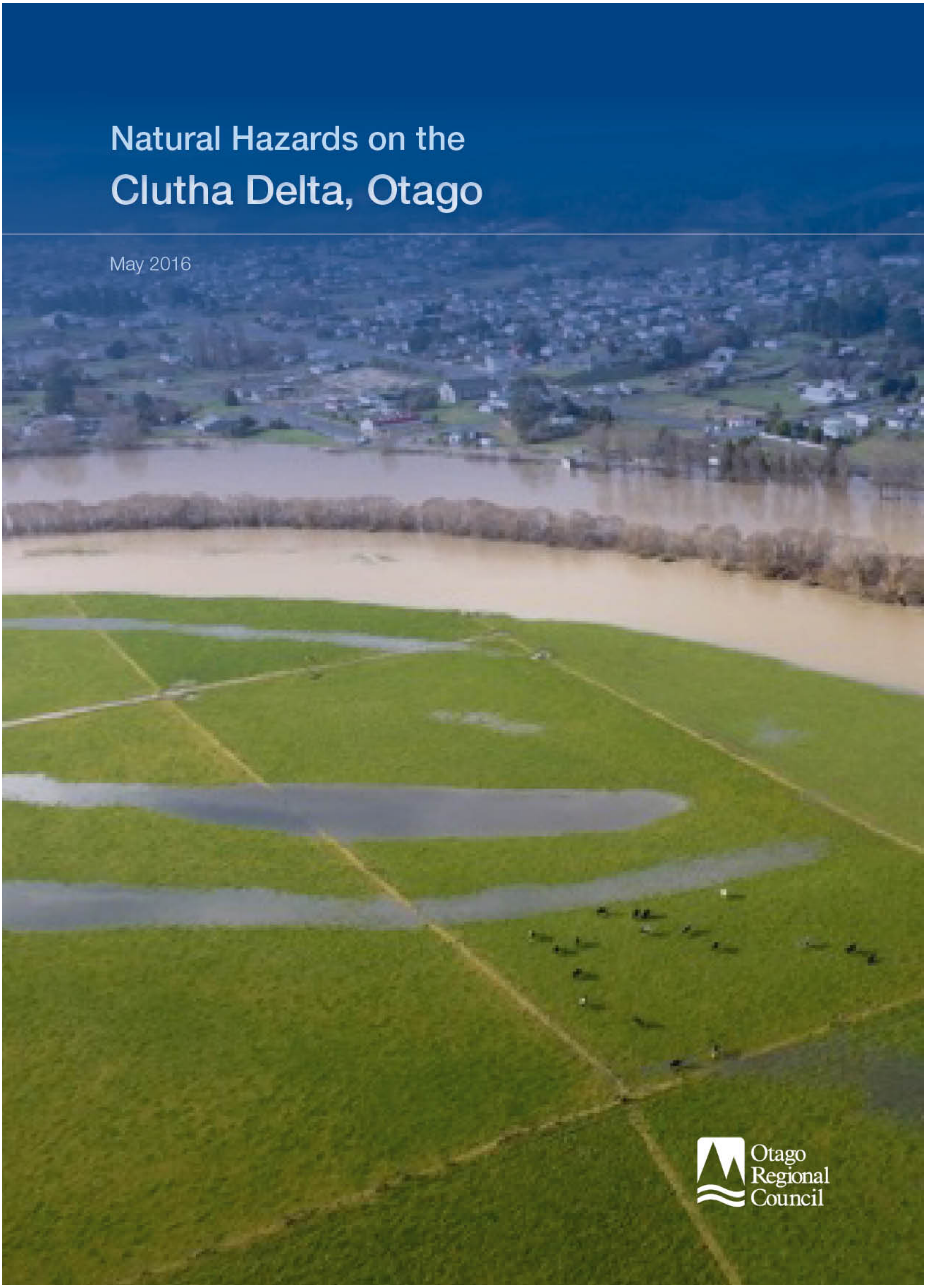
Natural Hazards on the Clutha Delta, Otago

May 2016



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ISBN 978-0-908324-33-0

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Published May 2016

Cover image:	The lower Clutha Delta in flood (looking from Kaitangata towards Paretai) 15 October 1978.

Executive summary

The Clutha Delta is a low lying alluvium-filled basin, approximately 130 km^2 in size, surrounded by rolling hills to the north, east and west, and Molyneux Bay to the southeast. The delta is characterized by its gently sloping topography, which grades from an elevation of approximately 10m in the northwest to sea level near Molyneux Bay in the southeast. The Clutha River/Mata-au (New Zealand's largest river, in terms of catchment size and flow volume) traverses the delta in a south-easterly direction, with its two branches (Koau and Matau) encapsulating Inch Clutha island. Regular flooding of the delta in the past has created a richly fertile plain that provides an ideal setting for dairy farming and meat production. These two main industries present on the Delta employ much of the resident population of the townships of Balclutha, Katangata and smaller rural settlements on the Delta (approximately 5400 people in total).

The Clutha Delta presents a complex natural hazard setting, influenced by the combination of the natural processes that have helped form the delta and the land uses that have developed since the mid-19th century. The natural setting of the delta exposes the area to flooding, alluvial fan hazard, seismic activity, and coastal processes such as elevated sea levels, tsunami and coastal erosion. The level of risk that each of these hazards presents varies greatly across the delta, depending on the scale and type of hazard and the nature and vulnerability of the features exposed to that hazard.

Flooding is the most recognised hazard on the Clutha Delta due to its frequency of occurrence, and has always been a fact of life for those living on the delta. A number of significant floods having occurred since early European settlement began in the mid-19th century. Modification of the flood hazard began in the late 1800s, with ad-hoc drainage and flood protection infrastructure being developed. These were initially implemented by landowners and later by various flood control and drainage agencies set up under the River Boards Act 1884 and the Land Drainage Amendment Act 1898. In 1920 the Rivers Commission reported to the Government on the Clutha River and recommended a range of measures for the effective control and improvement of the delta's rivers and riverbanks, and also recommended that a single controlling authority be appointed for carrying out the proposed works.

The Lower Clutha River Trust was ultimately established, by way of the Lower Clutha River Improvement Act 1938, to implement the Rivers Commission's remedial works recommendations. The Otago Catchment Board (constituted under the Soil Conservation and Rivers Control Act 1941) took over the Trust's functions in 1952. The Catchment Board prepared comprehensive flood control and drainage proposals for the Lower Clutha River and delta, which were approved by the Government in 1960 as the Lower Clutha Flood Control and Drainage Improvement Scheme. That scheme was implemented over the next 30 years and by the time the Otago Regional Council assumed the functions of the Otago Catchment Board in November 1989, an extensive flood protection scheme was in place. This has subsequently reduced the incidence of flooding across the Clutha Delta.

Past assessments of the flood hazard on the Clutha Delta have generally focused on mitigating flood risk through the engineering works that constitute the Lower Clutha Flood Protection and Drainage Scheme. This report takes an approach of combining information about residual flood risks and other natural hazard information (principally seismic and coastal hazard), together with a description of the social and environmental settings in order to establish a *hazardscape* of the Clutha Delta. The report also provides a detailed description (Chapter 4) of how the flood hazard varies across the Clutha Delta and the risk associated with the interactions between different types of hazards. In particular it investigates the effect coastal processes (including elevated sea levels, tsunami and coastal erosion) have on flood risk, including information about the possible effects of climate change and higher sea levels.

The rate of shoreline retreat is assessed in detail along the beaches between Kaka Point and the Matau Mouth and an average rate of approximately 10 m per year found on the faster-eroding sections of beach. The low lying nature of the lower Clutha Delta will provide limited topographical resistance to inundation from the sea or the river. For the most part, those areas with the greatest combined exposure to coastal hazards are largely unpopulated and used primarily for livestock grazing. However, ORC infrastructure such as the coastal flood-banks and proposed Paretai outfall structure are becoming increasingly exposed to storm events as the coastline retreats. The Koau Mouth training line is also under threat as it becomes more exposed to storm swells on the north and south sides.

If the Molyneux Bay shoreline continues to retreat, there will be a number of implications for the Lower Clutha Flood Protection and Drainage Scheme and other assets, including reduced drainage capacity and potential damage to floodbanks and roads (ORC, 2014). The hazard associated with elevated sea level (storm surge) and tsunami events for low-lying areas of the Clutha Delta is likely to increase if shoreline erosion continues, as the buffer between the open ocean and the floodbanks becomes smaller. In addition, sea-level has been continuously monitored at Green Island since 2002. Information such as this will help to understand how a wide range of physical processes (including climate change, sea-level rise, and sediment supply) are interacting to influence the coastal hazards of the Molyneux Bay shoreline and the lower Clutha Delta.

The efficiency of some pump stations and outfall structures that drain the lower delta, especially those that drain to the Puerua Estuary, will decrease in the coming decades as sea levels and associated groundwater levels rise in relation to the land being drained. Sea level is projected to rise around 20 cm by ~2050-2060. A significant portion of the land on the lower delta is <0.5 m above mean sea level and hence could require continuous pumping in order to remain dry by approximately the 2050s, even in low-river conditions. The combination of these factors, the expected retreat of the coastline by several hundred metres, and the expected increase in severe weather events (including storm surges and rainfall events) over the coming decades mean that the viability of parts of the Lower Clutha Flood Protection and Drainage Scheme will likely be under threat within the next few decades. Continued monitoring of sea-level, coastal retreat and accretion is suggested, as well as monitoring of groundwater levels on the lower Delta in order to establish the efficiency of land drainage systems as sea-level rises.

Land use decisions in the future will need to take the complex hazard setting of the Clutha Delta into consideration to ensure that proposed and existing activities are compatible with the hazard exposure and the residual risks posed by a range of natural hazards.

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1. Introduction

The Clutha Delta is the relatively low-lying, flat land located on the lower reaches of the Clutha River/Mata-au, between Balclutha and the Pacific Ocean (Figure 1.1). The delta covers an area of approximately 130km^2, bordered to the north, northeast and southwest by gently rolling hills that rise to 200m above sea level. A combination of natural processes formed the delta; these are most recently characterised by the combined interaction of estuarine and fluvial processes.

Figure 1.1 Balclutha, located at the upstream end of the Clutha Delta. The Clutha Delta is shown in the background, with Molyneux Bay visible on the horizon (David Wall Photography).

Approximately 2,400 people reside on low-lying parts of the delta (less than 20m above mean sea level), including much of the townships of Balclutha and Kaitangata, which are the main settlements in this area. Population decline has occurred across the wider Clutha District over the last two decades, and the Clutha District Council (2008) predicts that the populations of Balclutha and Kaitangata will continue to decline by 2 to 6% between 2011 and 2021. 2013 census data has validated this prediction.

Land use on the delta includes rural, residential, commercial and industrial activities. The predominant land use is agriculture, an activity that was established with the arrival of the first European settlers in the mid to late 19th century (Waite, 1948). The land is highly productive with fertile soils providing ideal conditions for pasture growth.

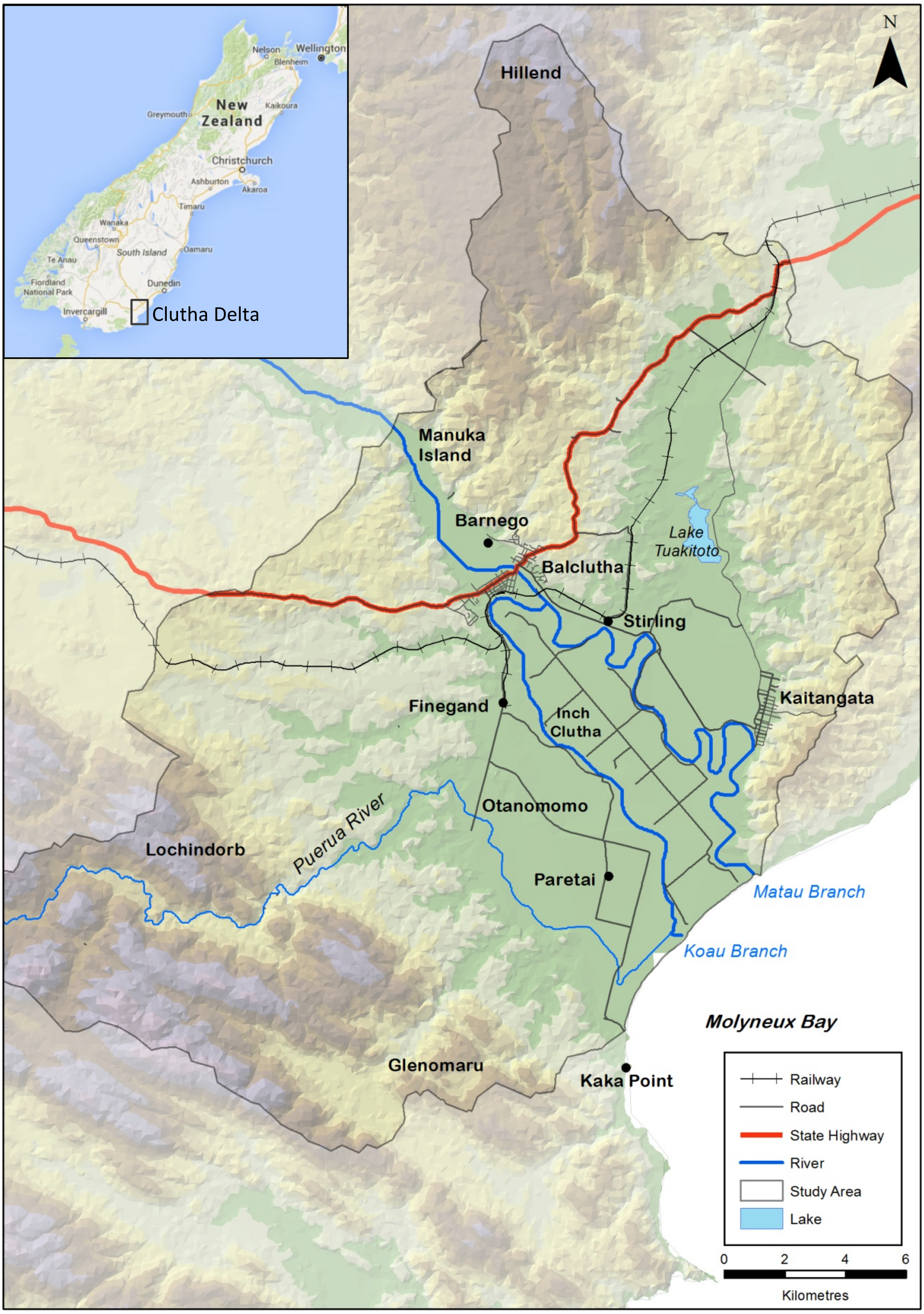


Figure 1.2 Communities within the study boundary (the natural catchment of the Clutha Delta).

The alluvium-filled valley that makes up the Clutha Delta forms a topographically gentle plain grading from ~10 m elevation in the northwest to sea level in the southeast. There is a large expanse of fertile, flat land within close proximity to Balclutha, the largest settlement in the Clutha District (Figure 1.1).

Downstream of the township of Balclutha, the Clutha River/Mata-au divides into two branches that cross the delta on their way to the Pacific Ocean. The southwestern branch, the Koau, carries ~70% of the Clutha's flow over 18 km to the coast. The more northern Matau branch is more sinuous, passing through the townships of Stirling and Kaitangata over its 29 km path to the sea. Between these two branches lies an island known as the Inch Clutha. Lake Tuakitoto and the settlement of Kaitangata are situated north of the Matau Branch and the Puerua River and the Paretai district lies to the south-west of the Koau Branch (Figure 1.2).

The Clutha/Mata-au is the largest river in New Zealand in terms of volume and catchment area. Originating in the Southern Alps of the South Island, the river flows gradually eastwards and is joined by a number of prominent tributaries including the Hawea, Kawarau, Manuherikia and Pomahaka Rivers. The Kawarau River and Lake Wanaka are the main contributors of flows in the Clutha River/Mata-au, having average annual flows of 211 m^3/s (at Chards Road) and 271 m^3/s (below the Cardrona River confluence), respectively. Flows further downstream are modified by the Hawea, Clyde, Roxburgh Dams.

The Clutha Delta and its environs have a complex hazard setting which has helped shape the delta and which influences the way it is used. The Clutha Delta is exposed to flood inundation, seismic activity, coastal hazards, and, to a lesser degree, alluvial fan hazard. Other weather related hazards such as strong winds, snow and landslides can also present a hazard across the Clutha Delta, although they are not discussed in any detail in this report. The level of risk that natural hazards present varies greatly across the delta, depending on the nature, scale, and relative frequency of occurrence of the particular hazard, and the nature and vulnerability of the features, and activities exposed to that hazard.

This report describes the natural hazard variability within the floodplain area of the Lower Clutha/Mata-au catchment and Figure 1.2 shows the study area, which includes the relatively flat Clutha Delta and the catchments of the contributing tributaries. The report synthesises the results of previous investigations and knowledge into specific natural hazards, and applies these to the local setting of the Clutha Delta.

2. Social Setting

Many centuries before European settlement, the mouth of the Mata-au was home to southern Maori. Evidence suggests the Maori villages were of limited size, with a written transcript from 1830 identifying approximately 28 huts, with accounts suggesting up to 200 people resided in the area (Waite, 1948). Whalers and sealers were among the first Europeans to visit the Clutha Delta, establishing shore stations at Port Molyneux (DSIR, 1957). At this time, the Clutha Delta was covered in dense swamp vegetation, such as flax and rush, only broken by the narrow strips of forest and scrub on the margins of the Clutha River/Mata-au (Figure 2.1) (DSIR, 1957).

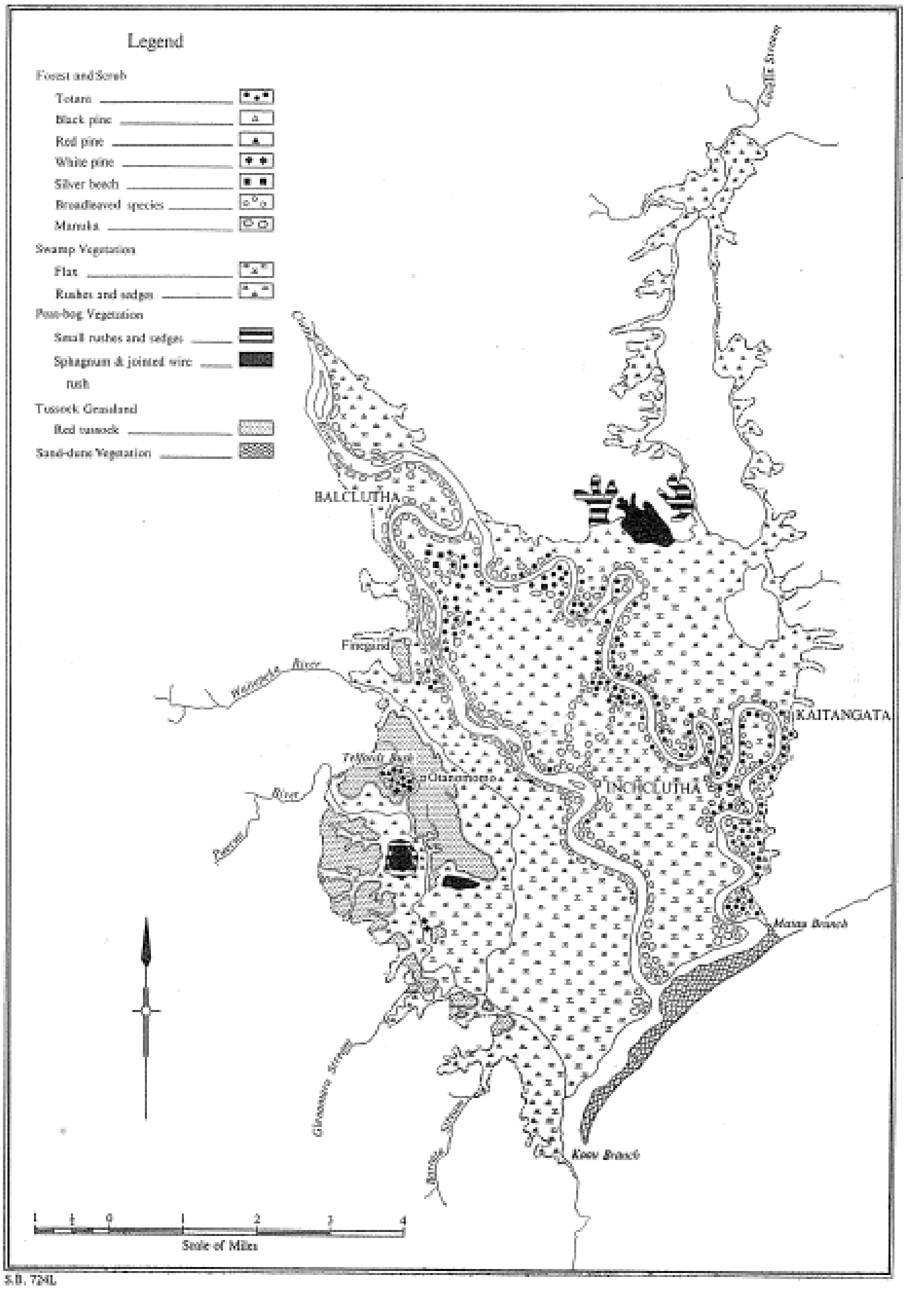


Figure 2.1 Generalised map of vegetation and drainage at the time of early settlement (c. 1850). Map obtained from the reminiscences of early settlers (DSIR, 1957).

In search for the New Zealand Company's proposed 'Otago Settlement', Frederick Tuckett (official surveyor to the New Zealand Company) and Dr. David Munro (a politician and speaker of the House of Representatives) were in 1844 accompanied by Maori guides to the area now referred to as the Clutha Delta. During this visit Tuckett noted:

> *"The Matau district alone would afford all the land required for the settlement, and there I would have established it could I have entered the Matau with the schooner.... Here there is rather more than 12 feet of water at low water on the bar."* (page 23, Waite, 1948)

Having previously inspected the Otago Harbour, Tuckett rejected Port Molyneux as the major port of Otago due to the difficulties around the formation of river and sand bars. His early reservations about establishing a settlement in this location were justified, when the great flood of 1878 demolished Port Molyneux and the river mouth subsequently silted up, diminishing the ability of the port to establish in this location (Waite, 1948). The flood of 1878 is discussed in more detail in Chapter 4 of this report.

Despite the early concerns, the Clutha Delta land was purchased by the New Zealand Company, with Charles Henry Kettle arriving in the area in 1847 to arrange the survey of the Otago Block (McLintock, 1966). As illustrated in the 1852 'Second Survey' of the Clutha Delta, two main settlements were proposed for the area, Balclutha and Port Molyneux (described as 'a site for a town' in Figure 2.2). Kaitangata, which had previously been identified by Tuckett for its coal seams in 1844, is also identified in these early plans as a 'site for a village'.

Figure 2.2 Second Survey of the Clutha Delta, Charles Kettle 1852

Permanent settlement of the lower Clutha Plains by Europeans is thought to have begun around 1848, with James McNeil establishing a farm on the present Balclutha town site and establishing a river ferry. The river provided the earliest means of transportation to the hinterlands and in August 1863, the SS *Tuapeka* began a regular service on the river as far as Tuapeka Mouth. After the discovery of gold at Tuapeka in 1861, the previously primitive road system was improved and a coach service established between Dunedin and Balclutha. As the hinterland opened for settlement, the township of Balclutha replaced Port Molyneux as the centre of the district. The new township grew steadily and in 1863 town sections were surveyed (Waite, 1948). There is limited evidence that illustrates with any certainty why Balclutha was established in its current location, though its early importance as a ferry link across the Clutha River/Mata-au allows some assumptions to be made in this regard.

The first bridge across the Clutha River/Mata-au was opened in 1868. By 1870 most of the better drained land on the delta was under cultivation to provide for the growing number of miners working the nearby goldfields (McLintock, 1966). Open drains were cut across the swamps, but the falls were insufficient to make them effective and the land remained wet and prone to flooding (DSIR, 1957). After the severe flood of October 1878 (Chapter 4) floodbanks were built to protect the town from such a repeat event. This marked the beginning of the modification of the delta's natural-drainage systems, and the ongoing reliance on these changes for land-drainage and flood protection.

The early administration of flood protection works was divided amongst a number of controlling authorities. These included:

- The Inch Clutha Road, River and Drainage Board (established in 1884) that administered the Koau Branch of the Clutha River/Mata-au and the Inch Clutha;
- The Telford Estate, initiating drainage and flood protection works in the Otanomomo and Paretai areas (later subsumed by the Otanomomo Drainage Board in 1914);
- The Matau River Board (established in 1919) which administered the Matau Branch and areas to the north, including Lake Tuakitoto and Kaitangata (Scarf, 1997);
- The Clutha River Board (established in 1898), which also shared an early interest in the river, though its role was restricted to matters around river navigation and boating facilities.

Early flood protection and drainage work was completed independently by each board, with works often being bitterly opposed by the board on the opposite side of the river. Following serious flooding in January 1919 (the third largest flood recorded on the Clutha River at that time) the Government established a Rivers Commission to investigate the causes of flooding, bank erosion and flood damage on the Clutha River (with similar, but separate, commissions for several other rivers in Otago and Canterbury). The Commissioners' investigations for the Clutha River identified the progressive silting of the river (thought to be caused by denudation and mining operations upstream) as the main cause of flooding. In regard to this they made a number of recommendations, as summarised by Scarf (1997), including:

- Balclutha and the delta be protected against a flood of 5100m^3/s;
- The Matau Branch be shortened by two cut offs and the banks raised to contain flows of up to 2550m^3/s;
- The Balclutha Borough banks be raised 1.8m, and the banks below the bridge be continued to meet the railway bridge abutment and subsequent embankments extending as far as Rosebank;

- The Koau Branch floodbanks be raised to accommodate the remainder of the flood flows; and
- The establishment of a River Trust to complete the work.

It was not until 1938 that the Lower Clutha Trust was established. Despite its work being impeded initially by the Second World War and subsequently by a series of successive floods, the Trust achieved a number of flood protection and drainage improvements on the Inch Clutha prior to its dissolution and absorption into the Otago Catchment Board in 1948. Such works included the construction of the Rutherford's Locks (described in Chapter 4) and the cutting of a new mouth for the Koau Branch which had become blocked in 1939 (Scarf, 1997). Additional ongoing works since the establishment of the Otago Catchment Board, and later the Otago Regional Council, are also discussed further in Chapter 4.

The wider Clutha Delta is now primarily comprised of rural land uses, with three main clusters of residential activity found around Balclutha, Kaitangata and Stirling (Figures 1.1 and 2.3). Smaller rural settlements can also be found around Benhar, Kakapuaka and Finegand.

Figure 2.3 Township of Balclutha, looking eastward towards the Balclutha Bridge (source ODT, 2008).

The Clutha Delta accommodates around 15% of the Clutha District's total population with approximately 2400 people residing on the low-lying parts of the delta. Population decline has occurred across the wider Clutha District over the last two decades, and the Clutha District Council (2008) predict that the populations of Balclutha and Kaitangata will decline by 2 to 6% between 2011 and 2021. The population trends in the 2013 census are consistent with this prediction (Figure 2.4).

Agricultural activities first established by the early settlers, are still the predominant land use of the Clutha Delta and the wider Clutha District. The highly productive and fertile soils, particularly on the Inch Clutha, provide ideal conditions for crop and pasture growth. The dominance of this land use is reflected in the Clutha District Plan, with approximately 57,620 hectares or 98% of the Clutha Delta catchment zoned for 'Rural Resource' purposes (Figure 2.5). This is consistent with the wider Clutha District average in which 98% is zoned rural resource.

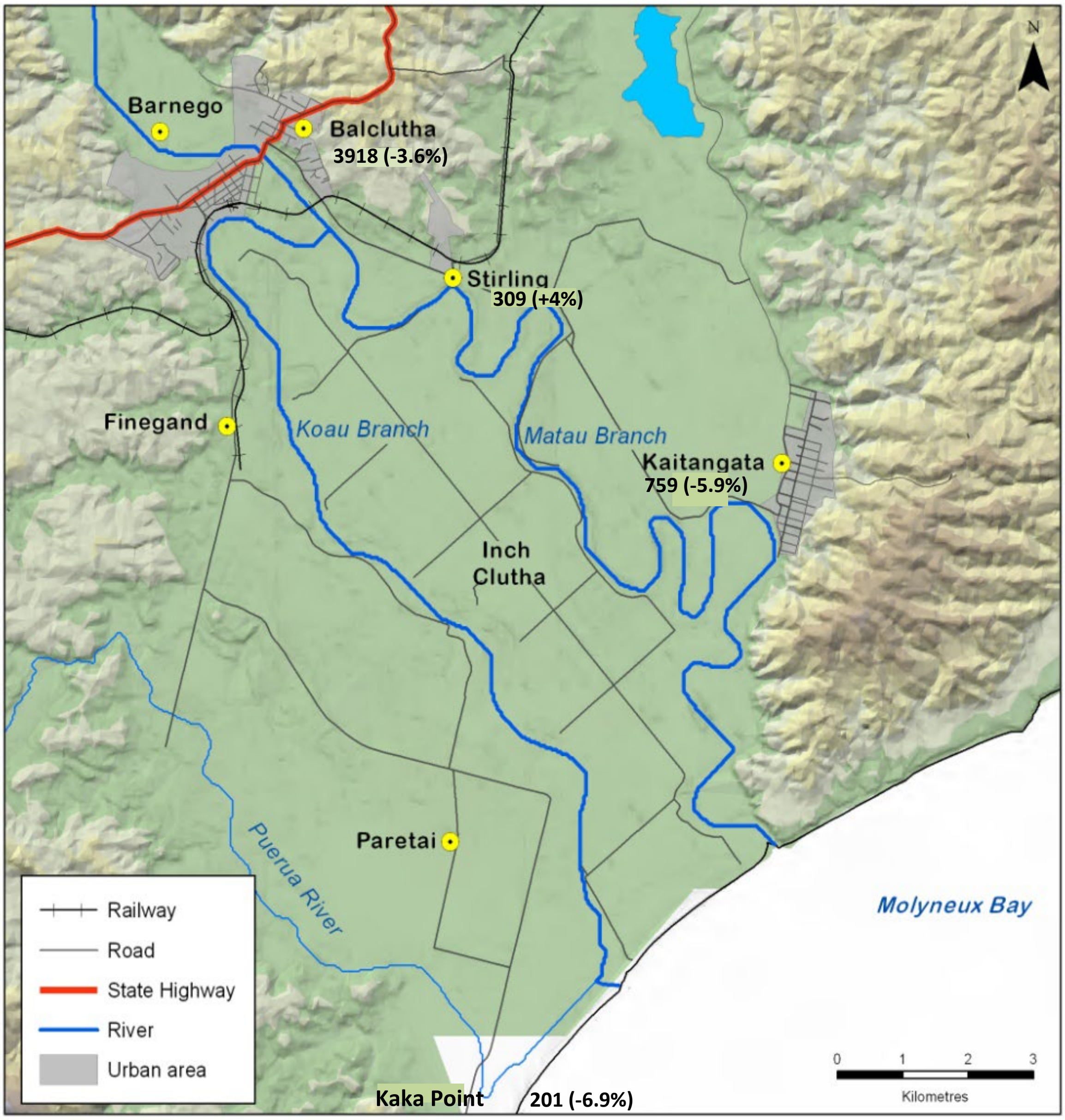


Figure 2.4 Population trends in the Clutha Delta Catchment based on the 2001 to 2013 Census (data obtained from Statistics New Zealand).

The Clutha District Plan is reasonably permissive in relation to future residential development within the Rural Resource Area. Subdivision is provided for by way of restricted discretionary activity, with no minimum allotment size specified in the Plan. Subdivision is instead managed via subdivision performance standards. Under this regime, the Clutha Delta has the potential to accommodate a significant amount of residential development should the demand arise; though it does provide the council with discretionary considerations in regard to the effects of natural hazard events. Population trends demonstrate a gradual population decline over at least the past decade (Figure 2.4) suggesting that the demand and pressure for residential development in this area may be relatively low.

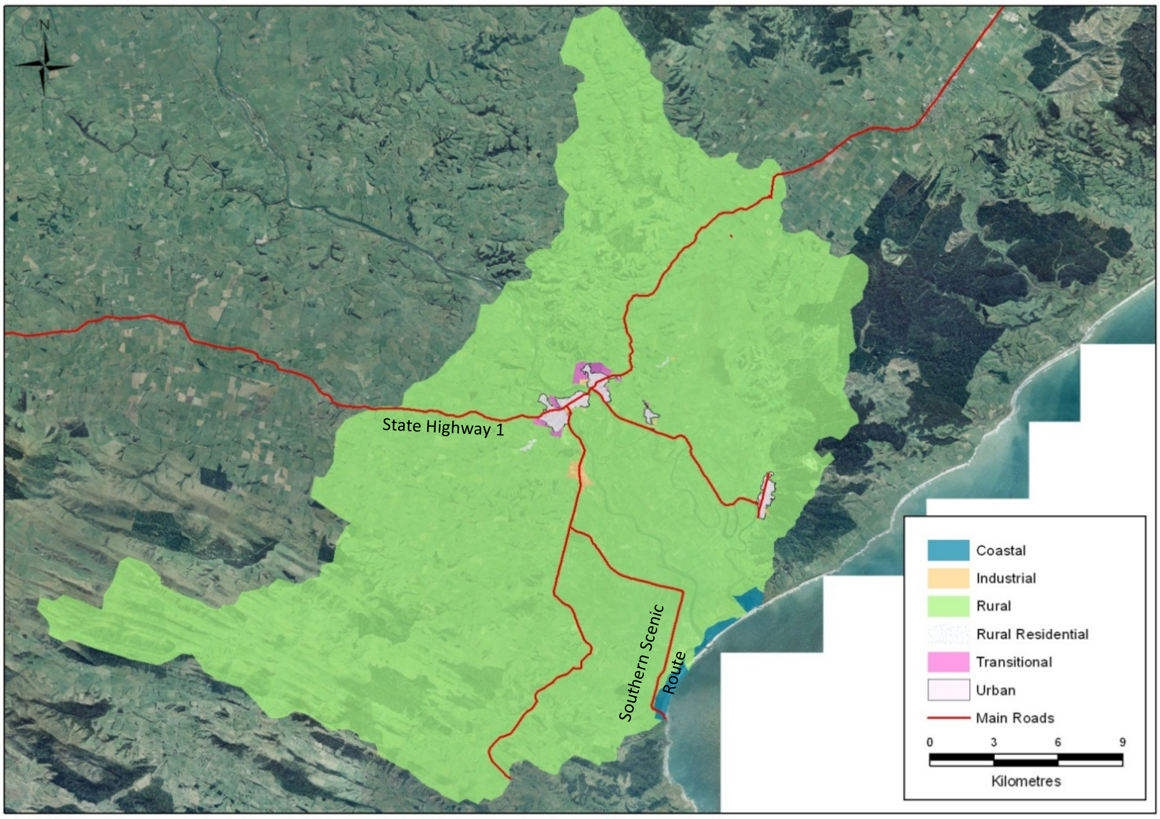


Figure 2.5 Land use in the Clutha Delta study area, as defined in the Clutha District Plan (CDC, 1998).

Figure 2.6 Silver Fern Farms Finegand Plant located on the true right bank of the Koau Branch, during the November 1999 flood event (see Figure 2.4 for location).

The main areas of industry are located on the periphery of the Balclutha settlement, with spot zoning of industrial activities in Kaitangata, Finegand, Stirling and Benhar. These areas accommodate the Silver Ferns Farm Meat Processing Plant at Finegand (Figure 2.6), the Fonterra cheese factory at Stirling and the Kaitangata coal mining facilities (see Figure 2.4 above for locations). All three of these operations provide a major source of employment within the area.

State Highway 1 (SH1) connects Dunedin City with Invercargill City and the smaller communities between, and passes through the town centre of Balclutha (Figure 2.5). Traffic volumes on the SH1 Balclutha Bridge (the main route across the Clutha River) average 11,820 vehicles per day, significantly reducing to 4,630 vehicles per day north and 3,280 vehicles per day to the south (NZTA, 2016). The larger traffic volumes around Balclutha reflect the urban characteristic of this township. The original Balclutha Bridge was opened in 1868 and was subsequently washed away in the flood of 1878 (Figure 2.7).

Figure 2.7 Top: Balclutha Bridge following the October 1878 flood event. The largely wooden bridge structure was washed away on 14th October 1878 and was not rebuilt until 1881. Bottom: The modern SH1 bridge in approximately the same location, during moderately high summer flows (2014).

The Southern Scenic Route, a major tourist route between Queenstown and Dunedin, also passes around the edge of the Clutha Delta and is locally referred to as the 'Owaka Highway', as it provides the main route to the settlement of Owaka in the Catlins (Figure 2.5).

The South Island Main Trunk Railway crosses the northern portion of the study boundary in a northeast to southwest direction (Figure 1.2). The railway line runs parallel with Lake Tuakitoto in the southeast before travelling north past Stirling and across the Clutha River/Mata-au at Balclutha. The railway runs parallel with the Clutha/Mata-au for a short distance before diverting inland near Finegand. A railway siding at Finegand provides the

Silver Fern Farms Meat Processing Plant with direct access to the railway network. The railway is generally built on an embankment elevated above the surrounding delta, but can be overtopped by floodwater at several locations (Figure 2.8).

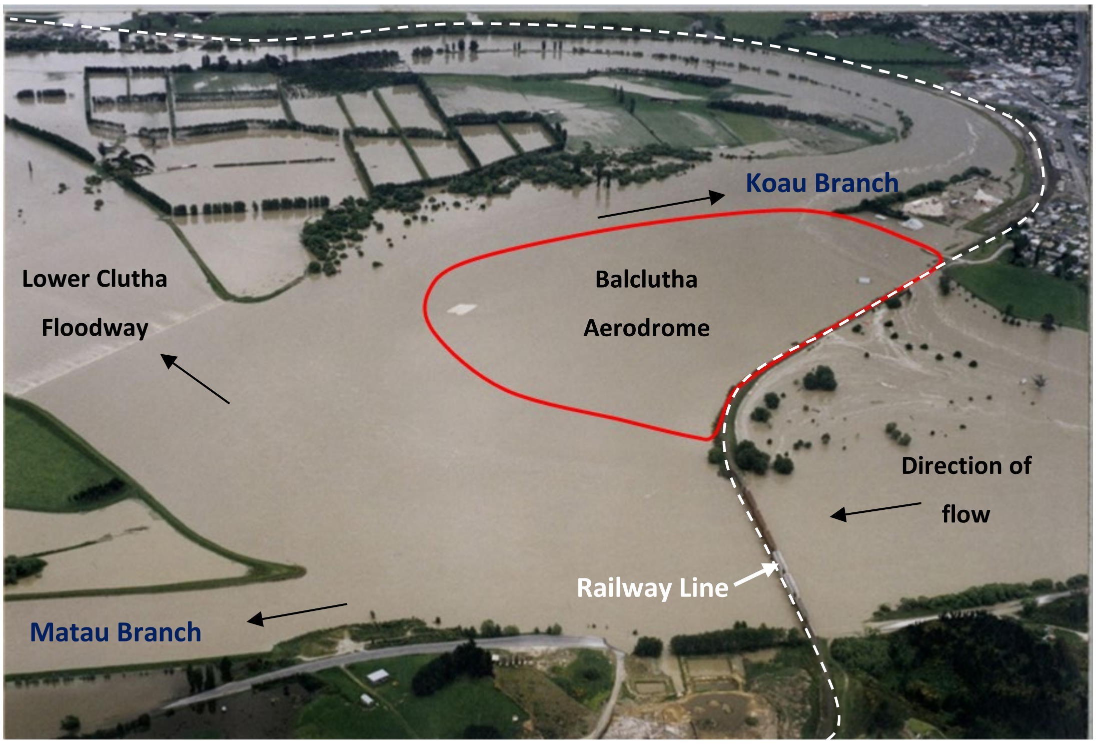


Figure 2.8 South Island Main Trunk Railway (highlighted with white dashed line), during the November 1999 flood on the lower Clutha Delta. The Balclutha Aerodrome is completely underwater (approximate location outlined in red).

3. Environmental Setting

The landscape of the Clutha Delta and its environs has historically been influenced by tectonic and fluvial processes, and changes in sea level. This has created a complex environmental setting, which engineering and land drainage works have further modified. The environmental setting gives rise to the Clutha Delta's natural hazards, which in some cases (such as flooding) are the same characteristics that contribute to its positive attributes, such as its fertile land and reliable rainfall.

The topography of the Clutha Delta has largely been determined by its underlying geology, with the wider Clutha River catchment also contributing to the fluvial processes which have helped shape the current delta throughout the Quaternary period (last 2.6 million years). Changes in climate have also affected the surface water hydrology and extent of historical sea level rise and shoreline retreat. These aspects of the delta's natural environmental setting are discussed in the following sections.

3.1. Geology and Topography

The natural catchment of the Clutha Delta (the boundary of this study) extends northwards to Hillend and Manuka Island, southwards to Lochindorb and Glenomaru and eastward to the Pacific Ocean and the western side of the coastal hills (Figure 1.2 and Figure 3.1). Covering an area of approximately 590km^2, the Clutha Delta Catchment is part of the wider Clutha River catchment that covers an area of approximately 21,000km^2 and extends from the Southern Alps near the West Coast of the South Island, to the Pacific Ocean on the east coast (Figure 3.2). The main topographical feature of the Clutha Delta Catchment is the delta formation itself.

The Clutha Delta sits astride the Livingstone Fault which marks the boundary between the ancient basement rocks of the Caples and Maitai Terranes. These formations of folded and altered sandstones and siltstones outcrop to the northwest of the Clutha Delta (Irricon, 1998; Tonkin and Taylor, 2005) (Figure 3.1). To the east in the Kaitangata district, younger Tertiary-age sediments of both marine and terrestrial origin overly the Caples terrane and these host several large, high quality coal seams. These younger rocks are uplifted relative to the Clutha Delta by the active Castle Hill Fault and associated tectonic activity in the seaward range. In the south and southwest of the Clutha Delta catchment an enormous fold in the ancient rocks of the Murihiku Terrane[1], known as the Southland Syncline, marks the south eastern boundary of the study catchment. Alternating layers of harder sandstone and softer mudstone have been eroded to form long, parallel strike ridges (Figure 3.1) (Bishop and Turnbull, 1996; Irricon 1998; Turnbull & Allibone, 2003).

The Hillfoot and Little Hillfoot faults form the boundary between rocks of the Syncline and Dun Mountain – Maitai Group basement rocks beneath the Clutha Delta. Movements in the earth's crust over the past 65 million years[2] have led to the development of these and other large NW trending faults that run sub-parallel with major river courses; and a series of NE trending faults such as the Akatore and Titri Faults running parallel with the coast (see Chapter 5).

[1] The sandstones and mudstones making up the Southland Syncline were deposited during the Triassic and Jurassic periods, 145 – 250 million years BP. Refer to Appendix 1 for a geological timescale.
[2] The period is known as the Cenozoic. See the Glossary for a definition of this and other geological terms.

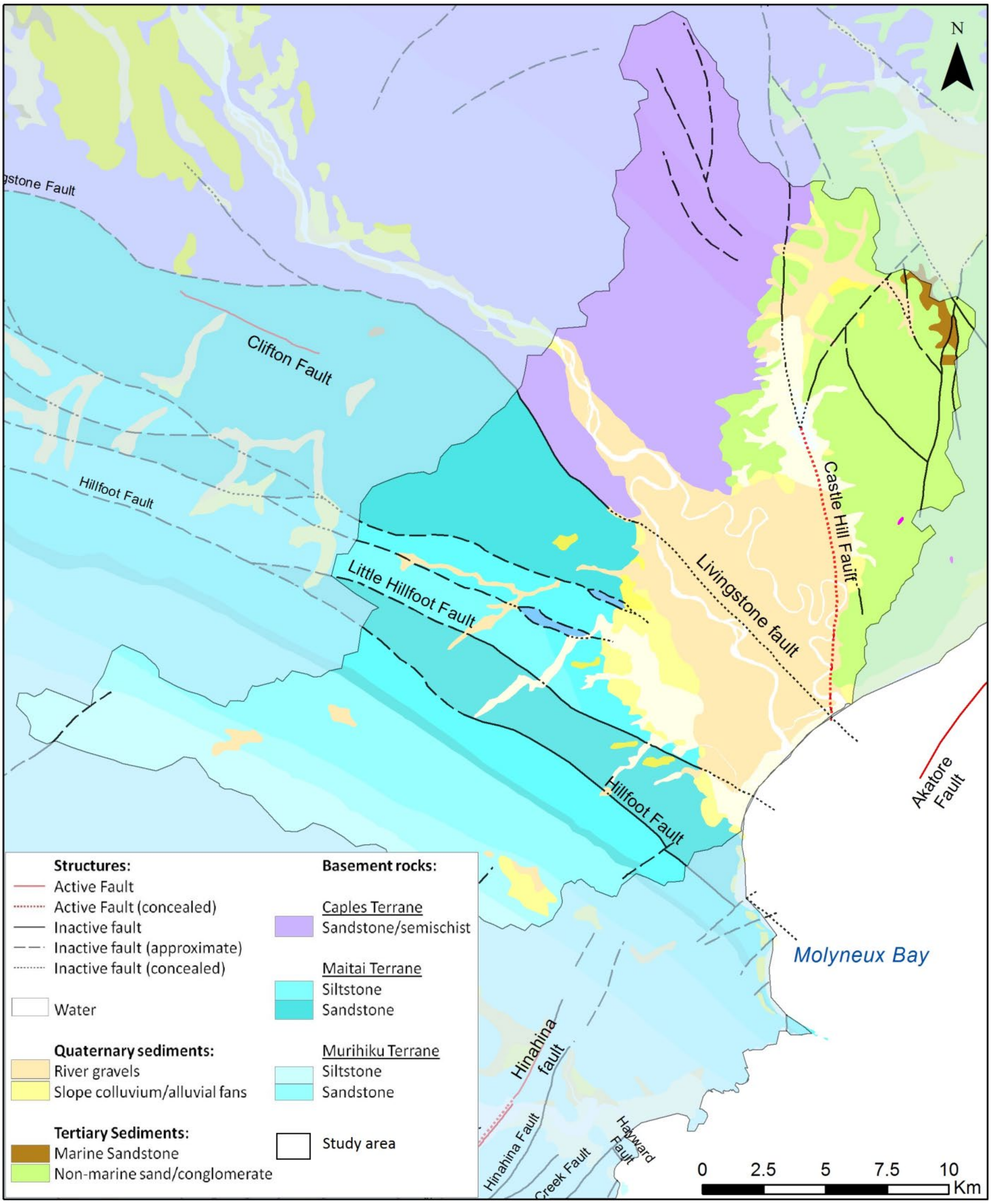


Figure 3.1 Geology of Lower Clutha Catchment (Adapted from Bishop & Turnbull, 1996).

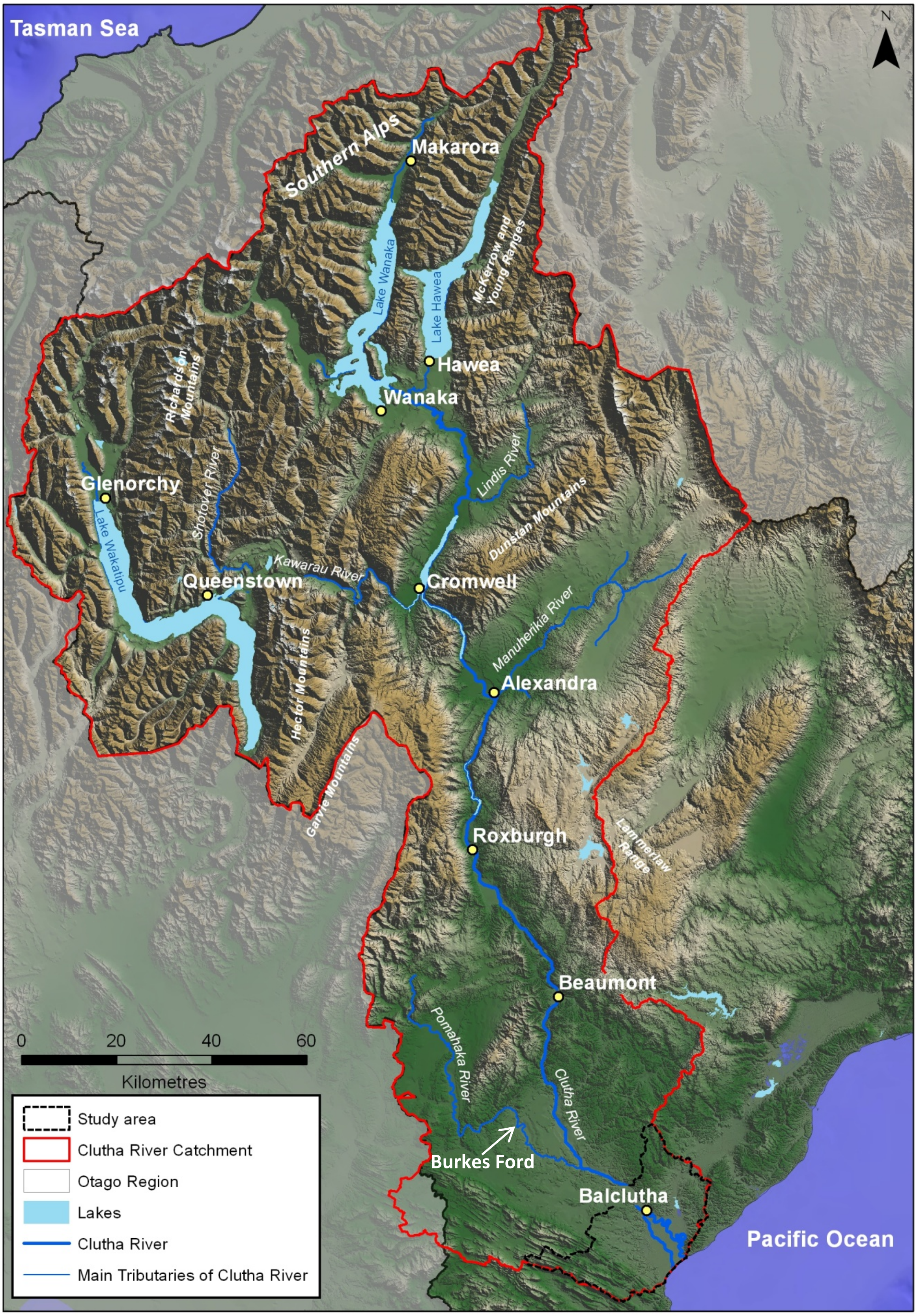


Figure 3.2 Topography of the Clutha River catchment.

The Lower Clutha Delta occupies a depression formed by this faulting and the basement rocks of the ancient erosion surface that is the Otago Peneplain are ~200 m below the valley floor in places (Bishop and Turnbull, 1996). Layers of young Quaternary-age deposits of alternating marine and terrestrial sands, muds and gravels fill the valley, deposited through periods of rising and falling sea-levels caused by multiple ice-ages over the past 2 million years. During the height of glacial episodes the sea level lowered by as much as 120m and the Clutha River/Mata-au incised deep into the alluvium of the delta. As the climate warmed, sea levels rose and transgressed into the Clutha Valley, most recently around 6,500 BP, forming large coastal embayments which deposited substantial quantities of marine silt and sands on the delta (Barrell *et al.*, 1998). Marine incursion of the Clutha Delta is evident in fossil sea cliffs and marine sediments found in drill-hole samples from the area (including shells found at a depth of up to 13m). Clearly distinguishable marine terraces are largely absent in this area, most likely due to the erosional nature of the delta which experiences vigorous storm and wave action, compounded with the constant supply of sediment from the Clutha River/Mata-au (Barrell *et al.*, 1998). As sea level lowered once again the continued deposition of alluvial gravels by the Clutha River/Mata-au formed the low lying gravel flats of the modern day Clutha Delta.

The Clutha Delta itself is an alluvium-filled valley formed by the interaction of the meandering Clutha River/Mata-au and a change in base level[3] during the Quaternary (Irricon, 1998). Base level changes occur through uplift of coastal ranges to the north along the Titri and Akatore Faults and possibly the Tuapeka Fault Zone, in addition to changes in sea level (Bishop and Turnbull, 1996). Other dominant factors contributing to the delta formation include the large quantities of sediment historically transported by the Clutha River/Mata-au (pre hydro-electric dam development on the river) and the longshore currents. The Lower Clutha floodplain (commencing approximately 6km upstream from Balclutha) is characterised by its flat, gently seaward-sloping topography. A great majority of the Delta lies less than 5m above mean sea level, with the northwestern end (near Balclutha) elevated only 10m above mean sea level (Figures 3.3 and 3.4).

The Clutha River/Mata-au meanders across the floodplain, bifurcating downstream of Balclutha to form two channels; the Koau Branch to the south and the Matau Branch to the north. Collectively, these two channels have captured the Inch Clutha, a large island formation bound on both sides by the Clutha River/Mata-au. Each of the river mouths open onto the wave-dominated coastline of Molyneux Bay. The mouths of the Clutha are dynamic features where sand dunes, gravel bars, lagoons and the mouths have a natural tendency to shift with floods, the tide and wind conditions. Prior to 1878 the Matau branch joined the Koau branch to flow toward a single outlet at the now-abandoned Port Molyneux. During a large flood event in 1878 the Matau Branch forged a separate outlet at the northern end of Molyneux Bay. The outlet of the Matau Branch was permanently secured in the late 1980's by way of strategically-placed rock lines (Figure 3.12) to a design established from physical model studies. The purpose of this was to minimise the mouth offsetting and blockage problems that had beset the Lower Clutha Flood Protection and Drainage Improvement Scheme in its early years. However, unlike the Koau Mouth Control Works, the Matau Mouth Control Works were approved as a separate project from the main scheme.

[3] Base level refers to the lower limit in the landscape, below which rivers cannot erode and is ultimately represented by sea level (Summerfield, 1991)

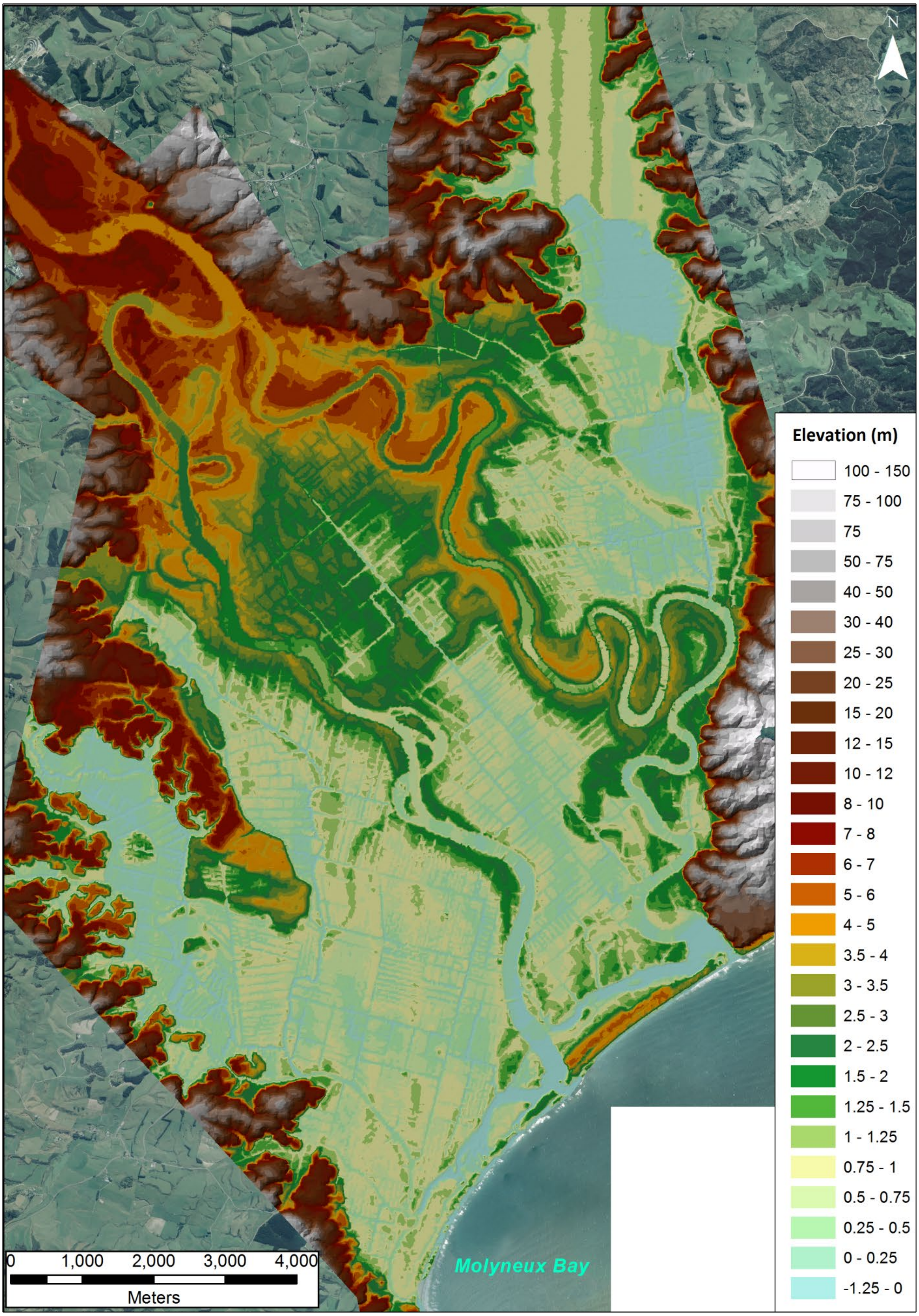


Figure 3.3 Elevation of the Clutha Delta. Land elevation is in metres, relative to msl.

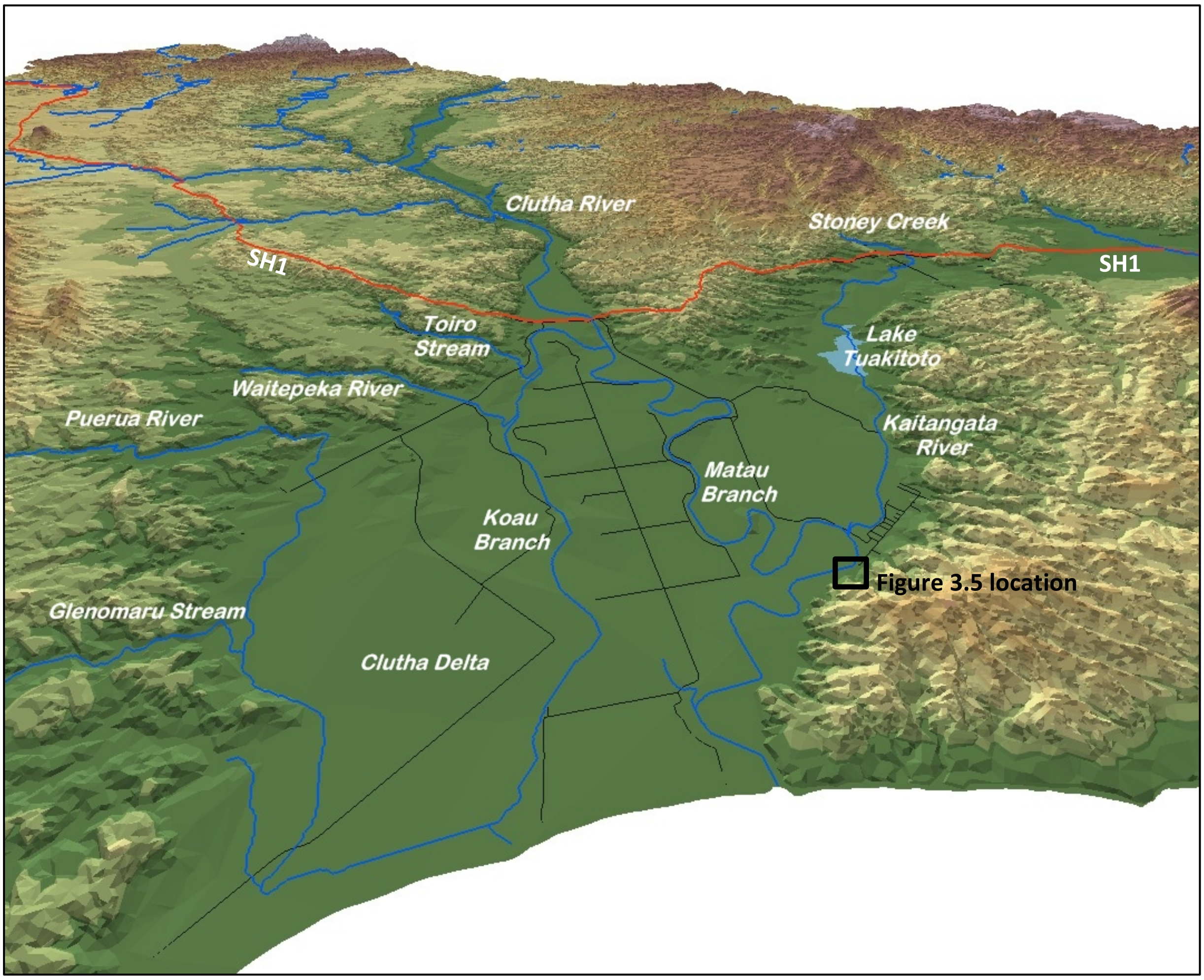


Figure 3.4 Digital Elevation Model (DEM) of the Lower Clutha and Delta. View towards northwest, with 3 times vertical exaggeration.

The sand dunes of Molyneux Bay were formed by the deposition of wind-blown sediment (Goff *et al.* 2003), and as a consequence consist of fine sands that are readily erodible. The form of the sand dunes and beaches of Molyneux Bay are influenced by the interaction of several processes. The supply of sediment to the beach and near shore, predominantly from the Clutha River/Mata-au is important, as are the forces that re-distribute sediment in Molyneux Bay (i.e. wind, waves and ocean currents). The balance of these forces determines whether the dunes and beach build upward and seaward (known as accretion), remain static or erode and retreat shoreward. This is discussed further is Section 6.3.

The majority of the sediment supplied to Molyneux Bay is still derived from the Clutha River/Mata-au, having been transported there from the upper catchment and other major tributaries (albeit of substantially reduced quantities due to the hydro dams now located on the river). This continued delivery of sediment has led to the formation of a large near-shore sand-wedge in Molyneux Bay (Andrews, 1979). Of the sediment delivered to Molyneux Bay by the Clutha River/Mata-au[4], a proportion remains in the near-shore zone and is cycled between the sand-wedge and the beach both inter-seasonally and during storms events (Hesp,

[4]It is estimated that the Clutha/Mata-au River delivers approximately 60 Kt of sediment to the coast each year (Hicks et al., 2000).

2011). However, much of the sediment deposited in Molyneux Bay is transported northwards by the Southland Current in a process known as longshore drift (Carter, 1986). In this regard, the Clutha River/Mata-au may be an important source of sand that replenishes beaches further northwards along on the Otago coast (ORC, 2010). Changes to the river and coastal morphology, due to sediment entrapment behind upstream hydro-dams, are discussed further in Chapter 6.

3.2. Alluvial Fans

A number of streams convey water from the surrounding hills to the delta. Many of these smaller watercourses are ephemeral, and only carry water during periods of prolonged or heavy rainfall. The flood waters can also carry appreciable quantities of sediment and debris from the upper catchment to the flat, low-lying floodplain. As these flows exit the confines of the valley, they lose energy, and their ability to carry sediment decreases, resulting in the deposition of layer upon layer of sediment along the boundary of the hill slopes and valley floor. The ongoing accumulation of river or stream (alluvial) sediments forms sloping landforms shaped like an open fan or segment of a cone that are, appropriately, referred to as alluvial fans. The formation and activity level of an alluvial fan is driven by the interaction of the geology and topography of the catchment, and its rainfall and runoff characteristics. Changes in any of these factors (such as rainfall or sediment supply) have the potential to alter the activity level of an alluvial fan.

The geology of the hill catchments surrounding the Clutha Delta that alluvial fan deposits tend to be topographically subtle features, usually comprised of fine-grained sediments, that are predominatly driven by the shallow 'sheet flow' of floodwaters following prolonged or heavy rainfall. 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)[5].

Alluvial-fan landforms throughout Otago, with a surface area greater than 0.5km^2, including the Lower Clutha Delta catchment, have been mapped (Figure), (Opus, 2009). Alluvial fans in this area are most common along the margins of the Clutha Delta where sediments have been deposited by streams draining surrounding ranges. For the purposes of the 2009 investigation, fans were 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. Alluvial fans in the Clutha Delta catchment are comprised mainly of active and inactive floodwater-dominant alluvial fans, experiencing sheet and channel floods. No debris-dominant alluvial fans have been identified on the margins of the Clutha Delta. An 'active' fan classification was assigned to those fans where flooding, deposition and/or erosion are considered possible within the next 100 years (Opus, 2009).

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

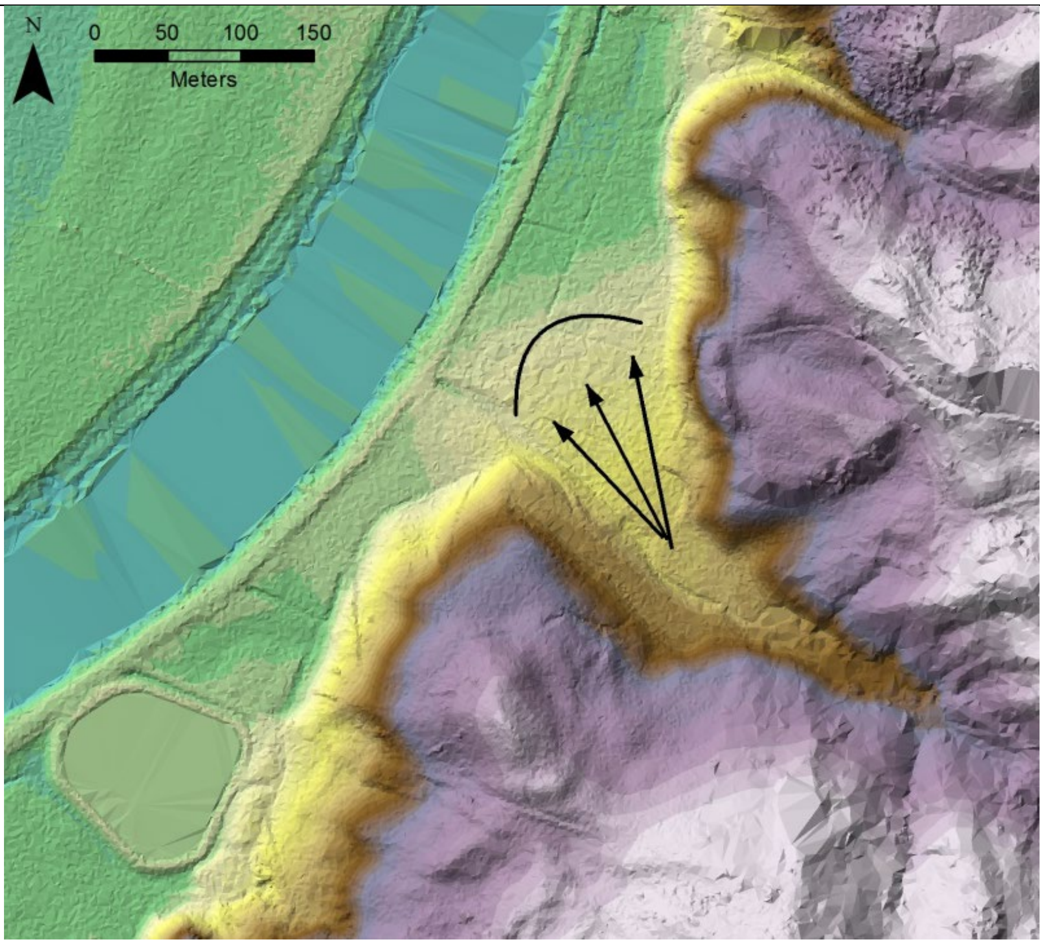


Figure 3.5 Looking south east across the upper reaches of an alluvial fan near Kaitangata. LiDAR of the area shows a distinct fan shape as the flows of the ephemeral stream exit the confines of the gully.

Alluvial fans always present an element of hazard due to their unpredictability (Davies & McSaveney, 2006). 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 margins of the Clutha Delta. The active floodwater-dominant alluvial fans to the west of the Clutha River are those of the Glenomaru Stream, Waitepeka River and Puerua River; and to the north east, Frasers Sream. A number of smaller fans have also developed from the smaller tributaries draining the surrounding hills, particularly around Kaitangata.

The majority of the mapped fan apron area is made up of inactive fan deposits. This means that there has been no significant sediment accumulation on the fans in the past few hundred years and the floodwaters conveyed down these fans during extreme rainfall events reach the river without significant depositon occurring on the fan apron. Active floodwater-dominated fans are for the most part confined to valley floors and active stream channels. Very few houses are located on these features, with the largely undeveloped rural character of the lower Clutha providing a compatible land use for areas prone to alluvial fan hazard.

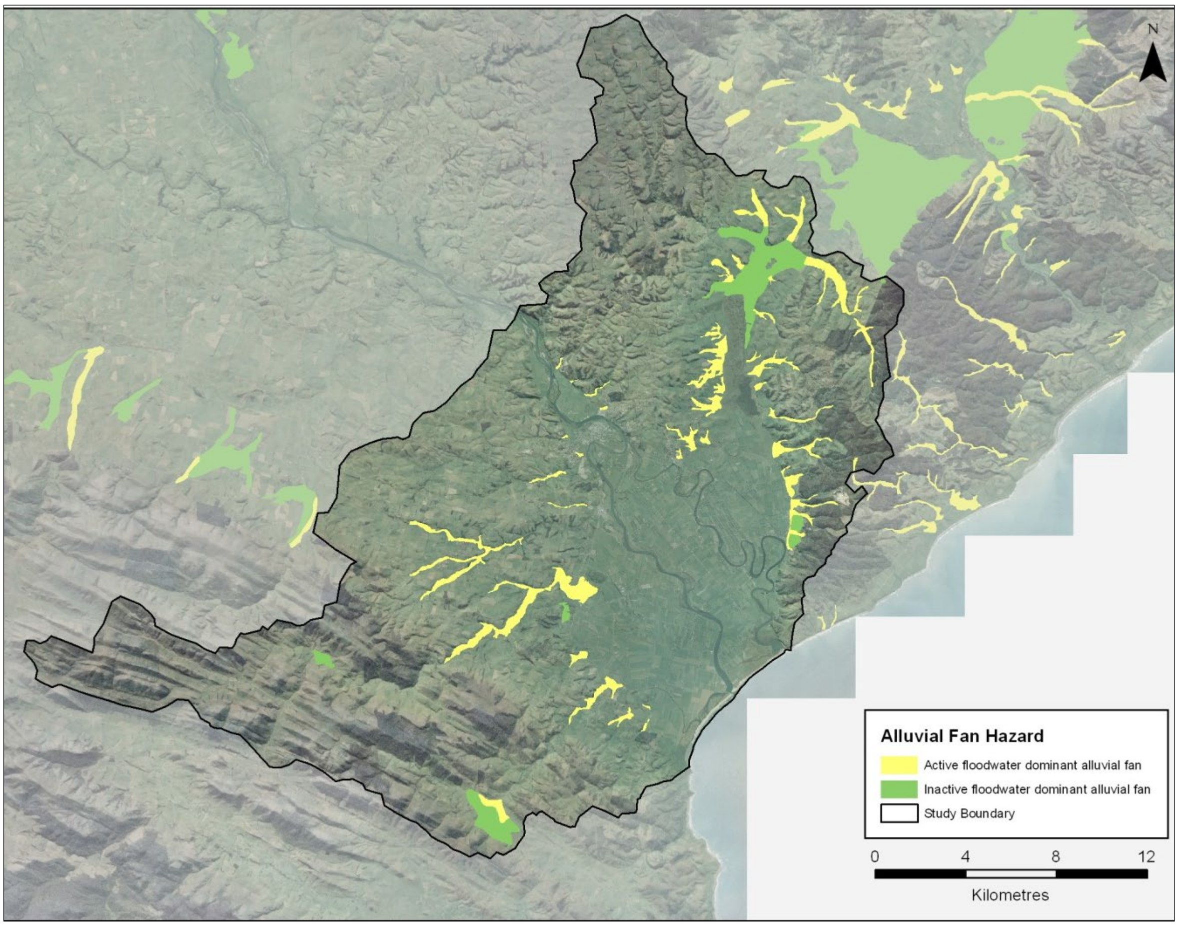


Figure 3.6 Alluvial-fan deposits greater than 0.5km² in and around the Clutha Delta (Opus 2009).

3.3. 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 Clutha River catchment is characterised by a cool, temperate, sub-humid maritime climate. Mean annual rainfall is approximately 680mm/year at the head of the delta (Table 3.1), and up to 972mm/year along the Southern Syncline (Glenomaru) to the south.

Further inland towards the headwaters of the Clutha River/Mata-au, the more elevated areas experience a colder, wetter climate, typical of mountainous environments (Figure 3.2). Annual precipitation in the headwaters exceeds 2000mm/year, with much of this falling as snow during the winter, which influences the flood hazard downstream.

Table 3.1 Rainfall characteristics of the Lower Clutha and the surrounding catchment, as at December 2012. The location of the measurements is shown on Figure 3.6.

Site and length of record	Altitude (m)	Mean annual rainfall (mm)	Maximum annual rainfall (mm)	Minimum annual rainfall (mm)	Maximum daily rainfall (mm)
Clutha at Balclutha (1988-2011)	12	680	897 (1992)	498 (2003)	101 (19 February 1991)
Owaka (1914-1988)	12	920	1686 (1918)	122 (1988)	105.4 (1 January 1925)
Clutha at Finegand (1965-2012)	6	657	921 (1980)	394 (1985)	117 (14 October 1978)
Glenomaru at Glenbrook Station (1988-2010)	155	972	1182 (1991)	638 (1999)	101 (19 February 1991)
Lovells Creek at Hillend Road (1967-2012)	261	825	1121 (1967)	469 (1985)	116 (26 April 2006)
Nuggets combined (1930-2012)	129	807	1197 (1972)	424 (1985)	95 (15 August 1980)

Across the lower South Island, a number of perceptible trends in annual rainfall were observed during the latter part of the 20th century by Mojzisek (2005) in the unpublished PhD thesis *"Rainfall variability in the South Island of New Zealand"*. These observations included a general increase in rainfall in the west and south of Otago, and a trend towards drier conditions in the east.

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).

Figure 3.7 Locations of the rainfall measurement sites presented in Table 3.1.

The Otago Regional Council has adopted the methodology outlined by Mojzisek (2005) and have repeated his investigations into precipitation extremes for the Lower Clutha Delta Catchment, extending the duration of the rainfall record used (to 2012) and also adopting some additional rainfall sites not previously used by Mojzisek (2005). Based on updated calculations, no obvious trends have been identified at rainfall sites on the Lower Clutha

Delta during this period, although these sites generally have relatively short records, or extensive periods of missing record.[6]

Figure 3.8 gives an updated analysis of precipitation extremes for the full length of continuous record up to December 2012 at stations within the Lower Clutha Delta 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[7] (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 3.8 shows that only one of the six trends investigated shows a statistically significant trend. This was demonstrated at the Balclutha and Lovells Creek (at Hillend Road) rainfall stations where a significant downward trend in the number of wet days was observed. There were no other statistically significant trends observed in the Lower Clutha Delta Catchment.[8] A significant upward trend in the number of wet days, very wet days and percentage of annual rainfall falling on very wet days was observed in Owaka, however this rainfall station is located beyond the boundary of the study area.

Average temperature is predicted to increase by another 2ºC by 2090. 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).

A number of factors may influence regional trends in heavy rainfall patterns, including the topography of the hills surrounding the delta, the susceptibility of the lower catchment to heavy rainfall events approaching from the east, and that the wider Clutha River catchment's location is largely on 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 on the Lower Clutha Delta.

For the wider Clutha River catchment however, changes to rainfall patterns in the headwaters of the Clutha River/Mata-au are anticipated. As discussed in the following section (Section 3.3), rainfall in the upper catchment is one of the major drivers of flooding on the Lower Clutha Delta. Average annual rainfall in the upper catchment is predicted to increase 12% by 2090, with average winter rainfall anticipated to increase up to 29% (MfE, 2008). As discussed in Section 3.4, high lake and river levels in the upper catchment could increase flows in the Clutha River. The predicted reduction in annual snowfall may also reduce the moderating effect that snow currently has on flows in the Clutha River/Mata-au during the winter months.

[6] ORC has provided additional information about the spatial distribution of average (annual and seasonal) rainfall on the Lower Clutha Delta and surrounding area through grow OTAGO (http://growotago.orc.govt.nz).
[7] Wet days are those where daily precipitation exceeds 1.0mm.
[8] '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.

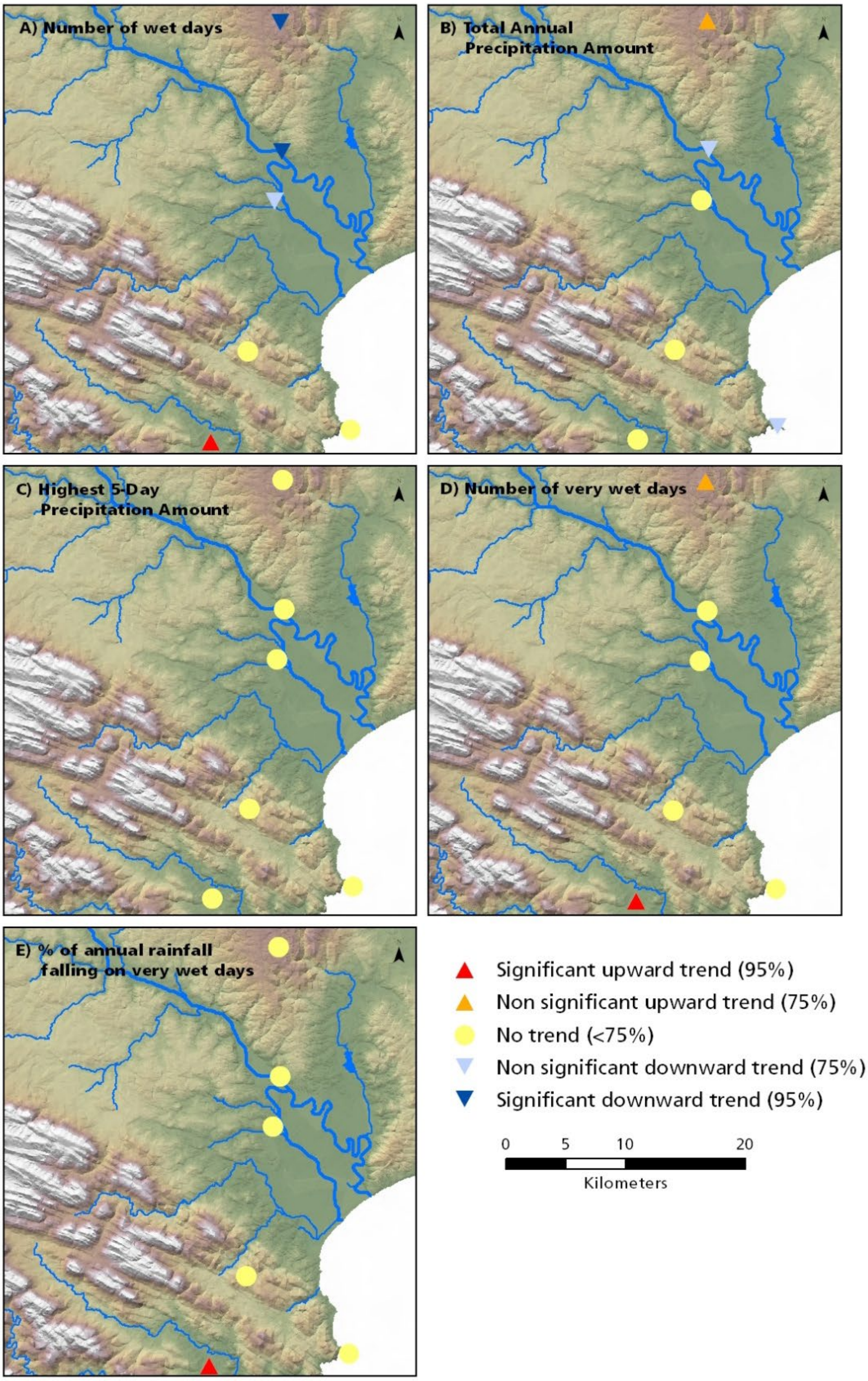


Figure 3.8 Spatial variability of extreme precipitation trends on the Clutha Delta and surrounding hills. The trends shown are for the full length of record, until the end of 2012. See Figure 3.7 for rainfall station names.

3.4. Surface Water

In terms of its volume and catchment area, the Clutha River/Mata-au is the largest river in New Zealand. Originating in the Otago headwaters in the Southern Alps of the South Island, the Clutha River flows for approximately 340km before discharging 6% of the South Island's freshwater into the Pacific Ocean at Molyneux Bay.

Three large lakes are located within the wider catchment – Lakes Wanaka, Wakatipu and Hawea (Figure 3.2). Collectively, these lakes contribute more than 84% of the flows into the Clutha River. The river has four main tributaries: the Kawarau and Upper Clutha Rivers in the upper catchment (the largest contributor of flows in the Clutha River), the Manuherikia River in the central reach and the Pomahaka River in the lower reaches of the catchment[9]. A number of smaller tributaries, such as the Cardrona, Luggate, Lindis, Fraser and Teviot Rivers can also contribute reasonably large flows into the Clutha River during heavy rainfall events.

From its headwaters, the Clutha River/Mata-au flows through a number of gorges and basins before emerging onto the river delta near Barnego. Downstream of Balclutha, the river bifurcates to form two channels; the shallow, wide and straightened Koau Branch to the south, and the meandering, narrow and deep Matau Branch to the north. Collectively these two branches of the Clutha/Mata-au define the Inch Clutha, a low lying river delta island bound by the Clutha River/Mata-au to the north, west and south, and the Pacific Ocean (Molyneux Bay) to the east.

There are two main water courses that traverse across the Lower Clutha Delta – the Clutha River (Koau and Mata-au branches) and the Puerua River to the south. To the north east of the delta is Lake Tuakitoto (and the former Lake Kaitangata) which flows via the Kaitangata River into the Matau Branch of the Clutha River. There are also a number of smaller watercourses, drains, paleochannels and oxbows across the lower delta that are associated with flood hazard in this area (refer to Chapter 4).

Flooding of the Lower Clutha Delta can result from storm conditions occurring across some or all of the Clutha River catchment. There are three main types of floods that can affect this area; an upper catchment flood originating from the Kawarau and Upper Clutha catchments (the Otago headwaters); a lower catchment flood resulting from storms affecting the eastern half of the South Island; and the most severe, a combination of upper and lower catchment flooding simultaneously arriving on the Lower Clutha Delta.

Upper catchment flooding is generally associated with north-westerly fronts moving over the southern part of the South Island resulting in heavy rainfall in the headwaters of the Upper Clutha and Kawarau catchments. These fronts can sometimes stall over the Southern Alps for a number of days. The presence of three large lakes in the upper catchment, Lakes Wakatipu, Wanaka and Hawea (Figure 3.2), moderate the effects of such events through their ability to naturally store inflows from the headwaters. While Lakes Wakatipu and Wanaka respectively discharge outflows into the Kawarau and Upper Clutha Rivers naturally, Lake Hawea's outflows are controlled by the presence of a hydro-electric power scheme. Flows in the Clutha River/Mata-au can be further moderated through the operation of hydro-electric dams

[9] Mean annual flows for the main tributaries of the Clutha River are as follows (averaged over last 5 years of mean annual flow records): Kawarau River at Chards Road, 197 m^3/s; Clutha River at Cardrona confluence, 263 m^3/s; Manuherikia River at Ophir, 14.1 m^3/s; Pomahaka River at Burkes Ford, 24.2 m^3/s.

at Clyde and Roxburgh, although their storage is insufficient to significantly control extreme flood peaks. It generally requires a series of fronts, or a combination of fronts and snow melt to significantly raise the lake levels. High lake levels and thus high outflows from the lakes take approximately 36 hours to reach Balclutha (Figure 3.6) (ORC, 2007).

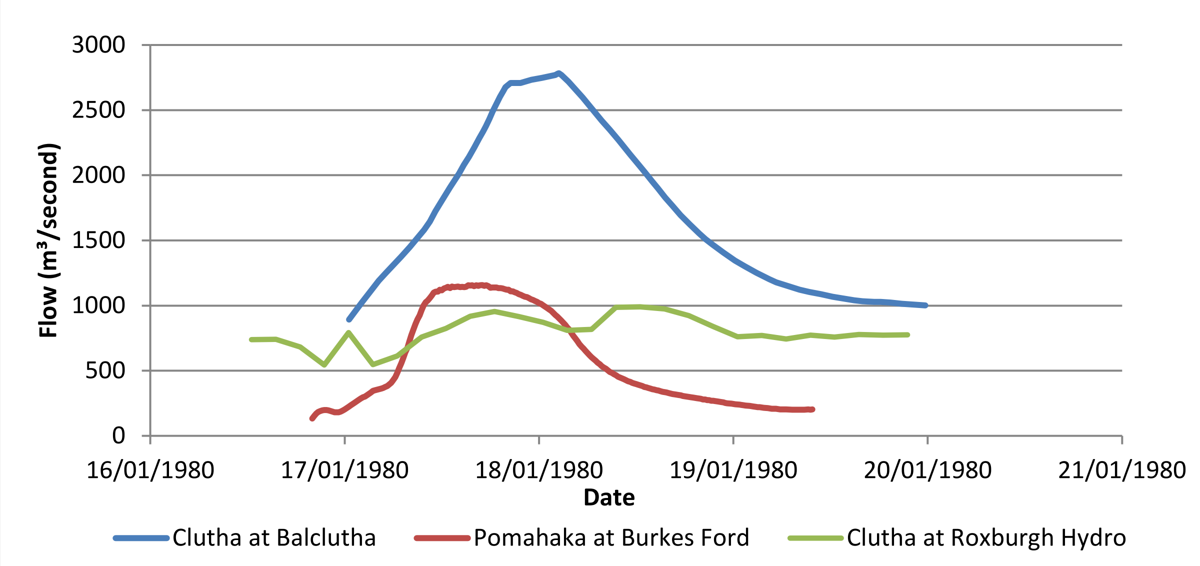


Figure 3.9 Hydrograph demonstrating the approximate travel time between high flows in the Pomahaka River and high flows in the Clutha River/Mata-au at Balclutha, during January 1980 easterly storm event.

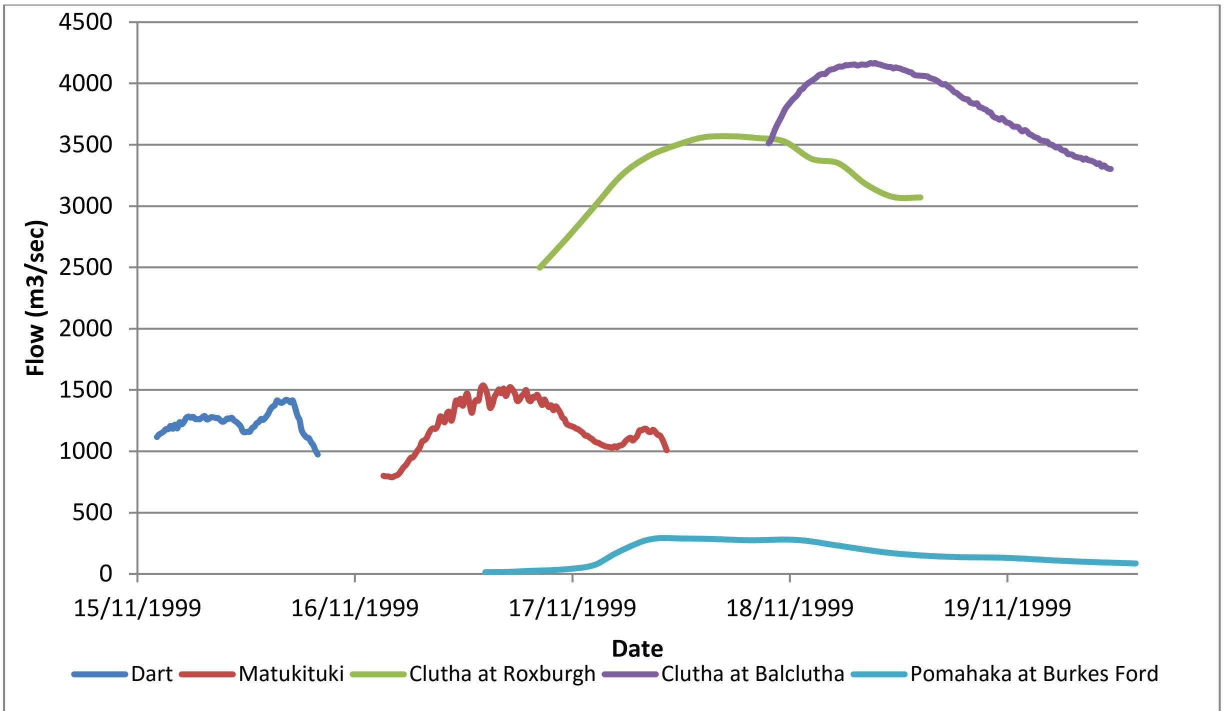


Figure 3.10 Hydrograph demonstrating the approximate travel time between flows in the headwaters of the Clutha River/Mata-au catchment and high flows in the Clutha River/Mata-au at Balclutha for the November 1999 flood event.

Lower catchment flooding is generally associated with storms along the east coast of the South Island. The Pomahaka Catchment can contribute major flows into the lower Clutha River/Mata-au during easterly flood events and has historically produced a number of extremely high floods. High flows in the Pomahaka River (at Burkes Ford, see Figure 3.2) take approximately 9 hours to reach Balclutha (Figure 3.9). The flood of January 1980 is an example of lower catchment flooding where over 70% of the peak flow at Balclutha originated from the catchment below Roxburgh (Scarf, 1997).

The third, and most critical flood producing event is one where significant rain falls in both the upper and lower catchments, with flows arriving simultaneously at Balclutha (Figure 3.10). The flood of September 1878, and more recently November 1999 are examples of such flooding, with heavy rainfalls recorded for several days initially in the headwaters and subsequently over the whole catchment. Major flooding was experienced over the entire catchment, however destructive and widespread flooding occurred on the Lower Clutha Delta as a result of peak flows from the upper catchment coinciding with the peak flows from the Pomahaka catchment at Balclutha. The flood of October 1878 is still today the largest flood since records began in this catchment.

Flooding on the Lower Clutha Delta can also be amplified by blockages at either or both of the Clutha River mouths. Offsetting or blockages of the river mouths can reduce the efficiency in which the Clutha River/Mata-au discharges flows into Molyneux Bay. This results in river levels being higher than would ordinarily be expected near the river mouths and immediately upstream (Scarf, 1997). In the June 1972 flood event the water level at the Koau Mouth was approximately 1.6m above the expected flood level due to offsetting of the mouth. What should have been a flood that was safely contained within the floodbank system, overtopped the Paretai floodbanks inundating a large area (Figure 3.8). Works completed at both mouths since the 1980s, including the construction of rock training walls at each mouth, has substantially reduced the potential for the mouths to move and offset (Figures 3.12 and 3.13). This is discussed further in Section 6.3.

Figure 3.11 Flooding of the lower Paretai area during the June 1972 flood event.

Figure 3.12 Training line at the Koau Mouth of the Clutha River/Mata-au in August 2012.

Figure 3.13 Training line on the true right of the Matau Mouth of the Clutha River/Mata-au. Left image is looking eastwards, towards the Matau Mouth (September 2006), right image is looking westward towards Molyneux Bay (March 2013).

Much of the Lower Clutha Delta (in the vicinity of Molyneux Bay) relies on pumping stations for drainage due to the limited fall across the delta and its position relative to sea level (Figure 3.5). For operational drainage purposes, the Lower Clutha Delta is separated into four drainage areas: Barnego, Matau District, Inch Clutha and Paretai/Otanomomo (ORC, 2000). This drainage system is designed to deal with runoff of 10mm in 24 hours for the flat land and 25mm in 24 hours for any contributing hill catchment. Contour Channels and large drains are strategically located along the base of the surrounding hills to intercept run off from the hill catchments and divert them directly to the nearest water body and away from low lying areas (ORC, 2000).

The drainage scheme includes five pumping stations that ensure that the design drainage standards are being provided even when river levels prevent gravity drainage (see Figure 4.3). During and following periods of heavy rain, the pumping stations require close attention to ensure the intakes are kept clear of weed.

A tidal influence is known to exist on the eastern parts of the Lower Clutha Delta. During low flow conditions, stage levels at Rutherfords Locks, Kaitangata Locks and the Paretai Pump Station (Figure 4.3) can fluctuate up to 2m due to the tidal influence. These three sites are located approximately 1.5km, 3.7km and 5km respectively from their nearest river mouth at Molyneux Bay. During large flood events, tides become less influential in the lower Clutha River/Mata-au and the estuaries near the mouth (Figure 3.14).

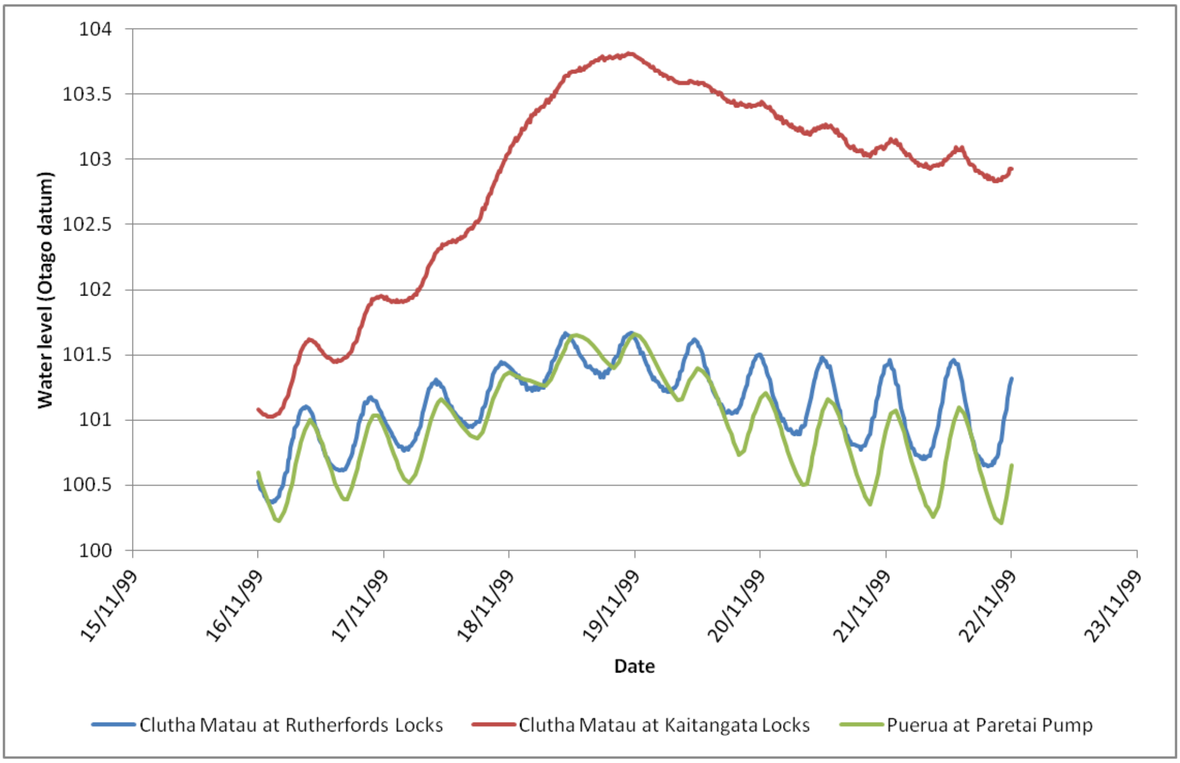


Figure 3.14 Water levels in the Clutha River/Mata-au at Rutherford Locks and Kaitangata Locks, and the Puerua River at Paretai Pump during the November 1999 flood. The distinct tidal fluctuations become less apparent during the peak of the flood on 18 November 1999.

Limited formal investigations have explored the extent of the tidal influence on the Clutha River/Mata-au. Based on changes in the observed ecosystems within the Koau and Matau Branches, the saltwater wedge[10] is thought to extend to just downstream of Kaitangata in the Matau Branch and approximately the equivalent distance in the Koau Branch. The tidal influence on water levels in Clutha River/Mata-au due to freshwater not being able to penetrate the saltwater wedge is thought to extend potentially as far upstream as Mosleys Loop, Finegand and Lake Tuakitoto (Hickey, pers. comm. 2013). Further investigations are required to confirm the tidal influence.

3.5. Groundwater

As previously outlined in Section 3.1 the Lower Clutha Delta is an alluvium-filled valley formed by the interaction of the meandering Clutha River/Mata-au. The landscape has been shaped by a combination of transgression and regression of sea level and sediment carried and placed onto the land by the rivers and along the shore by sea currents. The alluvium deposits consist of unconsolidated, angular to well-rounded gravel, sand and mud to fine grained well sorted sand and silt with reworked beach sand nearer the coast. The thickness of the alluvium is unknown; however bore-logs indicate that the alluvium is at least 24m thick. Groundwater is some 0 to 3m below ground level on the floodplain and some 4 to 6m on the slightly elevated terrace exposed between the Koau Branch of the Clutha and the Puerua River (Morris, pers. comm., 2013).

[10] The intrusion of salt water into freshwater.

4. Flood Hazard

Flooding has been a fact of life for residents of the Clutha Delta for over a century, with a number of significant floods having occurred since European settlement in the mid-1800s. But, it has been the number, and the relative frequency, of significant floods over the intervening years that has established river flooding as the principal natural hazard for the delta. The current flood protection scheme was only partially completed when the October 1978 flood occurred (as the next largest flood event since the devastating flood of September 1878, 100 years earlier) with overtopping and breaching of the floodbanks occurring in several locations. Like the 1878 flood, the October 1978 flood was also a catchment-wide event. Flood maps, retrospectively reconstructed to show the extent of that flooding, illustrate the underlying flood hazard for the Clutha Delta (see Figure 4.1).

The Lower Clutha Flood Protection Scheme has significantly modified the flood hazard for much of the Lower Clutha floodplain and delta, and the Clutha River/Mata-Au and its major tributaries have all been modified in some way by engineering works. But, despite the scheme works now in place, a residual flood risk still remains for those parts of the Lower Clutha floodplain and delta that rely on these works for protection. That is, the possibility of the floodbanks being overtopped or breached can never be totally eliminated, so flooding can occur in a particular area in an event of lesser magnitude than the 'design' flood for that area.

In this chapter, the flood-hazard characteristics of the Lower Clutha floodplain and delta are outlined, with reference to past flood events and the engineering works that have modified the effects of that flooding. The interaction between the different parts of the floodplain is explained in relation to the operation of the Lower Clutha Flood Protection Scheme, as determined from modelling and observation of performance. The variation in flood hazard is then described in more detail for specific areas of the floodplain and delta. This report does not present a complete record of the flood history for the Lower Clutha floodplain and delta, but it does refer to historical events to illustrate the flood-hazard characteristics of the various areas. The flood mapping is not necessarily complete because not all floods have been comprehensively mapped, and some floods have only been mapped in certain areas. The absence of mapping does not mean that an area is flood-free or less-affected than areas that have been mapped.

The flood hazard for a particular area is determined in part by the capacity of the watercourses and their ability to contain and convey floodwater along assured pathways, which can sometimes be augmented by the floodbanks. However, that capacity can also be reduced by sediment and/or debris deposition, and by bed and bank erosion, and by lateral spreading and settlement of floodbanks as the result of seismic-induced ground shaking. The consequential effects of all these potential influences must be taken into consideration when assessing the flood hazard for a particular location on the Clutha Delta. Information on the other natural hazards is presented in later chapters of this report.

4.1. Significant flood events

A number of major flood events have occurred in the Lower Clutha floodplain and delta, with the earliest record being for a flood in 1851 (Soil Conservation and Rivers Control Council, 1957). Table 4.1 lists all the significant flood events of the past 150 years that have been either estimated or recorded at Balclutha since 1863 (with a significant flood event for the Clutha Delta area being where the peak flow at Balclutha exceeded 2000 m^3/s).

Table 4.1 Flood flows in the lower Clutha River/Mata-Au in excess of 2000 m^3/s (at the Balclutha Recorder).

Date	Estimated or recorded peak flow (m^3/s)
July 1863	2400
January 1866	3700
September 1878	5600
March 1904	2400
October 1912	2400
March 1913	2700
May 1917	3350
September 1917	2100
January 1919	3950
January 1924	2250
October 1928	2400
November 1936	2450
May 1940	2100
February 1945	2550
October 1946	2250
November 1948	2700
March 1949	2100

Date	Estimated or recorded peak flow (m^3/s)
May 1957	2160
November 1957	3190
February 1958	2420
April 1967	2040
March 1968	2050
September 1970	2050
September 1972	2580
October 1978	4580
January 1980	2780
June 1980	2310
January 1983	2190
December 1984	2090
March 1987	2300
February 1991	2570
January 1994	2920
December 1995	3420
November 1999	4160

Note: There have been no significant floods (exceeding 2000 m^3/s) since 1999. The only other decades in the past 150 years that did not experience events of greater than 2000 m^3/s were the 1880's and 1890's.

September 1878 Flood

The flood of September 1878 is the largest event on record to have occurred on the lower reaches of the Clutha River/Mata-Au since records began in the late 19th century, with flows having reached approximately 5600 m^3/s at Balclutha (estimation). An event of that magnitude is currently considered to have a return period (average recurrence interval) of between 100 and 200 years. The 1878 flood event occurred prior to any comprehensive flood protection measures having been established and was caused by exceptional meteorological conditions. Namely, the extensive snow-melt after an unusually severe winter in the upper parts of the catchment was combined with exceptionally heavy and long-lasting rainfall. The flooding was widespread and lasted several days (observations at the time indicating that there were three consecutive, very high peaks in a period of just two weeks). A large number of bridges along the Clutha River/Mata-Au were destroyed or swept away, including the Balclutha Road Bridge (Figure 2.6). The flooding at Balclutha was extremely severe, where the river overtopped its true right bank and took the path of least resistance through the town, inundating the streets under several feet of water, with strong currents in many places. All the low-lying land downstream of Balclutha (from Lovells Flat across to Otanomomo, including Inch Clutha) was also inundated and the Clutha River/Mata-Au opened two new mouths, after which the original mouth at Port Molyneux gradually silted-up and closed.

October 1978 Flood

The October 1978 flood is the second largest flood event on record, with flows peaking at just above 4500 m^3/s at Balclutha (in excess of the 1:50-year flood), and very extensive flooding of the rural areas of the Lower Clutha River/Mata-Au occurring; due partly to overtopping of the uncompleted floodbanks along the Matau Branch, and partly as a result of the Koau Mouth offsetting and raising water levels in that branch, which caused overtopping and extensive breaching of the lower Koau left and right floodbanks (see section 4.2 for more details on mouth offsetting).

Figure 4.1 shows the extent of the flooding that occurred during that event (Paretai area in foreground) including the off-set position of the Koau mouth. The Barnego Flats and the land on the true left bank of the Matau Branch, between Stirling and Kaitangata (known as the Matau District) were all extensively flooded by the river; in addition to the lower parts of Inch Clutha, and the Paretai and Otanomomo areas that are also shown in Figure 4.1. Refer also to Figure 4.2 for the full extent of the flooding for the October 1978 flood event.

Figure 4.1 Flooding of the coastal Clutha Delta during the October 1978 event.

Flood waters from tributaries such as the Puerua River and the Waitepeka River (refer to Figure 3.4) exacerbated the flooding in some areas. In some low-lying areas, such as the Matau District, sustained high water levels in the Matau Branch prevented gravity drainage and the flood water had to be pumped out. It is reported that it took twenty days of continuous pumping to remove the ponded floodwater from the area (Otago Regional Council, 1995). Parts of Balclutha township (around the Town Hall and at the Showgrounds) were inundated through floodwater seeping beneath the floodbanks (see section 4.2 for more details on seepage). The industrial area on the landward side of the floodbanks was inundated by water from Hospital Creek (refer to Figure 3.3 for location). However, none of the floodbanks protecting Balclutha were overtopped during this flood event. In addition to building damages and agricultural losses (stock losses, destruction of crops and pasture), roads, bridges, culverts and related infrastructure on the Clutha Delta were also extensively damaged.

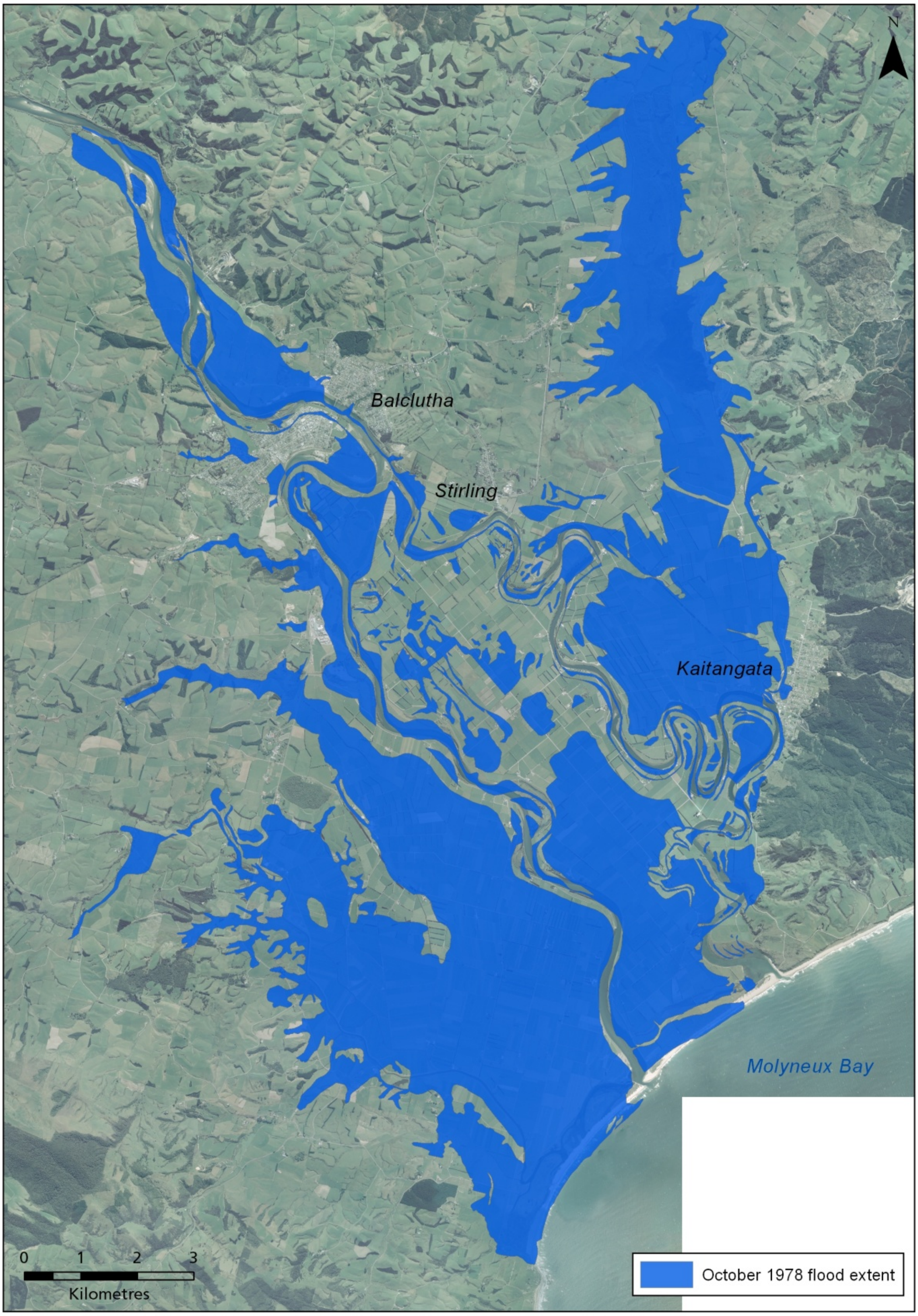


Figure 4.2 Mapped inundation extents during the October 1978 flood.

November 1999 Flood

The flood of November 1999 is the third largest and the most recent major flood since flow measurements began at Balclutha in July 1954. The flow peaked at just above 4000 m^3/s (or just above the currently estimated 1 in 40 year return period flood) which slightly exceeded the design standard for the rural areas of the Lower Clutha Flood Protection Scheme (see section 4.2 for details). However, other than at Barnego where the peak flow was some 50% above the design standard for that area, the November 1999 flood was largely contained within the floodbank system. In general, the flood protection works performed in accordance with the design, although some sandbagging was required at Paretai and at a number of locations along the Koau and Matau branches. Seepage under the floodbanks (see section 4.2) was observed in Balclutha and rural locations but did not cause any significant damage. Some low-lying areas, although protected against river flooding, were inundated by the tributaries draining the surrounding hills or by localised rainfall accumulation. This flood event highlighted areas where further work was needed to ensure that the scheme's design standards would continue to be met, and the necessary improvement works were undertaken after that flood.

No flows exceeding 2000 m^3/s have been recorded at Balclutha since the November 1999 flood event (i.e. within the last 15 years). The 15-year duration since that last major flood, together with the presence of the flood protection scheme, could potentially establish a degree of complacency within the community and so create the impression that the residual flood risk is less than it actually is.

4.2. Modification of the flood hazard

The Lower Clutha floodplain and delta is generally flat and low-lying (Figure 3.3) and is naturally prone to inundation from river flooding, with the tide also affecting river levels in the area. Those conditions allowed large parts of the Clutha Delta to become covered in dense, swampy vegetation, with poor natural drainage, which was the scene presented to the early settlers of this area. So it was inevitable that the early European settlers would start to clear the land and construct flood protection and drainage works on the delta.
Initially these works were carried out privately or by one of a number of independent authorities that each administered a relatively small area. As a result of this disjointed jurisdiction there was a distinct lack of co-ordinated effort and in many instances the work done by one of those authorities would be bitterly opposed by another, particularly if the latter was attempting to improve the land on the opposite side of the river.

The "Lower Clutha River Trust" (the Trust) was established in 1938 (by way of the Lower Clutha River Improvement Act 1938) in order to implement the March 1920 remedial works recommendations of the Rivers Commission, which the Government had appointed in April 1919. The Rivers Commission had been set up to investigate river channel siltation, bank erosion and flooding of the adjacent land in the Lower Clutha River with the aim of ascertaining the best method of river control and the extent of drainage work that may also be required. The Trust was constituted as a body corporate that was deemed to be a River Board under the Rivers Board Act 1908, but also having all the powers conferred on a Drainage Board under the Land Drainage Act 1908. Therefore the Trust was the first river and drainage authority to have overall responsibility for the whole of the Clutha Delta.

The Otago Catchment Board was constituted in February 1948 (under the Soil Conservation and Rivers Control Act 1941) and took over the Trust's functions in 1952. The Catchment

Board was then requested by the Soil Conservation and Rivers Control Council (the national body that had been set up under the Soil Conservation and Rivers Control Act 1941) to prepare comprehensive flood control and drainage proposals for the Lower Clutha River and delta, which were eventually approved by the Government in 1960 as the Lower Clutha Flood Control and Drainage Improvement Scheme. A unique feature of the works proposed for Government approval had been the integrated nature of the various components of the scheme, whereby the Clutha Delta was for the first time being considered as a single entity. The scheme not only provided for protection against floods in the Clutha River/Mata-Au but also included protection against flooding from local rivers and streams on the delta, together with a significant improvement in drainage standards. The scheme was then implemented over a three decade period, between 1960 and 1991.

The Current Scheme

The scheme, now known as the Lower Clutha Flood Protection and Drainage Scheme (Figure 4.3) is a combined flood control and drainage scheme, incorporating open drains and pump stations to assist removal of floodwaters from the protected areas beyond the floodbanks (this will be addressed in the following pages). It consists primarily of a series of floodbanks that assist the orderly passage of floodwaters across the Clutha Delta to the Pacific Ocean, combined with a floodway system that has been designed to provide the desired balance of flow between the two river branches during medium to high flood flow events. There are five different levels (or standards) of flood protection provided by the scheme to various areas behind the floodbanks (that are up to 5.5 m in height at some locations); but it is important to acknowledge that a residual flood risk still remains for all of those areas, in relation to their design flood standard. Flood Protection Levels (or Standards) for the Lower Clutha Flood Protection Scheme

(Otago Catchment Board, 1956; Otago Regional Council, November 2000):

- Balclutha township and the Finegand Freezing Works have a flood protection target of up to 5600 m^3/s in the Clutha River/Mata-Au (slightly less than the currently assessed 1:200-year return period flow) with the provision of 300 mm of freeboard;
- The rural areas downstream of Balclutha, including Inch Clutha, are protected against a Clutha River/Mata-Au flow of 4000 m^3/s (approximately a 1:40-year flood) with 600 mm of freeboard. This area is also generally protected against a theoretical 1:30-year flood from the smaller tributary streams with 300 mm freeboard (OCB, 1958);
- The inside area of Mosley Road Loop (true right bank of Matau Branch) is protected against a Clutha River/Mata-Au flow of 3200 m^3/s with no freeboard (approximately a 1:20-year flood);
- The Barnego Flats are protected against a Clutha River/Mata-Au flow of 2850 m3/s (approximately a 1:10-year flood) with 600 mm freeboard;
- The Lower Clutha Bypass Floodway is protected against a Clutha River/Mata-Au flow of around 1900 - 2000 m3/s with no freeboard (less than the 1:5-year flood).

The areas protected by the scheme to these various flood standards are shown on Figure 4.3.

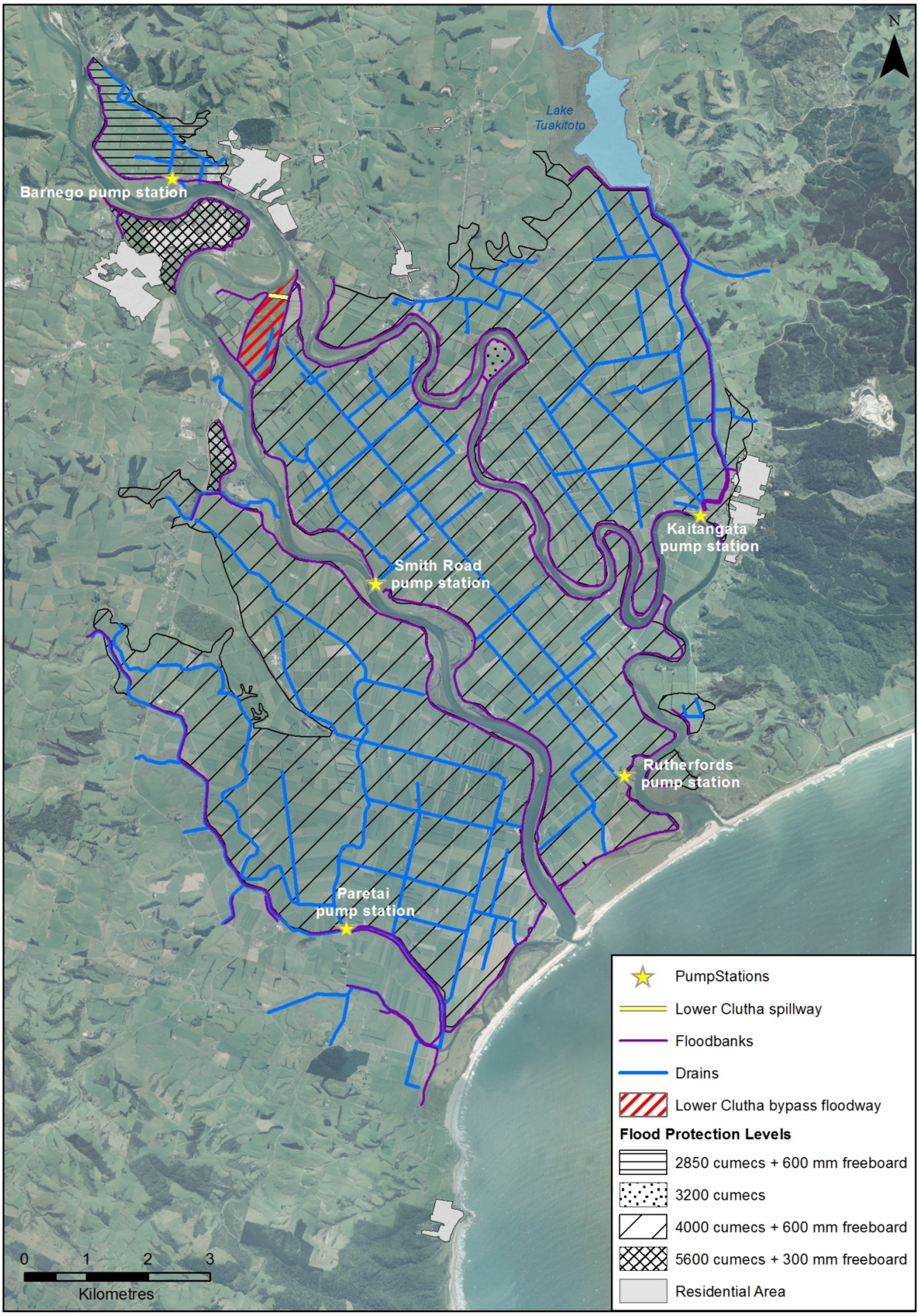


Figure 4.3 Lower Clutha Flood Protection and Drainage Scheme (engineered features of the scheme that modify the flood hazard).

The area encompassed by the scheme extends from Barnego to the two mouths of the Clutha River/Mata-Au and provides flood protection and drainage to the highly productive land of the Clutha Delta, as well as the townships of Balclutha and Kaitangata, and the Finegand Freezing Works. The scheme features over 100 km of floodbanks, 200 km of contour and drainage channels, tide-gate structures, five pumping stations, a series of river protection works (bank protection plus river and mouth training groynes) and a by-pass floodway that is designed to provide the required balance of flow between the two branches of the river during medium to high flow events.

The by-pass floodway consists of a channel with an entrance spillway (a 330 m long uncontrolled weir) designed to limit flood flows in the more constricted Matau Branch to between 1050 m^3/s and 1150 m^3/s under the design low conditions; and to increase the proportion of the flow entering the shorter, and larger capacity, Koau Branch. The floodway also provides flood relief to Balclutha by shortening the flow path of the Koau branch between the Bifurcation (point where the Clutha River/ Mata-Au splits into the Koau and Matau branches) and Finegand. The uncontrolled spillway structure has been designed to commence operating when the flow in the Clutha River/ Mata-Au is between 1880 m^3/s and 2000 m^3/s at the Balclutha recorder (less than the 1:5-year flood). At the downstream end of the by-pass floodway there is a sill to prevent the bottom end of the floodway being flooded by water in the adjacent Koau Branch when the flow in the Clutha River/Mata-Au is less than the operating threshold for the entrance spillway.

The scheme also includes works to improve land drainage and mitigate the flood hazard from tributary streams flowing from the hill catchments, including the Puerua River, the Waitepeka Stream, Lake Tuakitoto and the Barnego area (Otago Catchment Board, 1958). However, it is important to note that the primary objective of the scheme for these tributary catchments was to improve drainage and to mitigate the local flood hazard in order to increase the agricultural productivity of the delta land (and not to provide flood protection for dwellings). The drainage network in the minor tributary catchments does generally provide limited flood mitigation benefits. The drainage networks were designed to provide for 10 mm of runoff in 24 hours for flat land, and 25 mm of runoff in 24 hours for hill country (these figures represent the depth of water that can be removed by the drainage network in that time period).

The main factors considered for the design of the drainage network and local flood mitigation works in those secondary catchments were:

- The use of gravity drainage as much as possible to limit the operating costs. Wherever possible, drainage water is temporarily stored adjacent to the outfall when the tide level is high and released when the tide level is low. It was intended that pumping should only be needed in adverse conditions;

- As far as practical, the water flowing from the hill catchments is diverted away from low-lying areas by means of contour channels or floodbanked streams. This allows it to be safely conveyed (up to the design flow standards) to the Clutha River/Mata-Au or its lower branches. The main contour channels are the Puerua contour channel and the Kaitangata contour channel.

The design flows and water levels for the drainage network and the flood mitigation works for the tributary streams were, in the absence of measured data, derived by synthetic hydrograph analysis based on the relevant catchment characteristics and rainfall. However, there has been no further assessment made of the flood protection standard that was actually provided by the scheme in these areas since the works were first completed. A more detailed description of the drainage network and the flood mitigation works for these tributary catchments is provided in Section 4.3.

The five scheme pumping stations are located at Barnego, Kaitangata, Inch Clutha (Smith Road and Rutherfords) and Paretai, (with a combined total of 12 pumps) and ensure that the design drainage standards are provided for the respective drainage areas when high river levels prevent gravity drainage. The scheme also includes a number of outfall and gate structures, designed to stop river water (including seawater) from flowing back up into the drainage network, with the major structures being the Paretai Gravity Outfall, the Waitepeka Outfall, the Rutherfords Locks, the Inch Clutha Outfall and the Kaitangata Locks. A detailed description of the major structures is provided in Section 4.3.

In addition to the major structures listed above, there are many smaller flood-gated culverts that provide gravity outfall from the drainage network, often through the floodbanks. The majority of these structures are generally automatically controlled by hinged gates that open and close depending on relative water pressure (level) on either side of the gate. A small number of these structures (usually guillotine-style gates) require manual operation during high river flows.

Offsetting (mouth migration) or blockages of the river mouths (Koau and Matau branches), as can be brought about by sediment deposition, has happened several times in the past and is an on-going process that continues to be monitored. A river mouth can offset when the river channel pivots landward of the general shore line and then moves along that line, but is separated from the sea by a sand bar. The river channel then becomes protected from direct wave action by the sand bar. For normal river mouth conditions, the river outlet will enlarge quite rapidly under flood conditions to provide the necessary waterway for the flood flows. But, if the river mouth has offset, then the rate of outlet enlargement can be very slow and result in river levels being substantially raised immediately upstream of the mouth.

On some occasions for the Clutha Delta when one or other of the mouths has been offset, the upstream river levels have risen by more than 1.5 m during a flood event. Such elevations can impair the drainage outlets, even during normal flow conditions, and adversely affect the flood protection standards, with significantly aggravated flooding effects for the lower parts of the Delta. So the river mouths are monitored and works (training banks and mouth opening) have been undertaken in the past to help limit the potential for the mouths to offset.

The Koau Mouth control works have included:

- The construction of a rock access causeway across the Puerua River outlet;
- The installation of five culverts (2.4 m diameter) through the causeway; and
- The construction of a rock training bank with a bull-nosed strongpoint.

The Matau Mouth control works have included:

- The construction of a low level protective rock banks both adjacent and parallel to the narrow sandbank that separates the southern estuarine area from the sea, to prevent a southward migration of the mouth; and
- The construction of a short groyne on the northern side of the mouth to prevent the establishment of a northern blockage.

Figure 4.4 Koau Mouth works- June 1983 (during construction).

Figure 4.5 Matau Mouth works - September 1993

Offsetting of the Clutha River/ Mata-Au mouths is a natural process, but investigations (Otago Catchment Board, 1986) have shown that the process is affected by the management of the upstream, in-channel storages (primarily the Roxburgh Hydro Dam). The Roxburgh Hydro operation has an impact on flows and on sediment loads downstream of the dam. These impacts are monitored on a regular basis and mitigation measures are implemented when necessary, in accordance with the conditions of the consents held by Contact Energy Limited, who manage the operation of the upstream reservoirs. The mitigation measures include (but are not limited to) preparation of flood and sediment management plans, minimum discharges from the dams, riverbank and berm monitoring and maintenance work, coastal erosion monitoring programmes, and maintenance of the river mouths and opening work as necessary.

The ability of the Lower Clutha Flood Protection Scheme floodbanks to contain and convey flows across the delta is dependent on those banks having the necessary structural integrity. Soils and floodbank characteristics in some areas of the Delta (particularly in the vicinity of Balclutha, Matau right bank at Weirs Gap, Koau left bank near Palmer's and Milne's and Renton Road, and Koau right bank near Paretai) are such that there is an increased risk of floodbank failure due to seepage under the floodbanks. Namely, water up-welling on the landward side of the floodbanks, sometimes in the form of sand boils (Figure 4.6).

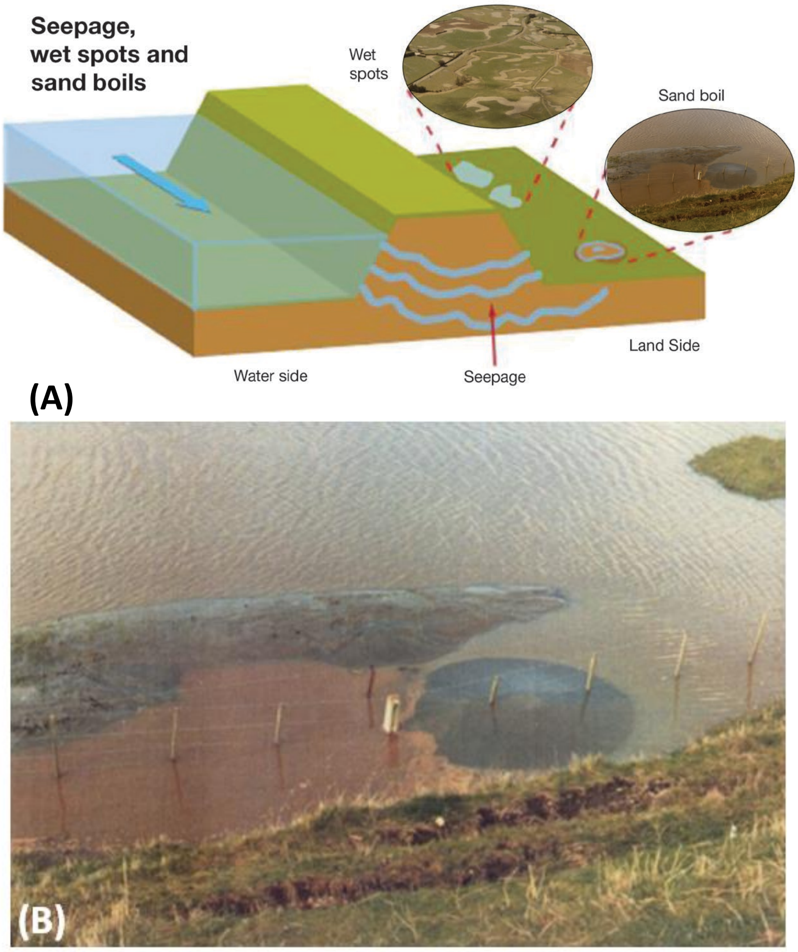


Figure 4.6 a) Illustration of floodbank failure by seepage under the floodbank. **b**) Example of sand boils in Inch Clutha during the October 1978 flood.

In Balclutha, the floodbank foundation conditions are less than ideal for the height of floodbank needed to provide the design flood protection standard. There is an upper silt layer ranging in thickness from a minimum of 1 m to a maximum of about 20 m underlying Balclutha. This relatively impervious silt unit sits on a layer of pervious gravel, 4 to 20 m deep. When the upward pressure caused by seepage from the river into the gravel layer exceeds the downward acting weight of the silt layer, boils (which mobilise fine material) can develop, resulting in floodbank failure or foundation-piping failure. Forty three relief wells (vertical bores lined with filter material, Figure 4.7) installed on the landward side of some floodbanks (mainly in the vicinity of Balclutha) mitigate the risk of floodbank failure. These are a critical feature of the scheme.

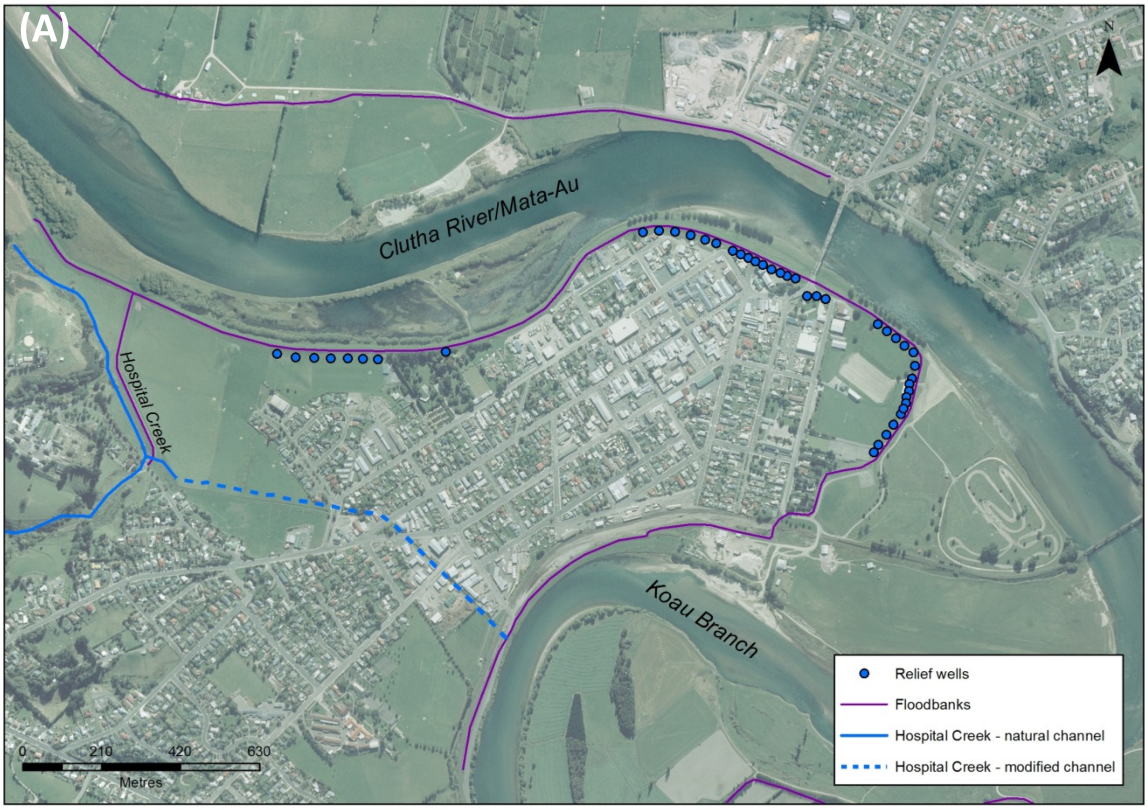


Figure 4.7 Location of the 43 relief wells in Balclutha **a**) and photos of the emerging part of two types of relief wells operating in the March 1987 flood event (**b** and **c**, below).

The relief wells connect the pervious gravel layer to the surface, thus allowing the seepage water to escape without taking the fine soil material with it, and so relieve the upward pressure that would otherwise cause a floodbank failure (Figure 4.7). Drains collect the under seepage water from the wells and, when required, this water is pumped back into the river via flood-gated pipes through the floodbanks. In 2005 a geotechnical assessment of the Lower Clutha Scheme Protection floodbanks was carried out. Figure 4.8 summarises the conclusions of that assessment in regard to the risk of piping failure (Tonkin & Taylor Ltd, 2005). The piping failure risk is presently being reassessed.

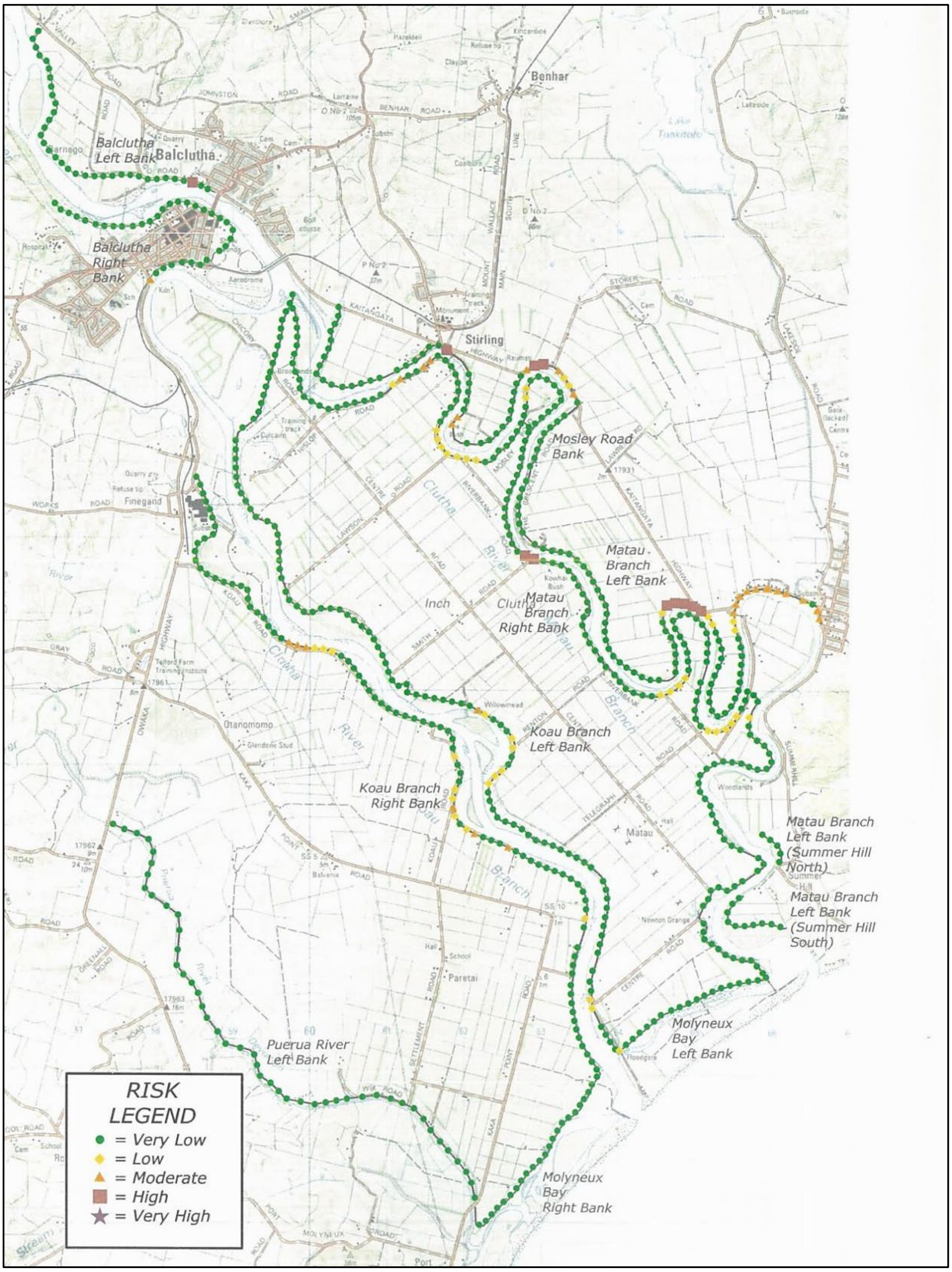


Figure 4.8 Assessed risk of piping failure of the Lower Clutha Flood Protection Scheme floodbank foundations (Tonkin & Taylor Ltd, 2005).

Although the risks of a foundation-piping failure have been mitigated, they are not totally eliminated. Furthermore, floodbank failure due to other mechanisms (such as floodbank overtopping) can still happen (Figure 4.9).

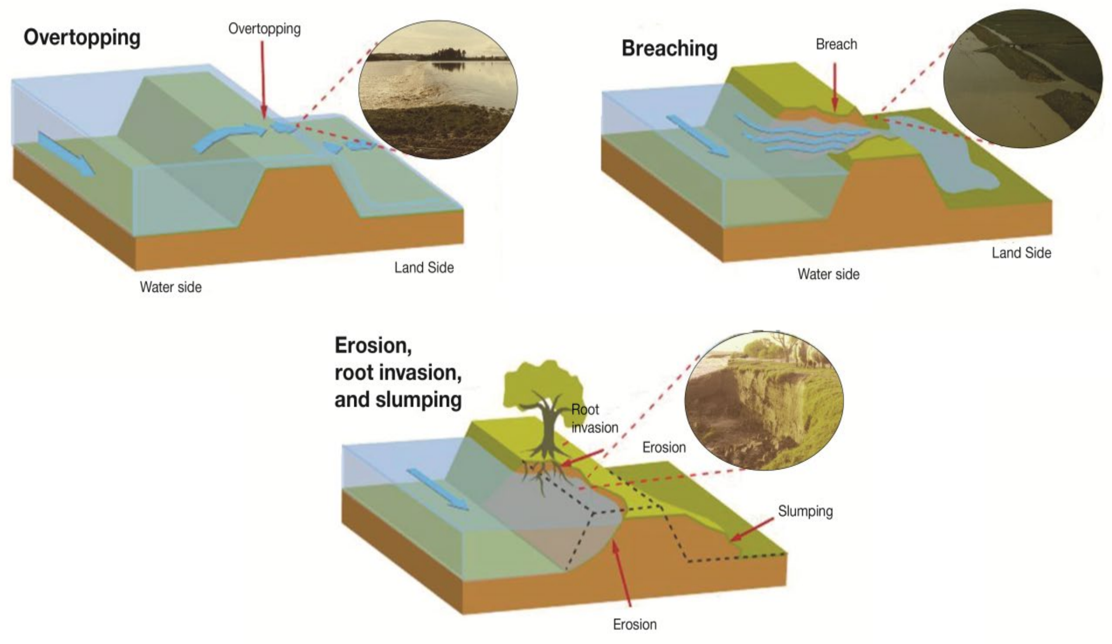


Figure 4.9 Floodbank failure mechanisms, other than piping.

A structural floodbank failure could also be caused by an earthquake. But that risk is not directly related to flooding effects and the expected seismic performance of the scheme's floodbanks is discussed in Chapter 5. In addition to the relief wells, the risk of floodbank failure during a significant flood event would be managed by way of targeted monitoring of the floodbank conditions and known areas under seepage risk.

Since the completion of the scheme the flood protection works have been subject to three significant flood events – in January 1994, December 1995 and November 1999. The November 1999 flood with a peak flow in the Clutha River/Mata-Au at Balclutha of 4160 m^3/s exceeded the design standard for the rural areas. But, other than at Barnego where the peak flow was some 50% above the design protection standard for that area, the November 1999 flood was largely contained within the floodbank system (refer to Section 4.1 for more details on the November 1999 flood event).

4.3. Variation in flood hazard by location

The nature and severity of the flood hazard varies across the Clutha Delta due to topography, variations in the proximity of watercourses, hydrological characteristics of those watercourses, and the presence or absence of protective elements of the Lower Clutha Flood Protection Scheme. For this report, the delta has been divided into 22 geographical areas, based on flood-hazard characteristics (Figure 4.10). The colour-coding and labelling of these areas is presented simply as a means of identifying and describing the flood hazard variation across the Clutha Delta and does not represent the significance of the hazard.

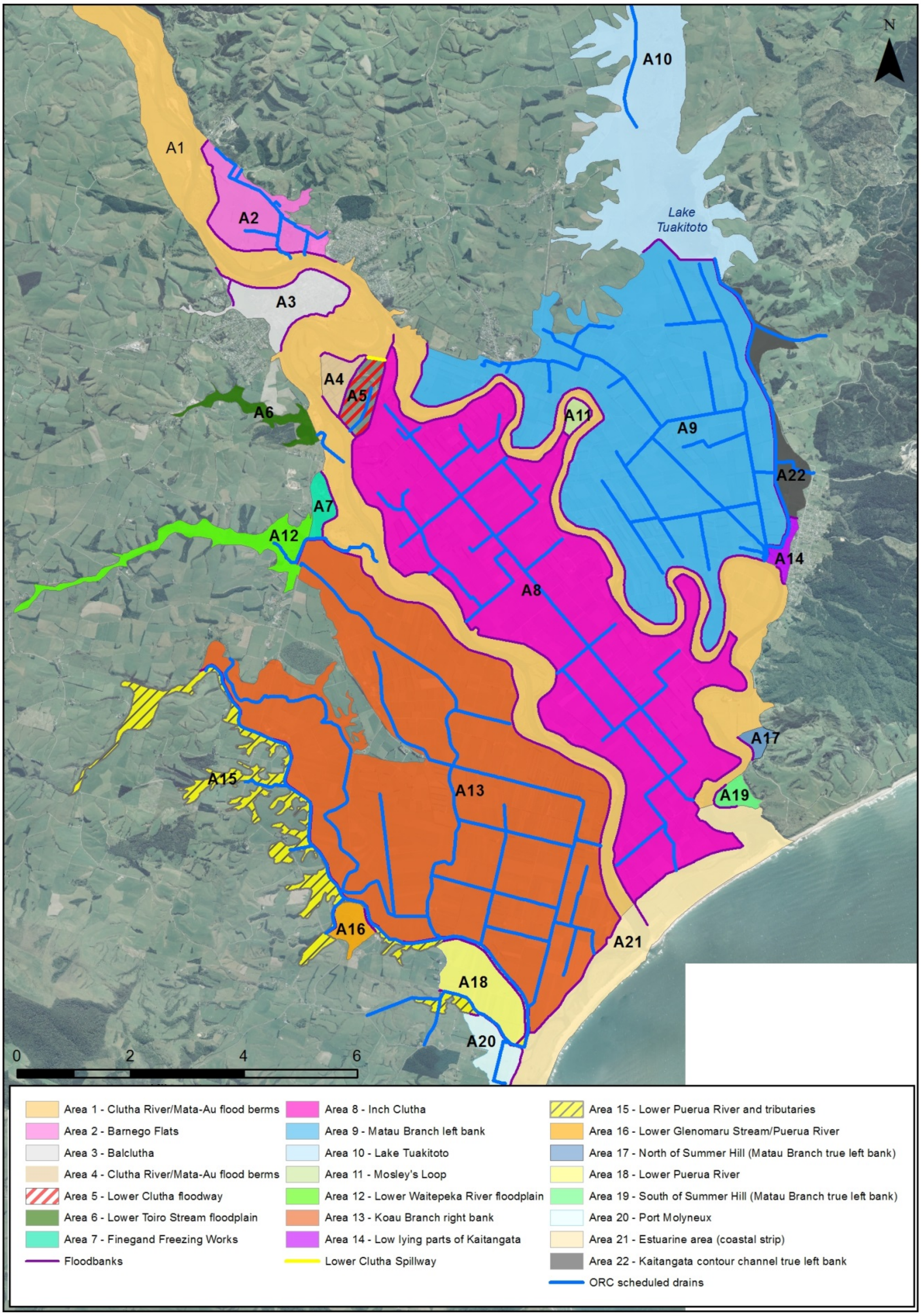


Figure 4.10 Flood-hazard areas on the Clutha Delta. Note that the flood hazard within each area is not uniform. Localised topographical features will also influence the flood hazard within each of those areas.

While each area presents a particular flood hazard characteristic, it does not mean that all the land in that area has the same flood risk. The actual flood hazard will be influenced by topography, overland flow paths and proximity to introduced features, such as fences, shelterbelts and buildings. During a flood event, some portions of an area may remain 'flood free', while others may be completely inundated. This report is not intended to present a complete record of the flood history for the Clutha Delta, although it does refer to historical events to illustrate the flood hazard characteristics for particular parts of the delta.

In 2005/2006, the ORC engaged NIWA to investigate the flood and erosion hazards of the Clutha Delta area and to assess the effectiveness of the Lower Clutha Flood Protection Scheme (NIWA, Nov.2005; NIWA, Feb.2006). Eight design flood scenarios were modelled to provide the base information for the investigation, with flood magnitudes ranging from 2900 m^3/s (a 1:10-year flood event) to 6600 m^3/s (a 1:500-year flood event) in conjunction with three different sea level scenarios (present mean sea level, plus storm surge combinations, and a sea level rise scenario of 0.5 m) and three representative floodbank breach scenarios, in addition to the no-breach case. One outcome of the investigation was that overtopping of the floodbanks (other than at Barnego) would not occur for flows less than 4300 m^3/s (1:50-year flood) which is slightly higher than the design flow standard of 4000 m^3/s for the rural area floodbanks. Depending on the floodbank breach scenario selected for downstream of Balclutha township, the floodbanks around Balclutha may or may not be overtopped when flows exceed 5200 m^3/s (1:100-year flood) which is less than the design flow (5600 m^3/s) for that area. The investigation has shown that the inundation characteristics (extent, depths and velocities) are very sensitive to breaches in the floodbank network.

The depth of inundation, and the water velocity, at the peak of a flood are the key parameters that characterise the flood hazard. During a flood event, the potential hazard to people, vehicles and buildings can be expressed as a combination of the depth and velocity of the flow at a particular location. That is, relatively deep, slow moving (or still) floodwater can potentially be as hazardous as shallow, fast moving floodwater. But the nature of the respective flood damages can differ, depending on the specific flood hazard characteristics and the structural/material characteristics of what is being subjected to those flood flows.

Inundation depths and flow velocities derived from the 2005/2006 NIWA investigation are used in this report to describe some of the flood hazard characteristics for each of the areas shown on Figure 4.10. Figure 4.11 shows the flood extent (shaded blue) for a 1:100-year flood event (peaking at 5200 m^3/s at Balclutha) for the present mean sea level scenario, and with a breach on the Matau Branch (true left floodbank, at Mosley's Loop). It also shows the potential flood hazard (expressed as a combination of the depth of inundation and the water velocity) for this flood flow and breach scenario - where the areas shaded purple (as overlaid on the blue flood extent) represent a high potential hazard from flooding to people and buildings. As already noted, the flood hazard characteristics for a particular area (and flood magnitude) are very sensitive to the assumed location for a breach in the floodbank network; so those characteristics could be very different for a particular area if a different breach scenario was to be considered. Also, the flood extent shown on Figure 4.11 does not include the contribution from the local hill catchments or internal run-off.

The relationship between depth and velocity, used to establish the threshold for the high potential hazard areas shown in Figure 4.11, assumes that the potential hazard (for buildings and their occupants) at a location where the estimated depth and velocity are 0.5 m and 3 m/s respectively, is the same as that for a location where the estimated depth and velocity are 0.9 m and 0.1 m/s respectively. A straight line drawn through these two threshold points, on a depth vs velocity diagram, then defines the high potential hazard threshold used for this report. This straight-line relationship has been adapted from ACER Technical Memorandum No.11 (USBR, 1988) as a suitable threshold to apply to the floodable areas of the Clutha Delta, particularly in regard to the velocity range that could reasonably be experienced in these areas. There are various ways of showing the flood hazard for the Clutha Delta, and the following figures (4.12, 4.13 & 4.14) present the individual component characteristics (depth and velocity) in the format provided in the report on the 2005/2006 NIWA investigation:

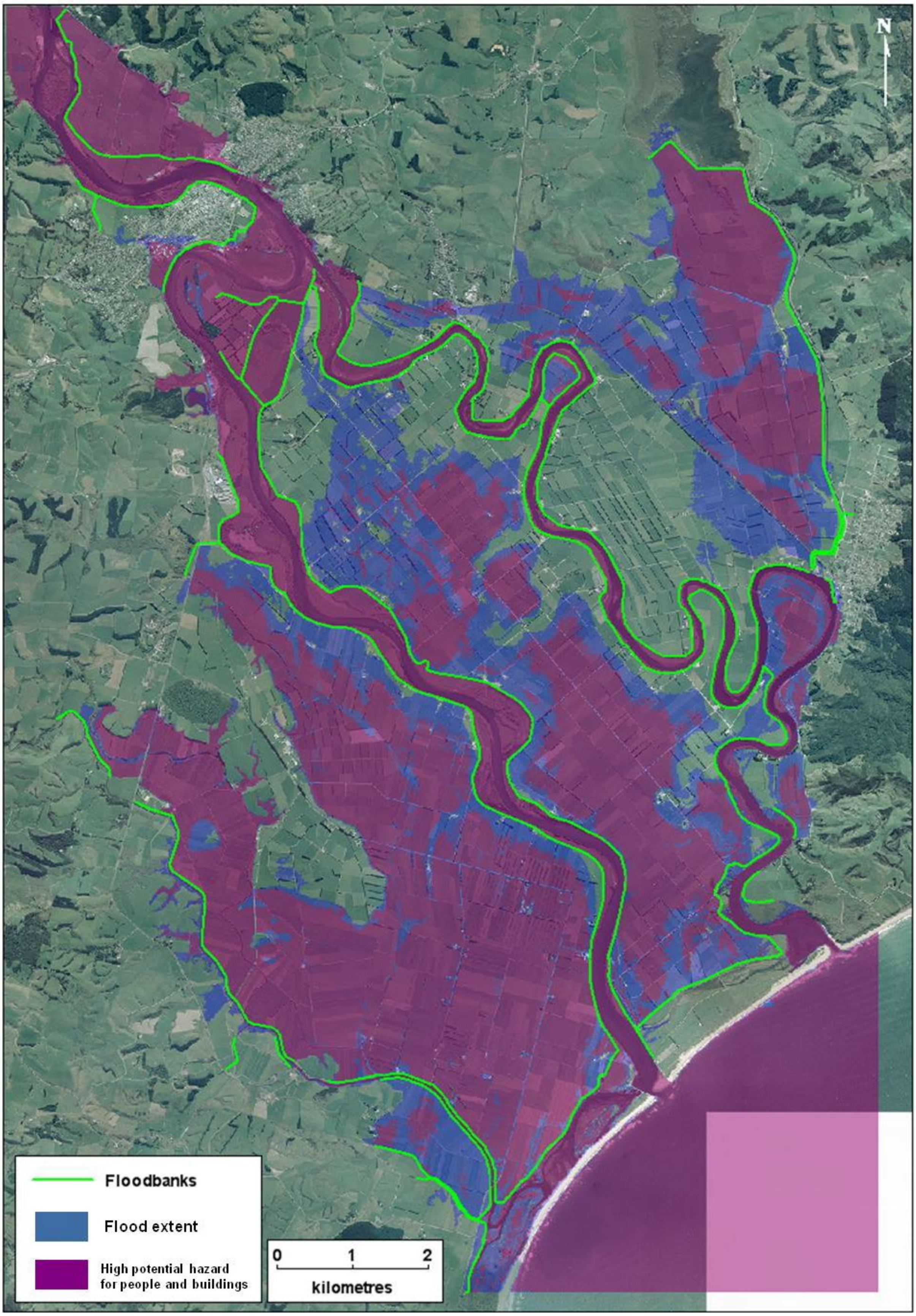


Figure 4.11 Flood extent (shaded blue) and areas with high potential hazard (overlaid in purple) for people and buildings, in a 1:100-year flood event (peaking at 5200 m^3/s at Balclutha) with a floodbank breach on the Matau Branch, at present mean sea level.

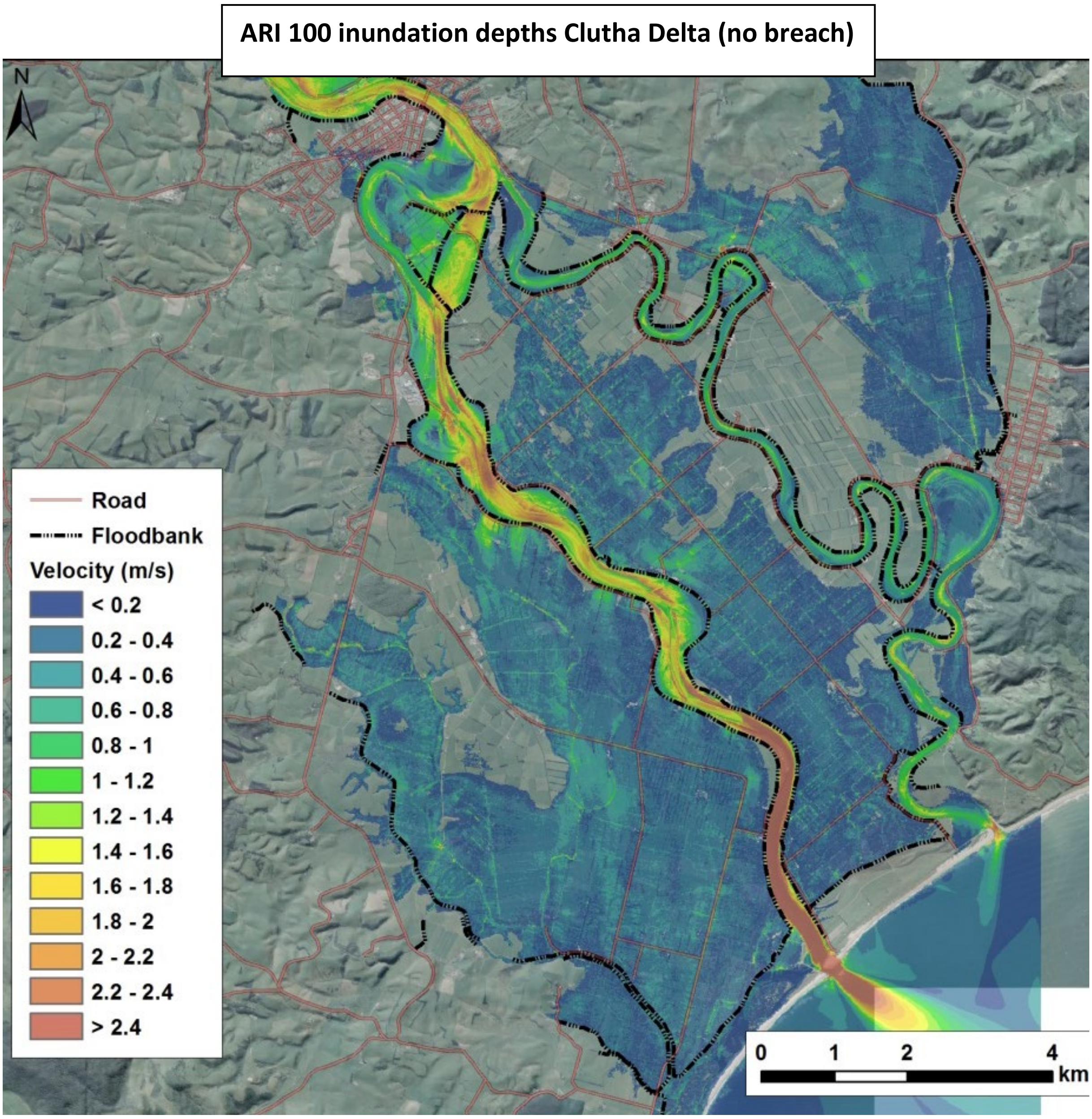


Figure 4.12 Inundation depths across the Clutha Delta at the peak of a 100-year flood event (peaking at 5200 m^3/s at Balclutha) at present mean sea level, but with no floodbank breaches.

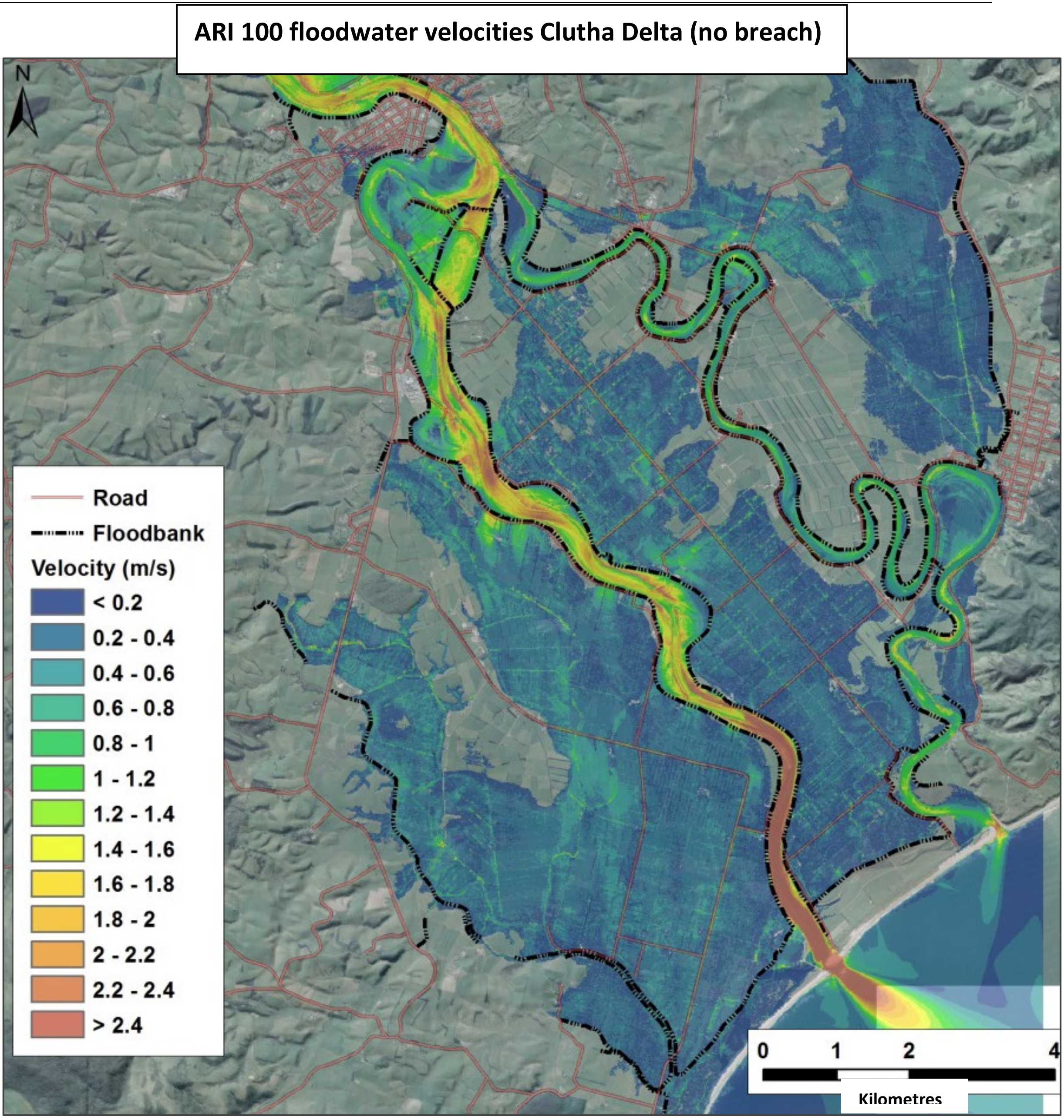


Figure 4.13 Floodwater velocities on the Clutha Delta at the peak of a 100-yr flood event (peaking at 5200 m^3/s at Balclutha) at present mean sea level, but with no floodbank breaches.

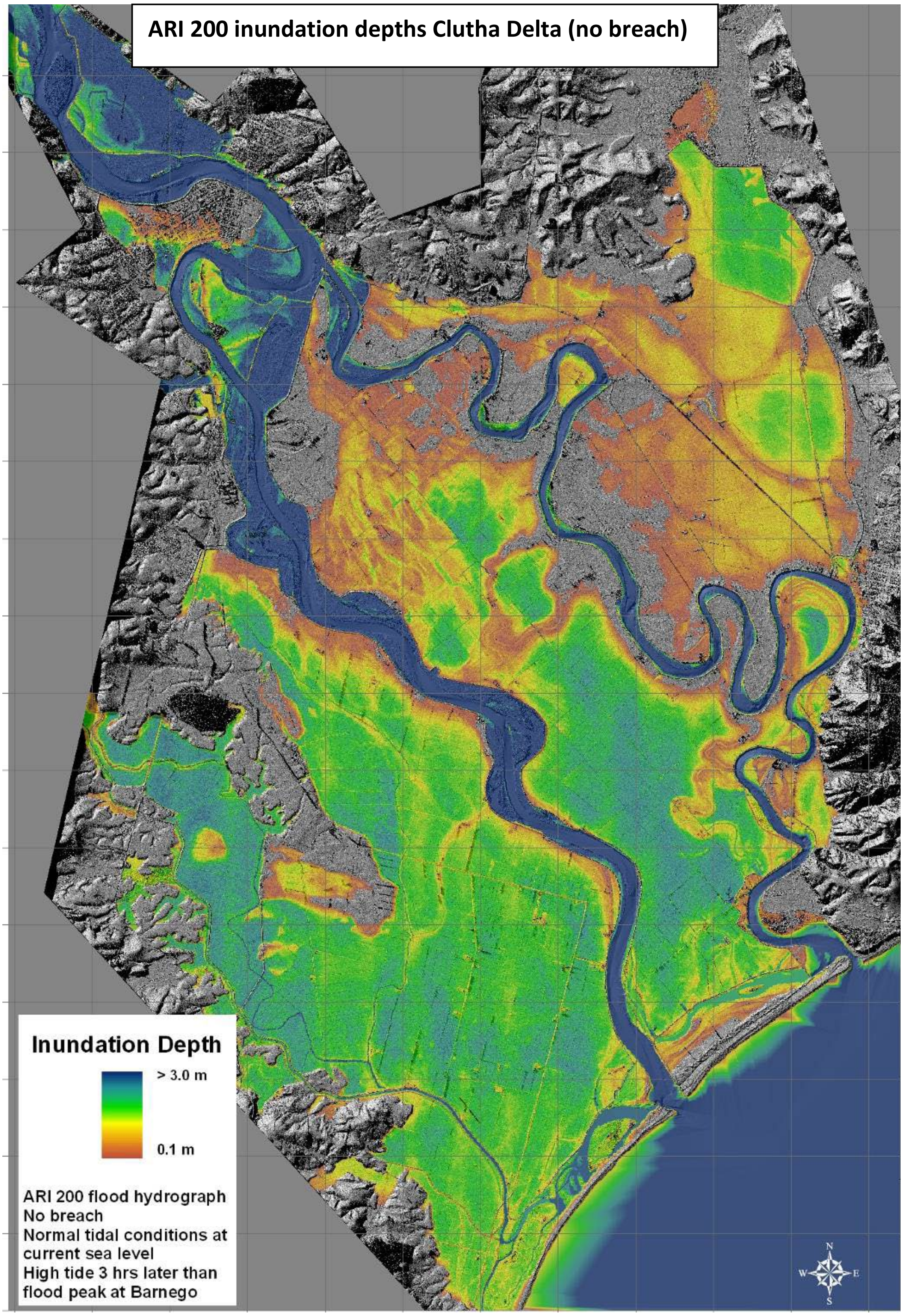


Figure 4.14 Inundation depths across the Clutha Delta at the peak of a 200-year flood event (peaking at 5800 m^3/s at Balclutha) at present mean sea level, but with no floodbank breaches.

The flood-hazard characteristics each area shown on Figure 4.10 are described below:

Area 1: Clutha River/Mata-Au flood berms

This area comprises the immediate flood berms of the Clutha River/Mata-Au and the Koau and Matau branches, including the river channel. Therefore there is no, or very limited direct or designed flood protection for that land. The area is bounded by the scheme floodbanks or by higher ground in the absence of floodbanks (e.g. upstream of Barnego Flats). So it includes the unprotected eastern part of Balclutha township (including the aerodrome), the low-lying areas of North Balclutha (on the true left side of the river), part of the small partially floodbanked area at the north-western end of Inch Clutha, the Koau Branch loop just downstream of Balclutha, and the Matau Branch loop (the furthest of the "Balloon Loops") opposite Kaitangata.

The land in Area 1 is generally flat, but includes several old river channel meanders, and is used primarily for agricultural activities with very few dwellings. There are also some secondary roads, and other facilities (aerodrome, silos, sale-yards and fertilizer storage areas) in the area, including a short section of the Main South Railway Line that crosses the area in the vicinity of the aerodrome, although it is built on raised ground (see Figure 2.8).

The inclusion of the main channel of the Clutha River/Mata-Au channel (and both branches) in Area 1 means that the river itself defines the flood hazard, to which the berms are directly exposed during the early stages of flooding. There are natural levees along some parts of the river, so that the immediate flood risk to the berms can vary somewhat. Small sections of floodbanks at the top (north-western) end of Inch Clutha complement the naturally higher ground to provide limited flood protection (of no specific standard) to a small area (Area 4) between the river and the Lower Clutha Bypass Floodway (Area 5) to the east.

Figure 4.15 Flooding in Area 1 during the November 1999 flood event, looking downstream to Molyneux Bay across Balclutha. Photo not necessarily taken at the peak of the flood.

The bulk of Area 1 is included in the Lower Clutha Flood Protection Scheme and plays a crucial role in the conveyance of floodwater, and hence in the mitigation of the flood hazard for other parts of the Clutha Delta. Area 1 is intended to be the main flow path during high river flows, and modifications (such as the erection of structures that may impede the flow) to this area could affect the safe and effective operation of the Lower Clutha Flood Protection Scheme.

Flooding would be widespread over the area in a 1:100-year flood event, with the depth of water likely to exceed 3 m on the berm areas (excluding the main river channel) and the water velocity could exceed 2 m/s at some locations (Figures 4.12 & 4.13). The potential hazard (expressed as a combination of the depth of inundation and of the water velocity) to people and buildings in this area is considered to be extremely high (Figure 4.11).

Area 2: Barnego Flats

This area comprises the protected part of the Clutha River/Mata-Au floodplain immediately upstream of Balclutha on the true left bank. The land within Area 2 is exposed to flooding from the Clutha River/Mata-Au and, to a lesser degree, from the minor tributaries that flow from the hill catchments on the northern and eastern sides of the area. The land in this area is relatively flat (elevation generally ranging between 5 m to 10 m above msl) and falls away from the river to the toe of the hills, thus forming a natural, shallow bowl shape (Figure 4.16).

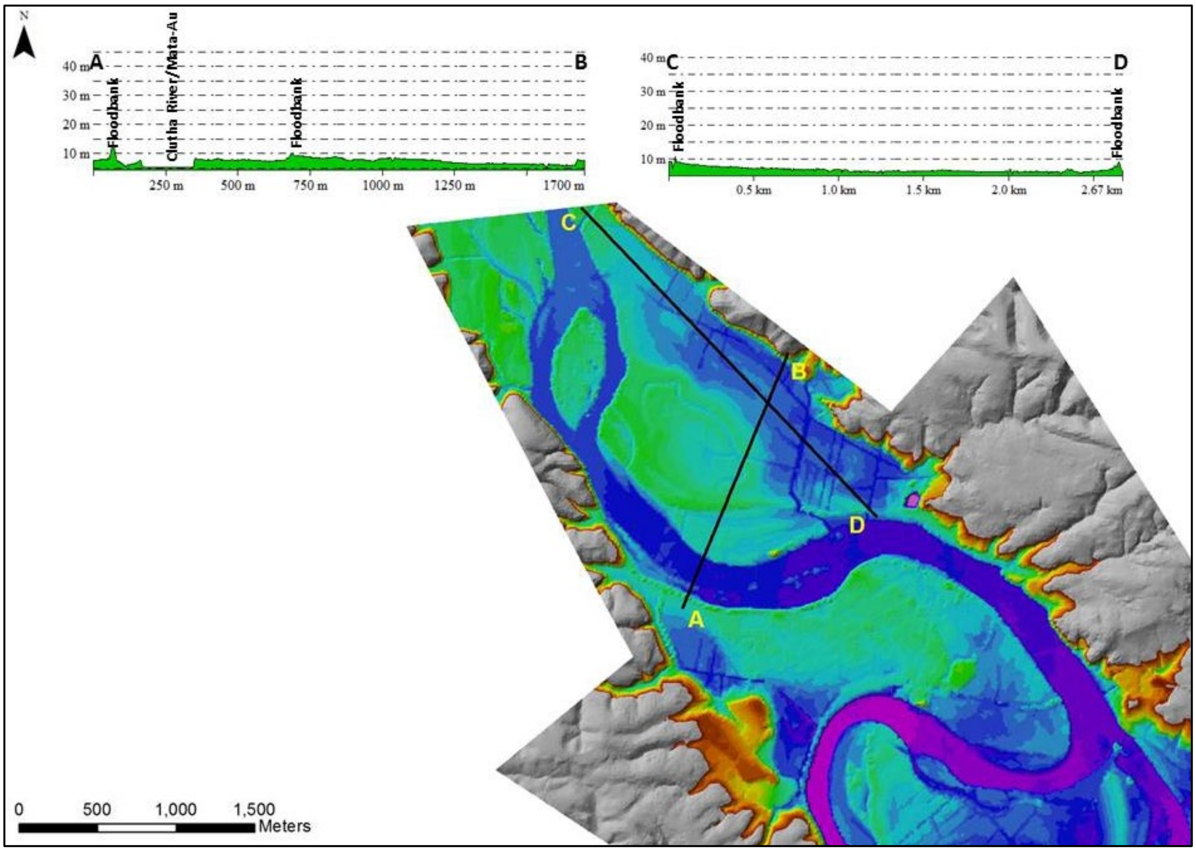


Figure 4.16 Elevation of Area 2 derived from LiDAR data. Land elevation is in meters relative to mean sea level.

The hill catchments discharging into this area consist of broad, gently-rounded ridges separated by relatively steep gullies. The main streams discharging to the flats are Glenthorn Creek (6.5 km^2), Plantation Creek (1.5 km^2), and Sunflower Creek (0.9 km^2). The land within Area 2 is used mainly for agricultural activities and has few roads.

The floodbanks along the true left bank of the Clutha River/Mata-Au are designed to contain flows up to 2850 m^3/s (approximately a 1:10-year flood) with 600 mm freeboard. Area 2 has a lower standard of protection than the rest of the rural protected areas because the work was originally carried out to compensate for the effects of providing significant protection for Balclutha township, downstream; rather than as a cost-effective flood protection measure in its own right, for an area of less than 200 ha. Flood hazard modelling (NIWA, 2005) indicates that Area 2 would be inundated for a flood peaking at around 2900 m^3/s at Balclutha (1:10-year flood) indicating that the design freeboard (600 mm) is not provided for this area.

There are no specific flood protection works to mitigate the flood hazard from the hill catchment streams in this area. However, the drainage network (Figure 4.3) complemented by a pumping station (used only when the water levels in the river impede the gravity drainage outflows) is designed to intercept water flowing from the hill catchments during normal flow conditions. The network is designed and maintained to provide land drainage to the area, but can also provide very limited flood relief for small floods from the hill catchment streams. This only happens effectively in situations where the water level in the river does not block the gravity outfalls. The pump station can only help to remove a fraction of the local tributary floodwaters and its effectiveness is also very limited during heavy rainfall, when ponding will still occur.

The flood hazard modelling (NIWA, 2005) indicates that, during a 1:100-year flood in the Clutha River/Mata-Au, flooding would be widespread and that the depth of water could exceed 4 m in places with velocities reaching around 1 m/s at some locations (Figures 4.12 & 4.13). The potential hazard to people and buildings in this area is considered to be extremely high (Figure 4.11).

Area 2 was inundated during the October 1978 and November 1999 floods (Figure 4.17) and there was also flooding in January 1980, though that was most likely a result of localised rainfall accumulation and drainage network overtopping.

Area 3: Balclutha

This area comprises the flood-protected parts of Balclutha township, on the true right bank of the Clutha River/Mata-Au, within the only major loop in the main stem of the river, where the channel splits into the two delta branches. As the area is bounded on three sides by the river, Balclutha is particularly vulnerable to flooding from the Clutha River/Mata-Au and, to a lesser degree, to flooding from Hospital Creek (Figure 4.7), and from localised rainfall accumulation and from overloading of the stormwater network. The land in this area is relatively flat (elevation ranges ~ 5 to 10 m), where buildings and roads also influence the potential overland flow paths and the areas where floodwaters can pond.

Area 3 is predominantly urban with extended residential, commercial and industrial sectors. There is also a significant amount of key local and regional infrastructures (e.g. hospital, schools, fire station, major roads and railway lines) located within this area.

The area is enclosed, on its northern, eastern and southern sides, by the floodbanks that are designed to protect it from flows of up to 5600 m^3/s (approximately a 1:200-year flood) with 300 mm of freeboard. The Lower Clutha Floodway (Area 5) provides a very important flood relief mechanism for Balclutha township, by shortening the flow path of the Koau branch between the main channel bifurcation and Finegand.

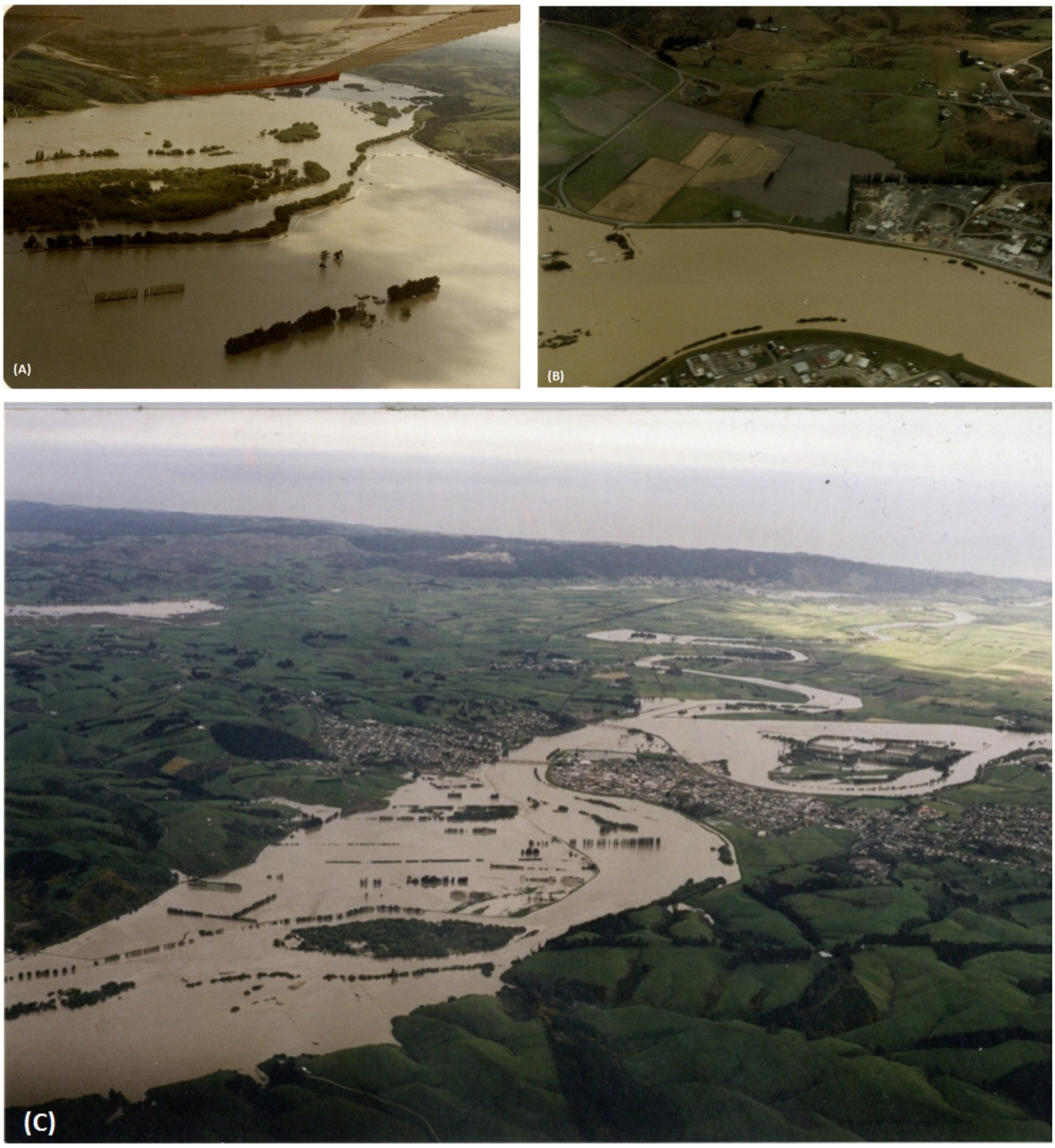


Figure 4.17 Flooding in Area 2 during the October 1978 flood event, with Barnego Flats in the foreground (A), January 1980 (B) and November 1999, with Barnego Flats in the foreground (C).

Flood hazard modelling (NIWA, 2005) indicates that floodwaters from the Clutha River/Mata-Au would start to enter Area 3 from the southern side when flows exceed 5200 m^3/s (1:100-year flood) as the design freeboard provided along this side is not guaranteed for flows exceeding 4000 m^3/s (1:40-year flood). The NIWA results assume that no floodbank breach occurs on the Koau Branch downstream of Balclutha township, but the modelling does indicate that the design standard of protection is not currently being provided in that area of Balclutha. Options to restore a satisfactory flood protection standard are currently being investigated.

In addition to the risk of flooding by overtopping of the floodbanks, there is also a risk of flooding associated with a floodbank breach, which could occur prior to a flood reaching the design threshold. The latter risk is exacerbated by the foundation soils and the floodbank characteristics at Balclutha, where under-seepage of floodwaters is a known problem that has been observed during several flood events in the past. A series of relief wells, drilled on the landward side of the floodbank, reduce the risk of a floodbank breach resulting from under-seepage (see Section 4.2).

The floodbank at the northern side of Balclutha is subject to severe erosion during significant flood events, due to the high velocities that develop along this floodbank on the outside of the adjacent bend in the river. As such, the risk of a failure of the floodbank due to erosion/scour in a major flood event is high. Failure of the floodbanks that protect Area 3 could also result from seismic activity (see Chapter 5), particularly given the make-up of the foundation soils below the floodbanks, where the deeper silt layers are susceptible to liquefaction. However, the potential for a breach of the floodbanks in an earthquake is significantly reduced due to the very low probability of a seismic event occurring during a major flood event. It is important to note that whilst the risk of flooding associated with a floodbank breach or overtopping can be managed, it can never be entirely eliminated.

Under seepage of floodwater can result in localised ponding of water on the landward side of the floodbank (Figure 4.18), depending on the local topography, land use and the ability of the drainage network to cope with the volume of seepage water. Such ponding can be a particular nuisance in urban areas, such as Area 3.

Figure 4.18 Localised ponding due to seepage coming from the relief wells on the landward side of the floodbank at the Balclutha Showgrounds during the March 1987 flood event (2300 m^3/s at Balclutha).

Given the characteristics of the river at Balclutha and the relatively tight river bend around the township, coupled with the large flow volumes and very high velocities (in excess of 3 m/s), plus the predominantly urban land use, the consequences of a floodbank failure or overtopping would be catastrophic for Area 3. Also, the river could potentially shortcut the Balclutha loop entirely, as occurred during the September 1878 flood (see Figures 2.6 and 4.19) prior to the construction of the floodbank around the town. During that flood event, it was reported that nearly the whole town was covered with flood water (OCB, 1956).

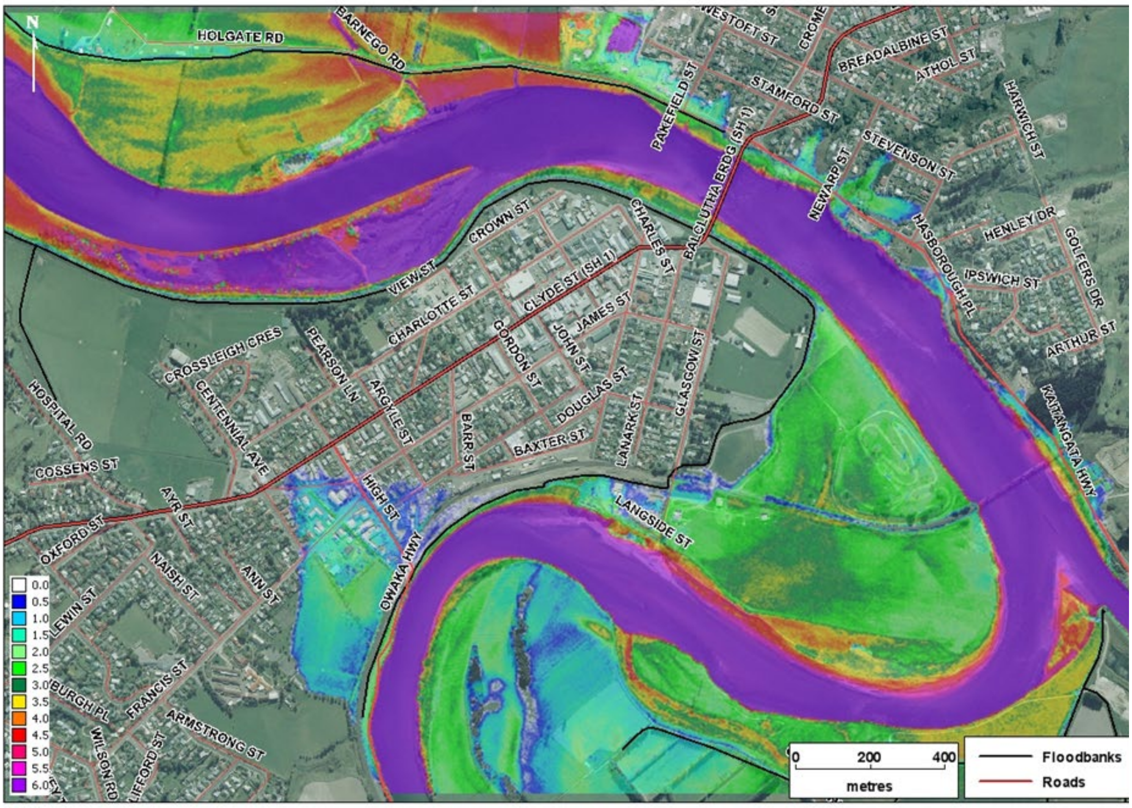
Figure 4.19 Flooding in Balclutha during the September 1878 flood event (estimated peak flow of 5600 m3/s at Balclutha) (Photograph taken by C Nicholas, courtesy of the Hocken Library). Also note Figure 2.7 from the same event. The photos were not necessarily taken at the peak of the flood.

A secondary floodbank, running perpendicularly from near the northern (upstream) end of the main floodbank, provides protection to Area 3 from flooding in Hospital Creek, up to the 1:30-year flood standard for that creek (see Figures 4.7 and 4.11).

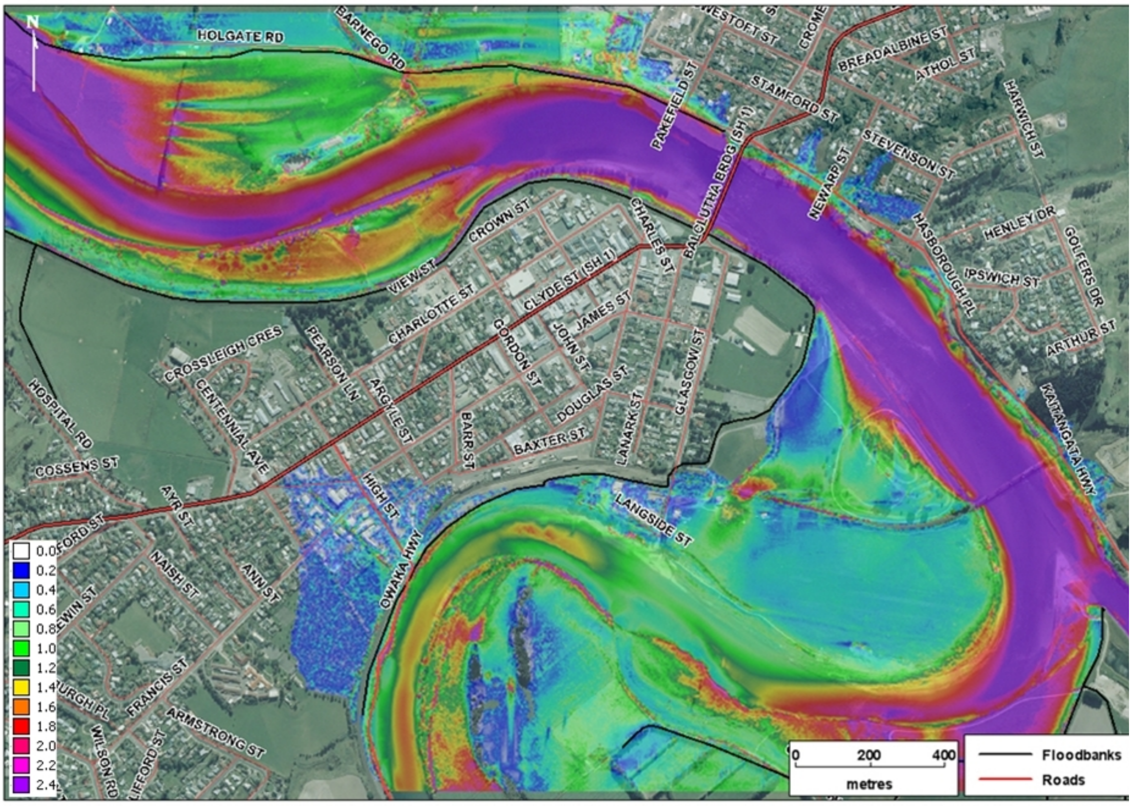
Flood modelling carried out by NIWA in 2005 indicates that during a 1:100-year flood (peaking at 5200 m^3/s at Balclutha), the extent of inundation resulting from overtopping of the floodbank at the southern end of the township would be limited to that end of the town only – that is, to the vicinity of High Street and Francis Street (Figure 4.20). The depth of the overtopping floodwaters could reach up to 2 m - 2.5 m in lower areas (southern end of Balclutha) with the water velocity not exceeding 1 m/s (NIWA, 2005).

Modelling of a 1:200-year flood event (peaking at 5800 m^3/s at Balclutha) indicates that overtopping of the floodbank at the southern end of the town would result in widespread flooding of Balclutha township (Figure 4.21) with the depth of water reaching up to 1 m - 1.5 m, and possibly exceeding a depth of 3 m in the very low parts of the town. Water velocities would generally be less than 1 m/s, but could reach up to 2 m/s in the vicinity of High Street (NIWA, 2005).

The potential hazard to people and buildings in parts of Area 3 is considered to be high (Figure 4.8). However, a breach of the floodbanks along the Koau or Matau branches (downstream of Balclutha) could result in a significant reduction in the depths of inundation for Balclutha township.

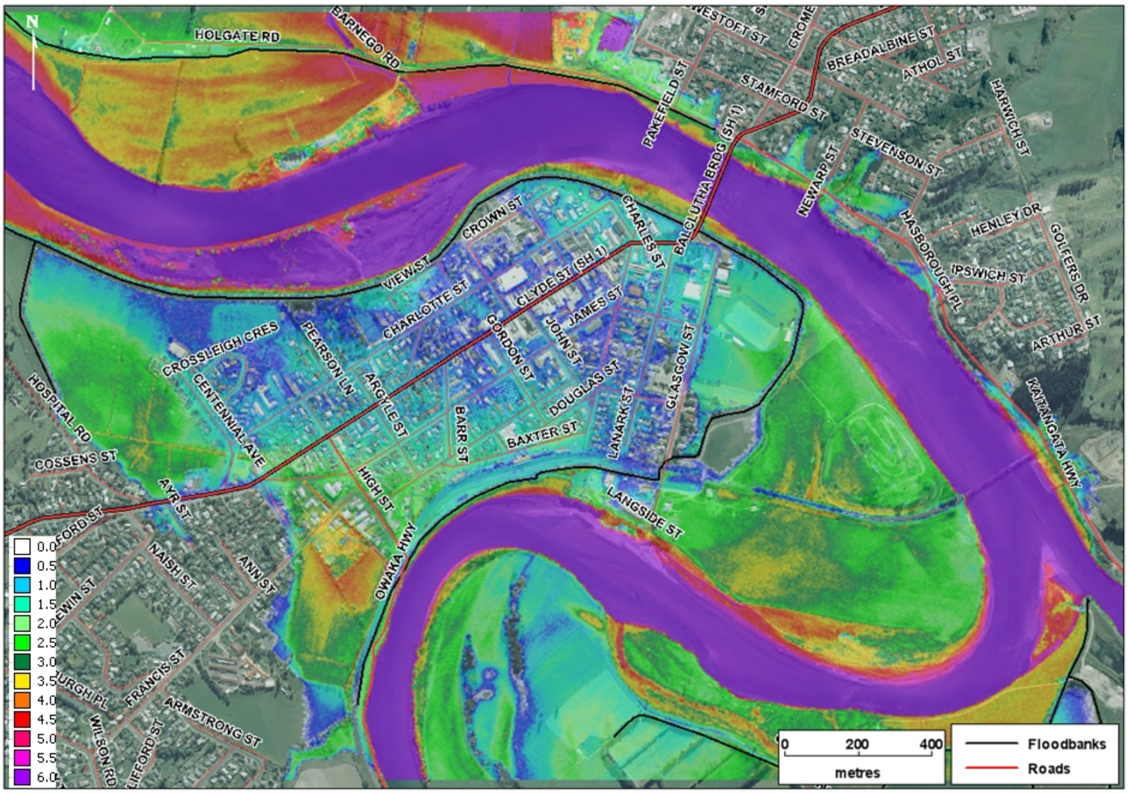


(A)

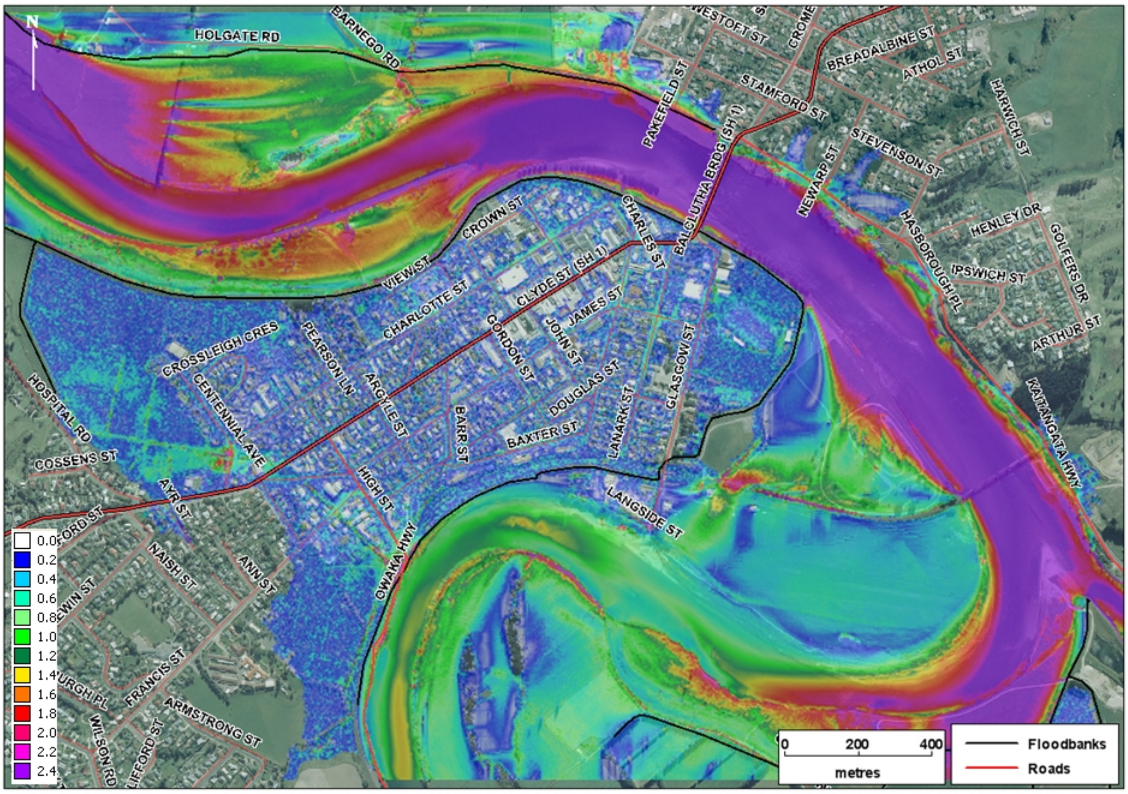


(B)

Figure 4.20 Estimated flood depth (A) and velocities (B) in Balclutha associated with a 1:100-year flood (peaking at 5200 m3/s at Balclutha). Depth is in meters, relative to msl and velocity is in m/sec.



(A)



(B)

Figure 4.21 Estimated flood depth (A) and velocities (B) in Balclutha associated with a 1:200-year flood (peaking at 5800 m3/s at Balclutha). Depth is in meters relative to msl and velocity is in m/sec.

The Clutha River/Mata-Au flooded Area 3 extensively in the September 1878 flood (before any floodbanks had been constructed) and it was reported that the streets were covered by deep and fast flowing water with several houses having been swept away (Soil Conservation and Rivers Control Council, 1957). The low-lying ground to the south and west of the town flooded in October 1978, but probably due to the accumulation of localised rainfall and run-off from Hospital Creek (Figure 4.22).

Figure 4.22 Flooding in Balclutha during the October 1978 flood event (estimated peak flow of 4580 m^3/s at Balclutha) (**a**) looking south. Note ponding behind the floodbank within Area 3. (**b**) Looking north. Note ponding from Hospital Creek and/or rainfall accumulation (not shown in a).

Area 4: Top end of Inch Clutha (partially protected area)

This area lies to the north-west of the Lower Clutha Floodway (see Area 5 below) which is partially protected by floodbanks that connect to some areas of higher ground. It is, however, isolated once the Lower-Clutha Floodway commences to operate (at less than a 5-year flood, as measured at the Balclutha flow recorder). As such, Area 4 has many of the flood hazard characteristics of Area 1.

Area 5: Lower Clutha Floodway

This area comprises the land located at the top (northern) end of Inch Clutha that is bound by floodbanks on its western and eastern sides. As previously described (section 4.2) the by-pass floodway consists of a grass-lined channel (500 m wide and 1.9 km long) with an entrance spillway (a 330 m long uncontrolled weir) at its upstream end, that is designed to limit flood flows in the more constricted Matau Branch to between 1050 m^3/s and 1150 m^3/s (under the design conditions) and to increase the proportion of the flow entering the shorter Koau Branch, with its larger flow capacity. The floodway also provides flood relief to Balclutha township by shortening the flow path of the Koau branch, between the main channel bifurcation and Finegand, above a pre-determined threshold.

The entrance spillway (uncontrolled weir structure) starts to operate when the Clutha River/Mata-Au flow, as measured flow at the Balclutha recorder, is between 1880 m^3/s and 2000 m^3/s (approximately a 1:3-year flood). At the downstream end of the spillway there is a sill to prevent the bottom end of the floodway being drowned by water from the Koau branch when the water level in the upstream channel is less than the operating threshold of the spillway. The manually operated gates that originally controlled the entrance of the spillway were decommissioned in 2010, as their operation was found to be problematic during flood events (Otago Regional Council, 2009).

The floodway is grazed (pastoral farmland) when it is not in operation and road access (via Chicory Road) to the top end of Inch Clutha (Area 4) is blocked when the flow in the river exceeds the operating threshold for the floodway. Area 5 plays a crucial role in the safe and efficient operation of the Lower Clutha Flood Protection Scheme and it is controlled by way of the ORC's Flood Protection Management Bylaw 2012.

Modelling by NIWA in 2005 indicates that during a 1:10-year flood peaking at 2900 m^3/s at Balclutha (approximately 1000 m^3/s above the threshold of operation of the spillway), the depth of water in this area would generally exceed 2 m, with the water velocity not exceeding 2 m/s. Modelling of a 1:100-year flood (peaking at 5200 m^3/s at Balclutha) indicates a depth of water in excess of 3 m and velocities of between 1 m/s and 3 m/s (NIWA, 2005). The potential hazard to people in this area would then be considered as extremely high (Figure 4.11).

The floodway operated during the October 1978 (4580 m^3/s at Balclutha), January 1980, (2770 m^3/s), December 1995 (3420 m^3/s) and November 1999 (4160 m^3/s) flood events (Figure 4.23). The manual gates were still in place during these events but have subsequently been removed.

Figure 4.23 The Lower Clutha Floodway operating during October 1978 (**a**), January 1980 (**b**), December 1995 showing the floodway gates partially dropped (**c**) and November 1999 (**d**) flood events.

Area 6: Lower Toiro Stream floodplain

Area 6 consists of the well-defined floodplain of the Toiro Stream between the toe of the hills and its confluence with the Koau Branch. Land-use within Area 6 involves mainly agricultural activities, including forestry.The upstream part of the Toiro Stream catchment (total area of 35 km^2) is generally grassed rolling hills and the lower part is relatively flat with elevations ranging between 5 and 6 m above Mean Sea Level. The area closest to the Koau Branch is swampy. The Main South Railway Line embankment, set approximately 2 m above ground level, runs through Area 6 but is not considered to be a detrimental barrier to flood waters (see Figure 4.24). Area 6 is exposed to flooding from Toiro Stream and its tributaries and from localised rainfall accumulation. High water levels in the Koau Branch may exacerbate the flooding by impeding the stream discharge into the river. Floodwaters would then pond on the floodplain until the water level in the Koau Branch has dropped sufficiently to allow gravity drainage to resume. Although the Toiro Stream has been realigned in a number of locations with the last 800 m of the channel forming part of the Lower Clutha Drainage Scheme (ORC scheduled drain) there are no specific flood protection works to mitigate the flood hazard from the stream in this area. This area flooded in October 1978 (4580 m^3/s at Balclutha), January 1980, (2770 m^3/s) and November 1999 (4160 m^3/s) flood events (Figure 4.24).

Figure 4.24 Area 6 during the October 1978 (**a**), January 1980 (**b**) and November 1999 (**c**) flood events. The photos were not necessarily taken at the peak of the flooding.

Area 7: Finegand Freezing Works

Area 7 is a small area containing the Finegand Freezing Works, located on the true right bank of the Koau Branch, approximately 3 km downstream of Balclutha. The land in this area is flat and is part of the Koau Branch floodplain with very limited natural protection from flood hazard.

The main source of flood hazard for Area 7 is the Koau Branch and to a lesser degree minor realigned tributaries flowing from the western hill catchments (with catchment areas not exceeding 2 km^2) and discharging into the Koau Branch. The floodbanks along the true right of the Koau Branch (eastern side of Area 7) are designed to contain <5600 m^3/s flows (approximately a 1:200-year flood, at Balclutha) with 300 mm freeboard. This is the same standard of flood protection that applies to Balclutha township, and it was provided for the freezing works at that time because of their economic importance to the region (Otago Catchment Board, 1956). Flood hazard modelling (NIWA, 2005) indicates that floodwaters from the Koau Branch will not enter this area for flows less than or equal to 5600 m^3/s (the design standard for this area) with freeboard of approximately 1 m, which exceeds the design freeboard.

The low-lying parts of this area had very limited flooding in October 1978 (4580 m^3/s at Balclutha), January 1980 (2770 m^3/s), and November 1999 (4160 m^3/s) that was due mainly to localised rainfall accumulation and overtopping of the drainage network (Figure 4.25).

Figure 4.25 Area 7 during the October 1978 (A, freezing works in the foreground), and November 1999 (B, freezing works in the foreground) flood events. The photos were not necessarily taken at the peak of the flood.

Area 8: Inch Clutha

Area 8 is an island of around 2300 ha comprising the bulk of the Inch Clutha. It is bound by the Matau and Koau branches to the north, east and west, and the southern side is defined by a floodbank running parallel to the coast, between 300 m and 800 m inland.

This area is exposed to flooding from the Koau and the Matau branches. As the area is relatively flat and has limited fall (elevations range from around 6 m above mean sea level at the top end of the island to sea level (0 m) at the bottom end) it is also exposed to flooding from the accumulation of localised rainfall and from overtopping of the drainage network. Large portions of Inch Clutha were swampy before European settlement and the subsequent extensive drainage of the area (refer to Chapter 2).

Some parts of Inch Clutha are exposed to the seepage of water under the floodbanks, although it is not as widespread as in Balclutha. The most problematic area for under-seepage is located on the Matau Branch, true right floodbank along Hislop Road, some 3 km downstream of Balclutha. In this area, known as Weirs Gap (Figure 4.26), under-seepage can be severe and relief wells are not sufficient to mitigate the risk of floodbank failure. While works have been completed to seal the known seepage areas, these works have not completely removed the problem. As an alternative solution, a low bund has been built around the vulnerable section of floodbank, on the landward side, to enable seepage water to pond against the floodbank, in order to reduce the differential head and so control the under-seepage by way of a balancing pond. When under-seepage in this area begins to cause concern, a control gate (guillotine-type gate) at the upstream end of the drain servicing this area can be manually shut to close-off the bund. And, when the danger has passed, this gate may be opened to allow the ponded water to drain away.

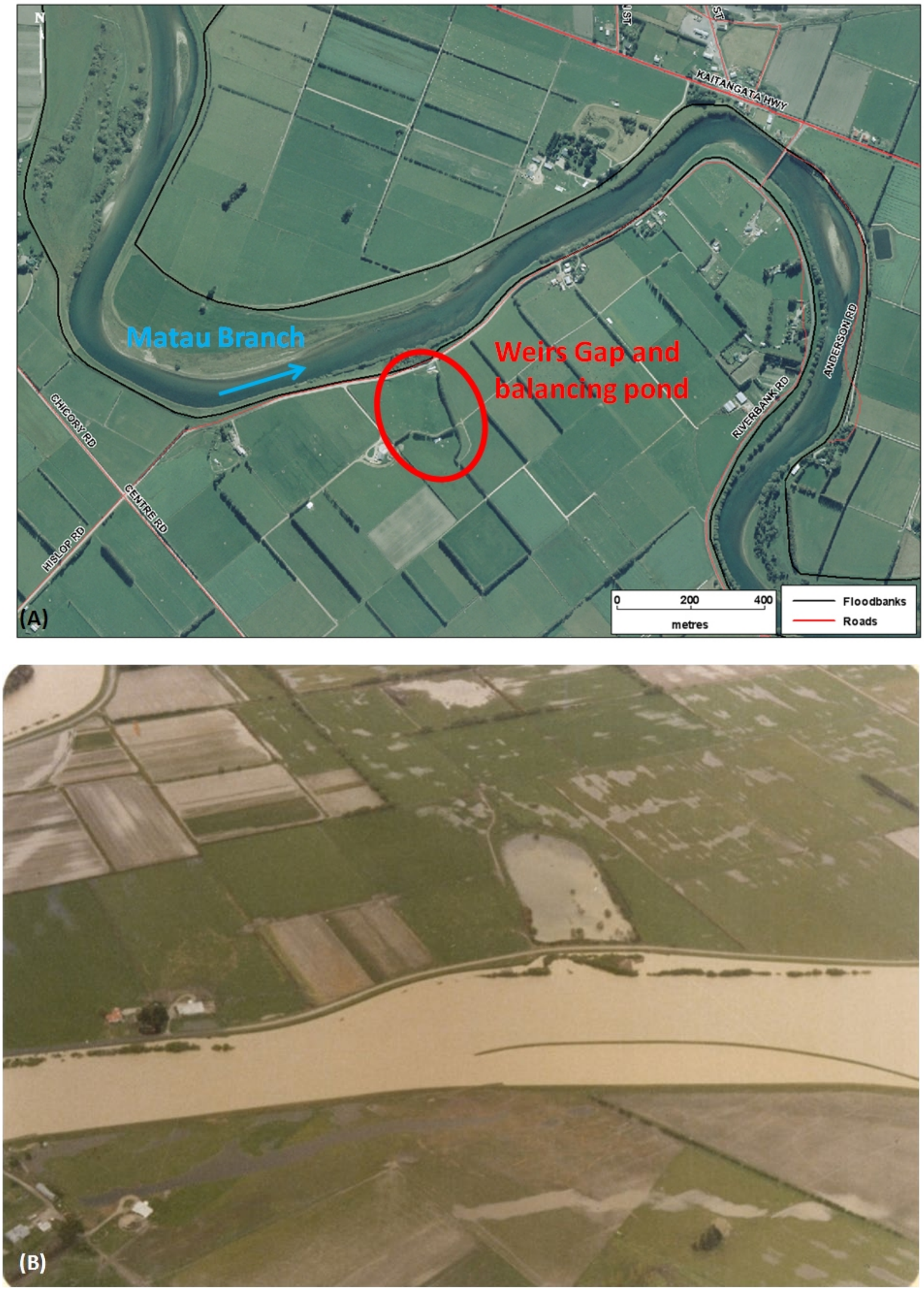


Figure 4.25 Location of Weirs Gap (A) and Weirs Gap during the October 1978 flood event (B). Note the water from seepage under the floodbank ponding on the landward side of the floodbank in the balancing pond.

The land within Area 8 is very fertile, making it very suitable for intensive agricultural activities. The area contains between 40 and 50 residential dwellings and has a network of secondary roads crossing it. Inch Clutha can be isolated during extreme flood events as there are only two road bridge accesses (to Hislop Road and Riverside Road), both over the Matau Branch. Advance warning based on the meteorological and hydrological situations for the Clutha catchment is provided for this area in order to facilitate stock evacuation, equipment removal and to limit the damage due to floods. Predetermined flood evacuation procedures, in relation to those warnings, are also in place for this area and are coordinated by the Clutha District by way of their Civil Defence "Adverse Events Plan", in conjunction with the ORC.

The area is surrounded by floodbanks designed to contain flows are designed to contain a Clutha River/Mata-Au flood of up to 4000 m^3/s at Balclutha (approximately a 1:40-year flood) with 600 mm of freeboard. Flood hazard modelling (NIWA, 2005) indicates that flood water from the Koau and the Matau branches would be on the verge of entering this area when the flow at Balclutha reaches 4000 m^3/s. It is estimated that overtopping would initially commence on a short section of the Matau Branch floodbank (true right bank) of some 500 m in length, in the vicinity of Mosley's Loop.

Modelling has also demonstrated that, during a 1:100-year flood (peaking at 5200 m^3/s), flooding (from both branches) would be widespread over Area 8 (Figure 4.10). The depth of water could reach up to 1.5 m in low-lying areas, with the water velocity not exceeding 1 m/s (Figures 4.12 and 4.13) (NIWA, 2005). Modelling of the 1:200-year flood event (peaking at 5800 m^3/s, at Balclutha) indicates that the depth of water in this area could exceed 2 m in low-lying areas (see Figure 4.14) (NIWA, 2005). The potential hazard to people and buildings in parts of this area is therefore considered to be very high.

Any breaches of the floodbank network could significantly modify the flooding characteristics in Area 8 and could also result in significantly reduced inundation depths at Balclutha. Figure 4.27 demonstrates the potential variation in flooding characteristics for a 1:100-year flood event, if two breaches should occur on the true right floodbank (Koau Branch), as an example of how those characteristics (extent and depth of inundation) could be modified for a 1:100-year flood in that situation. The two breach locations assumed for this example are near the Finegand Freezing Works, and a northeast of Otanomomo. Under this scenario the majority of Area 8 would not be flooded and, for those parts of the area that would be flooded, the depth of inundation would be less than 1 m. There would also be no overtopping of the floodbanks around Balclutha (compared with Figure 4.12 for the same flow but no-breach).

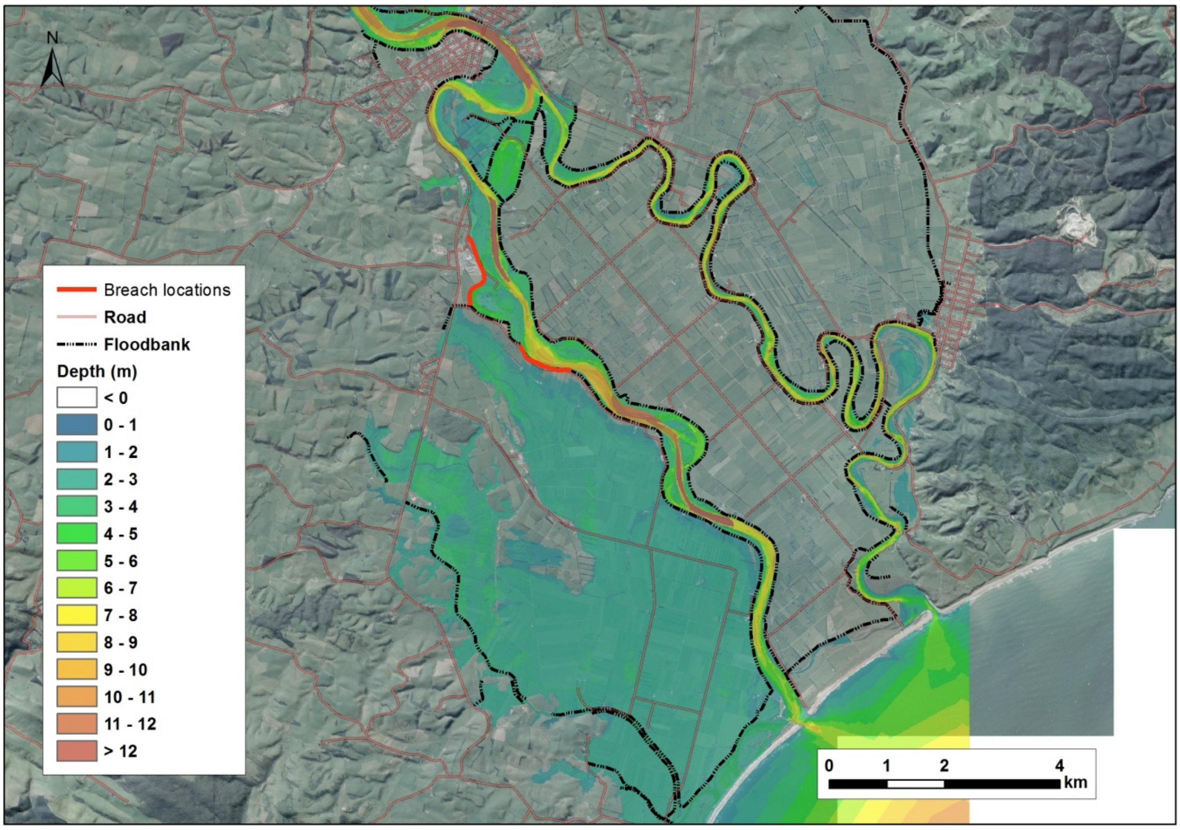


Figure 4.26 Estimated flood depth in Inch Clutha associated with a flood peaking at 5200 m^3/s at Balclutha (1:100 year-flood) and with two Koau floodbank breaches. Depth is in meters relative to msl.

An early design for the scheme considered using Area 8 as a primary over-design flow path for floods exceeding the protection standard (i.e. for floods in excess of 4000 m^3/s) (Otago Catchment Board, 1958). It was envisaged that emergency spillways (in the form of fuse-plug sections of floodbank) could be established along the floodbank network, in order to allow spill at those defined locations and so minimize the damage of flood events that exceeded the design protection standards. It was proposed that the primary, over-design flow path would be down Inch Clutha and, if the flows continued to increase, then spills would gradually occur into the Otanomomo (Koau Branch, true right bank) and Matau (Matau branch, true left bank) districts. This proposed approach was based on observations made during the 1957-1958 flood events (prior to the completion of the current flood protection scheme). During the latter flood events water flooded Inch Clutha (an estimated 700 m^3/s flow spilled into Inch Clutha) with little damage being observed in that area. The only lands to be severely damaged were in the immediate vicinity of the river itself and at the southern end of Area 8, where the water returned to the river. The use of Area 8 as the primary super-design flow path was considered logical, due to the relatively better gravity drainage (as compared to the Otanomomo or Matau districts) so allowing a faster removal of floodwater, and all with the minimum use of pumps. These proposals for managing flood events that exceeded the design protection standards were, however, abandoned after the evaluation of the performance of the scheme following the October 1978 flood event (OCB, 1979).

Blockages of the river mouths and their potential to offset, also has a significant influence on the flooding characteristics in Area 8. When the river mouths are blocked or offset, the resultant backwater levels in the lower reaches of the Koau and Matau channels are significantly increased for all flows. Analyses following the June 1972, September 1972 and October 1978 flood events, where the Koau mouth was offset, indicated that the water level in the lower reaches of the Koau Branch was up to 1.6 m higher than it would otherwise have been, had the river mouth not been offset (Scarf, 1997). The consequences of an offset or blockage of the Matau mouth on water levels in that channel would be similar and could result in floodbank overtopping before the design flow had even been reached. The river mouths are monitored and works are undertaken as necessary to prevent, or limit the potential for the mouths to block or offset (see Section 4.2 for details).

Area 8 has an extensive drainage network complemented by two pump stations (Smith Road, on the Koau Branch, and Rutherfords, on the Matau Branch). The pumps are used when high river levels prevent gravity drainage. The parts of Area 8 close to the sea were extensively flooded in October 1978 (4500 m^3/s at Balclutha) due to overtopping of the lower section of the Koau true left floodbank and due to the uncompleted floodbanks on the Matau Branch (Figure 4.28). The flood protection scheme was not fully operative during that flood event and the overtopping was also aggravated by the Koau Mouth being offset (OCB, 1979).

Figure 4.27 Area 8 during the October 1978 flood event. Looking toward the sea with lower Inch Clutha in the foreground, Matau Branch on the left and Koau Branch on the right. The photos were not necessarily taken at the peak of the flood.

Area 9: Matau Branch left bank (Matau District)

Area 9 is the flat land located on the true left bank (eastern side) of the Matau Branch, between the townships of Stirling and Kaitangata. The northern boundary of this area is the floodbank (closure bank) at the southern end of Lake Tuakitoto, and the eastern boundary is the Kaitangata Contour Channel. The Matau Branch true left floodbank forms the south-western boundary of Area 9 and the toe of the hills limits the north-western extent.

Area 9 is exposed to flooding from the Matau Branch, and from hill catchments to the north of Stirling and to the east and north of Kaitangata, and also from the accumulation of localised rainfall. These local catchments, including the Lake Tuakitoto catchments, are relatively small but can produce significant volumes of water during heavy rainfall events that overload the drainage network. The land in this area generally falls away from the Matau Branch to the toe of the hills (Figure 4.29) with a minimal gradient and elevations ranging from between 3 m to 6 m on the western side, to between 3 m to less than sea level for the rest of the area. The land below sea level (shown in red on Figure 4.29) corresponds to the land that has been reclaimed from Lake Kaitangata (now completely drained) and of parts of Lake Tuakitoto.

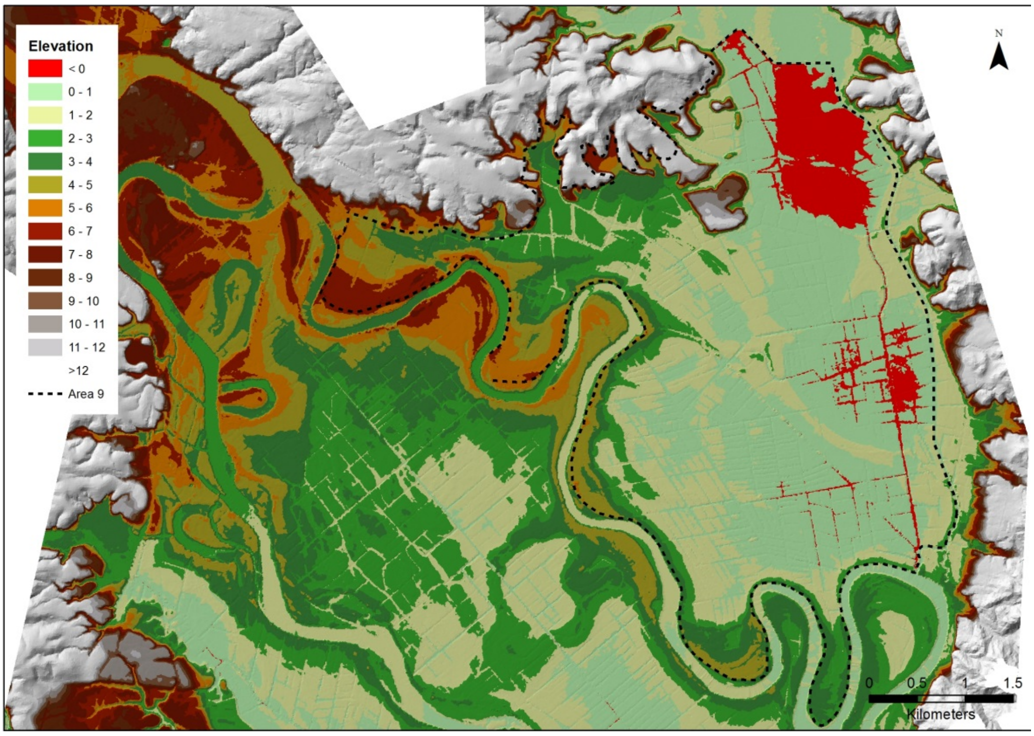


Figure 4.28 Land elevation of Area 9 derived from LiDAR data. Land elevation is in meters relative to msl.

The land within Area 9 is predominantly used for agricultural activities. It includes the low-lying parts of Stirling township (between the Main South Railway Line and the Matau Branch) and some dwellings at Clyde Terrace. The Kaitangata Highway, linking the townships of Kaitangata and Stirling, crosses the area.

The floodbanks along the true left of the Matau Branch are designed to contain a Clutha River/Mata-Au flood of up to 4000 m^3/s at Balclutha (approximately a 1:40-year flood) with 600 mm of freeboard. Overtopping or breaching of this floodbank would result in the river flowing through Area 9 and completely filling it, like a reservoir, due to its natural bowl shape. Given the topography (very limited fall) flood waters could pond for several days. Flood hazard modelling (NIWA, 2005) indicates that floodwaters from the Matau Branch would not enter Area 9 for the design flow (4000 m^3/s at Balcluth a). The freeboard levels could, however, be less than the design (600 mm) at some locations (just downstream of the channel bifurcation, at Mosley's Loop, or near the junction of Blackie Road and Kaitangata Highway).

Flood hazard from the hill catchment streams in this area is mitigated mainly by contour channels and drains designed to intercept and divert the hill catchment flows away from low-lying areas (with a theoretical 1:30-year flood protection standard). Small scale floodbanks at the southern end of Lake Tuakitoto and along the Kaitangata Contour Channel complement the other contour channels and the drainage network. Lake Tuakitoto provides limited flood water storage during heavy rainfall events. The contour channels and drainage network converge towards a gated outfall structure that discharges to the Matau Branch near Kaitangata (Kaitangata Locks). As very limited fall is available in this area, gravity drainage is nearly absent during medium to high flows in the Matau Branch. A pump station (Kaitangata Pump Station) assists the drainage of this area. However, it is important to note that the effects of the pump station are very limited during significant flood events.

Modelling (NIWA, 2005) indicates that, during a 1:100-year flood (peaking at 5200 m^3/s at Balclutha), the floodbanks would be overtopped downstream of the bifurcation (at a section of floodbank known as the Hermitage Bank) and at Mosley's Loop. But the modelling also shows that this flooding would be mainly limited to the low-lying areas of reclaimed land and the low-lying parts of Stirling. The depth of water (from the Matau Branch) in this area would not likely exceed 1.5 m, with the water velocity not exceeding 1 m/s (Figures 4.12 & 4.13). During a 1:200-year flood (peaking at 5800 m^3/s at Balclutha), the modelling indicates that overtopping would occur at more locations with resultant widespread flooding. The depth of water in Area 9 could then exceed 2 m in low-lying areas (Figure 4.14). The potential hazard to people and buildings in some parts of Area 9 is considered to be very high (Figure 4.11).

Breaches of the true right floodbanks on the Matau Branch, or of the Koau Branch floodbanks, could result in significantly reduced inundation depths in Area 9. This area was extensively flooded in October 1978 (4580 m^3/s at Balclutha) (Figure 4.30). In November 1999 (4160 m^3/s at Balclutha) no water from the Matau Branch entered the area, although, low-lying parts were inundated, most likely due to localised rainfall accumulation and overloading of the drainage network.

Figure 4.29 Area 9 during the October 1978 flood event (looking towards Stirling) Matau Branch on the left, Old Kaitangata Railway and Kaitangata Contour Channel in the foreground). The photo was not necessarily taken at the peak of the flood.

Area 10: Lake Tuakitoto

Area 10 comprises Lake Tuakitoto and its immediate surrounds, including the low-lying parts of several hill catchment streams and the transitional swampy areas that surround the lake. The Lake Tuakitoto catchment area is approximately 134 km^2, consisting of rolling hills converging onto a relatively broad, flat floodplain (of between 1 m to less than sea level). The outlet from the lake is mainly via the Kaitangata Contour Channel discharging to the Matau Branch at the Kaitangata Locks. The land within Area 10 is predominantly used for agricultural activities. It includes only a few dwellings, some secondary roads, and small sections of State Highway 1 and the Main South Railway Line. Area 10 is exposed to a flood hazard from the hill catchment streams (e.g. Stony Creek, Lovells Stream and Frasers Stream), from Lake Tuakitoto itself, and from localised rainfall accumulation. This area is not directly exposed to the flood hazard for the Matau Branch, but high water levels in the Matau Branch can impede Lake Tuakitoto outflows via the Kaitangata Contour Channel.

Limited flood protection and drainage works provide some mitigation against the flood hazard from the hill catchment streams in this area. Those works mainly comprise privately owned and maintained contour channels and drains designed to intercept and divert hill catchment flows away from the low-lying areas. A diversion channel situated at the north-western edge of the wetland complex diverts Stony Creek and Lovells Stream directly into the main body of Lake Tuakitoko. Much of the flat land on either side of Frasers Stream is subject to inundation (Otago Regional Council, 1999), including buildings on Station Road, and several roads including parts of SH1. Parts of Area 10 were flooded in October 1978 (4580 m^3/s at Balclutha), January 1980, (2770 m^3/s) and November 1999 (4160 m^3/s) flood events (Figure 4.31).

Figure 4.30 Area 10 during the January 1980 (A) and November 1999 (B) flood events. Area 10 left background in B.

Area 11: Mosley's Loop

Area 11 is a small strip of farm land (of about 21 ha) located on the inside (true right bank) of a loop of the Matau Branch (Mosley's Loop) at the end of Mosley Road. The area is flat with elevations ranging from 4.5 m to 5.5 m.

This area is exposed to flood hazard from the Matau Branch. It is surrounded by floodbanks that are designed to contain flows up to 3200 m^3/s (approximately a 1:20-year flood, at Balclutha) with no freeboard, with the exception of the south-western floodbank across the neck of the bend. The latter floodbank protects Inch Clutha (Area 8) from flows up to 4000 m^3/s (approximately a 1:40-year flood) with 600 mm of freeboard. Flood hazard modelling (NIWA, 2005) indicates that flood water from the Matau Branch would enter the loop area in a flow exceeding 3200 m^3/s, at Balclutha.

It is estimated that, during a 1:50-year flood (4300 m^3/s, at Balclutha), flooding would be widespread over Area 11, where the depth of water could reach 1 m, with a velocity not exceeding 1 m/s (NIWA, 2005). During a 1:100-year flood, the depth of water in this area could reach up to 1.5 m, in low-lying parts, with a velocity of just over 1 m/s (NIWA, 2005). This area was flooded in the October 1978 (4580 m^3/s at Balclutha) and November 1999 (4160 m^3/s at Balclutha) flood events (Figure 4.32).

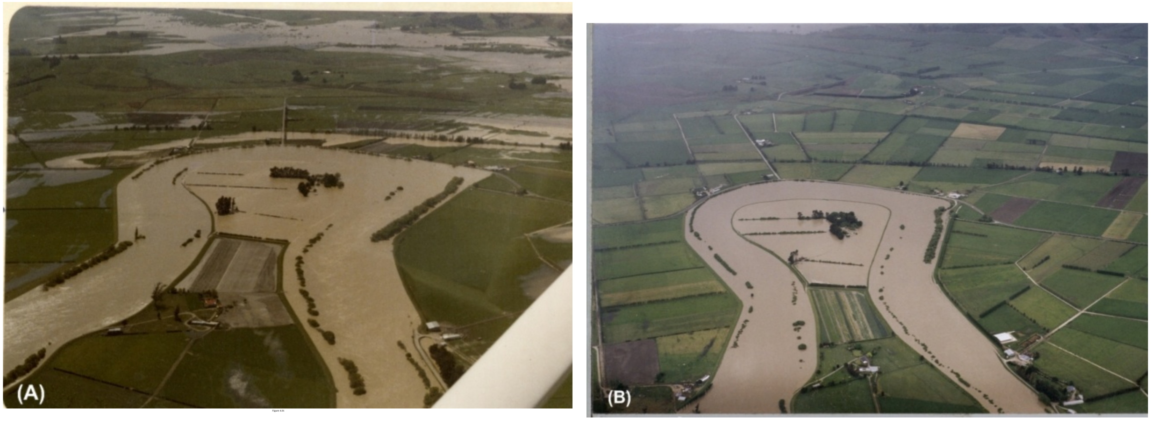


Figure 4.32 Area 11 during the October 1978 (**A**) and November 1999 (**B**) flood events. The photos were not necessarily taken at the peak of the flood.

Area 12: Lower Waitepeka River floodplain

Area 12 consists of the floodplain of the Waitepeka River, extending from the toe of the hills to the current confluence with the Koau Branch. The Waitepeka River is a tributary of the Koau Branch and has a catchment area of 44 km^2. Its catchment begins in the hills south-west of Balclutha and it joins the Koau Branch just downstream of the Finegand Freezing Works. The upper part of the catchment is generally steep, with scrub covered hills, and the lower part is flat with elevations ranging between 3 m to 4 m, with the area closest to the Koau Branch being swampy. The land within Area 12 is used mainly for agricultural activities, including forestry. Flood mitigation works (other than the diversion floodbank at the downstream end) are limited to channel reconstruction works, down to the highway. These works only provide flood mitigation to around a 1 to 2-year flood standard.

The Waitepeka River was diverted to its present course in 1906 to improve the drainage of the Otanomomo and Paretai area, and a diversion floodbank was erected to direct the river flow along a new channel to the current outlet below Finegand. However, high flows in the Koau Branch can impede the outlet of the Waitepeka River and cause water to pond in the low-lying area behind the diversion floodbank, until such time as Koau has dropped sufficiently to allow gravity drainage. During times of very high flows, the water that ponds behind the diversion floodbank can overflow via a spillway across the Owaka Highway (SH 92) to the old Waitepeka channel.

Before the diversion was constructed, the Waitepeka River flowed into the Puerua River, where the Paretai pumping station is now located, and this section of the old channel remains part of the Otanomomo/Paretai Drainage area. But there is also an artificial (drainage) channel of around 2.6 km, that takes the drainage flows from above the highway directly (via the drainage network) to the Koau Branch via a flood-gated outlet, which is part of the Lower Clutha Flood Protection Scheme works.

Area 12 is exposed to flooding from the Waitepeka River and its tributaries and from localised rainfall accumulation. Waitepeka township is located at the upstream end of Area 12 and can be subject to ponding floodwater during heavy rainfall events. The Old Port Road/Balclutha-Waitepeka Road, above the township, can also be inundated by floodwater from the upper catchment (Puruhaua Stream) (ORC, 1999). Area 12 was flooded in October 1978 (4580 m^3/s at Balclutha), January 1980, (2770 m^3/s) and November 1999 (4160 m^3/s) flood events (Figure 4.33)

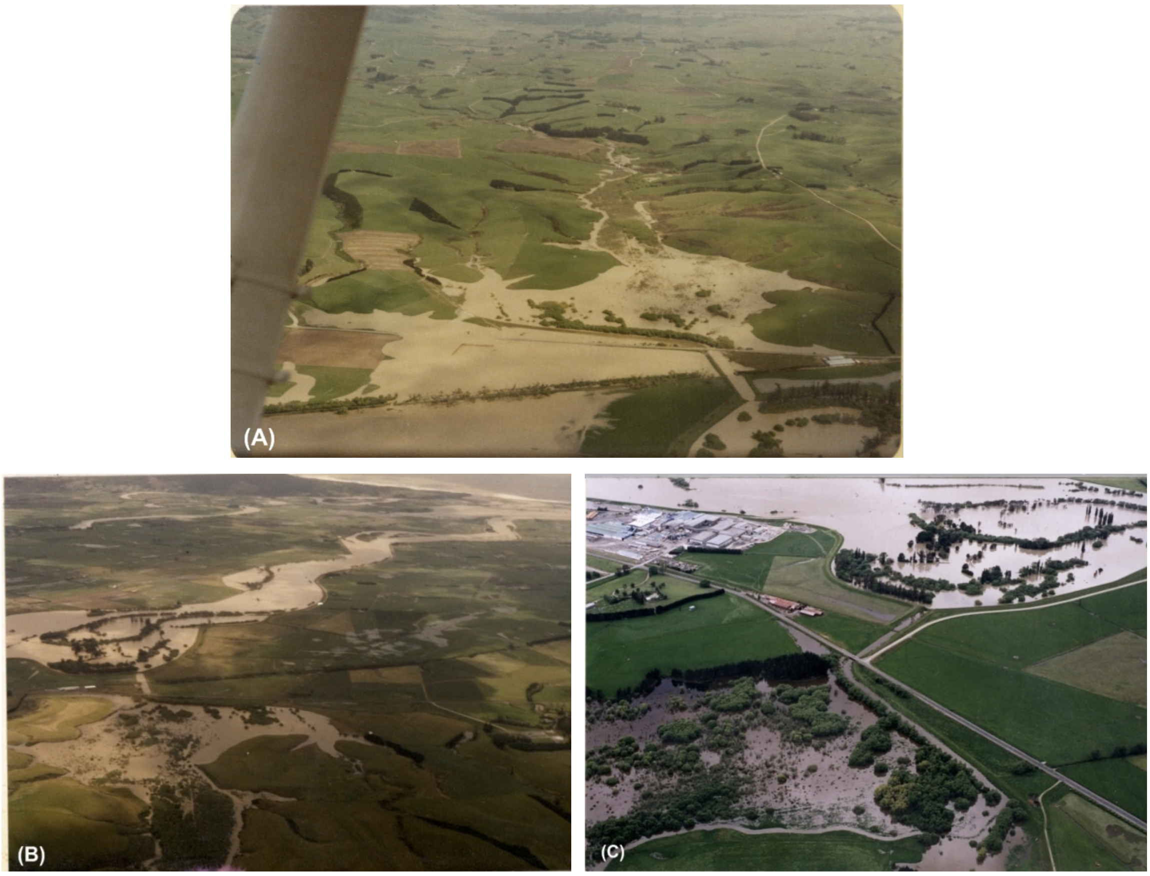


Figure 4.33 Area 12 during the October 1978 (A) January 1980 (B) and November 1999 (C) flood events. The photos were not necessarily taken at the peak of the floods.

Area 13: Koau Branch right bank (Otanomomo and Paretai)

Area 13 corresponds to the flat land located on the true right bank (West) of the Koau Branch between Finegand and Port Molyneux. The area is bounded by the Koau Branch to the east and the Puerua Contour Channel (also called the Puerua River Deviation) to the west. The toe of the hills limits the northern-western extent of the area, and to the south-east a floodbank, running parallel to the sea, separates the area from the estuarine land adjacent to Molyneux Bay. Area 13 is exposed to flood hazard from the Koau Branch and from the Puerua Contour Channel, which collects flows from the western hill catchments, including the Puerua River (220 km^2), Glenomaru Stream (48 km^2) and Barrata Creek (9 m^2). These hill catchments, to the west, generally consist of steep bush covered hills in the upper parts, with more gently-rolling grassed downlands in the middle sections. But the land in Area 13 is extremely flat with very limited fall (elevations usually range from just above mean sea level to approximately 1 m) so that the accumulation of localised rainfall adds to the flood hazard.

A large part of Area 13 consists of existing and former swamps and the predominant landuse is for agricultural activities, with some dwellings scattered across the area. Kaka Point Road and some other secondary roads cross the area.

The floodbanks along the true right bank of the Koau Branch are designed to contain a Clutha River/Mata-Au flood of up to 4000 m^3/s at Balclutha (approximately a 1:40-year flood) with 600 mm of freeboard. Overtopping or breaching of these floodbanks would result in extensive inundation of Area 13, and, given the topography of the area (very limited fall) floodwaters could pond for several days. Flood hazard modelling (NIWA, 2005) indicates that floodwaters from the Koau Branch would not enter this area for floods up to the design flow (4000 m^3/s). However, freeboard levels at some locations could be less than the design freeboard of 600 mm, particularly in the reach from opposite Lawson Road (Inch Clutha) to Botting's Bend, just downstream of Renton Road (Inch Clutha).

Modelling (NIWA, 2005) indicates that during a 1:100-year flood (peaking at 5200 m^3/s at Balclutha) a large section of the Koau true right bank floodbank adjacent to Area 13 would be overtopped resulting in widespread flooding in this area. The depth of water (from the Koau Branch) would not exceed 1.5 m and the water velocity would be less than 1 m/s (Figures 4.12 & 4.13). During a 1:200-year flood (peaking at 5800 m^3/s at Balclutha), it is estimated that the depth of water in this area could exceed 3 m in low-lying areas (Figure 4.14). The potential hazard to people and buildings in Area 13 is considered to be very high (Figure 4.11). Breaches of the Matau Branch floodbanks or of the Koau Branch true left bank floodbanks only, could result in significantly reduced inundation depths and extents for Area 13.

The flood hazard from the hill catchment watercourses in Area 13 is mitigated by way of contour channels, stream diversions and drains (principally, the flood-banked Puerua Contour Channel and the Waitepeka diversion channel) that have been designed (to a theoretical 1:30-year flood protection standard) to intercept and divert the hill catchment flows away from the low-lying areas.

The very limited fall available in Area 13, coupled with its proximity to the sea and the associated tidal impacts on the drainage outlets, means the effectiveness of the gravity drainage system and outlets is limited at the best of times. So pumped drainage (via the Paretai pumping station) is generally required on a daily basis, and gravity drainage is therefore practically non-existent during times of medium to high flows in the Koau Branch. But during a flood event the effectiveness of the pumping station can also be reduced due to high water levels in the Puerua River, to which it discharges. The pumping station does, though, provide good capacity for removing locally accumulated water once the external river levels have dropped.

The Puerua River flows around the southern tip of Area 13 and turns to the north through the estuarine area to join the Koau Branch at its mouth, via an un-controlled outlet structure (5 x 2.4 m diameter culverts) through the right-bank training groyne. The floodbank along the landward side of the estuarine area, adjacent to Molyneux Bay, completes the protective flood mitigation works around Area 13.

Area 13 was extensively flooded in October 1978 (4580 m^3/s at Balclutha) due to large breaches in the floodbank at McNutt's Break (opposite Telegraph Road, Inch Clutha) and at Botting's Bend (opposite Renton Road, Inch Clutha). Flooding was also observed in January 1980 (2770 m^3/s at Balclutha). In February 1991 (2570 m^3/s at Balclutha), floodwaters overtopped the Puerua Contour Channel and flowed into the area, but no water from the Koau Branch entered the area in that event. Also, in November 1999 (4160 m^3/s at Balclutha), no water from the Koau Branch entered Area 13 but low-lying parts were inundated, probably from localised rainfall accumulation and drainage network overloading (Figure 4.34). Under-seepage has been observed in the Factory Road ponds (Paretai) in previous floods indicating a potential risk of piping failure.

Figure 4.34 Area 13 during the flood events of: (**A**) October 1978, Koau Branch on the right looking upstream; (**B**) January 1980, Inch Clutha in the foreground and Paretai in the background; and (**C**) November 1999, the Puerua River Contour Channel on the left. The photos were not necessarily taken at the peak of those floods.

Area 14: Low lying parts of Kaitangata

Area 14 comprises the low-lying parts of the Kaitangata township, as bounded to the North by a floodbank located at the end of Christchurch Street, to the West by the floodbank beside the Kaitangata Contour Channel, to the South by the Matau Branch floodbank and Clyde Terrace, and by Eddystone Street to the East. The area is exposed to flood hazard from the Matau Branch, from overtopping of the Kaitangata Contour Channel, from the small hill catchments to the east (with areas catchment ranging from 1 km^2 to 6 km^2) and from localised rainfall accumulation.

Area 14 includes flat land with elevations ranging from between 2 m to 4 m, with the area bounded by Clyde Terrace, St Alban Street, Eddystone Street and the Kaitangata Contour Channel forming a depression where water could accumulate during heavy rainfall events. A short section of the original course of Kaitangata Creek serves as the drainage/ stormwater outfall channel for parts of the Kaitangata township and the outlet to the Matau Branch is equipped with flapgates to prevent river water from entering this area. Gravity drainage from this area is prevented during times of medium to high flows in the Matau Branch. The land in Area 14 is mainly low density residential, with some small industrial/commercial premises.

The floodbanks along the true left of the Matau Branch are designed to contain a Clutha River/Mata-Au flood of up to 4000 m^3/s at Balclutha (approximately a 1:40-year flood) with 600 mm of freeboard. Any Overtopping or breaching of this floodbank would result in the river flowing into Area 14 and completely inundating the depression identified above.

Flood hazard modelling (NIWA, 2005) indicates that floodwater from the Matau Branch will not enter Area 14, up to the 4000 m^3/s design flow, but the freeboard could be less than the design freeboard of 600 mm. There are no specific drainage or flood mitigation measures in relation to the flood hazard from the small hill catchments to the East; but there are small-scale floodbanks at the northern end of the area and beside the Kaitangata Contour Channel that provide limited flood protection against floodwaters from those sources.

It is estimated (NIWA, 2005) that during a 1:100-year flood (peaking at 5200 m^3/s, at Balclutha) the floodbanks would not be overtopped (Figure 4.12). During a 1:200-year flood (peaking at 5800 m^3/s), it is estimated that the floodbank would be overtopped, but the depth of water would not exceed 0.5 m in low-lying areas (Figure 4.14).

This area was flooded in October 1978 (4580 m^3/s at Balclutha), January 1980 (2770 m^3/s) and November 1999 (4160 m^3/s). However, that flooding was most likely caused by local rainfall accumulation and water from the small hill catchments to the east (Figure 4.35).

Figure 4.35 Area 14 during the (**A**) October 1978; (**B**) January 1980 and (**C**) November 1999 flood events. The photos were not necessarily taken at the peak of the flood

Area 15, Area 16, Area 18 and Area 20: Lower Puerua River and tributaries and Port Molyneux

Areas 15, 16, 18 and 20 consist of the lower floodplains of the Puerua River, the Puerua Contour Channel (also called the Puerua River Deviation) and its tributaries including Glenomaru Stream and Barrata Stream. The areas are generally bounded by the Puerua River Contour Channel true left bank and by the toe of the hills. These areas are exposed to flooding from their respective hill catchments to the West, including the catchments of the Puerua River (220 km^2), Glenomaru Stream (48 km^2) and Barrata Creek (9 km^2), from localised rainfall accumulation, and from elevated sea levels in the Puerua estuarine/mouth area (mainly areas 18 and 20). The hill catchments to the west usually consist of steep bush covered hills in the upper parts and more gentle grassed rolling downlands in the middle sections. But the land within these areas is generally very flat and very low-lying, with elevations ranging from 0.5 m to 2 m. There are also existing swamps in the lower reaches of these areas. As very limited fall is available in these areas, floodwater from the Koau Branch can backflow into, or impede, the Puerua Contour Channel resulting in the inundation of parts of these areas.

The land within these areas is predominantly used for agricultural activities and SH 92 passes through much of Area 15.

There is no specific flood protection for Area 15 and limited protection by means of short sections of low level floodbanks for areas 16, 18 and 20 (although the standard of protection is not known). It is noted that the Puerua River Contour Channel will preferentially overtop its true right bank and flood Area 15. Two short sections of low level floodbanks provide very limited protection to Area 16 from flooding from Glenomaru Stream and the Puerua River Contour Channel, and floodbanks on both banks along the Puerua Contour Channel provide some flood mitigation to Area 18. Areas 18 and 20 are also provided with a limited level of flood protection from Barrata Creek by the means of creek diversions and floodbanking. And Area 20 is protected from elevated sea levels by a short section of floodbank running parallel to the shore line.

It is estimated (NIWA, 2005) that, during a 1:100-year flood (peaking at 5200 m^3/s at Balclutha), the depth of water (mainly from the Koau Branch) in these areas would range between 1 m and 1.5 m and water velocities would not exceed 1 m/s (Figures 4.9

& 4.10). During a 200-year flood (peaking at 5800 m^3/s), it is estimated that flooding would be more extensive, but the depth the depth of water would not exceed 2 m in low-lying areas (Figure 4.11).

The potential hazard to people and buildings is considered to be high in some parts of these areas (mainly in Area 18, Figure 4.8).

Parts of these areas flooded in October 1978 (4580 m^3/s at Balclutha), January 1980 and, to a limited extent, in November 1999 (Figure 4.36) where the flooding was probably caused by local rainfall accumulation. In October 1978 water from the Koau Branch impeded the outlet of the Puerua Contour Channel and flood water back-flowed up the Puerua Contour Channel and flooded these areas.

Figure 4.36 Areas 15, 16, 18 and 20 during (**A**) the October 1978 and (**B**) January 1980 flood events. The photos were not necessarily taken at the peak of the floods.

Area 17 and Area 19: North (Area 17) and South (Area 19) of Summer Hill (Matau Branch true left bank)

Areas 17 and 19 are small areas located on the Matau Branch true left bank, at around 2 km and 1 km upstream from the Matau Mouth, respectively. The land within those areas is flat and low lying (elevations ranging between 1 m to 2.5 m) and is part of the Matau Branch floodplain. The land within areas 17 and 19 is used predominantly for agricultural activities, though Area 19 includes one dwelling. Area 17 is drained by two drains that are part of the Lower Clutha Drainage Scheme.

The main source of flood hazard for these areas is the Matau Branch and, to a lesser degree, the minor tributaries flowing from the eastern hills catchments (of less than 1 km^2) and localised rainfall accumulation.

Short sections of floodbanks along the true left bank of the Matau Branch are designed to contain a Clutha River/Mata-Au flood of up to 4000 m^3/s at Balclutha (approximately a 1:40-year flood) with 600 mm of freeboard. Flood hazard modelling (NIWA, 2005) indicates that floodwater from the Matau Branch would not enter these areas for the flows up to the design standard (4000 m^3/s at Balclutha). Freeboard levels could, however, be less than the design freeboard (600 mm) for Area 17. This section of the Matau Branch includes sharp bends where erosion is severe. Erosion protection works (such as rock revetment) are in place at critical locations to limit the erosion (including in front of the floodbanks in areas 17 and 19).

The flood modelling (NIWA, 2005) indicates that, during a 1:100-year flood (peaking at 5200 m^3/s at Balclutha), the floodbank adjacent to Area 17 would begin to be overtopped. But more significant overtopping would likely be occurring on the true left of the Matau Branch just upstream of Area 17 (where there is no scheme floodbank for this section on the true left bank of the Matau Branch) and, given the topography, this would result in extended flooding in Area 17. The depth of water (from the Matau Branch) in Area 17 would not exceed 1.5 m and the water velocity would not exceed 1 m/s (Figures 4.9 & 4.10). During a 1:200-year flood (peaking at 5800 m^3/s), it is estimated that the depth of water in Area 17 would not exceed 2 m (Figure 4.14). The potential hazard (expressed as a combination of the depth of inundation and of the water velocity) to people and buildings in Area 17 is considered to be high (Figure 4.11).

For Area 19, the flood modelling indicates that the area would not be flooded by the Matau Branch during a 1:100-year or a 1:200-year flood event (Figures 4.12 & 4.13).

Area 17 was extensively flooded in October 1978 (4580 m^3/s at Balclutha), and to a lesser extent in November 1999 (4160 m^3/s at Balclutha) (Figure 4.37). The flooding observed in January 1980 (2770 m^3/s) was probably from water overtopping the Matau Branch (true left bank) upstream of Area 17. Area 19 was also flooded during these events, but to a lesser degree, and probably mainly due to rainfall accumulation in the lower-lying areas.

Figure 4.37 Area 17 during the (**A**) October 1978; (**B**) January 1980 and (**C**) November 1999 flood events. The photos were not necessarily taken at the peak of the flood.

Area 21: Estuarine area (Coastal Strip)

Area 21 includes the coastal strip of land between the mouth of the Matau Branch and Port Molyneux, north of Kaka Point, and it is physically divided by the Koau mouth. The area extends width-wise (landward direction) to the southern floodbanks of the Inch Clutha and Paretai districts (Areas 8 & 13) that form part of the Lower Clutha Flood Protection Scheme. The part of Area 21 that is located between the Koau and Matau mouths, at the bottom end of Inch Clutha is known as "The Spit". Area 21 is mainly very flat and low-lying estuarine/swamp land with limited agricultural activities. Ground elevations are generally between 0 m and 1 m, although the sand dunes that run parallel to the shoreline are a few metres higher than the general ground.

The main sources of the river flood hazard for Area 21 are the Clutha River/Mata-Au (both branches) and the Puerua River (including the Puerua River Contour Channel). But, the area is also exposed to inundation from elevated sea levels - tides, storm surges and tsunamis (refer to Section 6 and ORC, 2012 for more details). There is no specific protection provided against these flood hazards, so the area is frequently inundated (Figure 4.38). However, the sand dunes provide some protection against elevated sea levels.

Area 21 is also exposed to severe coastal erosion (coastal retreat) and that process is detailed in Chapter 6.

Figure 4.38 Area 21 during (**A**) October 1978, Area 21 is in the background; (**B**) January 1980; (**C**) November 1999 flood events. The photos were not necessary taken at the peak of the flood.

The Koau and Matau mouths each have training lines on both bank that are designed to limit off-setting of the mouths and to confine the outlet flows for the efficient discharge to the ocean in all river flow and sea conditions.

Area 22: Kaitangata Contour Channel true left bank

Area 22 consists of the lower floodplains of the small streams that drain the local, eastern hill catchments between Kaitangata township and Lake Tuakitoto; with the Kaitangata Contour Channel true right floodbank forming the western boundary and toe of the hills forming the eastern boundary of Area 22. The largest of those easternhill catchments is that of Camp Stream (approximately 9 km^2). The upstream parts of those catchments are generally grassed rolling hills, while the lower parts are flat (elevations ranging between 1 m to 2 m) with relatively well defined floodplains.

Area 22 is exposed to flooding from the hill catchments, from Lake Tuakitoto via the Kaitangata Contour Channel (with the true left bank of the channel more likely to be overtopped first) and from the accumulation of local rainfall. Also, high water levels in the Matau Branch can exacerbate this flooding by impeding the discharge of the Kaitangata Contour Channel into the river. Floodwaters can pond in Area 22 until the water level in the Matau Branch has dropped sufficiently to allow either gravity drainage or adequate pumping via the Kaitangata Pumping Station.

The land within Area 22 is used mainly for agricultural activities, and, although it includes the low-lying northern part of the Kaitangata township (between Christchurch Street and Smyth Street), which has very few dwellings. A section of Lakeside Road, which provides an alternative link from the Kaitangata township to State Highway 1, is also included in Area 22.

The area has no specific flood protection measures in place and it was extensively flooded in October 1978 and in November 1999 (Figure 4.39).

Figure 4.39 Area 22 during (**A**) the October 1978 flood, with Area 22 to the left foreground; (**B**) the November 1999 flood. The photos were not necessarily taken at the peak of those flood events.

5. Seismic Hazard

Earthquakes occurring locally and regionally present a risk to the Clutha Delta. Seismic risk, or the risk due to earthquakes, depends on the magnitude, frequency and nature of the earthquakes, their 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.

Limited, specific information exists about the exposure of the Lower Clutha Delta to seismic risk. While a number of investigations in and around this area have identified approximate fault locations, very few investigations have further expanded on this.

This chapter summarises the information the Otago Regional Council holds about seismicity in and around the Clutha Delta.

5.1 Known Faults on the Clutha Delta

The Clutha Delta is surrounded by a number of active and inactive fault systems (Figure 5.1). The northwest-southeast trending Livingstone, Castle Hill and Hillfoot Faults traverse across the wider Clutha Delta Catchment. The Clifton Fault is also located to the immediate north west of this area. Of these locally situated faults, only the Clifton and Castle Hill faults are considered active[11].

The Akatore and Alpine faults are not located on the Clutha Delta, however they both contribute to the overall seismic risk of the area. The Akatore Fault is considered to be one of the most active fault systems near the Clutha Delta and has been subject to numerous investigations, with its location and general characteristics reasonably well understood (Figure 5.1). The Alpine Fault is the largest, most prominent fault in the South Island, with a history of frequent and large seismic events the effects of which can be felt throughout much of the South Island. A number of other nearby and offshore faults also exist within the vicinity of the Lower Clutha Delta, including the Titri Fault running parallel with the coastal hills between Dunedin and Balclutha and the Takapu Fault which lies offshore and approximately parallel to the Akatore Fault (ORC, 2012a).

Castle Hill

The Castle Hill Fault is the only known active fault on the Lower Clutha Delta and forms the northern boundary of the low lying delta. A study by Norris and Litchfield (1996) estimates the return period of events of between M_W 6.5 and M_W 7 (which would cause uplift across the fault of around 1 m) on this fault to be approximately 10,000 years. The fault extends in a northwest-southeast direction for approximately 35km offshore (NIWA, 2007).

Livingstone and Clifton Faults

[11] A fault is described as 'active' when movement or evidence of movement demonstrates activity within the past 100,000 years (GNS, 2012).

The Livingstone Fault dissects the centre of the Clutha Delta and marks the boundary between the Dun Mountain-Maitai and Caples terranes[12] (Bishop and Turnbull, 1996) (see Figure 3.1 for geological terrane boundaries). While shown as inactive in Figure 5.1, any possible evidence of Quaternary movement is concealed beneath the Inch Clutha floodplain (Barrell *et al*., 1998).

The Livingstone Fault merges with the Titri and Castle Hill Faults and extends offshore (Mortimer *et al*., 2002). The Clifton Fault, located to the northwest of the study boundary is inferred to be a splinter of the Livingstone Fault system (Turnbull and Allibone, 2003). But little is known about either of these fault systems.

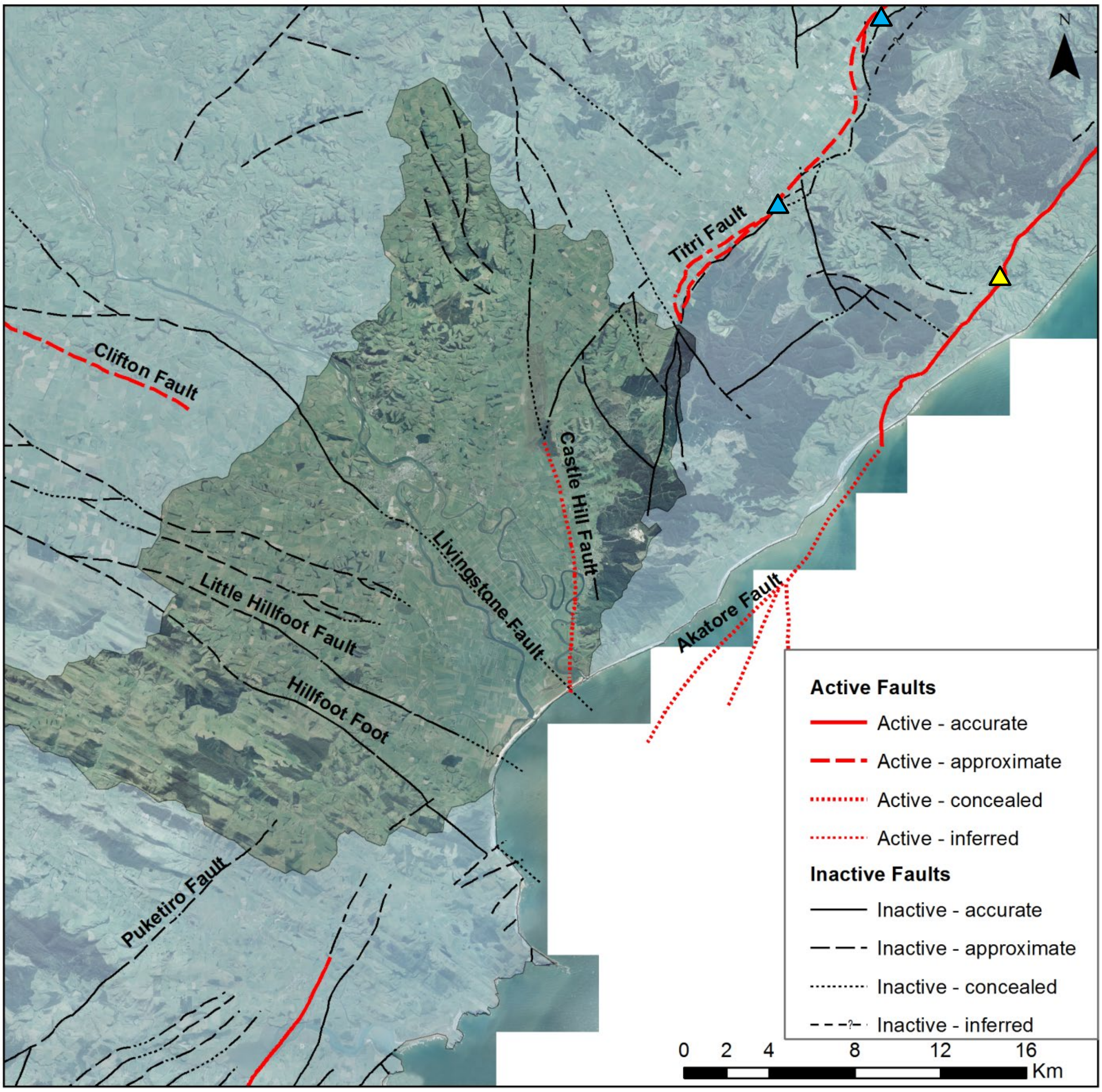


Figure 5.1 Faults in the vicinity of the Clutha Delta (GNS Science, 2012; GNS Science 1996). Active faults are shown in red and are defined as faults that have experienced a major rupture in the past 100,000 years. Triangles show location of paleoseismic trenching studies carried out in 2016, funded by EQC grants.

[12] A fault bounded area or region with a distinctive stratigraphy, structure and geological history.

Little Hillfoot and Hillfoot Faults

The northwest/southeast trending Hillfoot Faults mark the northern bound of the Southern Syncline, a distinct topographic feature which dominates the physiography south of the Lower Clutha Delta. The Hillfoot Fault also marks the boundary between the Murihiku and Dun Mountain-Maitai terranes (Turnbull and Allibone, 2003) (Figure 3.1). Little is known about the Hillfoot and Little Hillfoot faults.

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 Clutha Delta, the Alpine Fault contributes to the overall seismicity of the region (Opus, 2005).

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 of around M_W 8 (Sutherland *et al*., 2007). It is anticipated that the next large event along this fault will result in 8 m of lateral displacement, which is the equivalent shaking intensity of MMI 5 for the Lower Clutha Delta area (Opus, 2005).[13] This would be felt by most people, with unsecured objects becoming dislodged and potentially falling (Appendix 2).

Akatore Fault

The Akatore Fault is located east of the Clutha Delta and includes both onshore and offshore segments. The onshore portion of the Akatore Fault extends offshore just south of Toko Mouth. 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 behaviour[14], 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 vertical displacement of the order of 2-4 m (Litchfield and Norris, 2000). EQC provided funding for paleoseismic trenching studies that were undertaken on this fault in early 2016, in order to date the most recent ruptures of the fault (yellow triangle in Figure 5.1). Results of this study are due out in 2017.

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).[15] A series of faults splinter from the Akatore Fault, just south of Toko Mouth. These can be seen to the east in Figure 5.1.

Modelled earthquake scenarios for the Otago region most frequently cite the Akatore Fault as being the source of the maximum credible earthquake likely to affect the

[13] 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). See Appendix 2 for further discussion.

[14] Episodic behaviour 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 (i.e., a cluster of events) interspersed with long periods of quiescence during which displacement is accommodated on neighbouring faults.

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

Dunedin area. An earthquake event of magnitude 7.0 along this fault has been modelled to produce ground- shaking intensities on the Clutha Delta of up to 8 on the MMI scale (Opus, 2005).[16] 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) that will have varying degrees of consequence for Molyneux Bay and the Lower Clutha Delta. The tsunami hazard in this area is further discussed in Chapter 6.

Titri Fault

The Titri Fault system[17] is located to the east of the Lower Clutha Delta study boundary (Figure 5.1). 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 alluvial fans located along the Titri Fault scarp provide clues to the historical movements of this fault. Deformation of older fans and fan deposits suggest that Quaternary movement has occurred along this fault. The absence of any deformation of the youngest alluvial fans, as well as a continuous profile of Waihola sand/silt across the master fault (on the lower Taieri Plains) further suggests that no Holocene[18] activity has occurred along the fault.

EQC has funded two paleoseismic trenching investigations on the Titri Fault that aim to identify the timing of recent events on the fault (green triangles in Figure 5.1 show trench locations). Results of this study are due out in 2017. For Dunedin City (located approximately 70 km northeast of the Clutha Delta), the Titri Fault has been described as a less likely earthquake source than the Akatore and Alpine faults (Glassey et al., 2003).

5.2 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. 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 5.2). The length of any particular fault rupture trace will vary from tens to hundreds of kilometres, and is dependent on characteristics of the fault zone involved and the amount of stress being released.

Surface fault rupture can cause extensive damage to engineered structures and their associated features, such as flood banks, drainage channels[19], 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 on confining

[16] Appendix 2 provides additional explanation of the MMI scale.

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

[18] For a definition of this and other geological terms refer to the glossary. Refer to Appendix 1 for a geological timeframe.

[19] The drainage channels of the Lower Clutha Delta have a total length in excess of 143km. Effective drainage of the Clutha Delta also relies on drainage channels owned and maintained by landholders and the roading authority (Clutha Distirct Council).

soils (NZGS, 2010). The precise location of the faults on the Lower Clutha Delta is not known; however the inferred location (based on mapping completed at a 1:250,000 scale) suggests that Castle Hill and Clifton Faults are the only known active faults on the delta[20].

Figure 5.2 Example of surface-fault rupture on the Canterbury Plains after the M_W 7.1 Darfield earthquake, in September 2010. An average horizontal displacement of 2.5m was recorded along this fault (Quigley, *et al.*, 2011). (Photograph source, GNS Science).

5.3 Ground shaking

Ground shaking is one of the principal effects causing damage during a seismic event and is also the most recognised due to the propensity of people 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, tends to amplify ground shaking and can lead to liquefaction and lateral spreading occurring (e.g. Figure 5.3 a, b)(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 2.

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 for the Lower Clutha Delta catchment, with a predicted MMI of between 7 and 8 (Opus, 2005). 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.

[20] A fault is described as 'active' when movement or evidence of movement demonstrates activity within the past 100,000 years (GNS, 2012). It should be noted that some faults may have experienced movement within the past 100,000 years, however without a surface expression they cannot be mapped and therefore described as 'active'.

5.4 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, resulting in loss of shear strength and sediments losing their ability to cohere (Norris *et al.*, 1999). Coarser, heavier sediment is shaken down and becomes more compact, forcing fine silts and water to the surface, often in the form of 'sand boils' (Figure 5.3b). 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 Clutha Delta are considered 'possibly susceptible' to liquefaction during a seismic event that generates sufficient ground-shaking intensities (Figure 5.4). No significant liquefaction is expected for shaking intensities below MMI 6 (Opus, 2005).

Figure 5.3 a) Lateral spreading on the true-left bank of the Kaiapoi River, after the Christchurch magnitude 6.3 earthquake. **b)** Sand boils in Avonside after the Christchurch earthquake in February 2011 (after Quigley *et al.*, 2013).

The susceptibility to liquefaction is shown in Figure 5.4, based on the nature and density of the underlying soils.[21] 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 5.1).

Recent investigations completed by GNS Science have further refined the susceptibility of the Clutha District to liquefaction (Pondard, *et al.,* 2012). This report identifies that although 65% of Clutha District Council's underground assets and infrastructure (e.g. water supply and stormwater) are located on land not likely to suffer significant damage, at least a quarter of asset value is located in areas exposed to high liquefaction hazard. Figure 5.5 shows an example from this report of Balclutha's liquefaction susceptibility.

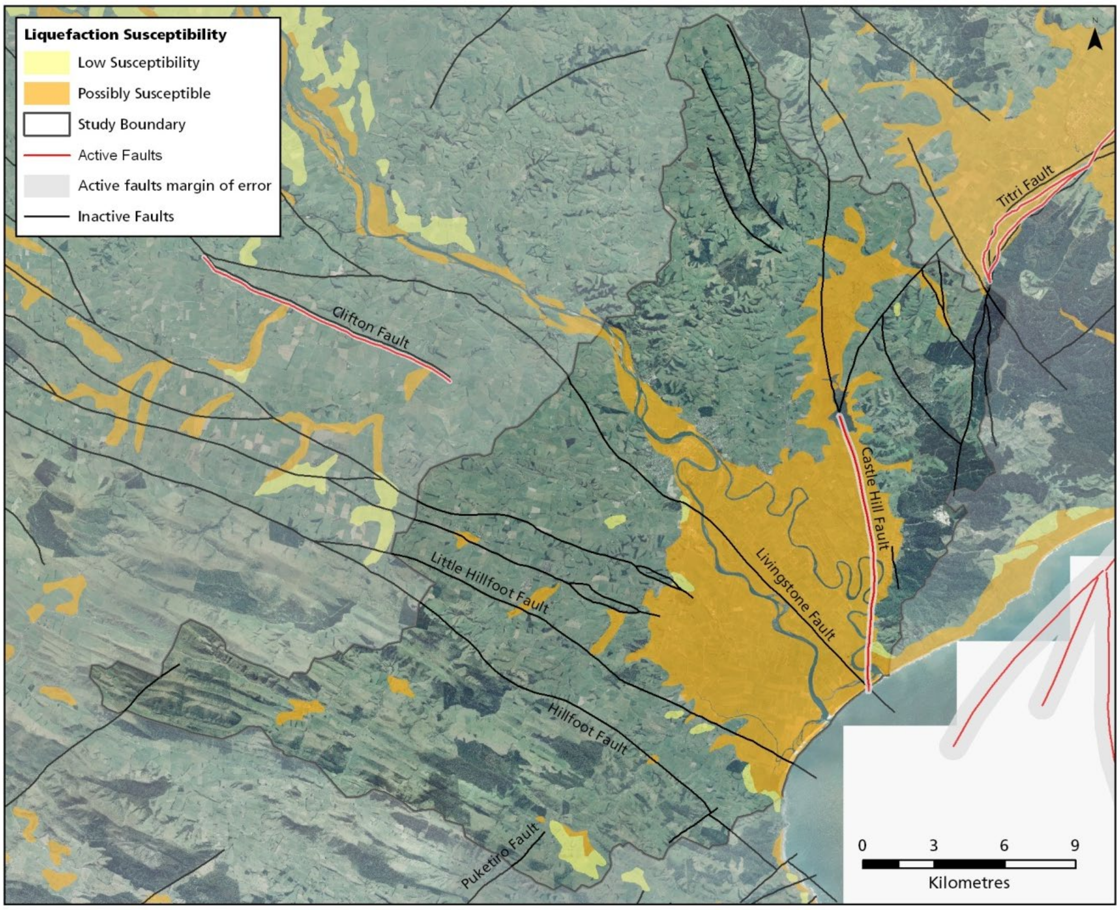


Figure 5.4 Susceptibility to liquefaction hazard on the Clutha Delta (Opus, 2005; GNS Science, 2012).

[21] 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.

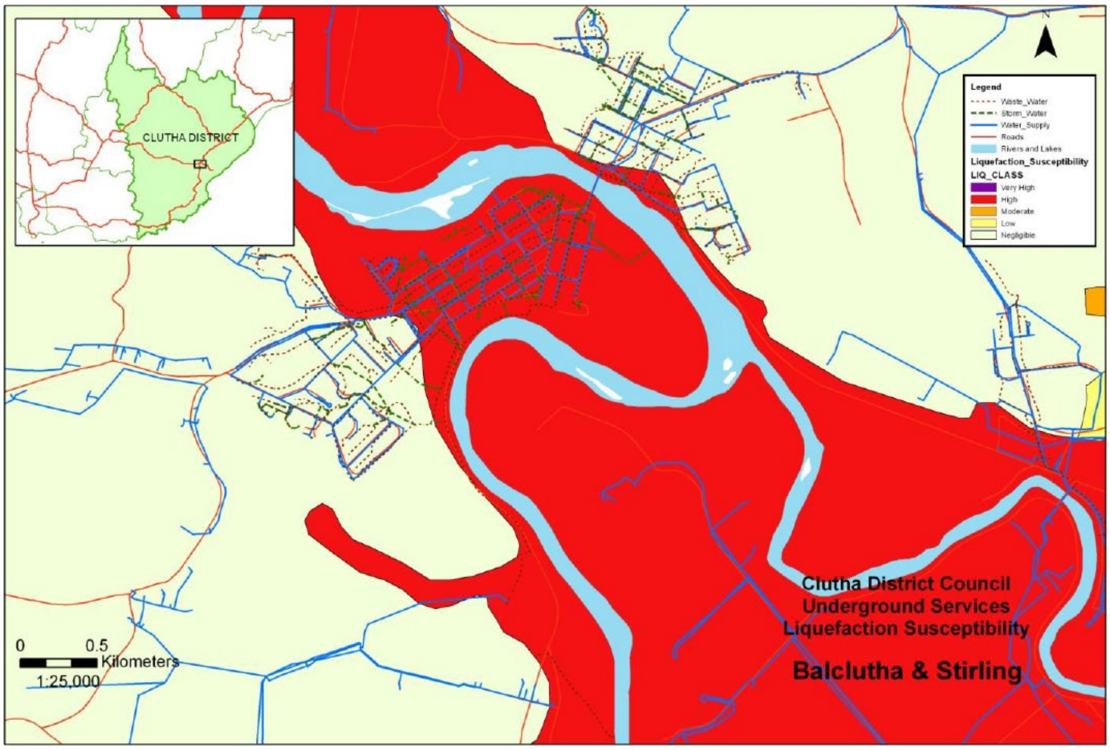


Figure 5.5 Clutha District Council, Balclutha and Stirling, liquefaction susceptibility (after Pondard *et al.,* 2012).

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 5.3a). 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.

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 5.3a). The latter was the dominant failure mode. The floodbanks on the Clutha Delta are likely to suffer damage similar in nature and extent to that experienced in Canterbury 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 provide flood protection and land drainage to much of the Clutha Delta. The Paretai, Rutherfords, Matau (Kaitangata), Barnego and Smith Road Pump Stations (locations, Figure 4.3) would likely be rendered inoperable for a prolonged period of time as none of the stations was expressly designed to withstand significant ground shaking.

Figure 5.6 shows the likely performance of the Lower Clutha Flood Protection Scheme following a significant seismic event. The event used to derive the information shown in Figure 5.6 was defined as a 'Maximum Design Earthquake' (MDE), estimated at 0.2 g peak ground acceleration (i.e. how hard the earth shakes in a given geographic area compared with gravity). This is a slightly conservative estimate of the 500-year return period of seismic acceleration for the Lower Clutha Delta (Tonkin & Taylor, 2005). The geotechnical evaluations that provided the information shown in Figure 5.6 suggest that the modelled seismic event could compromise many sections of the Lower Clutha Flood Protection Scheme flood banks (Tonkin & Taylor, 2005). The analysis was based on the Clutha River/Mata-au being at ‘normal’ rather than at flood levels. The graduations used in Figure 5.6 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.

5.5 Earthquake-induced landslides

A large earthquake, with sufficient ground shaking, could trigger the movement of existing landslides 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. The Otago Regional Council holds limited information regarding landslide activity within study area and the wider Clutha District.

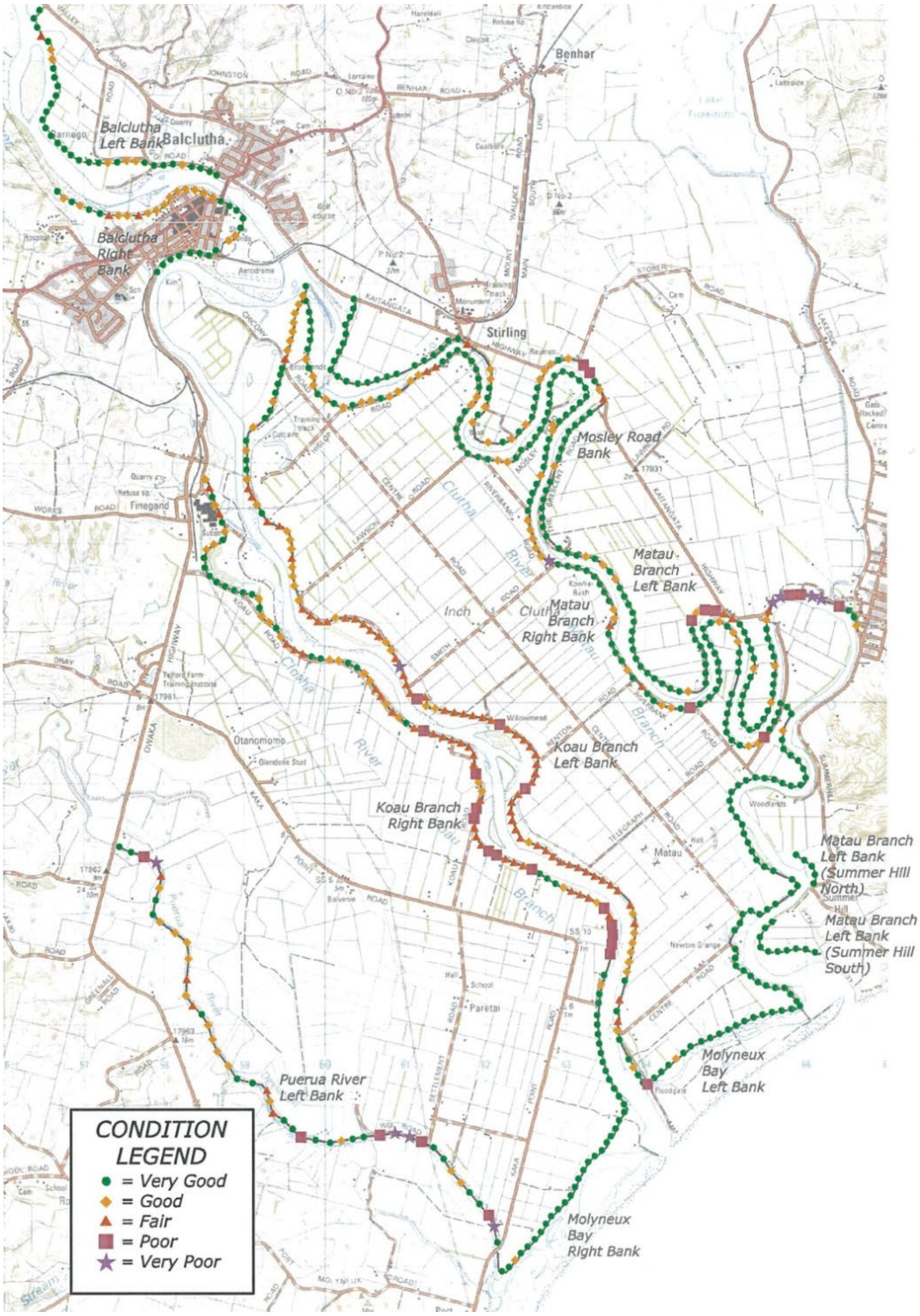


Figure 5.6 Seismic Performance Index of floodbanks on the Lower Clutha Delta Flood Protection Scheme (Tonkin & Taylor, 2005).

6. Coastal Hazards

From Kaka Point in the south to Summer Hill to the north, Molyneux Bay marks the seaward boundary of the Clutha Delta, where the Clutha River/Mata-au reaches the Pacific Ocean (see Figure 3.3). A series of natural and artificial features act as a buffer between the high-energy open coast and the low-lying parts of the delta. Flood banks line both the Koau and Matau branches of the Clutha River/Mata-au, while a sandy beach and dunes elevated between 3 and 5 m above msl mark the boundary between the delta and Molyneux Bay (Section 3.1).

The continuing interaction of coastal and fluvial processes is a prominent feature of the lower Clutha Delta. Changes in mean sea level, sediment movement and storm surge events have historically contributed to its present day formation. These dynamic processes continue to gradually shape the lower delta, and contribute to the coastal hazard[22] in this area.

Molyneux Bay is dominated by north-east and south-east winds which frequently exceed 30 km/hr. The Lower Clutha Delta lies in a wind belt known as the 'roaring forties' where strong westerly winds move across large expanses of the Southern Ocean to generate large swells (ORC, 2001). While the headlands to the south (including Nugget Point) provide a degree of shelter to Molyneux Bay, it is largely exposed and frequently subjected to stormy conditions. Stormy conditions coupled with high flows in the Clutha River/Mata-au can exacerbate flood hazard in the low lying areas of the Clutha Delta.

The typical range of astronomical tides at Nugget Point is between 1.1 m (Neap tides) and 2 m (Spring tides). However, elevated sea levels can occur due to a range of factors (section 6.2), and NIWA (2008) determined that an elevated sea level event with a return period of 20 years would be 1.1 m higher than the mean high water spring (MHWS) level in Molyneux Bay.

6.1 Historical shoreline change

The Molyneux Bay shoreline has a history of instability and change. Prior to 1878 (see Figure 2.2 and Chapter 4), the Koau and Matau branches of the Clutha/Mata-au River joined and discharged into the Pacific Ocean at the former Port Molyneux. During the flood of 1878, both branches of the Clutha River/Mata-au forged new mouths; the Matau branch at Summer Hill (its present location) and the Koau branch approximately 1km north of Port Molyneux (and 300 m south of its existing location). The original river mouth at Port Molyneux silted up, destroying the viability of a port at this location (Scarf, 1997). The former port is now used for farming purposes, with limited physical evidence of its former existence.

Prior to the construction of the Lower Clutha Flood Protection and Drainage Scheme in the 1950s, the Koau and Matau Mouths were subject to reasonably frequent migration. During large flood events the Clutha River/Mata-au would have sufficient force to scour the lower floodplain and cause the rapid migration of the river mouths. Mouth

[22] "Coastal hazard" is a generic term used to describe naturally occurring processes, such as coastal flooding, erosion, tsunami and storm surge (elevated sea level).

blockages, due to the deposition of river sediments during low flows and/or the movement of sand due to wave and tidal action also contributed to the migration of the river outlets. Such mouth blockages are more likely to occur in the winter months due to the increase in onshore movement of sediment and flows in the Clutha River/Mata-au are generally lower.

Offsetting and/or blockages of river mouths can reduce the rivers efficiency at discharging water into Molyneux Bay, causing elevated water levels immediately upstream. While the river mouths are still subject to these naturally occurring processes, these effects are mitigated by scheme works (Section 3.3). An extensive floodbank network assists in controlling the path of the Clutha River/Mata-au, reducing the likelihood of new paths being forged. The use of training lines at each river mouth (see Figures 3.12, 3.13) has also sought to moderate these effects. Engineering works can minimise the risk of future blockages and/or offsetting, however the risk of future blockages cannot be totally eliminated.

6.2 Elevated sea-level and tsunami events

Elevated Sea Level

The Molyneux Bay shoreline can be affected by strong winds and waves originating from the south-east. Swell and storm waves are generated over large ocean expanses originating in the 'roaring forties' and 'furious fifties' of the southern ocean (ORC, 2001). The exposed nature of Molyneux Bay results in the area being frequently subjected to severe coastal conditions, including elevated sea levels during low-pressure weather systems (often referred to as a storm surge).

Table 6.1 shows different factors that create elevated sea level events. For further descriptions of each of these processes, refer to ORC (2012a) and NIWA (2008).

Table 6.1 Components of elevated sea level (ORC, 2012a).

Component	Explanation
Wave run-up	Additional height gained by breaking waves. Wave run up is affected by weather, bathymetry and topography.
Wave set-up	Persistent elevation of sea level through the effect of waves.
Wind set-up	Piling up of water against the coast by prevailing winds driving water currents towards the land.
Inverse barometer (atmospheric pressure)	When atmospheric pressure falls, the mean level of the sea will rise by 1 cm for every hectopascal decrease in pressure.
Tide	Predicted local tidal cycle due solely to astronomical effects.

In 2008 the Otago Regional Council commissioned NIWA to estimate the level of inundation associated with elevated sea level events with average recurrence intervals (ARI) of 20, 50, 100 and 500 years (Table 6.2).[23] The elevation of the sea determined for these events is presented in the ORC (2012a) report "*Community vulnerability to elevated sea level and coastal tsunami events*", and the extent and depth of inundation associated with selected events is mapped in the accompanying map book (ORC, 2012b). The elevated sea level scenarios modeled by NIWA do not necessarily represent 'worst case' scenarios and were instead chosen as a representative range of credible events.

Importantly, NIWA's modeling assumed that the coastal dunes of Molyneux Bay and the flood banks on the lower Clutha Delta remain static (i.e. are not damaged or do not change prior to, or over the period of the scenario). The feasibility of this assumption is dependent on the structural integrity of the floodbanks and sand dunes being maintained during such an event. In addition, the topographic information (LiDAR) used by NIWA to model the extent and depth of inundation was obtained in 2004. Changes in the position of the shoreline and the form of the dune system continue to occur along the Molyneux Bay coast, and these changes can either reduce or accentuate the effects of coastal hazards such as storm surge or tsunami events.

It is also noted that the meteorological conditions that initiate elevated sea level events along the coast are also often those that lead to river flooding.[24] This increases the likelihood that storm surge events may coincide with flood events, further compounding pressure on existing infrastructure (refer to Section 6.5).

The maximum water depth (as modelled by NIWA, 2008) for a 1:100 year elevated sea level event is shown in Figure 6.1. In this modelled scenario, there is no inundation beyond the floodbanks of the Lower Clutha Flood Protection and Drainage Scheme, although parts of Kaka Point Road are shown to be affected. Figure 6.1 also shows the land (shaded in purple) which is below the height identified as the 1:100 year storm surge level (2.25 m above msl). This area could be affected by inundation if there was direct connection to the Pacific Ocean during a 1:100 year elevated sea level event (eg, due to a floodbank breach), or if surface runoff / floodwater were to reach the same height during such an event. The depth of inundation under this scenario would vary considerably across the area shaded purple in Figure 6.1, depending on local topography.

Figure 6.2 shows the effects of a 1:100 year storm surge event if sea level were 0.5 m higher than at present.[25] Future changes in the shoreline and dune system with significant sea-level rise are likely to be considerable, and the actual extent and depth of inundation associated with high magnitude storm surge events may therefore differ from those modelled by NIWA in 2008.

[23] ARI expresses the change of an event occurring in any given year, regardless of when the last event of a similar magnitude struck. A 1:100 year event has a 1/100 or 1% chance of occurring in any given year, and a 63% chance of occurring in the next 100 years. Such an event is therefore 'likely' (but not certain) to occur over any 100 year period.

[24] It is noted that flood events in the Clutha River/Mata-Au can result from heavy rainfall in the upper catchment only, which will take several days to reach the Clutha Delta. Flood peaks resulting from such an event are less likely to coincide with storm surge conditions at the coast.

[25] The modelling undertaken by NIWA (2008) considered the effects of up to 0.5m sea-level rise. More recent guidance on future changes in sea level was provided by the Intergovernmental Panel on Climate Change (IPCC) in 2013, in its Fifth Assessment Report. The IPCC report states that predicted sea-level rise at a worst *case* will be 0.98 m by the year 2100 (relative to 1986-2005).

Table 6.2 The level of the sea (relative to msl) at MHWS for a range of elevated sea level events in Molyneux Bay (ORC, 2012a).

Return period (years)	*Water level (m above msl)*
20	2.1
50	2.2
100	2.25
500	2.35

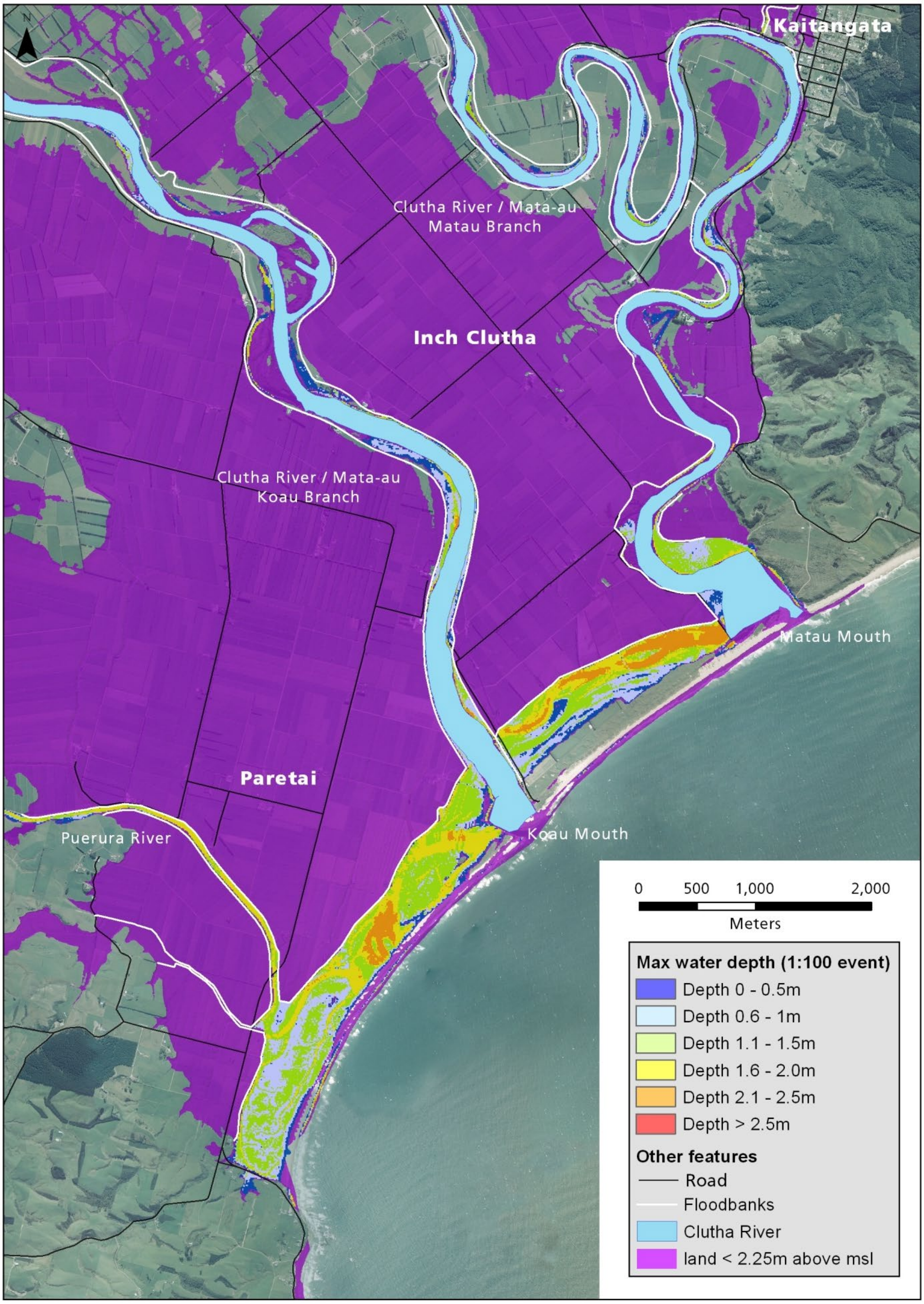


Figure 6.1 Maximum water depth for inundated land along the Molyneux Bay coastline during a 1:100 year elevated sea level event at current mean sea level, as modelled by NIWA (2008). Parts of the lower Clutha Delta which are below the 1:100 year level (but not shown to be inundated by NIWA's modelling) are shaded in purple.

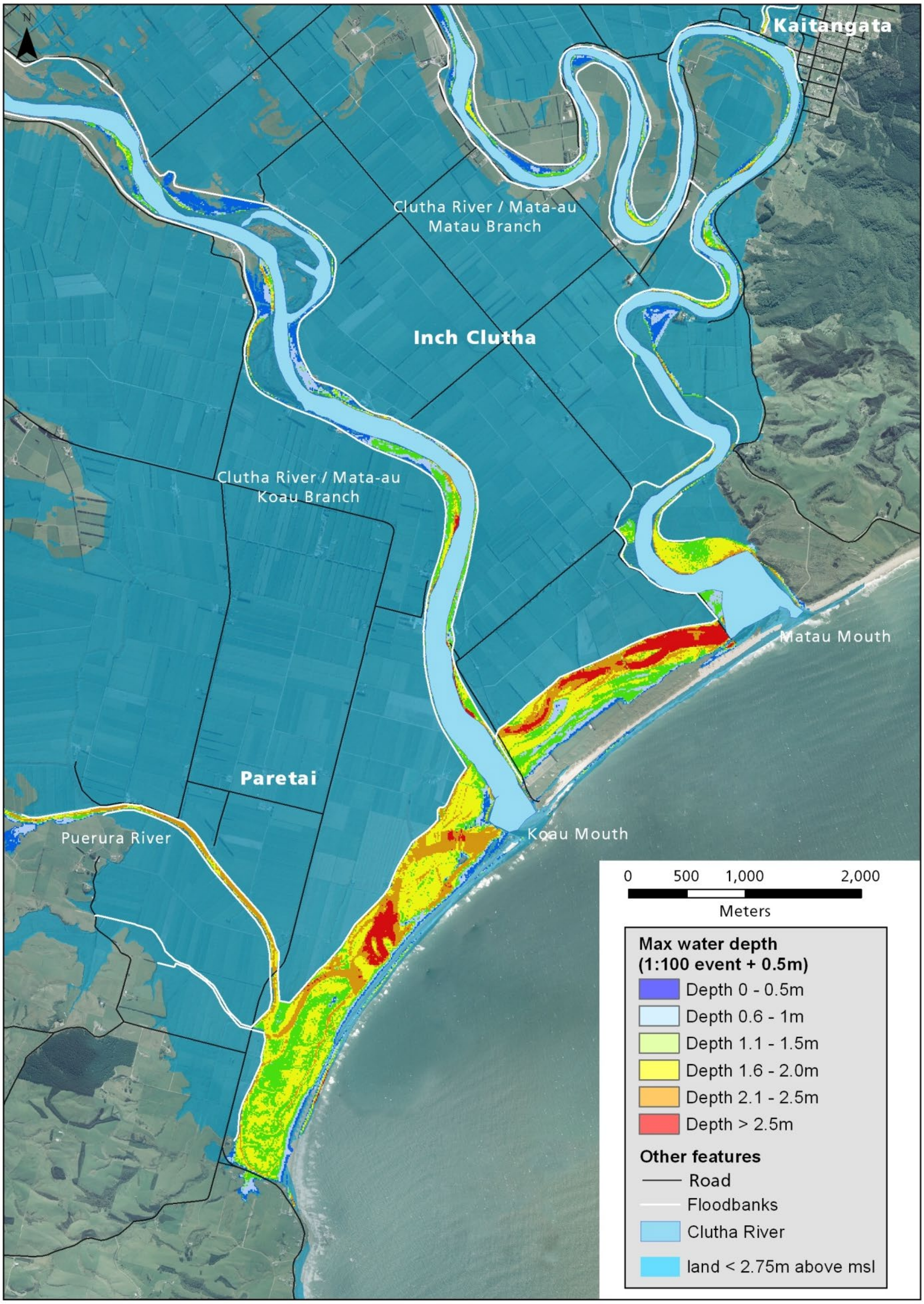


Figure 6.2 Maximum water depth for inundated land along the Molyneux Bay coastline during a 1:100 year elevated sea level event with 0.5 m of sea-level rise, as modelled by NIWA (2008). Parts of the lower Clutha Delta which are below the 1:100 year +0.5 m level (but not shown to be inundated by NIWA's modelling) are shaded in blue.

Tsunami

A tsunami is a series of waves that occurs when a large mass of earth beneath the ocean drops or rises suddenly, rapidly displacing the water above. While sub-marine landslides and under-sea volcanic eruptions are capable of causing tsunamis, large earthquakes (magnitude > 8) are the most likely cause of a tsunami that would affect the Lower Clutha Delta (NIWA, 2007). Possible local (near-field) sources of tsunami-inducing earthquakes are local faults such as the Akatore Fault (see Chapter 5) and nearby subduction zones such as the Puysegur Trench to the south of the South Island. Possible distant sources are subduction zones around the perimeter of the Pacific Ocean, such as the Chilean Trench. This feature, also known as the Atacama Trench, runs parallel to the west coast of South America and produced the great Chile earthquakes of 1877 and 1960.

The low lying elevation of the lower Clutha Delta and its proximity to the Pacific Ocean means the area is potentially susceptible to inundation by tsunami. The great Southern Chile earthquake of 1960 caused a tsunami along the coast of Otago. Evidence suggests it caused an initial rise in sea level of at least 0.5 m and continual fluctuations in water level were observed over the following three days (NIWA, 2007). It is noted that tsunami events are not weather related and can occur at any time of the year and at any time of the day or night. Any formal warning before the arrival of a tsunami generated locally or nearby (e.g., Puysegur Trench) is likely to be minimal or non-existent. The best warning of an approaching tsunami generated locally may be the ground shaking associated with the earthquake that triggers the tsunami. Not everyone may feel this shaking however, and those that do may not immediately associate it with the potential occurrence of a large tsunami. In some cases, a noticeable retreat of the ocean before the arrival of the tsunami may occur.

Possible inundation extents for near-field (Puysegur Trench) and far-field (South American) tsunamis were modeled for the Otago coastline by NIWA in 2007. Three credible tsunami scenarios (or ‘events’) were modelled, including an event generated from a large earthquake on the Puysegur Trench, and two scenarios associated with a major earthquake off the coast of South America. The results of the NIWA investigations are presented in detail in the 2012 ORC report “*Community vulnerability to elevated sea level and coastal tsunami events*”.

One of the key messages outlined in both the NIWA and ORC reports is that the sand dunes and floodbanks which separate the Clutha Delta from the Pacific Ocean may be damaged, either by the earthquake which generates the tsunami (Chapter 5), or by a series of waves associated with the tsunami itself. Erosion or damage to these natural and man-made defences may lead to more widespread inundation than the modelled results prepared by NIWA, which assumed that the sand dunes and floodbanks remained stable during and between successive tsunami waves. Changes in the position of the shoreline and the form of the dune system continue to occur along the Molyneux Bay coast (Section 6.3), and ongoing coastal erosion may also reduce the ability of the dune system to provide a buffer against tsunami events.

Figures 6.3 and 6.4 show cross-sections through the Clutha Delta, from the coast to Balclutha and Otanomomo respectively. Figure 6.5 shows the location of these two cross-sections. These sections combine surveyed transects (collected in April 2013) across the beach and dunes with LiDAR data (collected in 2004) further inland. The tsunami wave height information shown on these two figures represents the maximum height that a tsunami would reach at the coast, if it were to occur at MHWS. The lower level (2.7 m above MHWS) represents a specific scenario (a Puysegur Trench tsunami) as modelled by NIWA in 2007. The upper level (7.6 m above MHWS) represents the height of an event which could be expected to occur, on average, at least once within a time frame of 2500 years, from a range of different sources, as calculated by GNS in 2013.[26]

The actual effects of a tsunami (including the distance it travels inland and the height of wave run-up) will be influenced by the shape of the land over which the tsunami wave passes, as well as the velocity and height of the incoming waves. Although the actual effects of all the tsunami events which could potentially occur in Molyneux Bay have not been modelled, Figures 6.3 and 6.4 suggest that larger events could extend a considerable distance inland, particularly if they overtop or breach the floodbanks and dunes along the coastline.

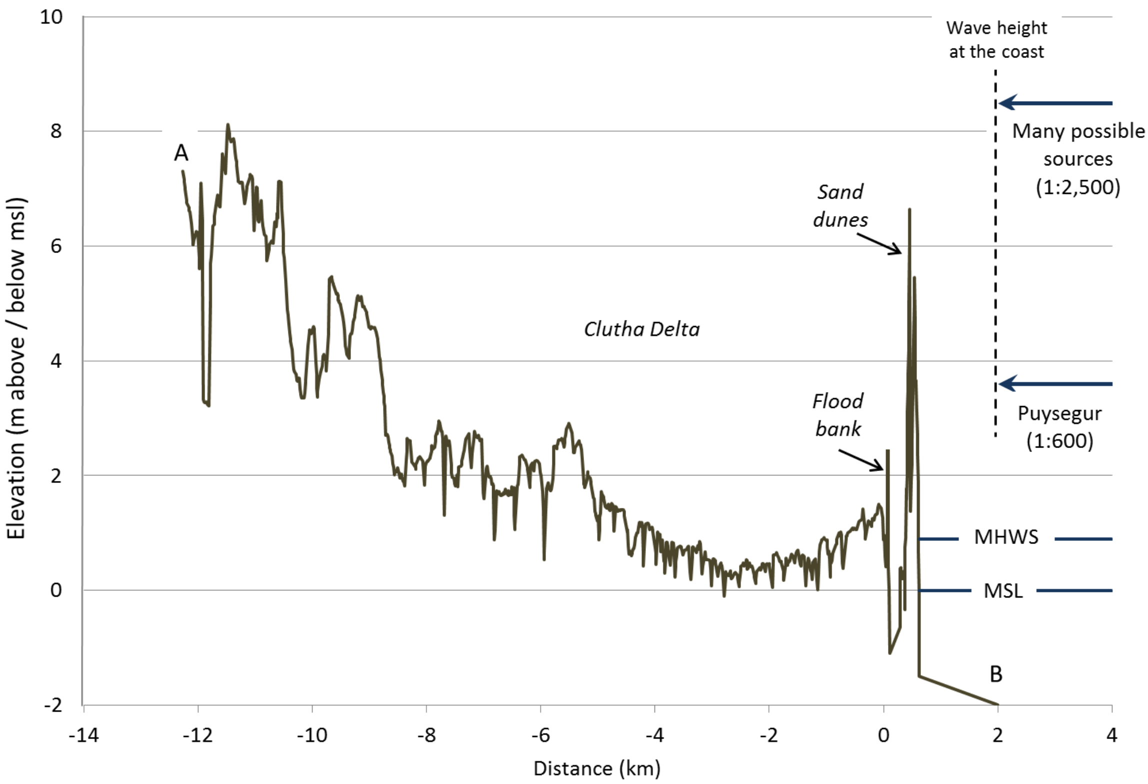


Figure 6.3 Cross section A-B through the Clutha Delta, showing the tsunami wave height (at the coast) for a Puysegur Trench event (1:600 year return period), and an event with a 1:2500 year return period.

[26] The GNS report "*Review of Tsunami Hazard in New Zealand (2013 Update)*" builds on the current knowledge and draws on recent research and changes to scientific understanding that has arisen from recent tsunami events in the Indian and Pacific Oceans. The report provides the latest assessment of all likely sources of tsunami that could affect the New Zealand coast and the likely size of tsunami waves.

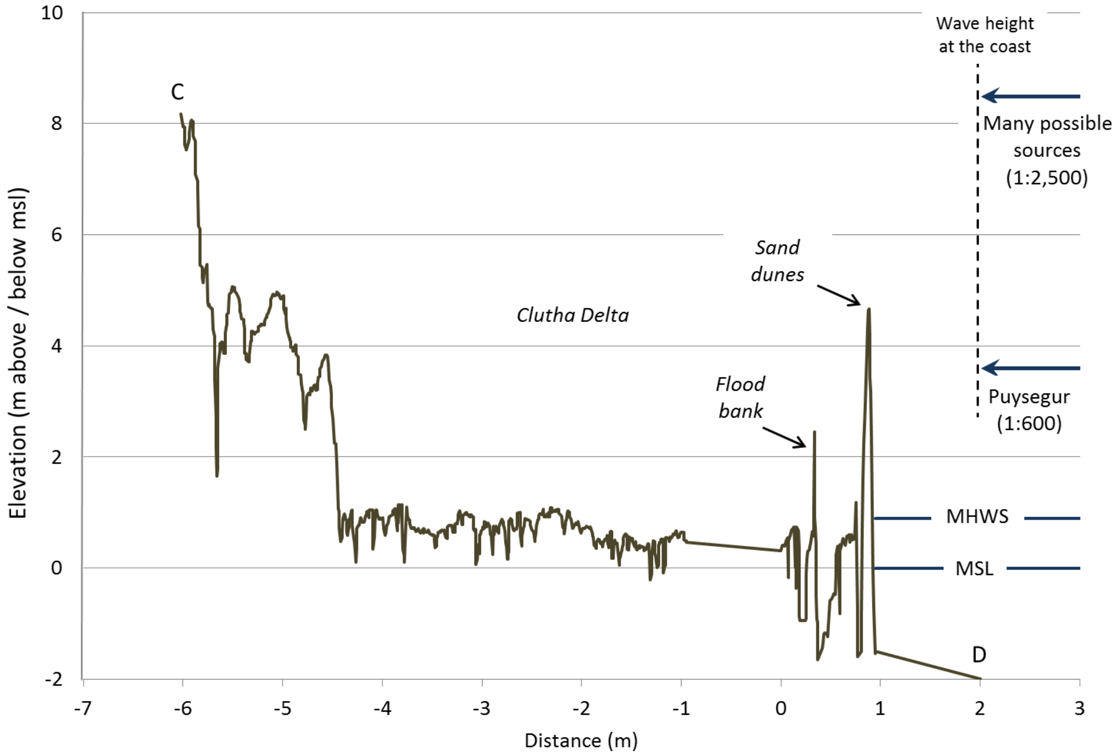


Figure 6.4 Cross section C-D through the Clutha Delta, indicating the tsunami wave height (at the coast) for a Puysegur Trench event (1:600 year return period), and an event with a 1:2500 year return period.

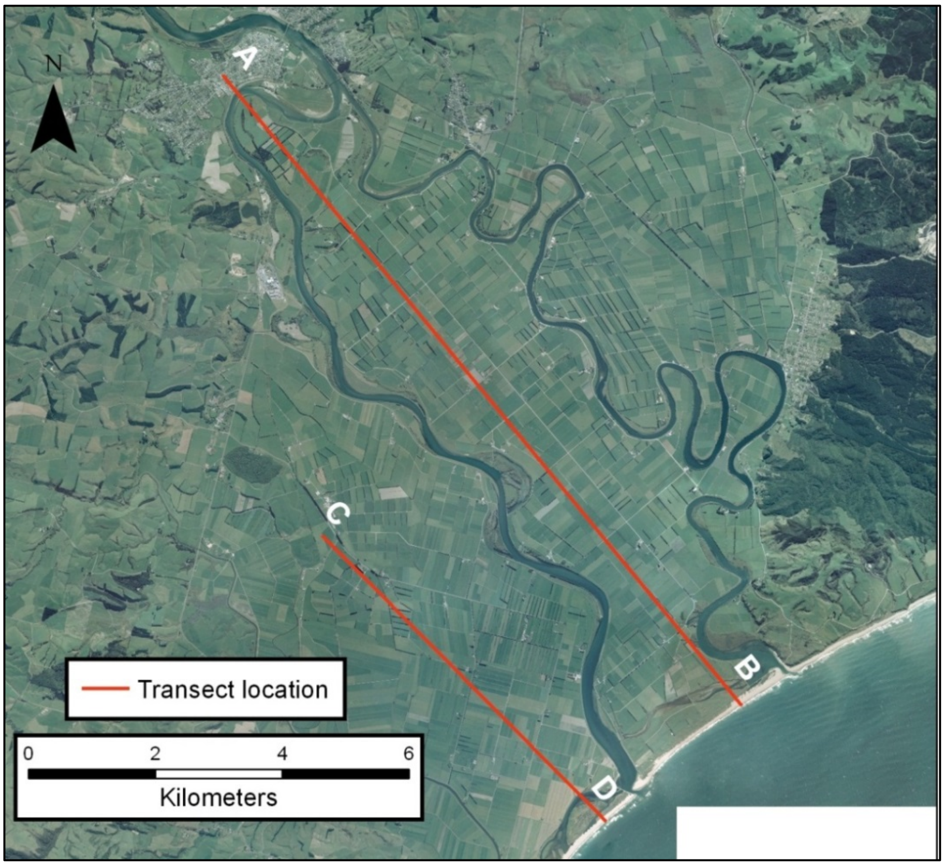


Figure 6.5 Location of Cross-sections A-B and C-D, as shown above.

6.3 Coastal erosion

Background

A series of dunes elevated between 3 and 5 m above msl mark the boundary between the Clutha Delta and Molyneux Bay. As described in Section 3.1, the sand dunes and beaches along Molyneux Bay were formed primarily by the deposition of wind-blown sediment (Goff *et al.* 2003). As a consequence, the dunes are formed of sands and fine gravels that can experience relatively rapid erosion and other morphological change.

Molyneux Bay has been identified as particularly sensitive to the effects of sea-level rise and lowered sediment supply due to the dams on the Clutha River. The lower Clutha Delta is made up of extensive low-lying soft sediment that has been deposited by regular floods on the Clutha River since the last sea level high-stand around 6500 years ago (Bishop & Turnbull, 1996). This land is naturally amenable to high-intensity dairy farming and therefore is of high value to the local economy. In order to ensure protection remains to a high standard in future, the long-term viability of the flood protection assets located nearest the coast must be investigated.

Figure 6.6 Evidence of the sediment accumulation (1 m+ of sand over previously deposited driftwood) and subsequent erosion which can occur on the Molyneux Bay shoreline. Left: looking south from near the Matau Mouth. Right: looking south from near the Koau Mouth. Photos taken September 2012.

Evidence presented at a resource consent hearing (Contact Energy Ltd Resource Consent Hearing 2002) was in disagreement as to the primary cause of the erosion observed at Molyneux Bay. However, it was generally accepted that the presence of the Clyde and Roxburgh Dams on the Clutha River at least partly contributes to coastal erosion due to the trapping of sediment behind the structures. This was recognised in Resource Consent 2001.294, condition 13, which states:
'The consent holder (in this instance Contact Energy Limited) shall contribute 50% of the costs of an Otago Regional Council coastal management programme specifically addressing:

i) *An analysis of historic shoreline positions using appropriate techniques at specific representative coastal sites that may be dependent on Clutha derived sediment.*

ii) *A comprehensive physical coastal monitoring programme at the representative sites covering the near shore transport zone between the limits of the beach foredune system and seaward limit of the near shore sand wedge between Nugget Point and Taieri Mouth.*

A report completed in 2014 detailed the historical morphology of the South Otago coastline between Nugget Point and Chrystalls Beach (ORC, 2014). A range of datasets were used to describe the shape of the shoreline and morphology of near-shore area. Historical and recent aerial photographs were used to map (in a GIS environment) the vegetated extent of the coastal foredune. In 2012 the foredune between Kaka Point and the Clutha Matau Mouth was walked with a GPS to establish a reasonably accurate (±5 m) vegetated extent. This data indicated overall retreat rates of approximately 3.3 m/yr between 1946 and 2012 with the rate increasing toward the end of that period. Accretion was observed at rates ~ 1-2 m/yr at the northern part of the beach between Koau and Matau Mouths, and to the north of the Matau Mouth.

Here a re-survey of the vegetated foredune extent, recorded in March 2016, establishes an updated record of spatial and temporal change of coastal retreat rates. The 2014 report highlighted parts of the coast which experienced heightened rates of retreat for a few years, followed by slowing of retreat or accretion. This resurvey is the best way to establish a clear long-term trend that takes fluctuations in retreat rates into account and is useful for estimating the inland extent of the future shoreline in coming decades.

Figure 6.7 Erosion of vegetated shoreline. Looking north from near Koau Mouth.

Methods

In March 2016 a re-survey of the foredune surveyed in 2012 was undertaken by walking along the coastal extent of the foredune vegetation with a GPS recording continuous position (see Figure 6.7). A desktop-study, mapping the vegetated extent of the coastal dune in 2013 aerial photography to further update the shoreline retreat dataset, has also been completed. Details of data capture and processing for this technique are given in the Coastal Morphology of South Otago report (ORC, 2014). 36 coast-perpendicular beach transects between the south end of the bay and the Koau Mouth of the Clutha, and 27 transects between the Koau and Matau Mouths were constructed, 100 m apart, perpendicular to the shoreline. These were used to measure shoreline retreat in a GIS environment. The datasets from 1946, 1972, 2006, 2012, 2013 and now 2016 were compared by measuring the coast-perpendicular retreat or accretion of the foredune along the transect line for each year's dataset.

Total retreat and accretion values for each transect and each year's data were entered into a spreadsheet and averaged annual rates of retreat calculated. Figure 6.8 presents the total shoreline change from 2006 to 2016 in map and graph form. Average rates of retreat over different time periods are presented in Figures 6.9 and 6.10, with rates averaged for southern and northern sections of each beach shown on Figure 6.8.

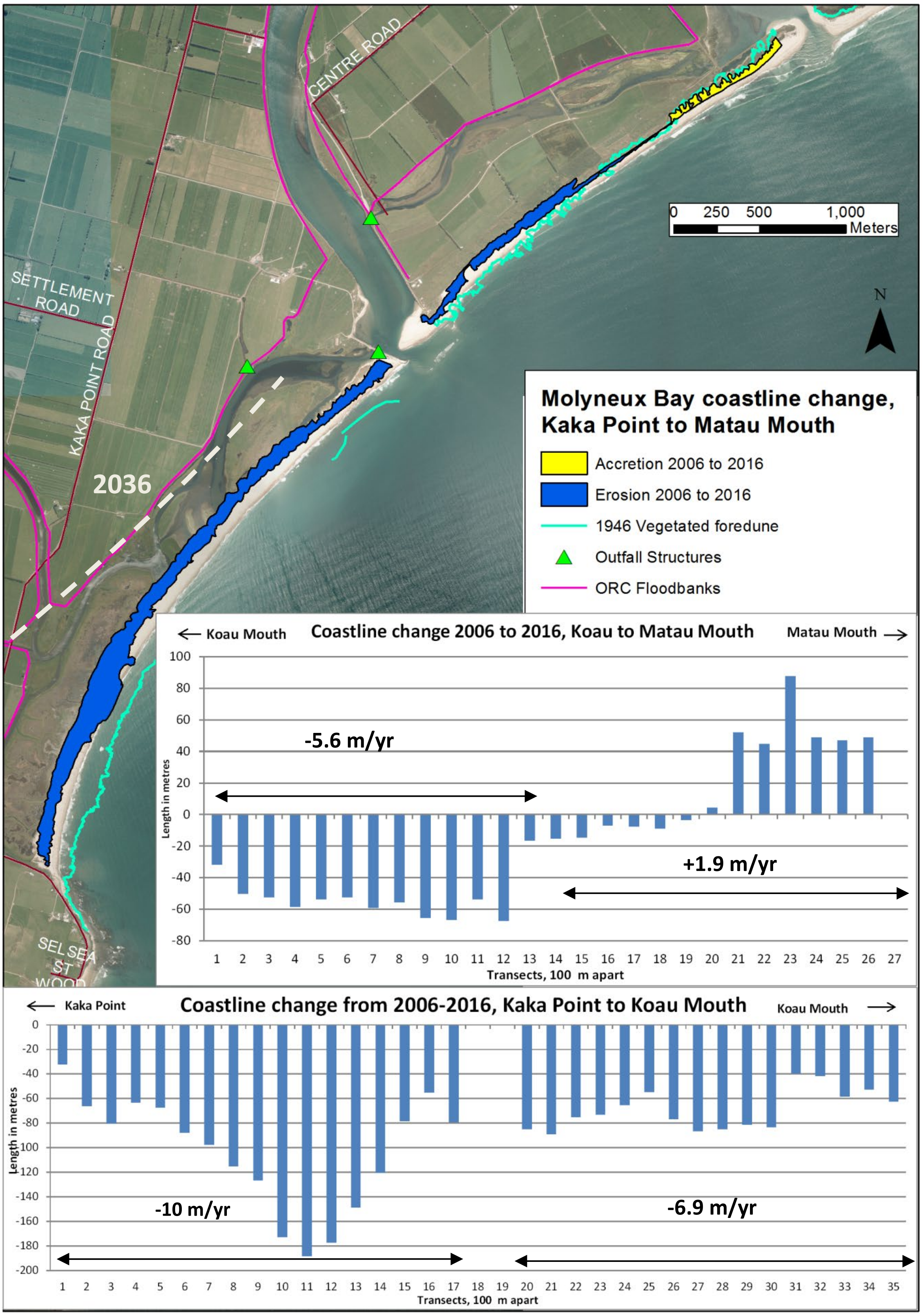


Figure 6.8 Shoreline change for Molyneux Bay from Kaka Point (southern end of map) to Matau Mouth of the Clutha River. Background is 2013 imagery. Dashed white line labelled 2036 is estimated landward extent of shoreline if the present 10-year-average retreat rate continues.

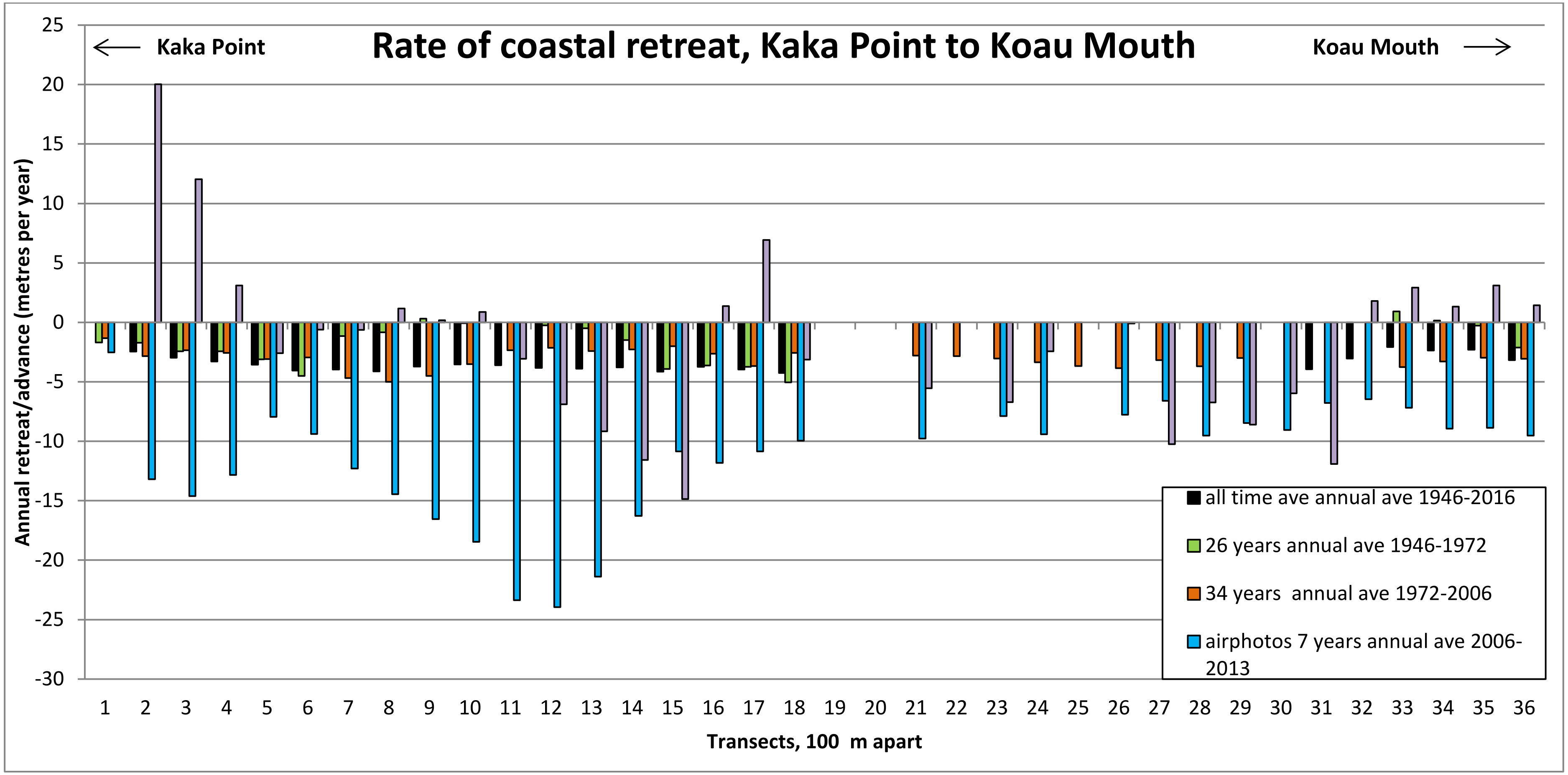


Figure 6.9 Rates of coastal retreat and accretion from Kaka Point to Koau Mouth of the Clutha River. Transects were taken 100 m apart, perpendicular to shoreline.

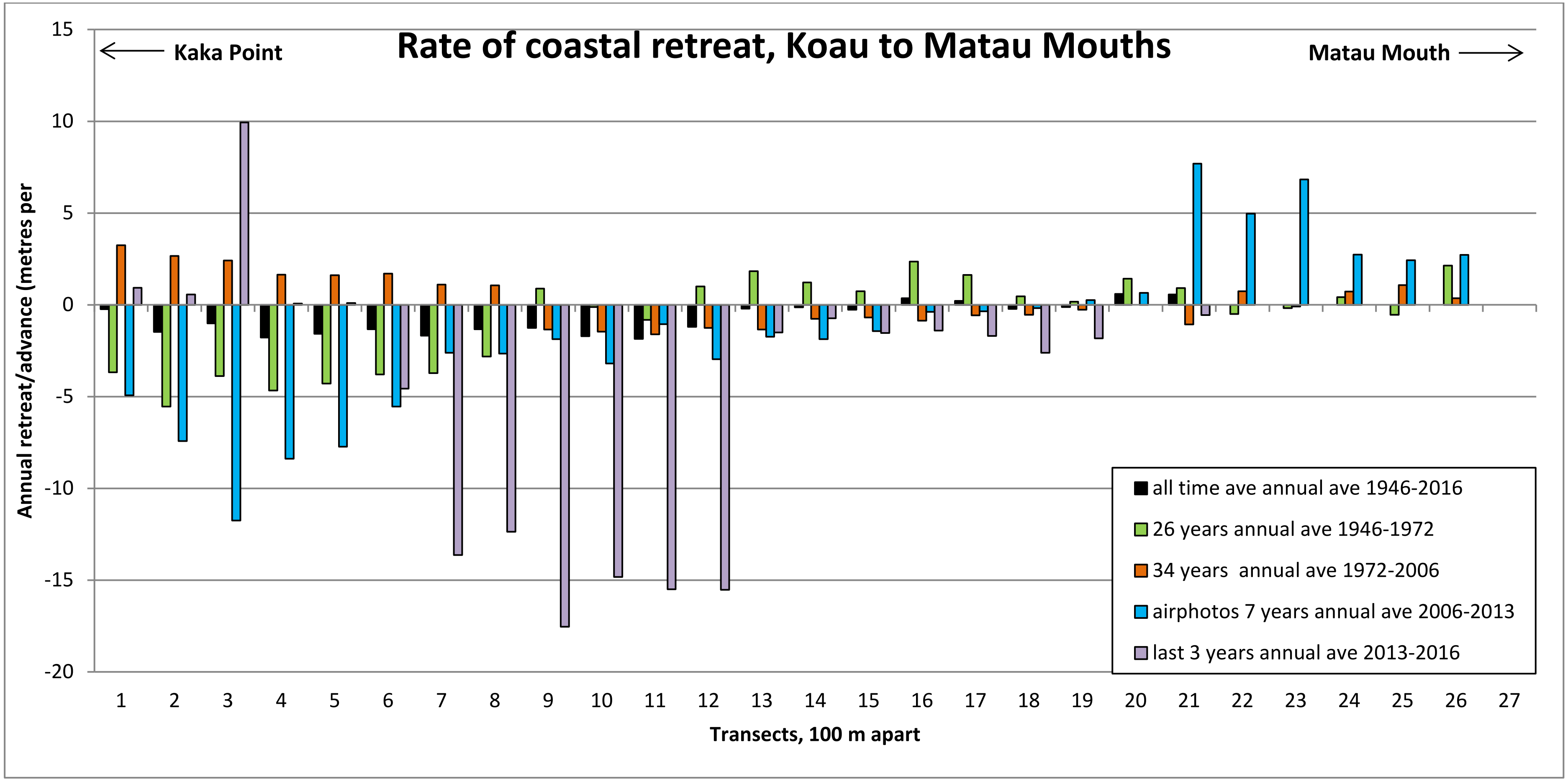


Figure 6.10 Rates of coastal retreat and accretion from Koau Mouth to Matau Mouth of the Clutha River. Transects were taken 100 m apart, perpendicular to shoreline.

Figure 6.11 Landward-advancing foredune at south end of Molyneux Bay. Flax bush has recently been buried by ~0.5 m of sand and now occupies the new high-tide line.

Rates of Shoreline Retreat

Along at least 50% of the surveyed areas, the protective foredune has retreated by between 50 and 150 metres in the past 10 years (see Figure 6.8). The most recent annual rates of retreat range from slight accretion of sand just south of the Matau Mouth, to >20 m per year of erosion in places. These extremely high annual retreat rates can sometimes be attributed to isolated storm events where tens of metres of the dune system are infiltrated in a single storm. For example, the ~1 km section of dune that was eroded between 2013 and 2016 between the Koau and Matau Mouths, creating average retreat rates ~8x the long-term average (see Figure 6.10). Such events should not be ruled out of long-term considerations as they may become more frequent with increasing sea level and storm intensity. This is backed up by the observation that the overall trend of the last 10 years is one of faster shoreline retreat than the average of datasets from 1946 and 1972.

The very soft sand that forms this coastal part of the Lower Clutha Delta is particularly susceptible to erosion, especially as it was part of the bed of the Clutha River until the floods of the 1870s. These unconsolidated sediments are likely to be preferentially eroded by the powerful southerly swell, which strikes the coast first at this point and dissipates to the north along Molyneux Bay (Mutch, 1978). Figure 6.11, a photograph of the coast at the southernmost part of the beach near Kaka Point, shows a flax bush being buried by the inland-advancing dune. The flax bush would have started growing in an estuarine backshore environment a few years before the photo was taken and is indicative of the rapid change taking place in this coastal environment.

The lack of medium-grained sediment reaching the Clutha Mouth since the construction of the Clyde and Roxburgh Dams also creates a relatively sediment-starved environment which is likely to exacerbate the erosion of sand from this stretch of beach (Contact Energy resource consent hearing, 2002).

6.4 Climate change and sea-level rise

The current vulnerability of the Clutha Delta and the Molyneux Bay shoreline to natural hazards is described in earlier sections of this report. In summary, this vulnerability results from the low-lying topography of much of the delta, and the effects of extreme flood and coastal hazard events. These existing hazards are likely to be exacerbated by predicted changes in climate, and sea-level rise. The effects of coastal erosion and inundation are increasingly likely to pose a threat to existing infrastructure and land-use. The effects of predicted increases in rainfall over the west[27] and south of the South Island is more difficult to predict, but may include an increase in the size and frequency of large flood events in the Clutha River/Mata-Au.

The above discussion of the accelerating rate of coastal erosion (section 6.3) highlights the part that increasing sea-level rise is having on the Clutha Delta. As the sea-level rises the land must come into equilibrium by eroding back to a new appropriate shoreline location. As the Clutha Delta has a very shallow fall (e.g. Figures 6.3 and 6.4) this means that a small change in sea level may cause the sea to advance inland by hundreds of metres. Another important concept is that as sea-level rises, smaller more frequent storm tide and flood events will be all that are needed to reach a level where impact occurs (such as inundation or erosion). Events which can have these severe effects will therefore occur more frequently.

Another important contributor to the future 'hazardscape' of the Clutha Delta will be changes in the supply of sediment to the coast. Offshore survey of the sand deposits in Molyneux Bay is scheduled to be updated in 2020/21 (ORC Long Term Plan, 2012-2022). In addition, sea level has been continuously monitored at Green Island since 2002. Information such as this will help to understand how a wide range of physical processes (including climate change, sea-level rise, and sediment supply) are interacting to influence the coastal hazards of the Molyneux Bay shoreline and the lower Clutha Delta.

During the 20th century, the average rate of sea-level rise recorded at New Zealand's major ports was approximately 1.7 mm/yr, similar to the global rate of rise.[28;29] Although the Green Island sea level monitoring site has a short record for deriving long-term trends, the data is of high quality, with a frequent (1 minute) recording interval, and an instrument accuracy of ± 1 mm. The average level of the sea at Green Island has increased at a reasonably consistent rate of 3.3 mm/yr since 2002. This is consistent with the global average rate of sea-level rise observed over more than two decades since 1993,[30] although somewhat lower than the

[27] This includes the upper reaches of the Clutha catchment

[28] Bell, R., Goring, D. & de Lange, W. 2001 Advances in understanding sea level variability around New Zealand. In: *Coastal Engineering 2000,* Billy L Edge (ed), *Vol 2: 1490-1500, Proceedings of 27th International Conference on Coastal Engineering, Sydney,* American Society of Civil Engineers, New York.

[29] There is some local variation in the rate of relative sea-level rise (with respect to the land) across New Zealand. The lower rate of rise during the 20th century (0.94 mm/yr) recorded at Dunedin is thought to be due to a lack of stability in the reclamation and wharf area where the tide gauge was situated.

[30] Church, J. & Whyte, N. *Sea-level rise from the Late 19th to the Early 21st Century.* Surveys in Geophysics, 2011, DOI 10.1007/s10712-011-9119-1.

average rate for New Zealand since 1993 of between 4–5 mm/yr.[31] However, a number of factors will influence regional rates of rise over the medium (annual – decadal) term, including El Niño / La Niña cycles, and the Interdecadal Pacific Oscillation (IPO).[32] A much longer record from Green Island is therefore required before local long-term trends of sea-level rise and acceleration rates can be determined.

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report[33] projects that global sea-level rise by 2100 will likely be in the range of 0.26 to 0.98 m (relative to the 1986-2005 period), with a caveat that a rise of a further several decimetres could occur if ice-sheet collapse accelerates. The most recently available guidance to local government in New Zealand regarding sea-level rise over the next 100 years (in line with the timeframe in the NZ Coastal Policy Statement) is from a NIWA guidance document *Pathways to Change* (Britton et al., 2011)[34]. This advises that a 1.0 m rise by 2115 relative to 1990 mean sea level should be considered for sea-level rise for New Zealand regions at this stage. This is equivalent to the 0.8 m rise by the 2090s provided as one of the rises to be considered within a risk-assessment framework in the Ministry for the Environment 2008 guidance manual for local government[35] and in line with their guidance that sea-level rise will continue beyond the turn of the century at a rate of 10 mm/yr.

Figure 6.12 shows the vulnerability of the Clutha Delta to sea level. Specifically, the figure shows the extent of inundation that would occur if the flood banks next to the Molyneux Bay shoreline did not exist, or were ineffective (e.g., if they failed due to significant ground shaking caused by a major earthquake).[36] The scenarios shown are:

1. The extent of inundation if the water level on the Clutha Delta was 0.5 m above msl (i.e. the level of the Pacific Ocean at Green Island at the current lowest high tide) (blue)
2. The extent of inundation if the water level on the Clutha Delta was 1 m above msl (as for 1, but with 0.5 m of sea-level rise) (green)
3. The extent of inundation if the water level on the Clutha Delta was 1.5 m above msl (as for 1, but with 1 m of sea-level rise) (yellow).

[31] R. Bell, NIWA. Pers.comm, June 2014.
[32] Hannah, J. and Bell, R. 2012. *Regional sea level trends in New Zealand.* Journal of Geophysical Research, Vol 117.
[33] ibid.
[34] Britton, R.; Dahm, J.; Rouse, H.; Bell, R.; Blackett, P. (2011). Coastal adaptation to climate change: Pathways to change. Externally peer-reviewed report prepared as part of the Coastal adaptation to climate change, NIWA publication. 106 p. http://www.niwa.co.nz/sites/default/files/pathways_to_change_nov2011.pdf
[35] MfE, 2009. *Preparing for coastal change.* A guide for local government in New Zealand
[36] Seismic performance and foundation piping risks for the flood banks of the Clutha Delta are discussed in Chapter 5)

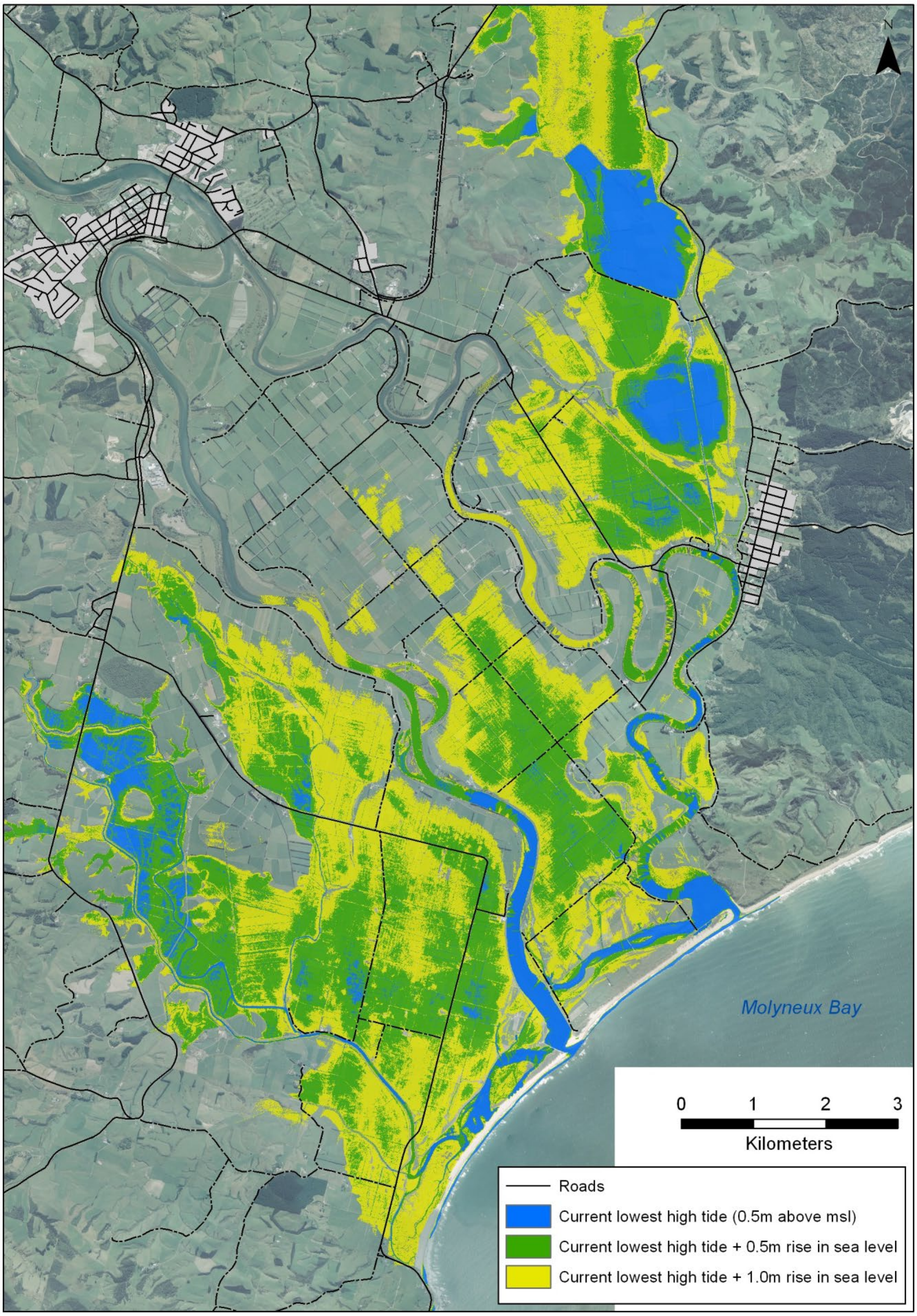


Figure 6.12 Potential landward extent of inundation during a 'flood banks down' scenario without the additional protection of sand dunes in Molyneux Bay.

6.5 Assets, infrastructure and land use on the Clutha Delta

Together, the floodbanks of the Lower Clutha Flood Protection and Drainage Scheme and the sand dunes of Molyneux Bay form a barrier between elevated sea and river levels and the surrounding landscape. As outlined in Chapter 2, a range of infrastructure and other assets are located on the Clutha Delta. Although it is primarily rural land, approximately 2400 people live in this area. The provision of roads, electricity and water utilities in this area represents a significant financial investment by utility providers. The Otago Lifelines Study (2014) provides additional discussion of these matters. As described above, a residual risk remains for residents and users of the delta, where there is a reliance on natural and man-made features for protection, should the integrity or performance of those features be compromised in the future.

Figures 6.9 and 6.10 show how the rate of shoreline retreat has generally increased over time, with the fastest rates and fastest increases all occurring at the southern end of the each surveyed beach. These are here identified as particularly susceptible to erosion, which, if it continued, would put flood protection assets in danger within coming decades. For example, flood banks south of the Koau Mouth, in the vicinity of the Puerua River, are only ~300 m from the current vegetated foredune. As the beach erodes and dune advances inland, the sand of the dune will envelop the flood banks with waves from storm events reaching over the top of the dune and into the area beyond the floodbank. Retreat rates in excess of 20 m/yr are observed in isolated areas where significant storm events have repeatedly infiltrated through the dune into the lagoon in recent years.

Based on an average retreat rate of 10 m/yr for southern Molyneux Bay, the flood banks in the Paratai area could be under threat of coastal erosion within 30 years. It is likely that parts of the flood protection and drainage scheme would be under threat sooner than this when climate-change effects of raised sea level and increasing severity and frequency of storm and extreme rainfall events is considered.

Projections provided by the IPCC are that global mean sea level will increase by between 0.26 and 0.82m by the end of the 21st century, compared with 1986-2005. The efficiency of pump stations at lowest elevation will decrease in the coming decades as sea levels and associated groundwater levels rise in relation to the land which the drains, outfall structures and pump stations are designed to protect from flooding. Figure 6.13 shows a map of the Lower Clutha Delta with areas of ground below 25 cm indicated in dark blue, and ground below 0.5 m in light blue. Much of this area could require continuous pumping in order to remain dry by approximately the 2050s, even in low-river conditions. This is due to the hydraulic fall of the water table from groundwater to sea- and river-level. Operation of the pumps to effectively drain the area would be required more frequently and for less severe events as sea-level rises by an expected ~20 cm in the next 3-4 decades (Figure 6.14).

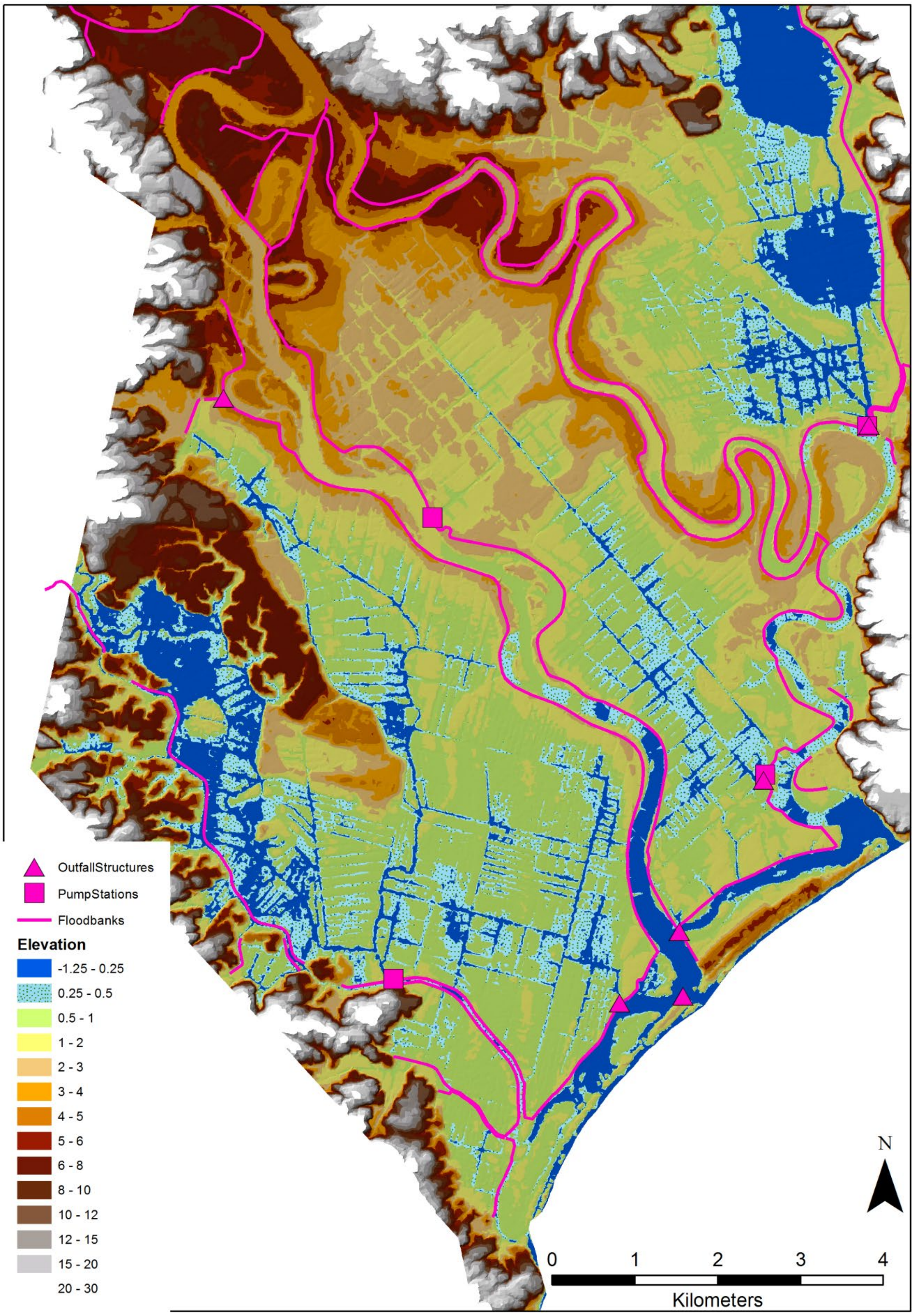


Figure 6.13. Elevation of land on the Clutha Delta. Land expected to be at risk of groundwater ponding as sea level rises by ~20 cm in the coming decades are highlighted in dark blue (<25 cm above MSL), with light blue showing areas likely to be similarly at risk (<50 cm above MSL). The southernmost outfall structures will also be negatively impacted as the hydraulic base level changes with projected sea-level rise (see Figure 6.14).

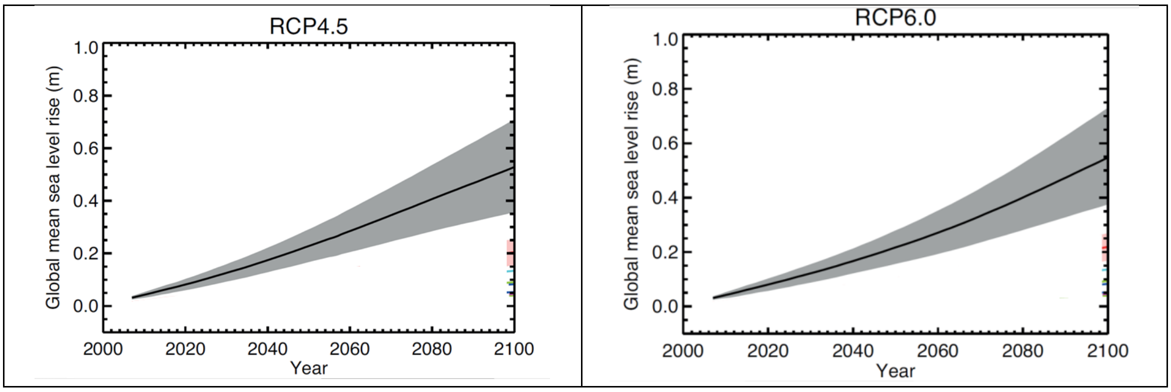


Figure 6.14 Projections of global mean sea level rise, relative to 1986-2005, for IPCC mid-range scenarios (RCP 4.5 and 6.0). The grey band represents the range within which actual sea-level is predicted to increase, under each scenario.

Drainage to the Paretai catchment is achieved using a combination of pumping and gravity outfalls. There are five gravity outfalls; adjacent to the Paretai pump station, into the Puerua off the end of Settlement Road, into the Puerua beside Kaka Point Road, into the Puerua estuary, and into the Koau at the end of Factory Road. Predicted increase in mean water levels will significantly reduce the viability of gravity drainage to the Paretai catchment. This along with increased seepage will result in increased pumping and longer duration to dewater after a rain event. This effect is noted but not quantified in this report.

6.6 Conclusions

The low lying nature of the Lower Clutha Delta will provide limited topographical resistance to inundation from the sea or the river. For the most part, those areas with the greatest combined exposure to coastal hazards are largely undeveloped and used for agricultural purposes. However, ORC infrastructure such as the coastal flood-banks and proposed Paretai outfall structure are becoming increasingly exposed to storm events as the coastline retreats. The Koau Mouth training line is also under threat as it becomes more exposed to storm swells on the north and south sides.

If the Molyneux Bay shoreline continues to retreat, there will be a number of implications for the Lower Clutha Flood Protection and Drainage Scheme and other assets, including reduced drainage capacity and potential damage to floodbanks and roads (ORC, 2014). The hazard associated with elevated sea level (storm surge) and tsunami events for low-lying areas of the Clutha Delta is likely to increase if shoreline erosion continues, as the buffer between the open ocean and the floodbanks becomes smaller. In addition, sea-level has been continuously monitored at Green Island since 2002. Information such as this will help to understand how a wide range of physical processes (including climate change, sea-level rise, and sediment supply) are interacting to influence the coastal hazards of the Molyneux Bay shoreline and the lower Clutha Delta.

The combination of these factors, the expected retreat of the coastline inland by several hundred metres, and the expected increase in severe weather events (including storm surges and rainfall events) over the coming decades mean that the viability of parts of the Lower Clutha Flood Protection and Drainage Scheme will likely be under threat by the 2030s.

Continued monitoring of sea-level, coastal retreat and accretion is suggested, as well as monitoring of groundwater levels on the lower Delta in order to establish the efficiency of land drainage systems as sea-level rises.

7. Conclusion

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

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

Land use activities on the Lower Clutha Delta therefore need to give careful consideration to the notion of residual risk to ensure that activities are compatible with the Lower Clutha Delta's hazard exposure. The intention of this report is to inform land use activities and other risk-reduction initiatives.

8. Glossary

Accretion: The growth or gradual increase of additional layers of sediment.

***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.*

Bifurcation: Where a river separates into or more parts which continue to flow downstream.

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.

Gravity drainage:

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.

Salt Water Wedge: The intrusion of salt water into freshwater.

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.

Stoss: Upward or windward side of a dune.

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.

9. References

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Appendices

Appendix 1 – Geological time-scale

GEOLOGIC TIME SCALE					
Time Units of the Geologic Time Scale					Development of Plants and Animals
Eon	**Era**	**Period**	**Epoch**		
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Earliest *Homo sapiens*
			Pleistocene	1.6	
		Tertiary	Pliocene	5.3	Earliest hominids
			Miocene	23.8	
			Oligocene	33.7	"Age of Mammals"
			Eocene	55	
			Palaeocene	65	Extinction of dinosaurs and many other species
	Mesozoic	Cretaceous	"Age of Reptiles"	145	First flowering plants
		Jurassic		208	First birds Dinosaurs dominant
		Triassic		248	First mammals
	Palaeozoic	Permian	"Age of Amphibians"	286	Extinction of trilobites and many other marine animals
		Carboniferous: Pennsylvanian		320	First reptiles Large coal swamps
		Carboniferous: Mississippian		360	Amphibians abundant
		Devonian	"Age of Fishes"	410	First amphibians First insect fossils
		Silurian		438	Fishes dominant
		Ordovician	"Age of Invertebrates"	505	First land plants First fishes
		Cambrian		545	Trilobites dominant First organisms with shells
		Vendian	"Soft-bodied faunas"	650	Abundant Ediacaran faunas
Proterozoic	2500	Collectively called Precambrian comprises about 87% of the geological time scale			First multicelled organisms
Archean	3800				First one-celled organisms Age of oldest rocks
Hadean	4600 Ma				Origin of the earth

Appendix 2 – 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.