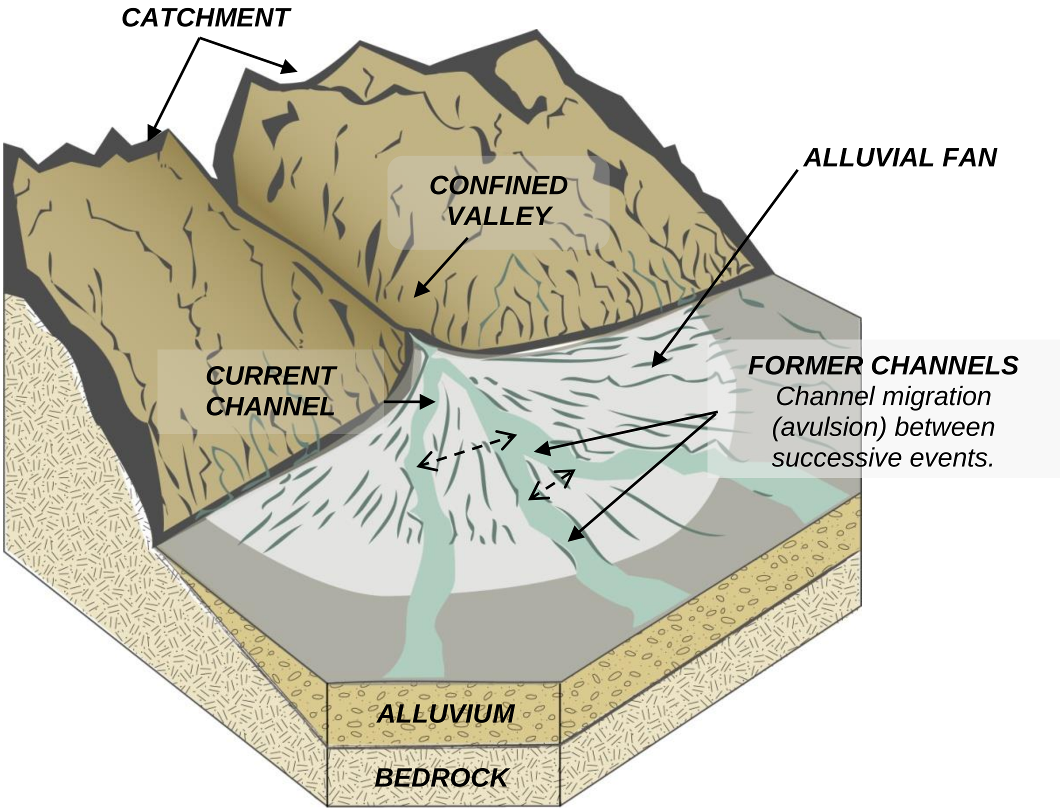

Figure 5.1 Stylised image of an alluvial fan.

Alluvial fans are composed of sediments derived from the rock and soils within the wider alluvial-fan catchment. While not part of the alluvial fan itself, the catchment plays an important role in initiating and sustaining alluvial-fan activity as it is the source of material for development of the fan. Water from the catchment flows downslope across the fan surface. Depending on the characteristics of the source catchment and the available sediment supply, these flows may also transport and deposit sediment down and across the alluvial fan.

Alluvial fans can experience long periods of inactivity, often from decades to centuries, only to re-activate due to extreme or unprecedented events, or due to environmental change (such as tectonic uplift or changes in the catchment sediment supply, climatic conditions and/or river/stream incision). Their often benign appearance between events does not give a full appreciation of their potential hazardous nature. On the Taieri Plains, fan streams are often ephemeral or inconspicuous, creating the impression that little or no hazard exists. In fact, these areas are often considered attractive places for development, with their elevated profile providing striking views and good on-site drainage. A limited understanding of alluvial-fan hazard may, therefore, lead to problems if these areas are preferred locations for development rather than areas with more obvious hazards (such as flooding across the surface of the plains).

Figure 5.2 Looking east across the lower reaches of an active floodwater-dominant alluvial fan that drains from the Maungatua Range (location of photograph is shown in Figure 5.3).

The main hazards associated with alluvial fans can include debris flow, debris flood, inundation by floodwater flow, sedimentation, erosion and/or channel migration across the fan (Opus, 2009).[15] These processes can impact on the long-term shape, elevation and characteristics of a fan surface and hence on how the surface of the fan is used. Furthermore, flood and debris flows generally occur suddenly without warning and can be unpredictable and destructive.

Alluvial-fan landforms throughout Otago, with a surface area greater than 0.5km^2, including the Taieri Plains (Figure 5.3), have been mapped (Opus, 2009). Alluvial fans on the Taieri Plains are most common along the margins of the basin where sediments have been deposited by streams draining the Maungatua, North Taieri and Titri fault scarps (Section 7) (Bishop and Turnbull, 1996). The fans located along the boundaries of the Titri and North Taieri faults are generally smaller and have experienced greater deformation than the Maungatua fans. This is probably a reflection of the higher elevation, the widely developed landslides, and the higher rainfall and erosion rates experienced along the Maungatua fault scarp (see Figure 7.1 for fault locations) (Barrell *et al*., 1998).

Fans have been classified based on the activity and type of depositional processes that have formed the fan surface, as these criteria reflect the scale and significance of the hazard.

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[15] See the Glossary for further explanation of these and other terms used within this report.

Alluvial fans on the Taieri Plains are mainly floodwater-dominant alluvial fans, experiencing sheet and channel floods. No debris-dominant alluvial fans have been identified on the margins of the Taieri Plains.

Floodwater-dominated alluvial fans, like those on the Taieri Plains are characterised by water-dominated processes. During heavy rainfall, sediment-laden water from the alluvial-fan catchment is concentrated into channels flowing downslope, eventually crossing the alluvial-fan surface. Figure 3.6 shows the location of ephemeral swales on the north-eastern section of the Taieri Plain that act in this manner.[16] Larger watercourses and features, such as open drains, may also capture and re-direct this sheet-flow across the Taieri Plain. Where flow is unable to be contained within these channels (due to limited channel incision or high magnitude 'super-design' flow events), floodwater spreads laterally across the surface of the fan as sheet flow. As the fan's gradient reduces and the flows begin to lose velocity, fine sediment suspended in the flows is deposited across its surface.

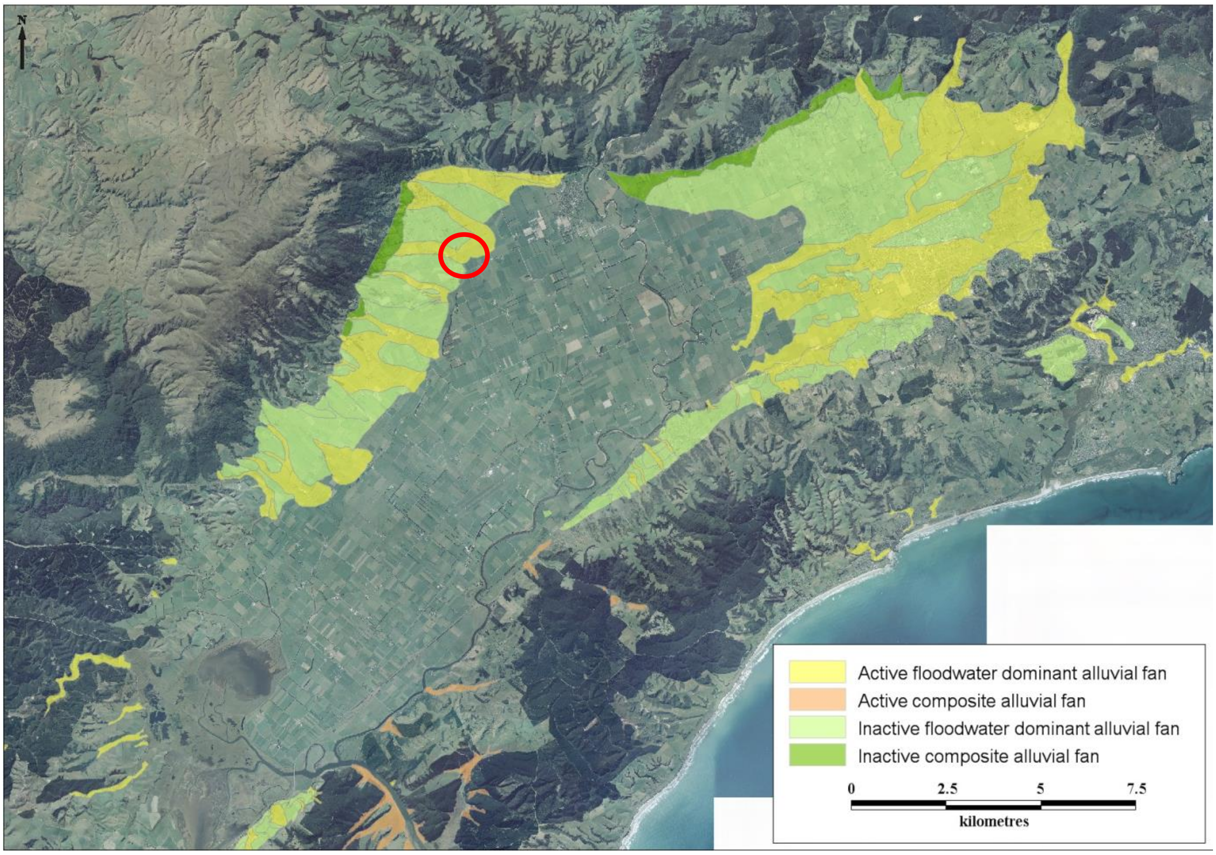

Figure 5.3 Alluvial-fan deposits greater than 0.5km^2 on the Taieri Plains (Opus 2009). The red circle indicates the approximate location of Figure 5.2.

The active floodwater-dominated alluvial fans on the east of the plains are those of Mill Creek, Silver Stream, Owhiro Stream, Quarry Creek, Gracie Stream and several smaller creeks that drain the hill catchments. They extend across areas of high-density, residential land use, including much of Mosgiel (Figure 5.3). Despite being identified as 'active' (Opus, 2009), there is little evidence of recent active sediment deposition across the fans, which may be due to a lack of recent storm events of sufficient magnitude to initiate alluvial fan activity,

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[16] Note that these features also exist elsewhere across the Taieri Plain (including the Mosgiel urban area), but they have not been mapped.

or to significant changes on the fan surface caused by human activity. Channels and open drains are now generally well incised into the fan surface, and the lower reaches of these fans have been modified due to changes in land use, stormwater and other works, such as the West Taieri Contour Channel (Figure 4.15).

Alluvial fans always present an element of hazard due to their unpredictability. They may continue to evolve in response to modifications to their upstream catchment (e.g. where changes in land use, landslide activity or earthquakes affect the availability of sediment) and changes in climate. Should long-term climate change bring about a change in rainfall intensity or storm frequency, this may affect alluvial-fan activity on the Taieri Plains.

6. Landslides

Landslides can take many forms and are widespread on the hills surrounding the Taieri Plains. Defined as ‘the movement of a mass of rock, debris or earth down a slope’ (Cruden, 1991), the term ‘landslide’ describes a variety of processes that result in the downward and outward movement of slope-forming materials, including rock, soil, artificial fill or a combination of these. The materials may move by falling, toppling, sliding, spreading or flowing, and may vary in size from a single boulder in a rock fall to large volumes of material in a debris avalanche.

The causes of slope movement can be quite complex, and include geologic, topographic and climatic factors. Slides have two things in common: they are the result of a failure of part of the soil and rock materials that make up the slope, and they are driven by gravity. Some slopes are predisposed to slope failure, with factors such as rock type, structure and steepness contributing to their overall susceptibility to failure (Saunders and Glassey, 2006).

Common natural triggers of landslides include prolonged or intense periods of rainfall (causing ground saturation), large earthquakes and the undercutting of banks by water, or any combination of these. Land-use activities and the alteration of the slope itself can also contribute to the occurrence of slope failures (Varnes, 1984). Although it is highly unusual for a particular landslide to be attributed to one definite cause, water is often identified as being the second most important factor in slope stability (next to gravity) (Varnes, 1984). Land which is inherently prone to movement may be more likely to experience landslides when heavy rainfall occurs, or when saturated by persistent wet conditions. The climate of an area can, therefore, play a role in the likelihood and extent of landslides.

Some areas on the margins of the Taieri Plains have a well-known history of slope failure. The combination of moderate to steep slopes, weak and unstable rock types and concentrated heavy rainfall events contribute to this hazard. The main types of landslide affecting the slopes that border the Taieri Plains are deep-seated slides and flows within bedrock, shallow surficial slides and slumps within loess or colluviums, long run-out debris flows, and rock fall or earth fall (Glassey *et al.*, 2003).

Landslide failures on the margins of the Taieri Plains include earth flows up to 100m wide on moderately steep (>20º) slopes that overlay schist, especially where the foliation dips downslope, providing planes of weakness along which sliding can take place (McKellar, 1990). A cluster of small landslides of this type occurs 1-2km east of Allanton on the scarp of the Titri Fault (Section 7) (McKellar, 1990). Landslide activity on the margins of the plains can also occur in areas where mudstone and siltstone are located within the sedimentary rock sequence. Shallow landslides can also occur within the upper-most layers of loess and regolith located on moderate to steep slopes bordering the plains.

Figure 6.1 shows landslide features on the margins of the Taieri Plains. The mapped landslides are a combination of slides mapped for various reports produced by GNS Science and its predecessors (Glassey and Smith-Lyttle, 2012) and properties identified within the Dunedin City Council Hazards Register (as at July 2012) as having been affected by landslide activity.

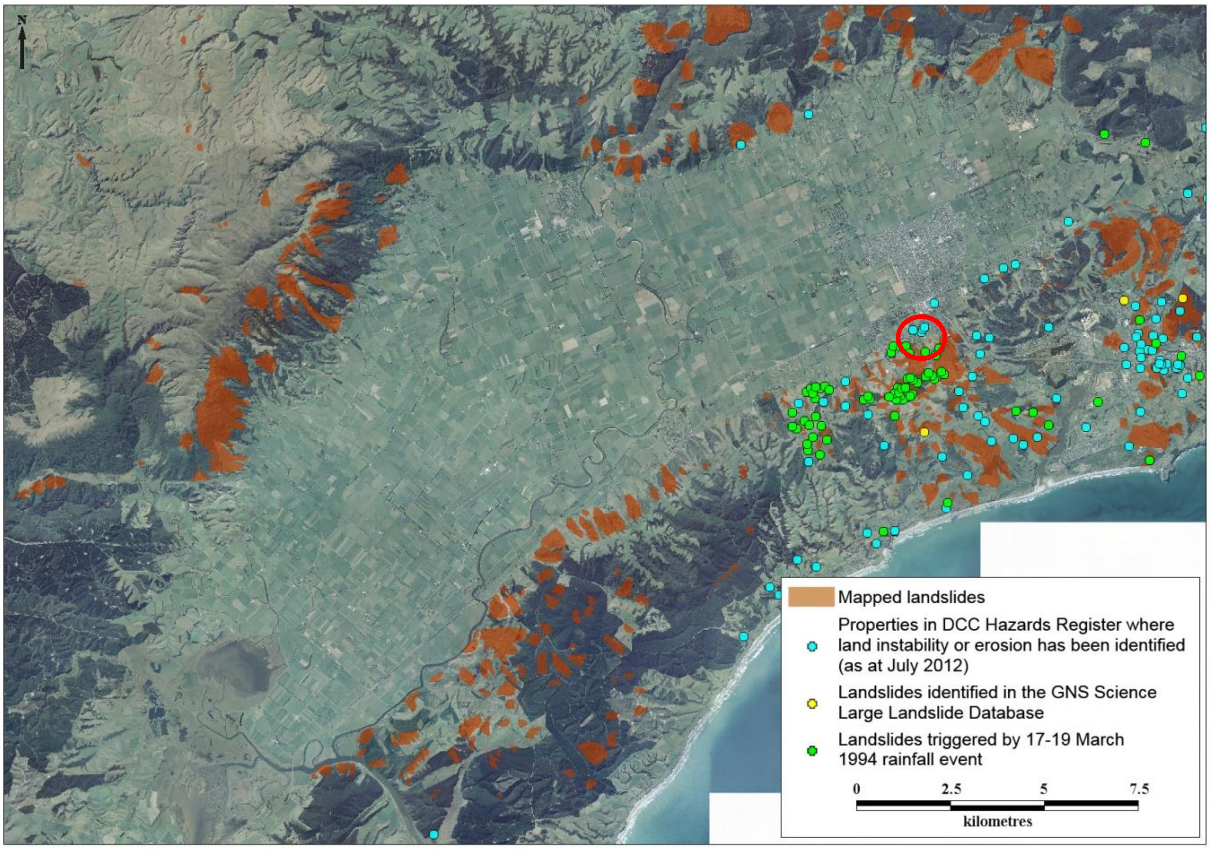

Figure 6.1 Mapped existing landslides surrounding the Taieri Plains. The red circle indicates the approximate location of Figure 6.3.

Saddle Hill - Scroggs Hill is an area where landslide activity has been closely observed, and has resulted from a range of different mechanisms (Figure 6.2). The susceptibility of the area was demonstrated during the March 1994 rainfall event, one of the most widespread landslide-inducing events to occur there in recent years. The same event caused high flows in the Silver Stream (Table 4.2) and probably also in other watercourses on the Taieri Plains. In the 48 hours from 17 March to 19 March 1994, between 104mm (Maungatua) and 150mm (Silver Stream at Riccarton Road) of rainfall was recorded on the Taieri Plains. Elsewhere in Dunedin, up to 225mm fell at Sullivan's Dam, and up to 200mm was anecdotally recorded by a local farmer on Saddle Hill (Stewart, 1996). A total of 186 landslides were recorded throughout the Dunedin area (including that part of the Taieri Plains and its margins as far south-west as Riverside Road and Allanton). Many more landslides probably occurred during this event but were not recorded, including those located away from built-up areas, which were concealed by vegetation, or those located beyond the mapped extent, such as the margins of the Maungatua Range.

The greatest concentration of recorded landslides during the 1994 event was in the Saddle Hill - Scroggs Hill area on the north-east margins of the Taieri Plains. A total 53 landslides were recorded on the northern face of this slope alone (Figure 6.1), with most failures occurring on angles between 15 to 25º. About two thirds occurred on former landslides that had already been identified (McKellar, 1990).

Figure 6.2 Evidence of historic landslides on the northern flanks of Saddle Hill. The cap of the hill is covered in resistant Dunedin volcanic rock, underlain by Henley Breccia. Source: GNS Science

Figure 6.3 Landslip on East Taieri after heavy rainfall on 19 March, 1994. The location of the photograph is shown in Figure 6.1.

Landslides can enhance the presence of an existing hazard with direct and indirect consequences, such as by supplying additional sediment to an alluvial-fan system or increasing the sediment yield of a river, thereby reducing its capacity during floods. The true risk for the Taieri Plains is best determined on a site-specific basis, where all variables that may contribute to landslide processes and consequences can be adequately identified.

7. Seismic hazard

Earthquakes occurring locally and regionally present a risk to the Taieri Plains. Seismic risk, or the risk due to earthquakes, depends on the magnitude, frequency and nature of the earthquake, its distance from the subject area and the susceptibility of the underlying ground to seismic shaking. Seismic activity can generate direct and indirect effects, including ground shaking, surface rupture, liquefaction/settlement of soils, lateral spreading and landslides.

Dunedin (including the Taieri Plains) is considered to be located in one of the least seismically active areas in New Zealand (EQC, 1993). Located more than 250km from the main tectonic plate boundary of the South Island, the Alpine Fault, Dunedin has experienced ground-shaking intensities in excess of Modified Mercalli Intensity (MMI) 5 on seven occasions in the past 200 years.[17] The exposure of the area to seismic hazard originating from active faults (both known and unknown) located in and around the Otago region remains uncertain, however.

In April 1974, a magnitude 4.9 earthquake struck approximately 10km off the coast of Dunedin, at a depth of 12km. Due to the proximity of Dunedin to the epicentre of this event, ground shaking of MMI 6 was experienced throughout much of the city with felt intensities reaching up to MMI 7 in the worst-affected areas, primarily around South Dunedin. Although a relatively small magnitude event, about $250,000 (1974 value[18]) of damage was caused, providing a reminder that damaging events can occur in the Dunedin area. There appear to be no readily available records of effects on the Taieri Plains.

7.1 Known faults on the Taieri Plains

As noted in Section 3, the Taieri Plains lies in a graben formation, created by the reverse fault movement of the Maungatua, North Taieri and Titri fault systems (Figure 7.1). While the Akatore and Alpine faults are not located on the Taieri Plains, they also contribute significantly to the overall seismic risk of the plains and are therefore discussed in this report. The Akatore Fault is the most active fault system near the Taieri Plains and has been subject to numerous investigations, with its location and general characteristics reasonably well understood. The Alpine Fault is the largest, most prominent fault in the South Island, with a history of frequent (in geological terms) and large seismic events whose effects can be felt throughout much of island. A number of other nearby and offshore faults also exist within the vicinity of the Taieri Plains, including the Castle Hill Fault near Balclutha, the Waihemo Fault south of Oamaru, and the Takapu Fault which lies offshore and approximately parallel to the Akatore Fault (ORC, 2012a).

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[17] Refer Section 7.3 for a description of ground shaking and other effects likely to be associated with different levels on the MMI scale.

[18] The equivalent in 2012 would be $2.6 million (www.rbnz.govt.nz/statistics/0135595.html).

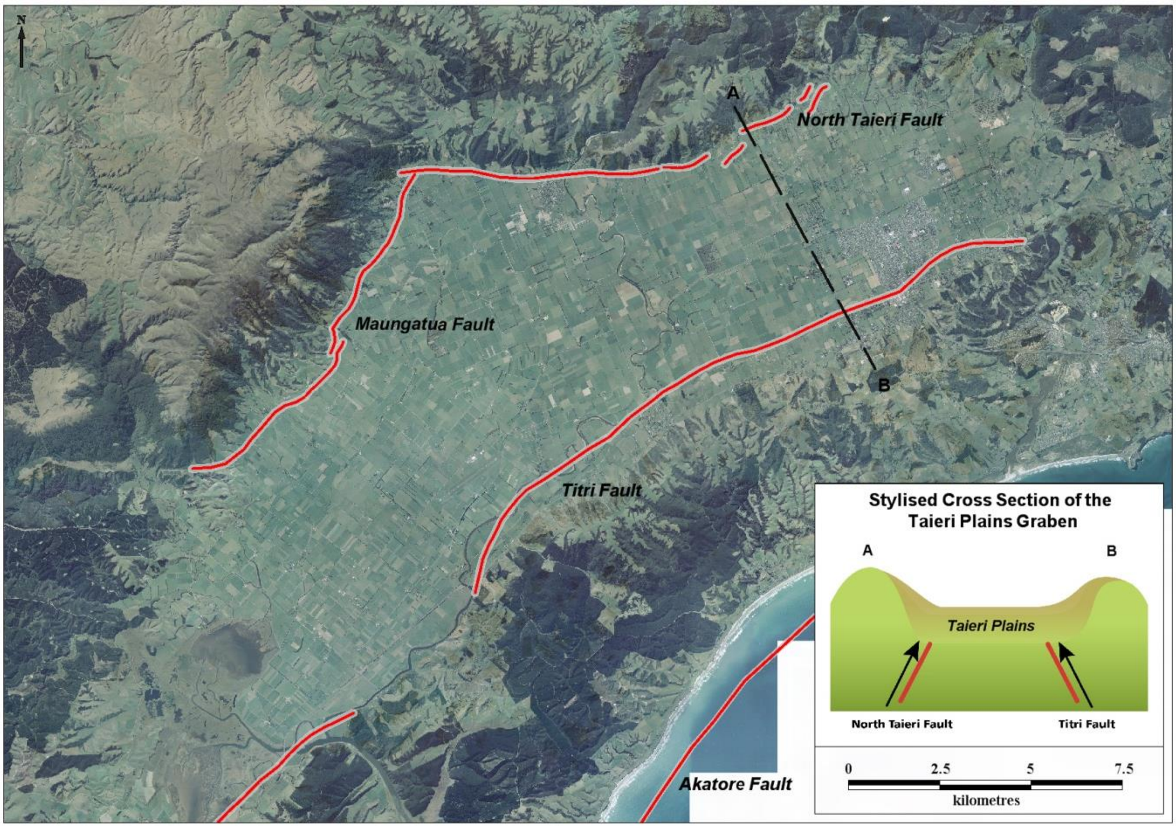

Figure 7.1 Active faults in the vicinity of the Taieri Plains (provided by GNS Science, 2012). A generalised cross section of a 'graben' formation is shown to the right (adapted from Irricon, 1994).

Akatore Fault

The Akatore Fault is located south of the Taieri Plains, off the coast of Taieri Mouth (Figure 7.1). The south-east dipping reverse fault has a rupture recurrence interval of between 2,000 and 3,000 years (Glassey *et al*., 2003; Opus, 2005), however records suggest this fault experiences episodic behavior[19], with two substantial ruptures in the past 4000 years but no ruptures in the 100,000 years prior (Norris and Nicolls, 2004). The most recent rupture is estimated to have occurred between 1350-1370AD, generating a vertical change in the order of 2-4m (Litchfield and Norris, 2000).

Deep and shallow surveys of the Akatore Fault system have identified a number of faults running parallel with it. Like the Akatore Fault, these faults strike northeast-southwest and dip south-eastward (Litchfield and Norris, 2000).[20] It is thought that the 4.9 magnitude earthquake located off the coast of Otago in 1974 resulted from movement along one of these parallel faults (Glassey *et al*., 2003).

Modelled earthquake scenarios for the Dunedin area most frequently cite the Akatore Fault as being the source of the maximum credible earthquake likely to affect Dunedin. An earthquake event of magnitude 7.0 along this fault has been modelled to produce ground-

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[19] Episodic behavior is described by Norris and Nicolls (2004) as a situation where each fault within a set does not exhibit a semi-regular 'return period' between ruptures, but instead exhibits periods of activity (ie., a cluster of events) interspersed with long periods of quiescence during which displacement is accommodated on neighboring faults.

[20] The location of offshore faults is often difficult to determine precisely.

shaking intensities on the Taieri Plains of up to 8 on the MMI scale (Opus, 2005).[21] Ground-shaking intensities of up to MMI 9 during such an event are considered possible by other authors (Glassey, *et al.*, 2003). Such an event is estimated to have a return period of approximately 3,000 years.

Offshore local faults, such as the Akatore Fault, the Takapu Fault or other unmapped or unknown faults, could potentially generate localised tsunamis (NIWA, 2007). The tsunami hazard for the Taieri Plains is further discussed in Section 8.

Alpine Fault

The Alpine Fault is one of New Zealand's most prominent fault lines, with a long history of movement. Although located on the margins of Otago and some distance from the Taieri Plains, the Alpine Fault contributes to the overall seismicity of the region (Opus, 2005). On average, Dunedin experiences five to six earthquakes annually, with felt intensities of MMI 4 to 5 (Appendix 3). Historically, these earthquakes have most commonly being centered off Fiordland; however, recent seismic activity in the Canterbury region has provided a second, reasonably frequent source of shaking.

Movement of the Alpine Fault has an average recurrence interval of 300 years (Glassey *et al.*, 2003), with the last known event occurring in 1717AD (Sutherland *et al.*, 2007). There is also evidence to suggest that this fault ruptured in 1620 and 1430AD, with both of these events producing an earthquake in the order of magnitude 8 (Sutherland *et al.*, 2007). It is anticipated that the next large event along this fault will result in 8m of lateral displacement, which is the equivalent shaking intensity of MMI 5 for the Taieri area (Opus, 2005).[22] This would be felt by most people, with unsecured objects becoming dislodged and potentially falling (Appendix 3).

Titri Fault

The Titri Fault system[23] is located on the south-east margin of the Taieri Plains (Figure 7.1). The south-east dipping reverse fault has a recurrence interval of between 70-80,000 years and last ruptured about 40-70,000 years ago (Opus, 2005; Norris and Nicolls, 2004).

The Titri Fault is responsible for the uplift of the coastal hills that separate the Taieri Plains from the coast (Barrell *et al.*, 1999; Glassey *et al.*, 2003; Norris and Nicolls, 2004). Rising between 200 to 450m in height, the rate of uplift along this fault is estimated to be no greater than 0.2mm per year[24]. This low rate is consistent with the mature landforms of the coastal hills which imply a relatively old landscape (Barrell *et al.*, 1999).

The alluvial fans located along the Titri Fault scarp provide clues to the historical movements of this fault (Figure 5.3). Deformation of older fans and fan deposits suggest that Quaternary movement occurred there. The absence of any deformation of the youngest alluvial fans, however, suggests that the fault did not rupture during the Holocene (Litchfield, 2001). A

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[21] Section 7.3 and Appendix 3 provide additional explanation of the MMI scale.

[22] There is some discrepancy in the estimated shaking intensities likely to be experienced from a magnitude 8 earthquake on the Alpine Fault, with other work suggesting that such an event will result in a shaking intensity of MM8 in Dunedin (Glassey *et al.*, 2003).

[23] Geological mapping and seismic reflection profiles show that the fault system is composed of a master fault and frontal, Quaternary-active strands (Litchfield, 2001).

[24] This rate of rise assumes the past 100,000 years is representative of the long term trend along this fault, and should therefore be regarded as tentative only (Barrell *et al.*, 1999)

continuous profile of Waihola sand/silt across the master fault further suggests that no Holocene activity has occurred along the fault.

The Titri Fault is probably a less likely local earthquake source than the Akatore and Alpine faults (Glassey *et al*., 2003).

Maungatua and North Taieri

The Maungatua and North Taieri faults are located to the north of the Taieri Basin (Figure 7.1). The north-northwest dipping faults are responsible for the uplift of the Maungatua hill catchment that bounds the Taieri Plains to the north (Litchfield *et al*., 2002).

Little is known about the Maungatua and North Taieri faults or their recurrence interval. Evidence suggests that the North Taieri fault has experienced some Quaternary activity, or activity within the past 1.8 million years (Barrel *et al*., 1998).

7.2 Surface-fault rupture

Surface-fault rupture hazard is associated with the potential for surface displacement along active faults, and, therefore is confined to a relatively narrow corridor where a fault meets the land surface. The total surface-fault displacement predicted for the faults in the immediate vicinity of the Taieri Plains is up to 2.3m for both the Titri and Akatore faults (Figure 7.1) (Opus, 2005).[25] Depending on the type of fault and the depth and nature of the surface soils, the land surface may displace horizontally and/or vertically (Figure 7.2). The length of displacement (i.e. the distance that the horizontal and/or vertical displacement will extend for) varies, based on the characteristics of the earthquake, and can range from tens to hundreds of kilometres.

Surface-fault rupture can cause extensive damage to structures and features located across them, such as flood banks, drainage channels,[26] dwellings, transport networks and utilities. Sometimes ruptures will deviate around heavy structures, such as large concrete buildings, because of the effect of the additional pressure of confining soils (NZGS, 2010). The precise location of the faults on the Taieri Plains is not known; however the inferred location (based on mapping completed at a 1:250,000 scale) suggests that they are largely located on the margins of the Taieri Plains. The south-eastern part of Mosgiel, small sections of SH1 and SH87 and the South Island Main Trunk Railway may be located along, or cross, these faults, along with the Taieri River, near Henley Ferry (Figure 7.1).

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[25] Information about the North Taieri and Maungatua faults is limited.

[26] The drainage channels of the West Taieri and East Taieri Drainage Schemes have a total length of 270km. Effective drainage of the Taieri Plains also relies on drainage channels owned and maintained by landholders and the roading authority (Dunedin City Council).

Figure 7.2 Example of surface-fault rupture near Darfield after the Darfield magnitude 7.1 earthquake, September 2010. An average displacement of 2.5m was recorded along this fault (Quigley, *et al*., 2011). (Photograph source, GNS Science).

7.3 Ground shaking

Ground shaking is one of the principal effects causing damage during a seismic event and is also the most recognised as people tend to feel it.

The intensity of ground shaking at a given location during an earthquake depends on many factors, such as the distance from the earthquake’s focus, the magnitude of the event and the underlying geology (NZGS, 2010). Soft ground, such as sandy or silty sediments, like that on much of the Taieri Plains, tends to amplify ground shaking (DPM, 2007). The impact on people and the environment, both built and natural, is greater with stronger shaking intensities.

Ground shaking hazard is often assessed based on the MMI scale. The MMI scale measures the intensity of shaking at a location by the effect that it has on people and the natural and built environment (Opus, 2005). A descriptive MMI scale is provided in Appendix 3.

Opus (2005) modelled the possible ground shaking intensities of four credible earthquake events in the Otago region: a magnitude 8.0 earthquake on the Alpine Fault, and a magnitude 7.0 earthquake on the North Dunstan, South Dunstan and Akatore Faults. Of the modelled events, a magnitude 7.0 event on the Akatore Fault is likely to generate the greatest ground-shaking intensities on the Taieri Plains, with a predicted MMI of between 8 (Opus, 2005) and 9 (Glassey, *et al*., 2003). The effects of these levels of ground shaking would include alarm (approaching panic) among many people, liquefaction and ground settlement and heavy damage to older buildings.

7.4 Liquefaction, settlement of soils and lateral spreading

Liquefaction occurs when saturated fine-grained sediments (such as sand and silt) are subjected to high-intensity shaking, losing their ability to stay cohesive. Intense shaking during an earthquake causes the sediments to compress, increasing the pore-water pressure and decreasing the shear strength of the soil (Norris *et al*., 1999). Liquefaction commonly occurs in saturated, loose sands and silty sands (Opus, 2005). A high ground-water table is also necessary. Loose, granular material, such as sands and gravels on sites with deep groundwater levels, will not liquefy but may settle as a result of seismic shaking (Opus, 2005).

Due to its composition of largely soft, unconsolidated sediment, and relatively high water table, areas of the Taieri Plains are likely to experience liquefaction during a seismic event that generates sufficient ground-shaking intensities (Figure 7.3). No significant liquefaction is expected for shaking intensities below MMI 6.

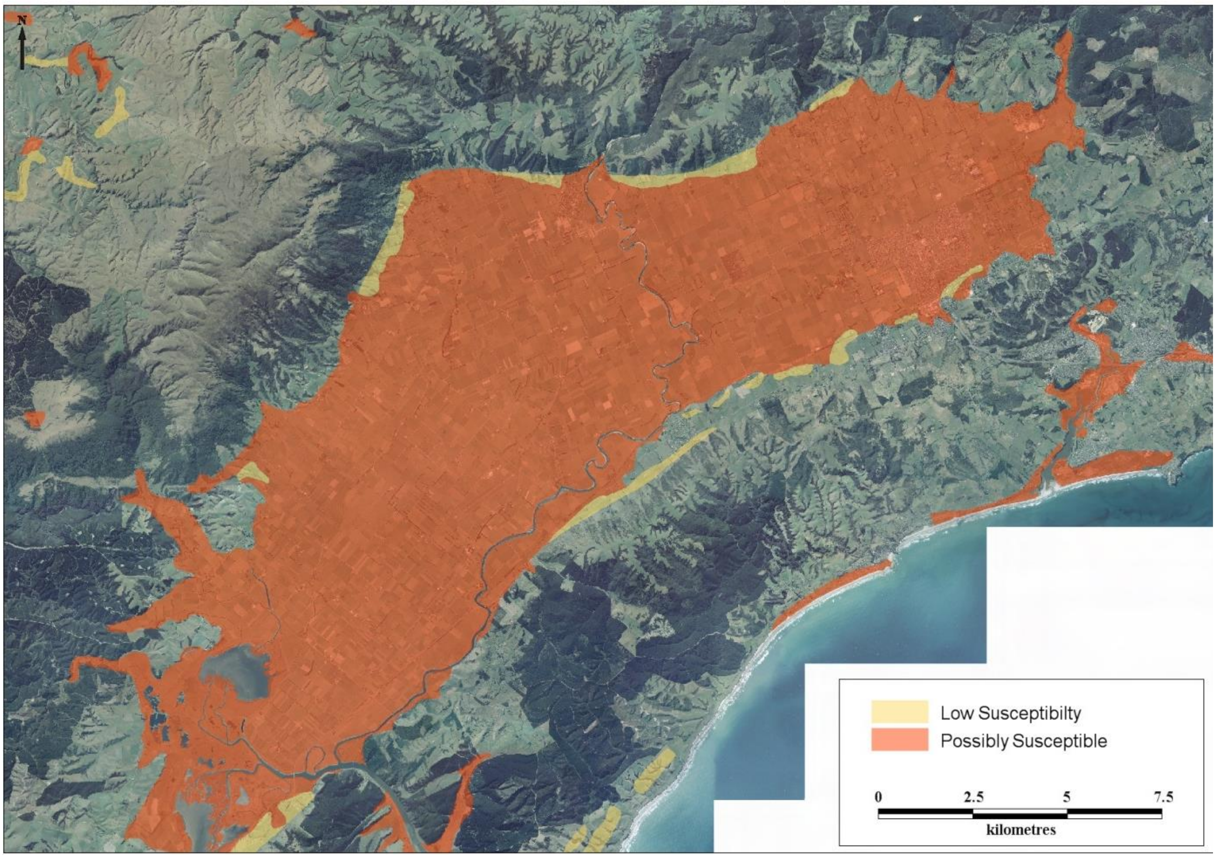

Figure 7.3 Susceptibility to liquefaction hazard on the Taieri Plains.

The susceptibility to liquefaction is shown in Figure 7.3, based on the nature and density of the underlying soils.[27] Areas defined as 'possibly susceptible' to liquefaction include those with very loose- to medium-dense sediments, where liquefaction is considered possible, with felt-shaking intensity of between MMI 6 to MMI 7. Areas considered to have a 'low susceptibility' include those containing denser, firmer sediments, where liquefaction and settlement are unlikely, but they may experience localised liquefaction during a large seismic event with felt-shaking intensities of MMI 8 or greater. The boundaries of these areas should be considered indicative only, as the nature and density of the soils was determined using geological mapping completed at a scale of 1:250,000 (Figure 3.1). Further investigations into the geological and groundwater characteristics of the Taieri Plains and the interaction of these characteristics would be needed to refine these boundaries and define the susceptibility and potential severity of liquefaction in this area.

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[27] The ground classification was assigned using the proposed draft Australia/New Zealand Loading Standard AS/NZS 1170.4 as the document had not been finalised at the time of the seismic investigation. This document has now been superseded by New Zealand Structural Design Actions, NZS 1170.5:2004.

Severe, widespread liquefaction can result in the loss of ground strength and load-bearing capacity. Surface structures, such as buildings, may settle and tilt, and buried structures, such as pipes and tanks, may 'float' to the surface (Norris *et al.*, 1999). Areas located on gentle slopes and/or in the vicinity of streams or rivers (or similar areas with a 'free face', such as open drains) can begin to slide laterally towards these features on the liquefied soils, a process known as 'lateral spreading' (Figure 7.4). Lateral spreading can severely damage structures such as buildings and pipes that span their surface and flood banks that are parallel to the edge of the ground that has moved.

Figure 7.4 Lateral spreading on the true-left bank of the Kaiapoi River, after the Christchurch magnitude 6.3 earthquake.

Observations of the Waimakariri Flood Protection Scheme in Canterbury, following the September 2010 earthquake on the Greendale Fault, identified two broad damage categories associated with floodbanks and river channels: foundation settlement, where the floodbank had been sited on poor ground; and longitudinal cracking due to lateral spreading (Figure 7.4). The latter was the dominant failure mode. These types of damage could also occur alongside the watercourses (including rivers, streams and open drains) that cross the Taieri Plains, should they be subjected to sufficient levels of seismic shaking. The effects of such lateral spreading would include damage to, or failure of, the flood banks and pump stations that prevent low-lying parts of the Taieri Plains from reverting to swamp.

As discussed in Section 3, damage to floodbanks and the Waipori Pump Station, even under extremely low-flow and tidal conditions, exposes a significant portion of West Taieri Plain to flooding due to the incursion of water from Lake Waipori (Figure 3.14). Observations following the September 2010 earthquake in Canterbury suggest that the effects of lateral spreading and liquefaction would probably render the Waipori Pump Station (Figure 3.13) inoperable for a prolonged period of time as it was not expressly designed for seismic response. The partial embedment of the station within the flood bank increases the likelihood of damage during a seismic event due to differential movement of the station and the flood bank. The risks and possible mitigation options are to be investigated (ORC, 2012c).

Figure 7.5 shows the likely ability of flood-bank foundations to survive a credible level of ground shaking during a seismic event. The event used to derive the information shown in Figure 7.5 was defined as a 'Maximum Design Earthquake' (MDE), estimated at 0.2g peak ground acceleration (i.e. how hard the earth shakes in a given geographic area). This is a slightly conservative estimate of the 500-year return period of seismic acceleration for the Taieri area (Tonkin & Taylor, 2005). The geotechnical evaluations that provided the information shown in Figure 7.5 suggest that the modelled seismic event could compromise many sections of the Lower Taieri Flood Protection Scheme flood banks (Tonkin & Taylor, 2005). The analysis was based on the Taieri River being at ‘normal’ rather than at flood levels. The graduations used in Figure 7.5 reflect the degree to which the flood-bank crest is likely to be compromised. The flood banks themselves are unlikely to deform to any great degree; the failure mode is mainly foundational (i.e. liquefaction/lateral spreading). Additional effects of lateral spreading, such as reduced-channel capacity (due to infilling and sedimentation), may further increase the risk of inundation after a significant seismic event, particularly during periods of higher than normal flow.

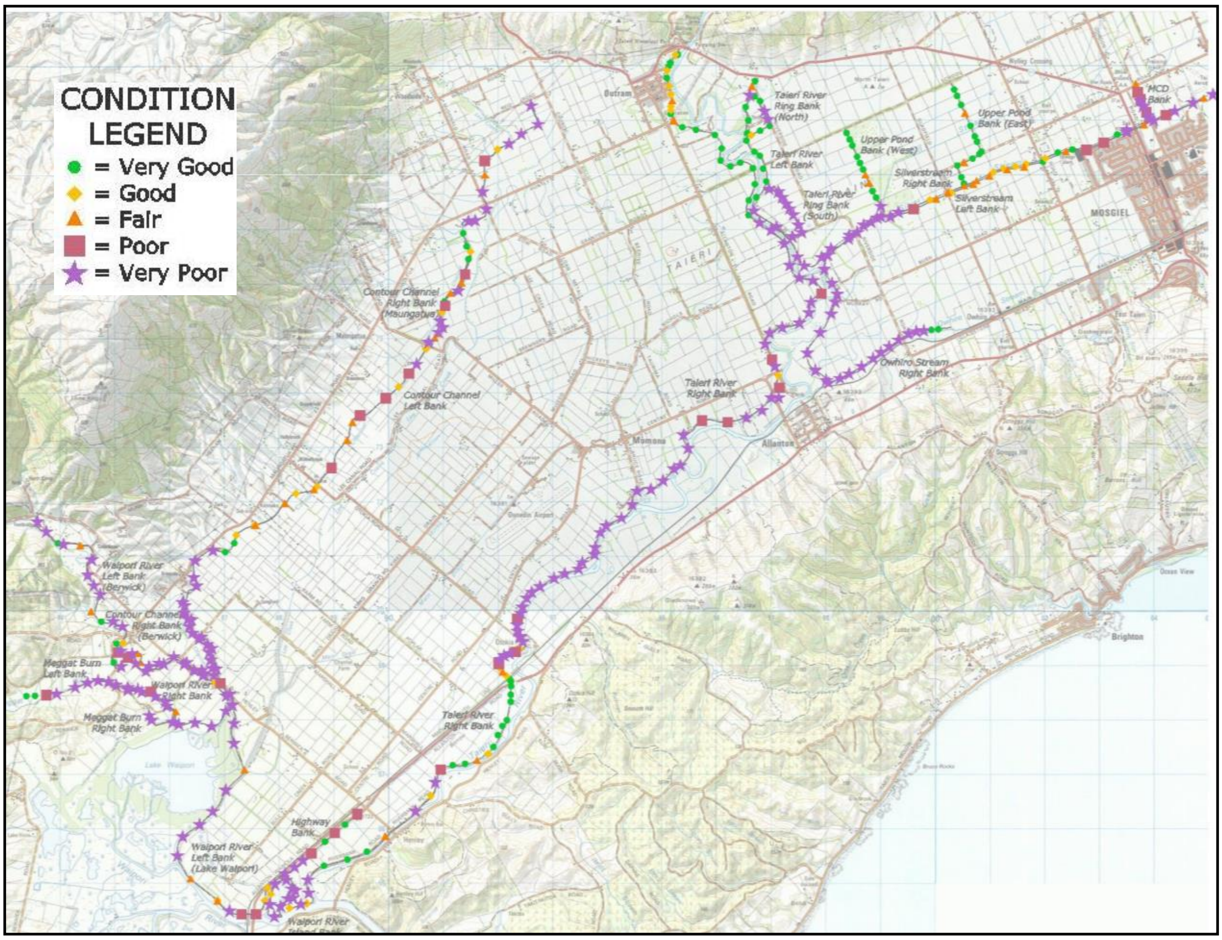

Figure 7.5 Seismic Performance Index of floodbanks on the Lower Taieri Flood Protection Scheme (Tonkin & Taylor, 2005).

7.5 Earthquake-induced landslides

A large earthquake, with sufficient ground shaking, could trigger the movement of existing landslides (as mapped in Figure 6.1) or generate areas of new movement on slopes with an existing marginal stability. It is difficult to determine where new landslides may be located; however, existing mapped landslides could provide some indication of areas that may be at greater risk of slope failure.

8. Tsunami hazard

The tsunami hazard on the lower, western part of the Taieri Plains is not well recognised, due to the ranges obscuring the Pacific Ocean from the Taieri Plains (Figure 3.3). However, this part of the plain is exposed to tsunami hazard from large events due to its low elevation.[28] The great Northern Chile earthquake in August 1868 caused a tsunami along the coast of Otago. The state of development of the Taieri Plains at that time is shown in Figure 2.1. Evidence suggests that the tsunami resulted in a sudden rise, followed by a sudden retreat of water on the Waipori River, as far upstream as lakes Waihola and Waipori, and on the Taieri River, as far upstream as the current SH1 bridge at Otokia (NIWA, 2007). This demonstrates that, despite the distance between the Otago coast and the Taieri Plains, risk exists for the low-lying areas of Henley, the Taieri River floodway and the margins of lakes Waipori and Waihola.

A tsunami is a natural phenomenon consisting of a series of waves that occur when a large mass of earth on the bottom of the ocean drops or rises, rapidly displacing the water above it (Saunders *et al*., 2011). The most likely source of tsunami events which may affect the Taieri Plains are large earthquakes (magnitude > 8), which cause a vertical displacement of the seabed along a fault line. Possible sources include distant (far-field) earthquakes around the perimeter of the Pacific Ocean; local (near-field) earthquakes on local, offshore faults, such as the Akatore Fault (Section 7); and nearby subduction zones, such as the Puysegur Trench to the south of South Island. Other possible causes of tsunami are volcanoes or underwater landslides (NIWA, 2007). As discussed in Section 7, a seismic event on a local, offshore fault could damage the flood banks on the Taieri Plains, increasing the vulnerability of parts of West Taieri to inundation from Lake Waipori and the lower part of the Waipori River.

The possible inundation extents for a range of credible tsunami scenarios, including near-field (Puysegur Trench) and far-field (South American) sources, have been modelled for the Otago coastline (NIWA, 2007). During such events, it is anticipated that a series of rapid fluctuations in water level would occur along the Lower Taieri Gorge. Figure 8.1 and Figure 8.2 show that land in the Henley Ferry area may be inundated by up to 1m, with water travelling upstream at speeds of up to 2 m/s. Any warning of rapid and large changes in water level, potentially carrying large amounts of debris, may be minimal or non-existent.

As discussed in Section 3, sea-level rise is predicted to accelerate during the 21st century (MfE, 2008). The scenarios were also assessed for a 0.3m and a 0.5m rise in sea level. The modelling completed for these scenarios showed greater inundation extents for each progressively higher sea-level rise scenario (Appendix 4). However, inundation remained largely contained within the existing lower floodway, between the confluence of the Taieri and Waipori rivers and downstream of Henley. The figures in Appendix 4 show that land may be inundated by up to 1.5m during the modelled tsunami events, if sea level were 0.5m higher than at present. The extent of inundation shown for all the modelled scenarios is based on the assumption that the seismic event generating the tsunami causes no damage to the flood banks that separate low-lying land from the Taieri and Waipori rivers.

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[28] The Taieri River is tidal at least as far upstream as Allanton, with lakes Waihola and Waipori also influenced by the rise and fall of the tide.

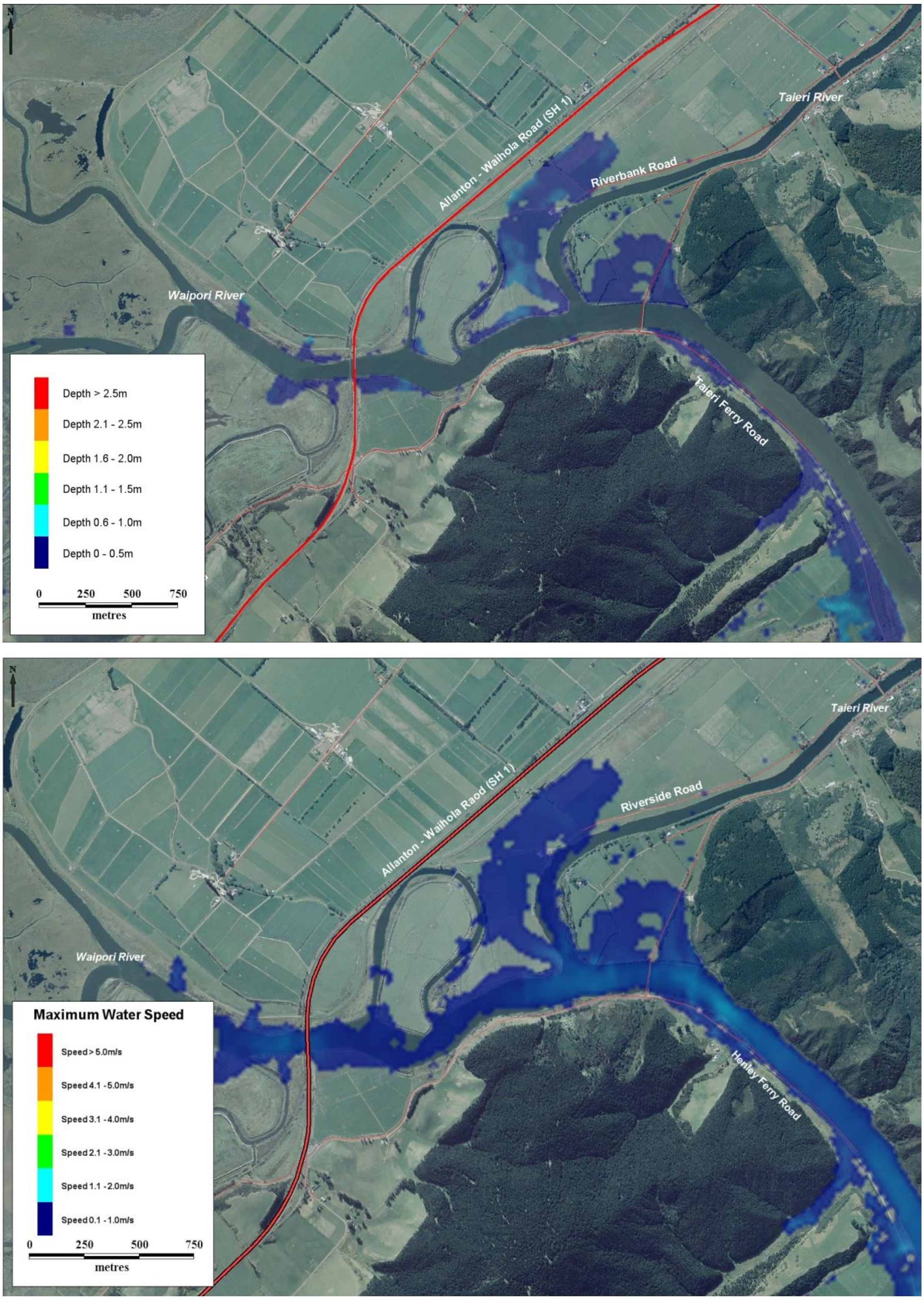

Figure 8.1 Maximum extent of inundation (top) and maximum water speed (bottom) at Henley Ferry during a modelled 1:500 year[29] far-field tsunami at MHWS (NIWA, 2007).

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[29] A return period was estimated by NIWA (2007) for each scenario. A ‘return period’ expresses the chance of an event occurring in any given year, regardless of when the last event of a similar magnitude occurred. For example, a 1:500-year event has a 0.2% chance of occurring in any given year, and an 18% chance of occurring in any 100-year period.

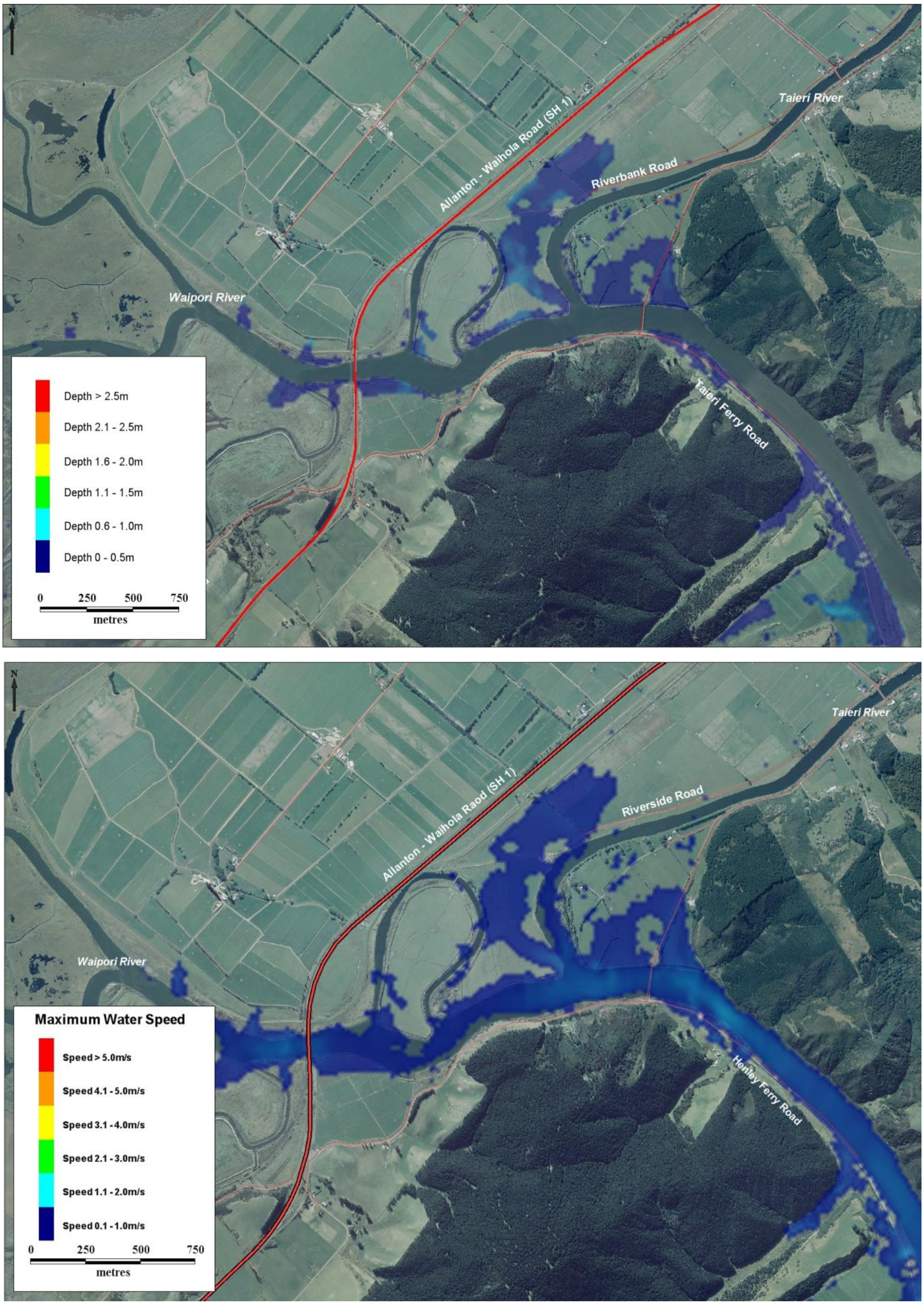

Figure 8.2 Maximum extent of inundation (top) and maximum water speed (bottom) at Henley Ferry during a modelled 1:600-year near-field (Puysegur) tsunami at MHWS (NIWA, 2007).

9. Conclusion

This report describes the current state of knowledge about natural hazards that could be experienced on the Taieri Plains: where their effects could be experienced, where they have actually been observed, and their characteristics. The report also describes the possible consequences of these hazards for those living on the Taieri Plains and for the wider community.

The report has shown that much of the Taieri Plains is vulnerable to some level of risk associated with one or more of these hazards (including flooding, alluvial fans, landslides, seismic activity and tsunami). The effects of a particular event will vary, however, depending on a range of factors, including antecedent conditions (such as soil-moisture levels and river flows), the location and magnitude of the event, the local topography and the effectiveness of any risk-reduction measures.

Therefore, any decisions on land use on the plains need to give careful consideration to the notion of residual risk to ensure that activities are compatible with the area’s hazard exposure. The intention of this report is to inform such decisions and other risk-reduction initiatives.

10. Glossary

***Aggradation*:** To raise the grade or level of the river bed primarily by depositing sediment accumulations.

Alluvial fan: Landforms that develop where a steep gully emerges from its confines onto a flatter valley floor, or at other sites where sediment accumulates in response to changes in stream gradient and/or width.

Antecedent: Preceding conditions.

Avulsion: The abandonment of a river channel and the establishment of a new channel at a lower elevation on its floodplain as a result of floodplain/channel *aggradation.*

Debris flow: A mass movement (often classified as a type of landslide) involving rapid (15-30km/hr) flow of debris containing coarse-grained, saturated material, confined in a steep channel and running out on to low-gradient fans and valley floors, often resulting from high intensity rainfall. Because of their high velocity (speeds faster than a human can run are common), high-density (like wet concrete) and entrained boulders, such flows are highly destructive and dangerous (Opus, 2009).

Debris flood: A very rapid (up to 5m/s), surging flow of water, heavily charged with debris (gravel, sand and silt), in a steep channel. A debris flood is not a landslide, but is a mass-transport phenomenon, with destructiveness similar to that of water, but less than debris flows. Objects impacted by debris floods are surrounded or buried by flood debris but are often largely undamaged. This is often the most common fan-building process on an *alluvial fan*. Debris flows and debris floods can occur during the same flood, with the latter often occurring in the initial and waning stages of an event (Opus, 2009).

Erosion: The wearing away of land-surface materials, especially rocks, sediments, and soils by the action of water, wind or a glacier. Usually erosion also involves the transport of eroded material from one place to another (GNS, 2009).

Graben: A portion of the earth's crust, bounded on at least two sides by faults, that has dropped downward in relation to adjacent portions.

Hazard: An unavoidable danger or threat to property and human life, resulting from naturally occurring events.

Holocene: One of two geological epochs within the Quaternary period. The Holocene refers to 10,000 years before present.

Incise: A stream or channel that has been down-cut or entrenched into a surface (Opus, 2009).

Lateral spread: The spread of sediments, often towards bodies of water such as a lake, as a result of seismically induced shaking.

***LiDAR*: Li**ght **D**etection and **R**anging is a mass of spot-height information captured over a wide area using an aircraft mounted laser. The Otago Regional Council's LiDAR dataset has a vertical accuracy of ±0.14m, and was collected in 2004.

Lifelines: The essential infrastructure and services that support life within a community, including utility services such as water, wastewater and storm water, electricity, gas, telecommunications and transportation networks, including road, rail, airports and ports

Liquefaction: The process by which sediments and soils collapse from a sudden loss of cohesion. Deposits lose strength after being transformed to a fluid mass, often by seismic shaking.

Longitudinal cracking: Ground cracking parallel to an edge, such as the edge of a drainage channel or river bank due to movement of the ground towards the unsupported edge (i.e. the river bank).

Mass movement: The downhill movement of surface materials under the influence of gravity, often induced or assisted by increased saturation of the slope.

Mean sea level (msl): The sum of average tides: the middle level between high and low tides. Current msl is relative to Dunedin Vertical Datum 1958 (DVD-58) + 12cm to account for sea-level rise since 1958 (DVD-58 is based on tide data collected in 1918, 1923-27, 1929, 1935 and 1937, with a mid-point year of approximately 1928).

Modified Mercalli Intensity: A measure of earthquake intensity by providing a descriptive list of effects based on the Richter scale of earthquake magnitude (Appendix 3).

Paleochannel: a remnant of an inactive river or stream channel. Paleochannels can be re-occupied by flowing water in response to heavy rainfall events or environmental change.

Peneplain: A relatively flat land surface produced by a long period of erosion.

Piping (risk/failure): The internal erosion of a mass of soil, due to seepage-flow forces exceeding the strength of the soil. The erosion creates a ‘pipe’, which causes an increase in seepage flow and can lead to rapid and sudden failure (usually collapse) of the soil mass.

Quaternary: The Quaternary Period is the most recent of the three periods of the Cenozoic Era in the geologic time scale. The 2.6 million years of the Quaternary represents the time during which humans have existed.

Regolith: The layer of loose material covering the bedrock of the earth, comprising soil, sand, rock fragments, volcanic ash, glacial drift.

Risk: The chance of something happening that will impact on objectives.

Schist: Medium- to coarse-grained metamorphic rock, composed of laminated, often flaky parallel layers.

Scroll plain: A floodplain with a meandering river that changes its course during flooding, leaving oxbow lakes and depressions that hold water for varying periods of time.

Seismic hazard: Hazards derived from effects of an earthquake.

Sedimentation: The deposition of sediment.

Spillway: A channel designed for the controlled and safe overflow of water.

Surface rupture: The displacement, upwards or across, of the earth's surface along a fault line, as a result of an earthquake.

Swale: Ephemeral drainage features which drain runoff following heavy rainfall.

Tidal range: The difference in height between consecutive high and low waters. The tidal range varies from a maximum during spring tides to a minimum during neap tides.

True-left river bank: The bank on the left-hand side of a person facing downstream.

True-right river bank: The bank on the right-hand side of a person facing downstream.

***Vulnerability*:** Liability or exposure to a hazard or disaster.

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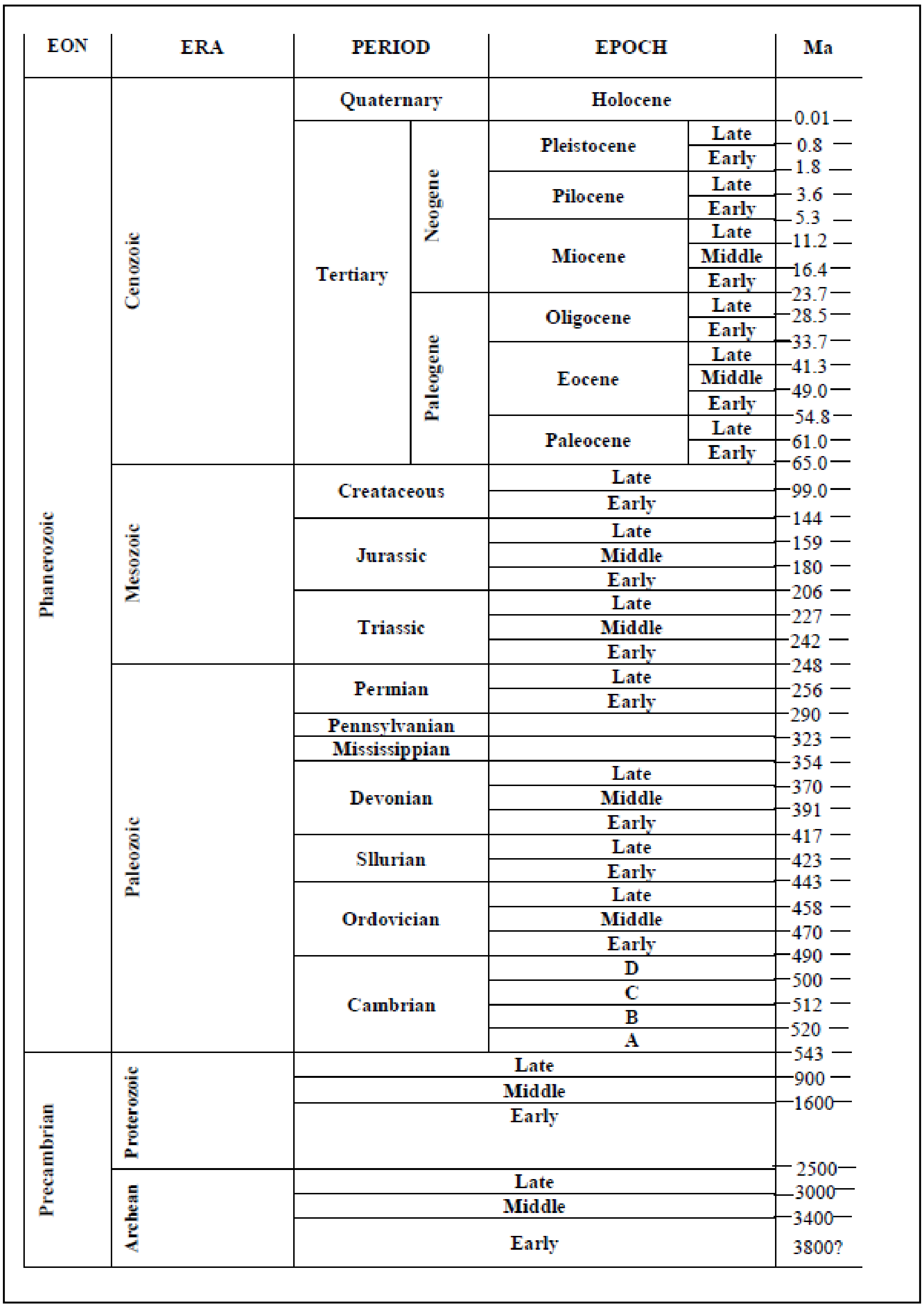
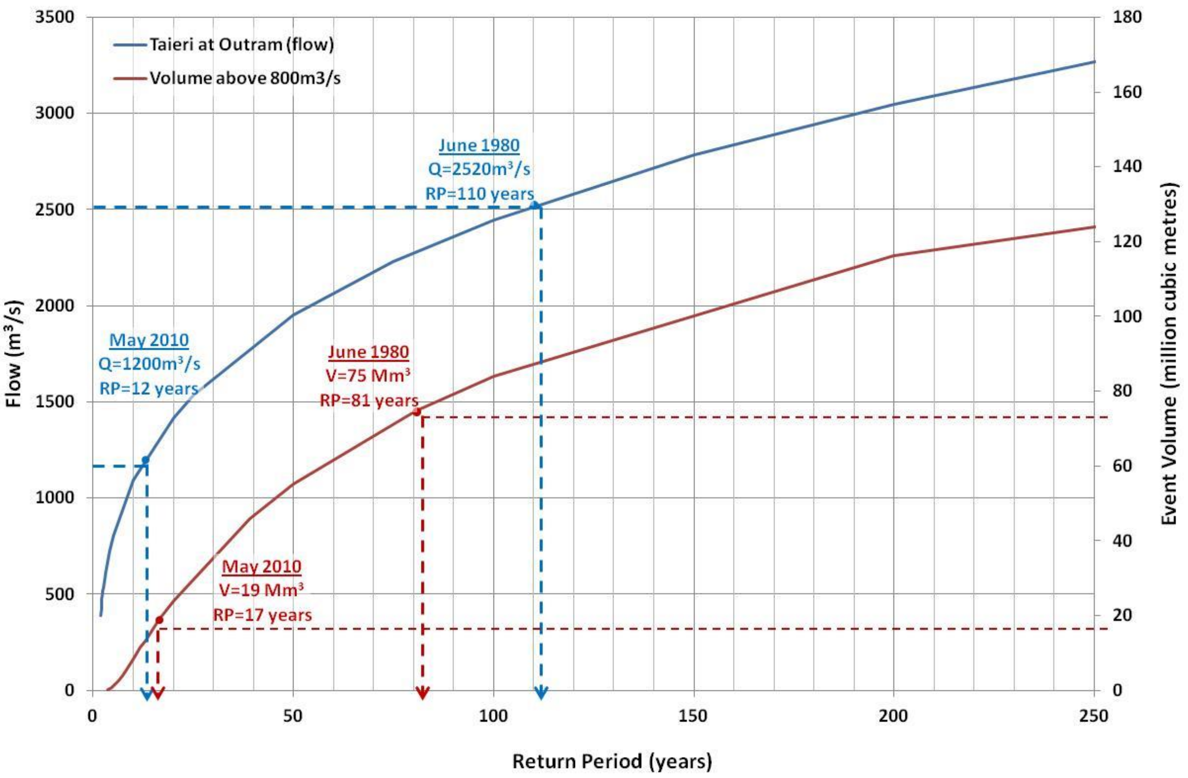
12. Appendices

Appendix 1 – Geological timeline



EON	ERA	PERIOD		EPOCH		Ma
Phanerozoic	Cenozoic	Quaternary		Holocene		0.01
		Tertiary	Neogene	Pleistocene	Late	0.8
					Early	1.8
				Pilocene	Late	3.6
					Early	5.3
				Miocene	Late	11.2
					Middle	16.4
					Early	23.7
			Paleogene	Oligocene	Late	28.5
					Early	33.7
				Eocene	Late	41.3
					Middle	49.0
					Early	54.8
				Paleocene	Late	61.0
					Early	65.0
	Mesozoic	Createaceous		Late		99.0
				Early		144
		Jurassic		Late		159
				Middle		180
				Early		206
		Triassic		Late		227
				Middle		242
				Early		248
	Paleozoic	Permian		Late		256
				Early		290
		Pennsylvanian				323
		Mississippian				354
		Devonian		Late		370
				Middle		391
				Early		417
		Silurian		Late		423
				Early		443
		Ordovician		Late		458
				Middle		470
				Early		490
		Cambrian		D		500
				C		512
				B		520
				A		543
Precambrian	Proterozoic	Late				900
		Middle				1600
		Early				2500
	Archean	Late				3000
		Middle				3400
		Early				3800?

Appendix 2 – Flood-storage frequency relationship for the East Taieri Upper Pond



Appendix 3 – Modified Mercalli Intensity Scale (Opus, 2005)

MMI
People
Not felt, except by a very few people under exceptionally favourable circumstances.

MMII
People
Felt by persons at rest, on upper floors or favourably placed.

MMIII
People
Felt indoors: Hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake

MMIV
People
Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be compared to the passing of a heavy traffic, or to the jolt of a heavy object falling or striking the building.

Fittings
Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock.

Structures
Walls and frames of buildings, and partitions and suspended ceilings in commercial buildings, may be heard to creak.

MMV
People
Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed.

Fittings
Small unstable objects are displaced or upset. Some glassware and crockery may be broken.
Hanging pictures knock against the wall.
Open doors may swing.
Cupboard doors secured by magnetic catches may open.
Pendulum clocks stop, start or change rate.

Structures
Some windows Type I cracked.
A few earthenware toilet fixtures cracked.

MMVI
People
Felt by all.
People and animals alarmed.

Many run outside.
Difficulty experienced in walking steadily

Fittings
Objects fall from shelves.
Pictures fall from walls.
Some furniture moved on smooth floors, some free-standing unsecured fireplaces moved.
Glassware and crockery broken.
Very unstable furniture overturned.
Small church and school bells ring.
Appliances move on bench and table tops.
Filing cabinets or easy-glide drawers may open (or shut).

Structures
Slight damage to Buildings Type I.
Some stucco or cement plaster falls.
Windows Type I broken.
Damage to a few weak domestic chimneys, some may fall.

Environment
Trees and bushes shake, or are heard to rustle.
Loose material may be dislodged from sloping ground (e.g. existing slides, talus slopes, shingle slides).

MMVII
People
General alarm.
Difficulty experienced in standing.
Noticed by motorcar drivers who may stop.

Fittings
Large bells ring.
Furniture moves on smooth floors, may move on carpeted floors.
Substantial damage to fragile contents of buildings.

Structures
Unreinforced stone and brick walls cracked
Buildings Type I cracked with some minor masonry falls.
A few instances of damage to Buildings Type II.
Unbraced parapets, unbraced brick gables and architectural ornaments fall.
Roofing tiles, especially ridge tiles, may be dislodged.
Many unreinforced domestic chimneys damaged, often falling from the roof-line.
Water tanks Type I burst.
A few instances of damage to brick veneers and plaster or cement-based linings.
Unrestrained water cylinders (water tanks Type II) may move and leak.
Some windows Type II cracked.
Suspended ceilings damaged.

Environment
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.
Instances of settlement of unconsolidated, wet or weak soils.
Some fine cracks appear in sloping ground.
A few instances of liquefaction (i.e. small water and sand ejections).

MMVIII
People
Alarm may approach panic.
Steering of motor cars greatly affected.

Structures
Building Type 1 heavily damaged, some collapse.
Buildings Type II damaged, some with partial collapse.
Buildings Type III damaged in some cases.
A few instances of damage to Structures Type IV.
Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down.
Some pre-1965 infill masonry panels damaged.
A few post-1980 brick veneers damaged.
Decayed timber piles of houses damaged.
Houses not secured to foundations may move.
Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment
Cracks appear on steep slopes and in wet ground.
Small to moderate slides in roadside cuttings and unsupported excavations.
Small water and sand ejections and localised lateral spreading beside streams, canals, lakes etc.

MMIX
Structures
Many Buildings Type I destroyed.
Buildings Type II heavily damaged; some collapse.
Buildings Type III damaged; some with partial collapse.
Structures Type IV damaged in some cases; some with flexible frames seriously damaged.
Damage or permanent distortion to some Structures Type V.
Houses not secured to foundations shifted off.
Brick veneers fall and expose frames.

Environment
Cracking of ground conspicuous.
Landsliding general on steep slopes.
Liquefaction effects intensified and more widespread, with large lateral spreading and flow sliding beside streams, canals, lakes etc.

MMX
Structures
Most Buildings Type I destroyed.

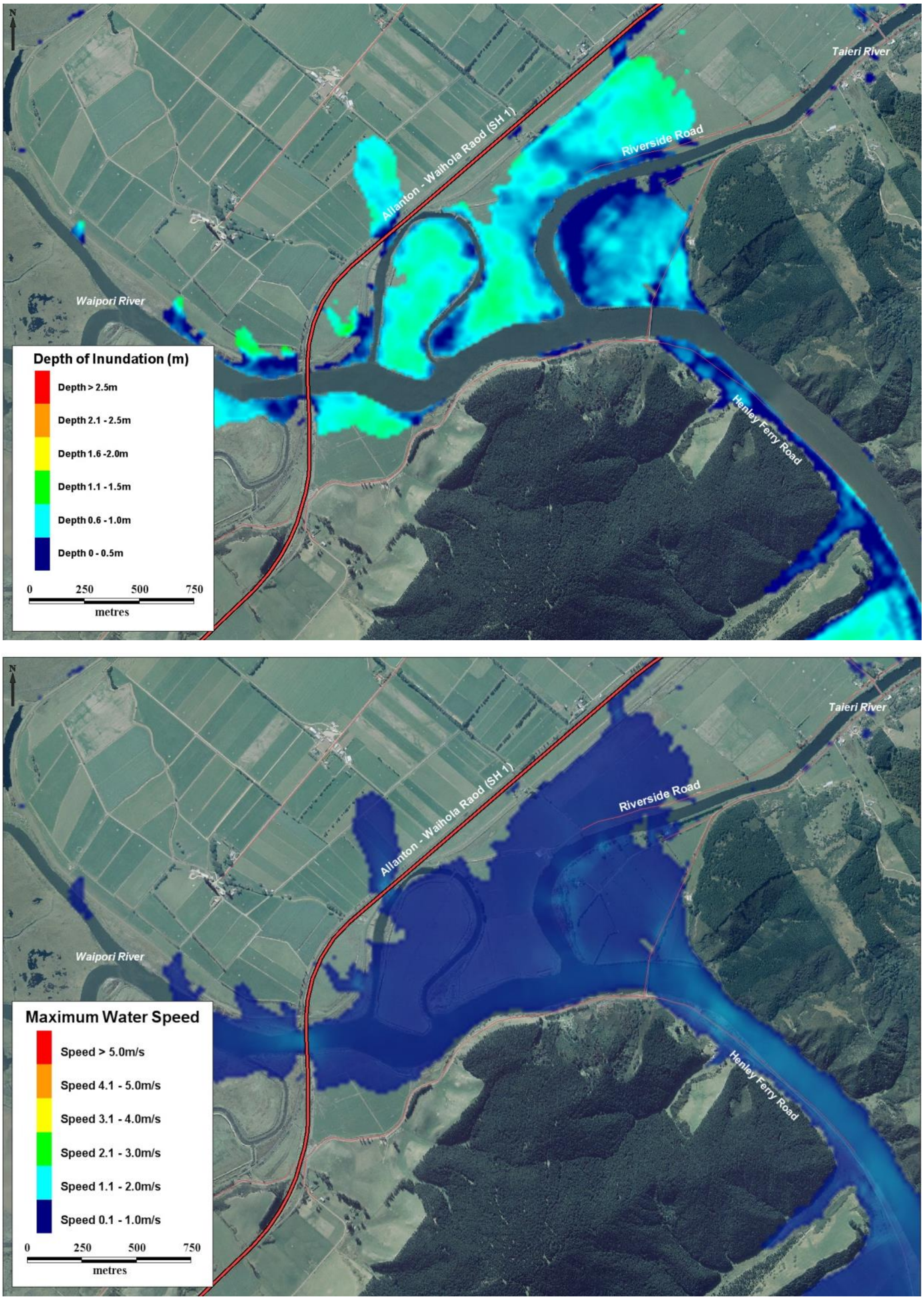
Many Buildings Type II destroyed.
Buildings Type III heavily damaged; some collapse.
Structures Type IV damaged; some with partial collapse.
Structures Type V moderately damaged, but with few partial collapses.
A few instances of damage to Structures Type VI.
Some well-built timber buildings moderately damaged (excluding damage from falling chimneys).

Environment
Landsliding very widespread in susceptible terrain, with very large rock masses displaced on steep slopes.
Landslide dams may be formed.
Liquefaction effects widespread and severe.

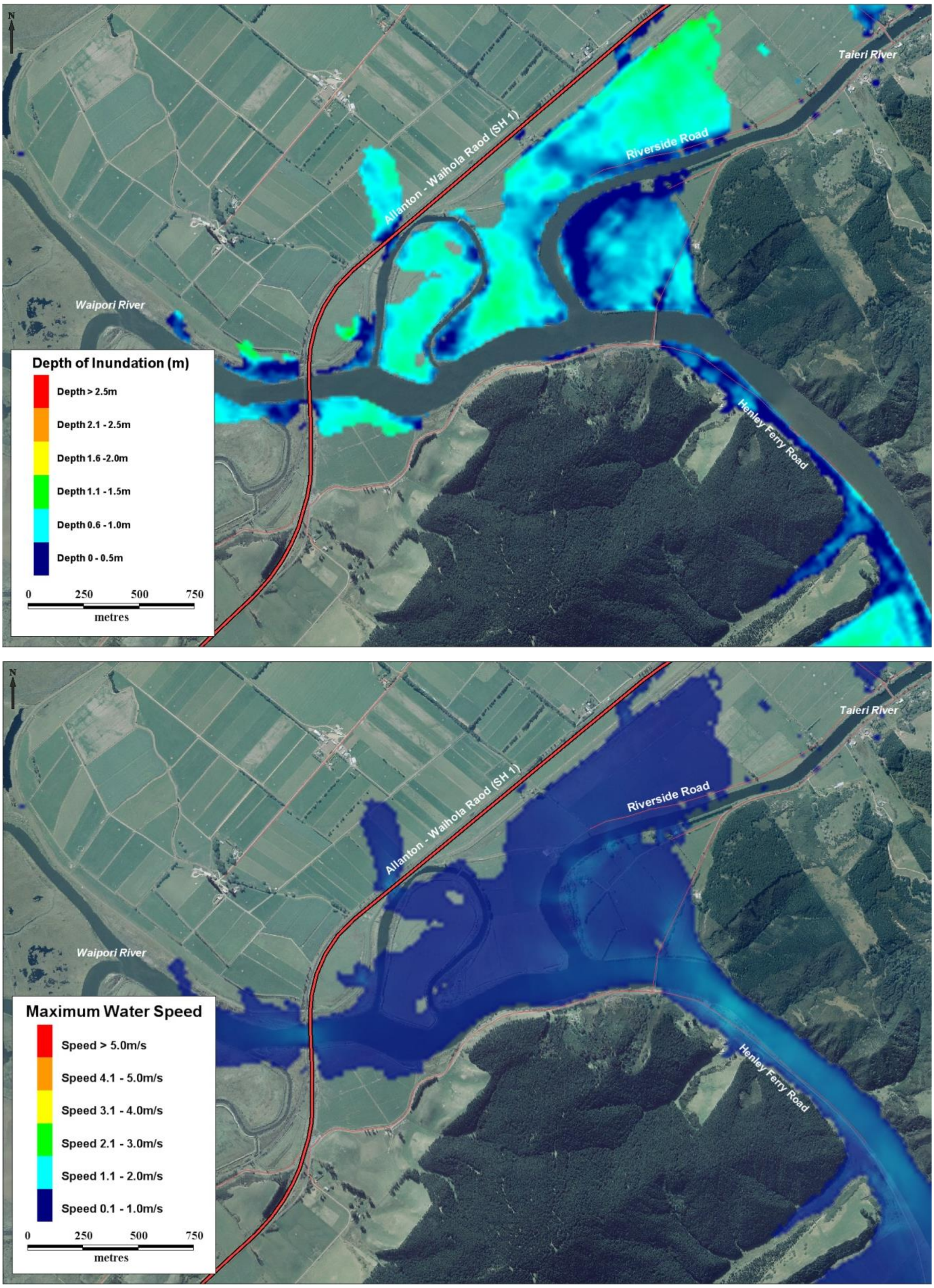
MMXI
Structures
Most Buildings Type II destroyed.
Many Buildings Type III destroyed.
Structures Type IV heavily damaged; some collapse.
Structures Type V damaged; some with partial collapse.
Structures Type VI suffer minor damage; a few moderately damaged.

MMXII
Structures
Most Buildings Type III destroyed.
Many Structures Type IV destroyed.
Structure Type V heavily damaged; some with partial collapse.
Structures Type VI moderately damaged.

Appendix 4 – Modelled tsunami-inundation extents – 50cm rise in sea level



Maximum extent of inundation (top) and maximum water speed (bottom) at Henley Ferry during a modelled 1:600-year near-field (Puysegur Trench) tsunami, with a base sea level 0.5 m higher than present day levels (NIWA, 2007).



Maximum extent of inundation (top) and maximum water speed (bottom) at Henley Ferry during a modelled 1:500-year far-field (South American) tsunami, with a base sea level 0.5 m higher than present day levels (NIWA, 2007).