Geomorphology of the Wairau Plains

Implications for floodplain management planning

L. R. Basher, I. H. Lynn and I. E. Whitehouse

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L. R. Basher

I. H. Lynn

Manaaki Whenua - Landcare Research
Private Bag 69, Lincoln

I. E. Whitehouse

Manaaki Whenua - Landcare Research
Private Bag 11-052, Palmerston North

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Cover:
The lower part of the Wairau Plains, with Blenheim on the far left. The braided Wairau River follows the northern edge of the Plains before swinging to the south below the bridge to flow in a meandering channel inland of the gravel beach ridges towards the sea. The man-made Wairau Diversion channel cuts directly through the beach ridges immediately below the bridge. Note the intensity of land use and the stopbank system adjacent to the river.

PHOTO: LLOYD HOMER, INSTITUTE OF GEOLOGICAL AND NUCLEAR SCIENCES

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Summary

Development of methods for understanding past evolution and for predicting likely future changes to major river floodplains is an integral part of the development of effective long-term plans for floodplain management. It offers the opportunity to design flood hazard mitigation procedures that recognise the geomorphic factors influencing medium- to long-term river behaviour. Likely future changes to the Wairau River floodplain that will be important to floodplain management (aggradation, channel avulsion, coastal progradation) are assessed from an understanding of the past and present behaviour of the river, coastal dynamics and tectonism. Synthesis of the nature and causes of late Holocene evolution of the floodplain, as determined from near-surface stratigraphy, geomorphology, soil pattern and radiocarbon dating, is the basis for this assessment.

The Plains are predominantly flat to gently undulating floodplains and low terraces of the Wairau River, gently sloping fans formed by south-bank Wairau tributaries, with smaller areas of dissected older terraces, sand dunes and gravel beach ridges. The present topography reflects the interaction between alluvial, coastal and tectonic processes during the Holocene. Detailed soil mapping for part of the Plains provides a good correlation tool for estimating the age of the floodplain and terrace surfaces and hence the time since last major flooding. Radiocarbon dates have been obtained from below many of the soils and from the coastal deposits. Four age groups of soils are recognised on the Wairau Plains:

- soils of the unprotected floodplains and river channels (flooded in historical times and unprotected from current flooding);
- soils of the protected and higher floodplains (flooded in historical times but now protected by channel protection works; radiocarbon dates suggest ages <250 years BP);
- soils of the young terraces (formed in post-glacial alluvium; radiocarbon dates suggest ages between 300 and 3500 years BP);
- soils of the undissected higher terraces (formed on late Pleistocene Speargrass Formation alluvium, although radiocarbon dates suggest a considerably younger age of <4000 years BP for the near-surface deposits).

Dates obtained from the coastal deposits are all less than 2000 years BP.

The major factors determining floodplain development have been changes of river gradient in response to sea level variation and tectonism, sediment source and sediment load variation, the passage of gravel waves down the Wairau, and coastal progradation. Future evolution of the Wairau Plains will be determined by the effect of climate change and sea level rise, continuing aggradation of both gravel and sand/silt, the effect of earthquakes, and the possibility of stopbank failure or overtopping. It is predicted that:

1. Gravel waves will continue to migrate down the river. If these are large enough they may overwhelm the channel and lead to reduced flood freeboard, and ultimately to channel avulsion, unless enough gravel is extracted.
2. Aggradation and sediment transport rates will be at least as high as over the last 100 years. Gravel aggradation may well be significantly higher if the river is able to transport its theoretical bed load. Gravel deposition will be restricted to within the vicinity of the main channel as dispersing flood flows from flood breakouts rapidly lose velocity. Fine sediments will be deposited at the margins of such flows and continue to accumulate in topographic lows and pondage areas, especially behind obstructions such as the Pukaka Stream embankment and the lower Wairau River stopbanks. Aggradation of sand and silt may increase

in the lower reaches below Tuamarina as sea level rises. The net effect will be reduced flood freeboard, and ultimately channel avulsion, unless enough gravel is extracted.

3. The Opawa overflow from the vicinity of Conders Bend will continue to serve as a major distributary of Wairau floodwaters and sediment. Sites of contemporary channel aggradation, such as those currently occurring between Wratts and Jefferies Roads, and between Hillocks and Cravens Roads, may also cause river avulsion by reducing waterway capacity and threatening stopbank stability. These are potential sites for development of distributary channels.
4. There will be an increased frequency of flooding below Tuamarina and adjacent low-lying areas due to the river gradient being reduced by coastal progradation and a possible rise in sea level. By AD 2050, sea level may be 0.5 m above its present level.
5. Strong northwards longshore drift will continue to maintain coastal progradation, although the rate may be reduced as a result of sea level rise. The bar will stay much in the same position as it is now, although there will be increasing instability of the river mouth and training wall as a result of sea level rise and increased tidal outflow.
6. Long-term subsidence will be greatest for the area of fine-grained wet sediments dominant in the southeastern part of the Wairau Plains.
7. Development of the Wairau Diversion to handle a greater proportion of the flood flows will reduce flood levels and potential ponding in the old course below Tuamarina, provided that upstream floodflows are contained within the main channel.
8. In the absence of a solution to longer-term problems arising from gravel aggradation, continuing progradation of the coastline and lengthening of the lower river channel, it is inevitable that the river will attempt to adopt a new course. It is within engineering capacity to control the location of that course.

Introduction

The highly productive and developed Wairau Plains were formed by sedimentation from the Wairau River and its tributaries. Blenheim, a town with a population of 23 500, is located on the south side of the Wairau Plains where the floodwaters from a number of rivers converge into the lower Opawa River. Flooding of the Plains and Blenheim was frequent until river control works effectively contained most floodwaters into stopbanked channels. A series of river control works has been carried out on the Wairau and its tributaries over the past 130 years, including the Wairau Valley Scheme, a comprehensive source-to-sea catchment works programme begun in 1960. The main effect of these works has been to divert floodwaters away from Blenheim and confine them to defined courses.

Suitable climate, soils and plentiful groundwater reserves have encouraged intensive horticultural and agricultural development and settlement of the Plains. Much of the area is at risk from flooding by the Wairau River and its tributaries should stopbanks be breached or overtopped, as happened twice in 1983 when it was partly inundated by large floods.

The Wairau River has some of the largest floods in New Zealand and is the most powerful river with a comprehensive river control scheme (Williman 1992). Despite this flood control scheme, the Wairau River and its tributaries still pose a substantial long-term flood risk to Blenheim and the intensively developed Plains.

There is a large investment in river control structures to protect Blenheim and the Plains from flooding and sedimentation. These structures must be regarded as long-term, with maintenance and modification but no major redesign likely in the next 100 years or more. Present structures are based primarily on historical records of river flow which may not include the rare (>100 year) large flood events that cause much damage to property and services. A geomorphic perspective provides qualitative data on the impact of extreme floods not recorded in the short historical record of river flow. Floodplain management should be based on a comprehensive understanding of the physical situation controlling flooding and sedimentation, and take account of long-term changes that affect floodplains (e.g. aggradation, river avulsion and sea level change) and their causes.

Thus an appreciation of the 'geomorphic past and future' of the Wairau Plains is relevant to present decisions regarding the maintenance and modification of the control structures and to the management of the flood hazard.

Predicting the geomorphic future of the Wairau Plains

To predict the future geomorphic development of the Plains it is necessary to understand:

- the nature and rate of processes that naturally formed and modified them;
- the factors controlling these processes;
- the human-induced changes in the nature and/or rate of these processes (e.g. those resulting from river control measures and gravel extraction); and
- the likely effect of any future changes to the factors controlling the processes (e.g. sea level rise, climate change, major earthquake).

This report presents background information on the Holocene history of the Plains and discusses the age of surface features as interpreted from radiocarbon dates, soil development, soil stratigraphy and correlation. On floodplains and river terraces, surface age is an indicator of flood frequency. An old surface age implies that flooding has not occurred for considerable time, otherwise the surface would be veneered with younger alluvium. Where rivers are entrenched, older surfaces are topographically higher than younger surfaces. However, where rivers are actively aggrading rather than entrenched, younger surfaces may bury older surfaces and be topographically higher. Soil development in alluvium can be used as an indication of surface age.

The geomorphology of alluvial and coastal landforms, subsurface stratigraphy, soil development and distribution, and radiocarbon dates from near-surface deposits are the bases for understanding the past evolution of the Wairau Plains and interpreting the major factors influencing floodplain evolution. These factors, in combination with an understanding of present 'controlled' river behaviour and an analysis of likely future events (such as climate change, sea level rise, earthquakes), form the basis for predicting the Plains' geomorphic future.

Physical description of Wairau River and floodplain

The river

The Wairau River drains a 3825 km^2 catchment comprising the steep mountain land of the south-bank tributaries of the Wye, Waihopai and Branch Rivers, the St Arnaud Range in the headwaters, and the north-bank tributaries of the Richmond Range (Fig. 1).

It is a large, steep, braided gravel-bed river that for much of its course flows in a narrow valley aligned along a fault angle depression between adjacent mountain ranges. Below the confluence with the Waihopai River, 26 km from the coast, is a triangular-shaped plain of approximately 170 km^2 formed by post-glacial and Last Glaciation alluvial and coastal deposits (Figs 1, 2). At the coast this plain is 14 km wide, narrowing progressively to some 4 km at the Waihopai River junction. Most of it is less than 30 m above sea level, with the lower Wairau/Dillons Point area only 1–1.5 m above sea level.

For most of its course across the Plains the river flows along the northern margin in a wide, braided gravel-bed channel. Before diversion, the river changed direction and character about 4 km from the coast (near Tuamarina) to flow to the southeast in a very gentle, narrow, meandering, sand/silt channel behind a series of gravel beach ridges that prevented a more direct exit to the sea.

The river cuts through these ridges near the southern side of the Wairau Plains to emerge at the coast through a narrow bar at the outlet to an extensive lagoon system. From Tuamarina the river now has an alternative direct course to the sea with part of the flow diverted down the Wairau Diversion, constructed as part of the Wairau Valley Scheme. Below Tuamarina the Wairau River is tidal, the river gradient is very low, and the bottoms of the deepest pools are below sea level.

The river gradient flattens progressively from the Waihopai to the sea (Fig. 3) and is almost flat from Tuamarina to the sea. Above Tuamarina the river gradient steepens from 0.0019 (1:526) to about 0.0042 (1:238) at the Waihopai River junction. Below Tuamarina the gradient is 0.000068 (1:14 612) down the Wairau Diversion and 0.000027 (1:37 645) down the channel to the Wairau Bar. The longitudinal profile is slightly irregular, with three areas upstream of Tuamarina where the river gradient steepens sharply as a result of deposition of sediment (Noell and Williman 1992; Fig. 3 and page 15).

Floodplain geomorphology

The Wairau Plains are an extensive alluvial plain formed by the Wairau River and its southern tributaries. Brown (1981a) divides this plain into a series of deposits that have distinctive topographic expression (Fig. 2):

- The Wairau fan. The upper part of the Plains comprises flat to undulating terraces and floodplains of both the Wairau and Opawa Rivers underlain by Holocene (Rapaura Formation) and Otiran (Speargrass Formation) gravels. West of Renwick, the Speargrass Formation surface forms a high terrace with a distinct scarp. The height of this scarp decreases progressively downstream, and the Speargrass Formation surface merges with the Holocene terrace surfaces east of Renwick adjacent to the Omaka River. The Holocene deposits form an extensive terrace surface and floodplain about 2–3 m lower and separated by a subdued scarp. Flood overflow channels are present, notably that leading from Conders Bend to the Opawa River system.

- Swamp deposits. The lower part of the Plains consist of flat to undulating terraces and floodplains of both the Wairau and Opawa Rivers underlain by Holocene sand and silt deposits.

- Beach deposits. Holocene beach deposits form a series of undulating gravel ridges near the coast, with remnants of sand dunes further inland.

- Lagoon deposits include a flat, swampy area on the southeast margin of the Plains underlain by alluvial silt and clay, the extensive mudflats and open water of the Wairau Lagoons, and the Boulder Bank that bounds the lagoon system.

- The Waihopai, Omaka, Fairhall and Taylor fans. Gently sloping radial fans underlain by gravel, that merge with the Holocene and Speargrass Formation surfaces of the Wairau fan

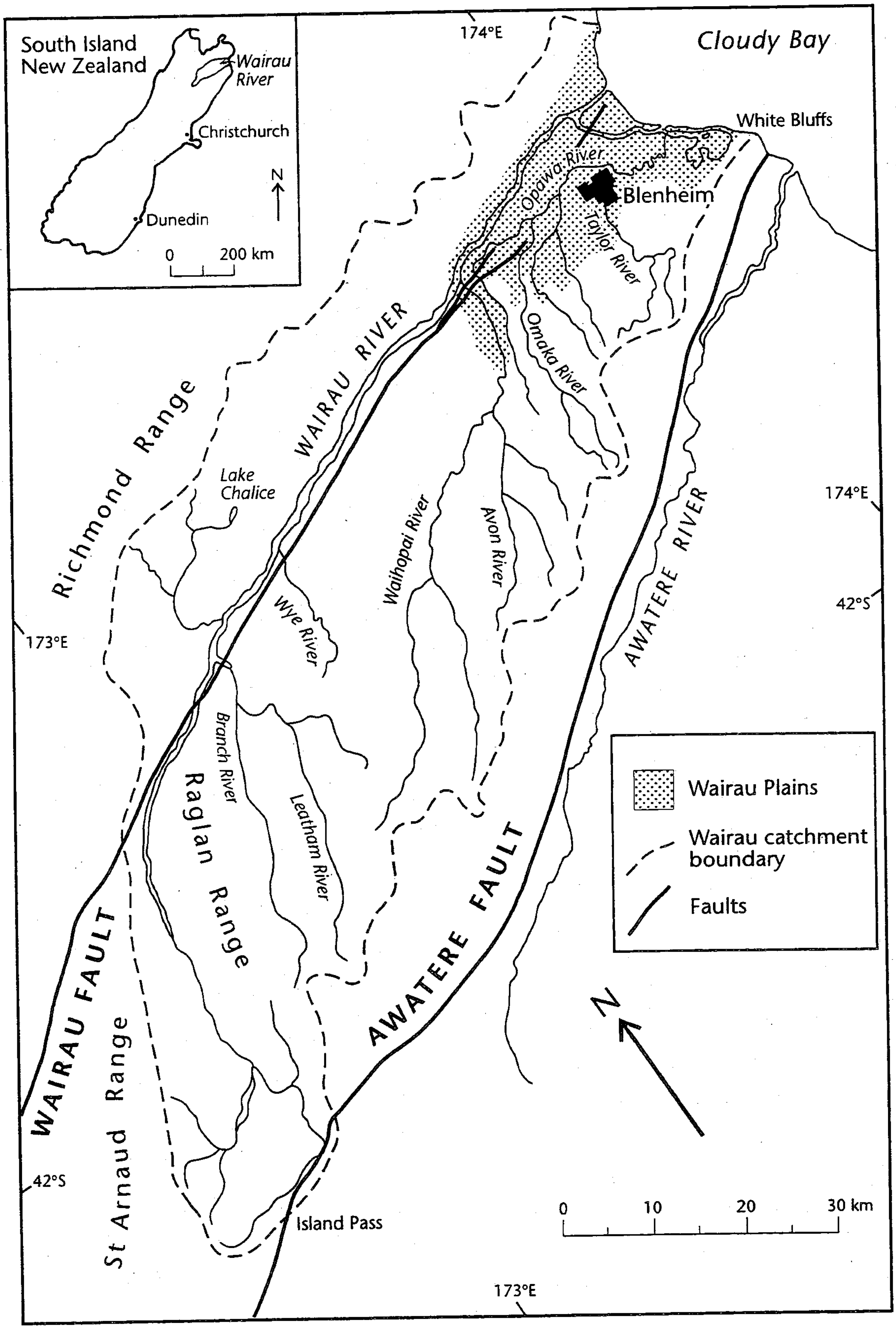

Figure 1. *Wairau catchment, showing localities mentioned in text.*

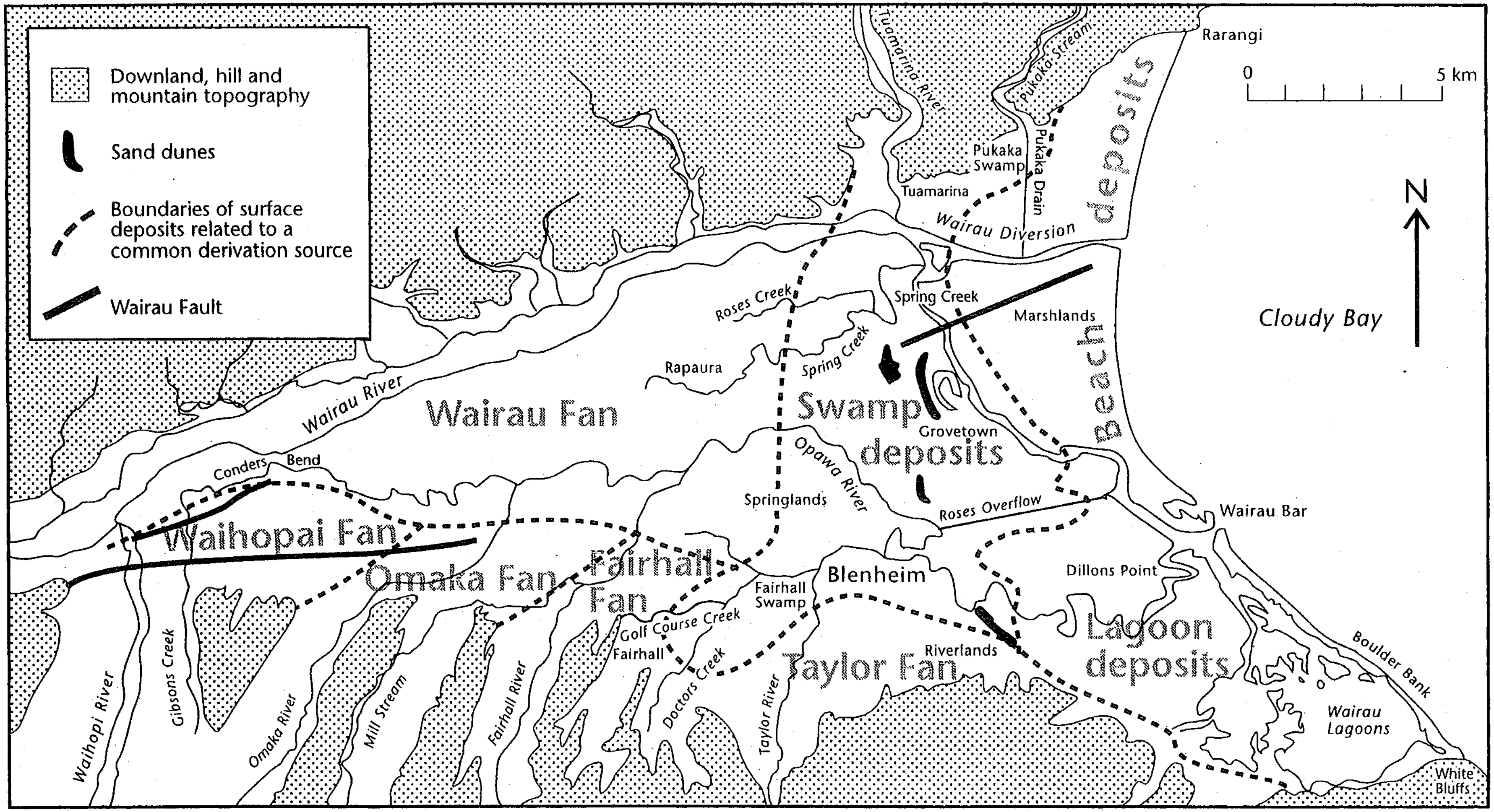

Figure 2. *Wairau Plains, showing localities mentioned in text, and geomorphology.*

and swamp deposits, form the southern margin of the plain from the Waihopai junction to Blenheim.

Vegetation history

Most of the lower Wairau Plains and the north-bank valleys were once a vast wetland. Blenheim was originally named Beavertown because mid-nineteenth century European surveyors had to live on logs in the swamps. Grovetown (originally named Big Bush) was the site of a forest of about 40 ha and was an 'island' in the swamp (Brown 1981a).

Other forests were at Tuamarina and adjacent to the Pukaka swamp on the north side of what is now the Wairau Diversion.

The pre-human vegetation of the Wairau Plains has been summarised by Rae and Tozer (1990). They suggest that the lower Plains, inland to about Renwick and extending into both the north-bank and south-bank valley floors, were predominantly flax, raupo, toitoi and cabbage tree swampland. The swampland on the Plains contained patches of swamp forest (kahikatea, pukatea and swamp maire) and on the drier soils of the upper Plains there would have been a more open, partly deciduous forest. The brackish Wairau lagoon system would have been much as it is today, characterised by salt-marsh and eel grass, and there would have been a narrow zone of coastal forest.

Data collected in this study (Tables 2–4, pages 24–28) suggest that forest was more widespread than suggested by Rae and Tozer (1990). Podocarps (totara, kahikatea, matai, rimu) were identified and dated at a wide variety of sites in the Fairhall, Spring Creek, Grovetown, and Rapaura areas on the deep, fine-textured alluvial soils (i.e. the swamp deposits of Fig. 2). Unidentified (but probably podocarp) wood was abundant in the former Fairhall swamp. Buried forests were observed over wide areas, suggesting an extensive cover of podocarp forest on the fine-textured alluvial soils.

Charcoal was commonly found with much of this buried wood, indicating that substantial forest destruction was achieved through fire, with burial occurring in floods following fire. Many of the sites where charcoal is associated with dated wood are 500–1000 years in age (Table 2, pages 24–26), indicative of fires during the Polynesian era of occupation, as recorded in many other parts of the eastern South Island (McGlone 1983). On the gravelly, very droughty coastal deposits manuka/kanuka and totara were

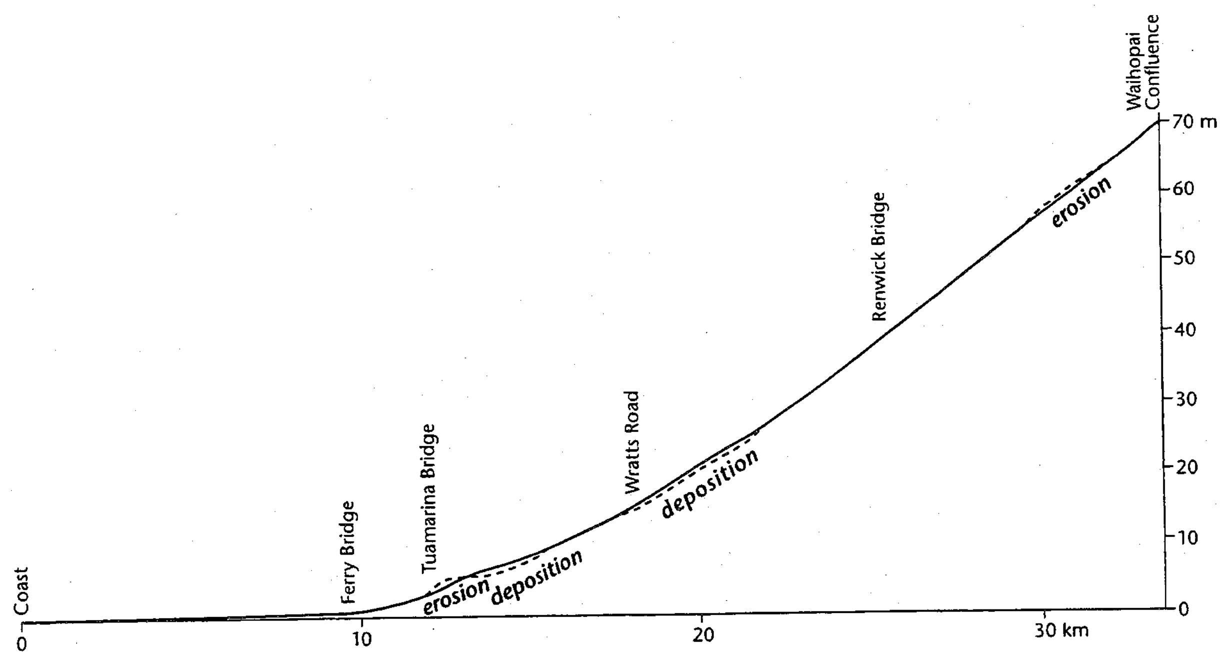

Figure 3. Longitudinal profile of Wairau River, showing sites of erosion and deposition between 1969 and 1991 (solid line shows bed level in 1991, dashed line shows bed level in 1969).

identified, and these may also have covered much of the stony soils on the Wairau fan.

Tectonic setting

The Wairau River valley is aligned along the Wairau Fault, the northernmost branch of the Alpine Fault (Fig. 1). An active trace extends almost without interruption from Tophouse in the upper catchment to the coast at Cloudy Bay. The displacement on the fault is predominantly horizontal (dextral) with a minor component of uplift (Lensen 1976). The upthrown side varies repeatedly along the Wairau Fault, associated with changes in strike of the fault trace. It has also varied through time. Northwest tilting of the Awatere block south of the Wairau Fault accounts for the course of the Wairau River along the northern edge of the Wairau Valley.

East of Landsdowne, 19 km upstream of the Waihopai junction, the Wairau Fault splays into two traces that progressively diverge until they are 2 km apart near Renwick (Figs 1, 2). The northern trace terminates at the Otiran terrace scarp northwest of Renwick, and the southern trace terminates on the Otiran terrace surface. Horizontal displacements are up to 40 m dextrally, and vertical displacements range from 0.5 to 5 m. From about 4 km eastnortheast of Renwick, a low trace, on the line of the southern trace, extends to within 0.5 km of the coast at Cloudy Bay (Grapes and Wellman 1986).

The ground on the northwest side of this latter trace is upthrown 2 m and there is 10 m dextral movement. The age of these fault scarps is not known, although it is at least 800 years since significant movement occurred near the coast (Grapes and Wellman 1986). At Branch River, terraces displaced by the Wairau Fault indicate that faulting has occurred about every 900 years (Lensen 1968, 1976).

Significant earthquake activity in the region is more frequent. Smith and Berryman (1986) estimate that, for the seismic region including the Wairau Plains, a Mercalli magnitude (MM) VIII (approximately Richter 6.2) earthquake has a probability of 0.02 of occurring in any one year and a MM IX earthquake (approx. 6.9) a probability of 0.005.

There is debate about whether the Wairau Fault has been active in the last 150 years, but most certainly the Plains have been affected by earthquake activity in this time. The Marlborough earthquake of 1848 (Richter magnitude 7.1) produced 1.5 m of subsidence along the Cloudy Bay coastline (Eiby 1973, 1980), enlarging the Wairau Lagoons and deepening the Opawa River. This increase in depth of the Opawa River probably enabled Blenheim to be established at the upstream limit of navigation, and become a sea port during the early days of settlement. It is uncertain whether this subsidence was the direct result of fault movement, or slumping and settlement of the fine-textured, saturated alluvium in the lagoon area. There was further subsidence of the coastal Wairau area in 1855, as a result of the Wairarapa earthquake. This time the lagoons were lowered a further 45 cm (Buick 1900; quoted by Brown 1981a).

Eiby (1980) suggests movement on the Wairau Fault was responsible for the 1848 earthquake. However, this is disputed by Grapes and Wellman (1986), since there is no displacement of beach ridges that are more than 800 years in age. At the very least, this earthquake was centred on the Wairau valley and caused considerable subsidence, although no surface rupture may have occurred. Brown (1981a) compared the heights of radiocarbon dated samples in marine deposits with the post-glacial rise in sea level, concluding that subsidence of the Wairau Plains is a long-term trend.

Ota et al. (in press) estimate the long-term rate of subsidence to be 4.2 mm/year, of which 50% may be due to tectonic subsidence and the remainder due to compaction.

Hydrology and river control

Rainfall and hydrology

Strong topographically controlled rainfall gradients characterise the Wairau River catchment, with annual rainfall rising to the west and southwest from 670 mm at Blenheim to more than 2000 mm in the mountains at the head of the catchment (Rae 1987). North-bank catchments generally receive more rain than those to the south, with up to 2400 mm on the Richmond Range. Southern parts of the Plains receive less than 700 mm and on the northern edge about 1000 mm.

Two different sets of meteorological conditions give rise to flooding in the lower Plains (Rae 1987). 'Wairau' floods originate from moist northwesterly airstreams and associated fronts that produce high rainfall over much of the upper catchment. 'Taylor' floods are associated with southeasterly flows, when heavy rainfall is generally confined to the coastal regions with flooding from the Taylor, Fairhall and Doctors Creeks. The appearance of tropical cyclones in the vicinity of Cook Strait is a less common event which can bring extensive flooding to the coastal catchments and heavy rainfall to the northern Wairau catchments. A large flood in 1868 was an extreme case of these conditions.

Mean flow of the Wairau River at Tuamarina is 114 m^3/s (Rae 1987). Flood records have been kept since 1936 and show that the three largest floods occurred between 1975 and 1984, with the two largest in July and October 1983. The flood of 10 July 1983 is the largest on record and was probably about 5800 m^3/s (Williman 1992, pers. comm. 1993). The stopbank breaches, stopbank overflow, overland flow and pondage pattern are documented by Thomson (1983). This event exceeded the original Wairau Valley Scheme design flood of 5100 m^3/s (Marlborough Catchment Board 1959), and Williman (1992) recommends that the July 1983 flood now be used as the design flood. The flood return period was originally estimated at greater than 1000 years (Thomson 1983), although this was subsequently revised downwards by Williman (1992) to 100–200 years. Williman (pers. comm.) suggests, from more recent analysis of this event, that the flood return period is about 150 years. Data gathered in this study support Williman's estimate, since the areas that were flooded have certainly been affected by sedimentation in the last few hundred years.

A flood in February 1868, before river control measures, may have been larger than the July 1983 event, since it is described as having inundated the entire floodplain (Rae 1987).

The drainage system and history of river control

It is difficult to appreciate from the present nature of the Plains that the area was once a vast wetland, fed by the Taylor and Fairhall Rivers, springs, and periodic inundation by floodwaters from the Wairau and its tributaries. The natural drainage system on the Plains was complex, with:

- major flood overflow channels (the Opawa Breach at Conders Bend carrying floodwaters from the Wairau to the Opawa, and Gibsons Creek carrying water from the Waihopai to the Opawa);
- numerous groundwater-fed streams (Spring Creek and tributaries);
- rivers that lost all their low flow to groundwater (e.g. Fairhall River, Taylor River);
- changes downstream from braided to single channel-forms (in both the Wairau and Opawa).

The drainage system has been greatly modified by swamp drainage, river channelisation, stopbanking and river diversion to provide protection from flooding and land for settlement.

Before river control, the Wairau River bed was at least 1500 m wide at some locations. Major flood overflows of the Wairau occurred above Conders Bend into a wide braided river bed (the Opawa River) now occupied by flows from Gibsons Creek and the Omaka and Fairhall Rivers. Budge's 1848 map of the Wairau Plains shows the Opawa River as a second channel of the Wairau. The Opawa Breach has provided one of the greatest challenges to the prevention of flooding of Blenheim and the Plains – it has carried floodwater that overtopped and breached the stopbanks of the Wairau as recently as 1983.

The history of river control measures is summarised by Rae (1987), with the major features being:

- closure of the Opawa Breach at Conders Bend;
- channelisation of the Fairhall and Taylor Rivers and diversion of the latter into the Omaka River;
- shortening of the Omaka River course by diversion into the Opawa River;
- diversion of the Fairhall River into the Opawa;
- straightening of meanders of the Wairau and Opawa Rivers;
- cutting of the Wairau Diversion to shorten the path to the sea and to carry 60% of flood flows (at present the diversion and the original channel carry approximately equal proportions of the flow);
- a flood detention dam on the Taylor River;
- a training wall to control the position of the Wairau Bar.

In addition, stopbanking and river training have been carried out on the Wairau River since about 1870, and the south bank now has continuous stopbanks as far upstream as the Waihopai. Extensive drainage works have also been carried out on all the swamps of the plain. River works have also been undertaken above the Waihopai confluence and a comprehensive soil conservation programme implemented in the upper catchment, aimed at reducing sediment input to the river channels and reducing flood flows.

Short-term river behaviour and aggradation

Historically, there has been a perception that the Wairau riverbed has been aggrading (Marlborough Catchment Board 1959; Williman 1992), and in-river control measures and gravel extraction were partly an attempt to reduce the sediment supply. Sites of major aggradation in the channel can reduce waterway capacity, threaten the stability of stopbank protection, and increase the probability of river avulsion. Noell and Williman (1992) have analysed the behaviour of the Wairau river bed between the Waihopai and Tuamarina from survey data covering two time periods: between 1969 and 1991 (when many of the Wairau Valley Scheme control works had been completed), and a less accurate analysis of changes between 1958 and 1969.

Between 1969 and 1991, the annual deposition of gravel and silt within the stopbanked floodway (including channels and berms) between Tuamarina and the SH6 bridge at Renwick was estimated to be 142 000 m^3/year, of which 90 000 m^3/year was gravel deposited within the active channel way (including 8500 m^3/year within the top of the Diversion and in the Lower Wairau below Tuamarina). This is a surprisingly low quantity of gravel in relation to the theoretical bed-load capacity of the Wairau River and by comparison with other similar rivers such as the Waimakariri (Noell and Williman 1992). It is uncertain whether this figure is representative of the long-term rate of aggradation in the lower Wairau. Gravel extraction (47 000 m^3/year) is only about half the estimated total gravel deposition and therefore net aggradation does occur, although not uniformly.

Noell and Williman (1992) identify three major sites of deposition based on variation in the slope of the river bed and measured changes in bed elevation (Fig. 3). Two of these are zones that have aggraded throughout the period of record, while the third, at and above Conders Bend, shows net degradation since 1969. Bed levels, generally, have been stable except for three areas:

- A 4 km reach from Wratts to Jefferies Roads has aggraded by 0.5 m since 1969.
- A 2 km reach from Hillocks to Cravens Roads has aggraded by 0.4 m since 1969. This site is above the major gravel extraction location at the Tuamarina bridge, where bed levels are stable, indicating that extraction is matching deposition.
- A 4 km reach in the Upper Conders area has degraded about 0.4 m since 1969. This reach was historically higher, and is possibly related to a previous breakout course of the Wairau into the Opawa River system.

Reduction in the river bed gradient is considered to be responsible for the aggradation of the first two sites.

Shorter-term variations of ±0.5 m were also detected as waves of gravel passed down the river. Thus, aggradation occurs in a few areas rather than consistently throughout the entire reach from the Waihopai to Tuamarina.

The major change to the river in the earlier period between 1958 and 1969 was the reduction in the active channel width due to river control measures. These typically reduced it from 660 m to 490 m, and stabilised its position. In this period aggradation occurred over the whole Tuamarina to Waihopai reach, although it was far less between Renwick and Waihopai than between Renwick and Tuamarina. The Wratts to Jefferies Roads reach aggraded at the same rate in both periods.

Noell and Williman (1992) also note that the rate of gravel deposition appears to have reduced since the Wairau River control scheme was completed in 1969, although they ascribe this to natural variation in sediment supply rather than the impact of river control measures (there are also many assumptions made in the analysis that limit the precision of the results). River control works on the Waihopai and Wairau above the Waihopai confluence appear to have little effect on sediment supply to the lower river (Noell and Williman 1992).

Recent rates of gravel movement are likely to be more related to in-river changes and the vulnerability of river banks to erosion, than to long-term geomorphic factors (Rae 1987). However, Noell and Williman (1992) suggest that the biggest factor determining the amount of gravel movement and deposition appears to be the lack of supply from the catchment upstream, rather than the transporting capacity of the Wairau, and note that it could theoretically carry at least twice the present amount of gravel. Both Noell and Williman (1992) and Williman (1992) note the dynamic behaviour of the Wairau River and suggest that regular monitoring of bed levels is necessary to assist management of the river as it continues to adjust to the imposed river control works and to other factors such as climate change and the impact of major storm events. Aggradation in the Wratts Road–Jefferies Road area has occurred throughout the 1958–1991 period and is a potential site of river avulsion.

It is impossible to compare present rates of gravel movement quantitatively with the geological rate as the total quantity of gravel deposited in the Wairau Plains is unknown and, at present, gravels do not reach the coast. However, the depth to gravels below the swamp deposits of the lower Wairau is generally no more than 1–5 m (Brown 1981b), which suggests that gravels have been transported down the Wairau system as far as Tuamarina probably within the last 1000 years. One radiocarbon date* of 1100±60 years (WK1951) was obtained from gravel underlying alluvial silt near Blenheim (Table 2, page 25).

* All dates are expressed as conventional radiocarbon ages, years BP.

Near-surface geology of the Wairau Plains

The subsurface geology of the Wairau Plains records the history of the aggradation that formed them. The Plains are built primarily of river gravel, sand and silt, with estuarine and marine deposits near the coast (Figs 1, 3). Apart from small areas on the southern side of the Plains underlain by Speargrass Formation outwash gravel (Otiran Glaciation), the near-surface deposits underlying most of the Plains are young – 10 000 years or less. These are mapped as Rapaura and Dillons Point Formations (Brown 1981a,b). The total depth of alluvial deposits may be as great as 300 m (Hunt 1969).

Older deposits are restricted to the upper part of the Plains south of Renwick and Woodbourne and to the fans of the Waihopai, Omaka, Fairhall and Taylor Rivers. These older deposits are fluvial gravel, sand and silt associated with the Otira Glaciation (14 000 to >20 000 years old) and are mapped as Speargrass Formation (Brown 1981a,b).

The prominent aggradation terrace underlain by Speargrass Formation in the upper part of the Plains lies around 6 m above the Rapaura Formation surfaces. This aggradation terrace has a steeper gradient than the younger surfaces, since it was formed during the last glaciation when the sea level was about 130 m lower than at present and the coast was about 40 km east of the present coastline (Ota et al., in press). The terrace scarp separating the Holocene and Otiran surfaces progressively decreases in height and disappears below the present surface of the plain in the vicinity of Renwick. Speargrass Formation deposits are gravelly to beyond the present coastline, and are one of the main aquifers for the Wairau Plains.

The Rapaura Formation consists of post-glacial fluvial deposits underlying the modern and recently abandoned floodplains and low terraces. The Formation is subdivided by Brown (1981a,b) into two units:

- Early Rapaura Formation – the lower unit formed in the early post-glacial (14 000 to 7000 years) when sea level was rising from its low glacial level. During this time there was degradation inland and aggradation towards the coast. This unit extends to the present coast and underlies post-glacial marine and lagoon deposits (Dillons Point Formation).
- Late Rapaura Formation – the upper unit formed since the post-glacial maximum inland incursion of the sea. Since then the Wairau has consistently aggraded while the sea level remains relatively constant.

Both units tend to be predominantly gravelly, although in the area shown as swamp deposits in Figure 2 there is a surface sand/silt veneer of variable thickness. In longitudinal section this forms a wedge, with the thickness of fines increasing from around 1 m near Rapaura to 5 m or more around Spring Creek and Grovetown. Total thickness of the Rapaura Formation is generally about 20–30 m, and subsurface dates (>5 m depth) (Table 4, page 28) range from 3000 to 8000 years BP. The Rapaura Formation indicates aggradation throughout the Holocene associated with, and following, the post-glacial rise in sea level. In the lower part of the Plains there was a change from coarse-textured to fine-textured deposits as a result of the lessening in river gradient associated with both the sea level rise and aggradation of the Plains.

Surface deposits of the Rapaura Formation are mapped by Brown (1981b) on the basis of lithology and elevation into:

- the youngest deposits largely within stopbanks, subdivided into two units
  - gravel, sand and silt in river flood channels occupied during historical flooding or in modern time before flood protection construction;
  - alluvial silt adjacent to present or historical river flood- or man-made diversion channels and reclaimed or drained swamps;
- undifferentiated alluvial gravel, sand and silt outside the stopbanks;
- alluvial gravel, sand and silt at a higher level and well-drained.

The more recent detailed soil mapping and near-surface (<5 m depth) radiocarbon dates provide a more accurate indication of the age of the surface deposits than does geological mapping (see pages 20–30).

The Dillons Point Formation consists of post-glacial marine, estuarine, and lagoonal sands, silts and gravels. These form the coastal margin of the Wairau Plains (Fig. 2) and below the surface they extend about 7 km inland, interfingering with the fluvial deposits of the Rapaura Formation (Fig. 4). Beach gravel and sand dominate in these deposits in the north, while sand, silt and clay dominate in the south, as they do in contemporary sedimentation. Maximum thickness of the Dillons Point Formation is 60 m. The sediments and associated fauna record the transition from terrestrial through estuarine to marine embayment environment as the sea level rose and transgressed across the land, followed by regression as sedimentation by longshore drift from the south and the Wairau River resulted in coastal progradation. Radiocarbon dates obtained by Brown (1981a,b) from the Dillons Point Formation range from <1000 to about 9000 years BP.

The surface deposits of the Dillons Point Formation are a series of gravel beach ridges, scattered remnants of sand dunes, and flat lagoonal and tidal flats on fine-grained sediments. Sand dune remnants form a prominent arc, approximately 5.5 km from the present coast, inland of the beach ridges (Fig. 2). The largest dunes (up to 14 m high) occur at Spring Creek and Riverlands, and are thought to mark a temporarily stable coastline about 6000 years ago (Brown 1981a). Smaller dunes occur in scattered bands 2–3 km seaward of this arc. Since about 4000 years ago the coastline has prograded, primarily as a series of parallel gravel beach ridges to the northeast of the Wairau River (Pickrill 1976). These ridges are very prominent near the coast but flooding by the Wairau has covered the inner ridges with silt, infilling the inter-ridge swales and smoothing the topography. The beach ridges display a progressive change in orientation, with the younger ridges parallel to the coast and the older ridges parallel to the Wairau River. Ridge heights are greatest in the youngest ridges, reflecting tectonic subsidence and settling, and partial burial of the older ridges. South of the Wairau there is a single gravel ridge (the Boulder Bank) which forms a spit 8 km long enclosing the Wairau Lagoons. Sediment derived from the south (Awatere River and White Bluffs) is responsible for the development of the gravel ridges, since the Wairau River does not transport gravel to the coast.

Pickrill (1976) measured contemporary progradation at 1.2±0.21 m/year, and suggested that the oldest of the exposed gravel ridges was about 4000 years. This rapid progradation is supported by radiocarbon dates associated with the beach deposits (Table 3, page 27). WK2182 (400±45 years) and WK2181 (720±50 years) provide minimum ages for two of the younger ridges and suggest progradation rates of 1 m/year. Similarly, WK1571 (1950±80 years), dating one of the older gravel ridges, suggests a progradation rate of 1.7 m/year. The dates all suggest rapid Holocene progradation, similar to measured contemporary progradation.

Pickrill (1976) synthesises the Holocene history of the Wairau coast. The lower Wairau valley was a shallow arm of the sea during the early Holocene. As the post-glacial rise in sea level slowed about 6000 years ago, a spit grew across the bay supplied by sediment sources to the south. It enclosed the Wairau Lagoons and extended across Cloudy Bay to near Tuamarina. A continuing supply of sediment from the south led to rapid progradation of the coastline as a series of gravel ridges and gradual infilling of Cloudy Bay. Aggradation of the Wairau River floodplain took place behind this beach barrier and appears never to have overtopped the beach ridges.

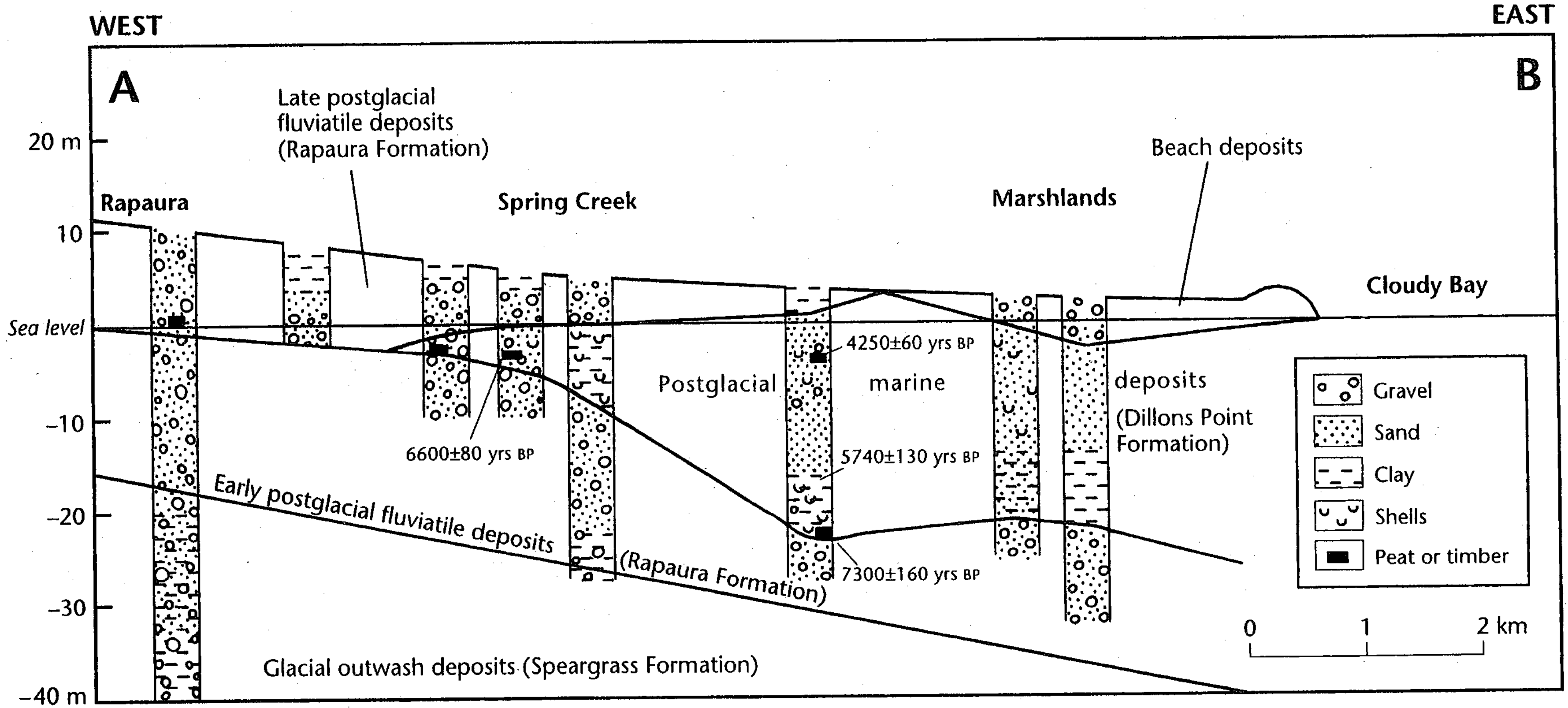

Figure 4. *Longitudinal cross-section of the Wairau Plains, showing subsurface stratigraphy.*

Soils of the Plains

Laffan and Vincent (1990) mapped the soils of much of the south side of the Wairau Plains west of State Highway 1, including the lower parts of the valleys of the Taylor, Omaka, and Fairhall Rivers and Mill Stream, at a scale of 1:25 000. The remainder of the Plains has been mapped at a scale of 1:250 000 (NZ Soil Bureau 1968), and the mapping units can be correlated (Table 1) with the units of Laffan and Vincent (1990). Soil distribution is shown on Map 1 and can be used to correlate surface age on the Plains. The results of radiocarbon dating allow quantitative estimates of surface age.

Laffan and Vincent (1990) recognise four different age groups of soils formed in alluvium and a suite of soils formed in dune deposits on the Wairau Plains (Table 1):

- soils of the unprotected floodplains and river channels (undifferentiated recent soils and river bed), mapped on Rapaura Formation alluvium;
- Awatere-age soils on the protected and higher floodplains (Awatere and Gibsons series), mapped on Rapaura Formation alluvium;
- Wairau-age soils on the younger terraces (Rapaura, Wairau, Grovetown and Spring Creek series), mapped on Rapaura Formation alluvium;
- Renwick-age soils on the older terraces (Renwick, Woodbourne, Brancott, Broadbridge, Hawkesbury, Paynter and Burleigh series), mapped on Speargrass Formation;
- soils of the sand dunes (Tahunanui and Murrays series), mapped on Dillons Point Formation.

The soils of the unprotected floodplains and river channels lie within the active floodways of the major rivers (Wairau, Opawa, Omaka, Fairhall and Taylor Rivers). These soils are shallow and stony and comprise raw river gravels and sand or weakly differentiated soils with A/C or AC/C profile forms (similar to Awatere series). They have formed in stony and sandy alluvium deposited in historical time and remain unprotected from frequent flooding.

The soils of the protected and higher floodplains are formed in alluvium deposited in historical times but now protected from regular flooding by stopbanks. Awatere series are formed in recent coarse-grained alluvium and have a weakly developed A/C profile form. They occur on flat to undulating land adjacent to the present river channels and major streams. Gibsons series are also well-drained recent soils of the higher floodplains with a weakly developed A/C profile form, but in contrast to Awatere soils are formed in fine-grained alluvium.

Several variants are recognised, based on textural variation, depth of fines, and development of mottles. These soils commonly show alluvial stratification and have buried A horizons at depths below 50 cm. The latter occur mainly adjacent to the Opawa River, near the Opawa Breach and Grovetown, where large floods have deposited recent alluvium over soils of the Wairau series in historical times. To the east of State Highway 1, equivalent soils are mapped as Waimakariri set along a narrow strip adjacent to the Wairau River.

Four soil series and a phase of one series (Rapaura, Wairau, Wairau mottled, Grovetown, and Spring Creek) are mapped on the younger terraces and levees. The alluvium is older than that on which Awatere and Gibsons soils occur, and forms a terrace about 2–3 m above the floodplain of the Wairau River. Adjacent to the Opawa River the terrace is not as obvious, and it has in places been overtopped by large historical floods. The two different age groups of soils recognised on the Rapaura Formation do not correspond to Brown's early and late Rapaura Formation units.

The Rapaura series, formed in stony alluvium, is found on the upper part of the plain and nearer to the Wairau River. The Wairau series, formed in loamy and sandy alluvium, occurs on flat to gently undulating land between the Wairau River and the Opawa overflow, and south of the overflow. Both series have A/BC/C profile forms with darker and thicker A horizons than the Gibsons series, indicating greater age. A mottled phase and several variants of the Wairau series are recognised, based on textural variation, depth of fines, and development of mottles. Buried profiles with a thin (<50 cm) cover of recent alluvium deposited during major floods in historical times also occur, especially adjacent to the Opawa River.

On the finer-textured deposits (silt loams and

Table 1. *Soils of the Wairau Plains (mapping unit names, correlations and land surface age groups from Laffan and Vincent 1990; names in italics are the equivalent mapping units from New Zealand Soil Bureau 1968).*

Decrease in drainage status or particle size class of alluvium ⟶

Drainage class					
Excessively drained	**Well drained**	**Moderately well drained**	**Imperfectly drained**	**Poorly drained**	**Very poorly drained**
Soils from alluvium:					
Protected floodplains (<250 years) on Rapaura Formation – Awatere-age soils					
Awatere Ah C *Waimakariri shallow*	Gibsons Ah C *Waimakariri*	Gibsons (mottled) Ah Cg			
Young terraces (300–3500 years) on Rapaura Formation – Wairau-age soils					
Rapaura Ah BC C *Waimakariri shallow*	Wairau Ah BC C *Waimakariri*	Wairau (mottled) Ah BC Cg	Grovetown Ah Bg Cg *Kaiapoi*	Spring Creek Ah(g) Bg Cg *Taitapu*	
Older terraces (600–3800 years) on Speargrass Formation – Renwick-age soils					
Renwick Ah Bw C	Woodbourne Ah Bw C	Brancott Ah Bw Bw(x) C	Broadbridge Ah EB Btg Bxg C	Paynter Ah Btg Cg	Burleigh O Cr
			Hawkesbury A E Btg Cg	Paynter (peaty) Ah Btg Cg	
Eyre–Paparua	*Templeton*			*Temuka*	
Soils on coastal deposits of Dillons Point Formation:					
Dunes					
Tahunanui A BC C		Murrays A BC Cg			
Beach ridges and inter-ridge areas					
Taumutu A Bw C				*Waimairi* A Bg Cg	
Saline areas					
				Motukarara A Bgn C	

clay loams) of the younger terraces, Grovetown series (imperfectly drained soils in recent loamy alluvium with an A/Bg/Cg profile form) and Spring Creek series (poorly drained soils formed in recent loamy alluvium with an A(g)/Bg/Cg profile form) are mapped in the area shown as swamp deposits in Fig. 2. Buried profiles with a thin (<50 cm) cover of recent alluvium deposited during major floods in historical times also occur in this area. To the east of State Highway 1, equivalent soils are mapped as Taitapu set where river silt has covered gravel and sand beach ridges to a sufficient depth to impede drainage.

On the Renwick-age older terraces seven soil series, forming a drainage sequence associated with a decrease in particle size of the parent material (Table 1), are mapped. These range from the excessively drained yellow-brown earths of the Renwick series formed in stony alluvium, to the very poorly drained peat soils of the Burleigh series. All seven series show an advanced stage of profile development, indicative of significantly greater age than the soils on the younger terraces (e.g. Ah/Bw/C for the Renwick and Woodbourne series, Ah/EB/Btg/Bxg/C for the Broadbridge series, and Ah/Btg/Cg for the Paynter series). The older terraces are underlain by Speargrass Formation gravels considered to be late Pleistocene in age (14 000 to >20 000 years).

Laffan and Vincent (1990) mapped two series on the sand dunes. Recent soils of the Tahunanui series are mapped on the sand dunes themselves, and soils of the Murrays series along the margins where the dunes have been buried by recent loamy alluvium. East of State Highway 1 recent soils, mapped as Taumutu set, are developed on the gravelly beach ridges, with organic soils (Waimairi set) in the swampy swales between beach ridges. Saline gley recent soils (Motukarara set) occur adjacent to and immediately inland of the lagoons where the saline influence is strongest.

Ages of alluvial and beach deposits

Soils provide a means of correlating land surfaces of the same age and distinguishing those of different age. To quantify the ages of the various surfaces recognised in the soil survey and provide an indication of the time since the last major flooding, as an index of flood hazard, a series of radiocarbon dates on wood and charcoal (Table 2) were obtained from near-surface (<5 m) deposits underlying the terraces and floodplains. Several dates were obtained from the coastal deposits (Table 3) to improve understanding of the evolution of the coastal landforms and the impact of coastal processes on floodplain evolution.

Near-surface alluvial deposits and soils

Most of the dates of near-surface alluvial material have been collected from the swamp deposits of the Rapaura – Spring Creek –Grovetown area, and from the Fairhall swamp (Fig. 2). The dates provide an indication of the ages of the deposits immediately underlying the Wairau Plains, and provide a time framework for the evolution of the land surfaces currently comprising the Plains. All the near surface deposits underlying the floodplains and low terraces (i.e. below the older terraces underlain by Speargrass Formation) appear to be younger than about 3500 years. Radiocarbon dates from the older terraces also suggest that the surface deposits underlying these terraces are late Holocene in age rather than Otiran. Location of the radiocarbon dated sites is shown on Map 2.

Four dates were obtained from buried soils underlying Awatere-age soils on the protected floodplain surface. All four were less than 250 years old, consistent with the deposition of this alluvium in historical times. Two of these dates were from the Spring Creek area (WK2497 and WK1572) and two near the Taylor River (WK1949 and WK1950). Two of the dates are from Wairau-age soils buried by more recent sediments (WK2497 and WK1949).

The age of the extensive low terrace with Wairau-age soils can be estimated from a large number of dates. These range from as young as 330±60 years (WK2496) to as old as 3480±60 years (WK2673), with the majority of the dates <2000 years. Most of the dates are from the silt/sand veneer overlying gravels and date the deposition of fine textured alluvium. However, NZ6988 (790±22 years) and WK2673 (3480±60 years) from the Taylor River, and WK1951 (1100±60 years) from Doctors Creek near the Taylor River, were obtained from wood within gravel (within 2 m of the surface) and date the deposition of coarse textured alluvium during major flood events. Similarly, NZ3965A (3010±80 years; Table 4) dates the deposition of gravel by the Opawa River and indicates 6 m of aggradation since that time.

Extensive areas of buried woody debris occur between Spring Creek township and Rapaura, and between Spring Creek – Grovetown and the Wairau River. Large quantities of debris, including tree trunks, large branches, twigs and bark, are exposed in the bed of Roses and Denton Creeks, tributaries of Spring Creek. They appear to form a continuous layer that extends along all the tributaries in at least a 500 ha area at a depth of about 1.5–2 m below the surface. The debris is not in growth position and includes branches of totara, matai and kahikatea. The presence of very large logs, accumulations of twigs and bark, and large, fragile, charcoal fragments suggests that while the debris would have been carried in a large flow, the flow dissipated quickly and subsequent flows did not winnow the site. The site shows a fining upwards sequence from gravel to sand to silt with the woody debris. This scenario would be consistent with deposition as a splay of gravel, silt and woody debris from a flooded main Wairau River channel to the north. It is dated at 610±50 years (WK1862) and deposition was also occurring in Giffords Creek (WK1861, 670±50 years) and near Watsons Road (WK1955, 720±50 years) at this time.

Extensive areas of woody debris and peat are also buried between Spring Creek–Grovetown and the Wairau River. Here there is a peaty layer containing abundant wood fragments and logs, buried 1–2 m below the surface by a silty veneer. The top of this peaty layer is dated at 1340±60 years (WK1954) and the base at 2470±60 years

Table 2. *Radiocarbon-dated wood and charcoal from near-surface deposits (<5 m depth), Wairau Plains.*

Laboratory number	Age (yr BP)	Locality	Grid ref.* P28/	Sample material	Vegetation identification	Depth from surface (m)	Type of sediment	Surface soil
Protected floodplains – Awatere-age soils								
WK2497	<200	Spring Creek	921713	wood	willow	1.4	wood in alluvial silt	Spring Creek
WK1949	<200	Springlands	879649	wood	kahikatea, rata	0.8	stumps in alluvial silt	Grovetown
WK1572	170±50	Spring Creek	917724	charcoal	beech	0.7	charcoal in alluvial silt	Gibsons mottled
WK1950	230±45	Springlands	885654	wood	hebe	1.1	wood and charcoal in silty alluvium over gravels (dated by WK1951)	Gibsons
Young terraces – Wairau-age soils								
WK2496	330±60	Grovetown	913687	wood	totara	0.75	wood in alluvial silt over peat	Spring Creek
WK1862	610±50	Spring Creek	881718	wood & charcoal	totara, matai, kahikatea	1.5	wood and charcoal in alluvial silt over gravel	Wairau
WK1861	670±50	Rapaura	860697	wood	totara	2.0	wood and charcoal at base of alluvial silt over gravel	Spring Creek
WK1955	720±50	Grovetown	911704	wood	kahikatea, totara	0.6	wood in alluvial silt	Grovetown
NZ6988†	790±22	Taylor River	885646	wood	matai	1.0	charred stump in gravel	Wairau
WK2676	1000±60	Spring Creek	906707	wood		1.8	wood and charcoal in alluvial silt over sand	Grovetown

*NZMS260. †collected by P. Simpson (all other samples collected by the authors).

Table 2. *(continued)*

Laboratory number	Age (yr BP)	Locality	Grid ref. P28/	Sample material	Vegetation identification	Depth from surface (m)	Type of sediment	Surface soil
WK1951	1100±60	Springlands	885654	charred wood	matai	1.2	wood in gravels below silt (see WK1950)	Spring Creek
NZ5191A*	1195±60	Tuamarina	941759	wood	totara, manuka, kanuka	1	wood in peat below alluvial sand/silt	Grovetown
WK1954	1340±60	Grovetown	913706	wood	kanuka, totara, rimu or kahikatea	0.9	peat within alluvial silt	Grovetown
WK2180	1640±50	Grovetown	914678	wood	kahikatea	1.4	peat with wood and charcoal in alluvial silt, over sand	Grovetown
WK2498	1700±60	Spring Creek	925725	wood in peat	matai	1.0	peat within alluvial silt	Spring Creek
WK2674	1980±50	Grovetown	912706	wood	manuka	0.8	peat within alluvial silt (see WK1954, 2675)	Grovetown
WK2178	2040±50	Grovetown	930685	wood	rimu	0.7	wood in alluvial silt	Spring Creek
WK2675	2470±60	Grovetown	912706	wood	kahikatea	1.3	peat within alluvial silt over sand (see WK1954, 2674)	Grovetown
WK2673	3480±60	Taylor River	887657	wood	kanuka	2.0	wood in alluvial sand over gravels	Wairau

*collected by L. Brown (see Brown 1981b) (all other samples collected by the authors).

Table 2. *(continued)*

Laboratory number	Age (yr BP)	Locality	Grid ref. P28/	Sample material	Vegetation identification	Depth from surface (m)	Type of sediment	Surface soil
Older terraces – Renwick-age soils								
WK1948	590±55	Fairhall	857630	wood	manuka	0.9	wood and charcoal in clayey alluvium below gravel	Paynter
WK1947	690±55	Fairhall	866648	wood	matai	2.4	wood and charcoal in gravelly silty alluvium below silt (see WK2179)	Paynter
WK1952	1670±50	Fairhall	849639	charred wood	totara, matai	1.5	stumps in alluvial silt	Paynter
WK2495	3300±80	Fairhall swamp	858644	roots within peat		1.0	base of peat over silt (see WK2495, 2494)	Burleigh
WK2495	3410±70	Fairhall swamp	858644	peat		1.0	base of peat over silt	Burleigh
WK1953	3620±70	Fairhall	863649	wood	kanuka, native conifer	0.8	stumps in alluvial silt	Paynter
WK2494	3750±70	Fairhall swamp	858644	organic silt with leaf fragments		1.3	organic silt below peat over clayey alluvium	Burleigh

Table 3. *Radiocarbon-dated wood, peat and charcoal from beach deposits, Wairau Plains.*

Laboratory number	Age (yr BP)	Locality	Grid ref. P28/	Sample material	Vegetation identification	Depth from surface (m)	Type of sediment	Surface soil
WK1860	modern	Wairau Diversion	945733	wood	kanuka or manuka	0.4	wood in beach gravels below thin alluvial sand	Waimakariri & Waimakariri shallow
WK1859	390±50	Wairau Diversion	947734	charcoal	manuka	0.6	charcoal in sandy gravel in gravel ridge	Waimakariri & Waimakariri shallow
WK2182	400±45	Marshlands	956730	peat		0.3	base of peat over beach gravels	Waimairi
WK2181	720±50	Wairau Diversion	954736	peat		1.0	base of peat over beach gravels (see WK1858)	Waimairi
WK1858	1450±50	Wairau Diversion	954736	wood	totara	0.5	wood in sand over beach gravels (see WK2181)	Taumutu
WK1571	1950±80	Wairau Diversion	927732	wood	totara	2.5	stumps in beach sand over gravel ridge	Taumutu

Table 4. *Radiocarbon-dated wood from the Rapaura Formation (from Brown, 1981a,b).*

Laboratory number	Age (yr BP)	Locality	Grid ref. P28/	Sample material	Vegetation identification	Depth from surface (m)	Type of sediment
NZ1972A	2980±70	Grovetown	906674	wood	kanuka	14	in silt, over sand, over Dillons Point Formation
NZ3965A	3010±80	Springlands	878688	wood	kanuka	6	in gravel
NZ1593A	7240±110	Spring Creek	892699	wood	totara	9	in gravel near base of Rapaura Formation
NZ4325A	7360±200	Spring Creek	906724	wood	totara	14	clay above gravel, below gravel and Dillons Point Formation
NZ4324A	8050±120	Spring Creek	906714	wood	totara	14	clay above gravel, below gravel and Dillons Point Formation
NZ4326A	8120±120	Grovetown	909681	wood	totara	21	clay at base of Dillons Point Formation, above gravel

(WK2675). In the Pukaka Swamp, numerous trees, including kanuka, manuka and totara, have been buried in a silty peat deposit in what appears to be growth position (Brown 1981a). This event is dated at 1195±60 years (NZ5191A), similar to the top of the peat layer between Spring Creek – Grovetown and the Wairau River. Preservation of the peat layer indicates deposition in a slackwater environment from overbank flows at relatively low velocity. This flood event appears to be older than that in the Spring Creek – Rapaura area, although it is buried at no greater depth below the surface. In both cases, extensive flooding and sedimentation is suggested.

The dates below the Wairau-age surface suggest a spatially complex pattern of deposition. While the dates range from 330 to 3500 years the amount of sedimentation at most sites is about 1–2 m. Brown (1981a) suggests that the presence of historical and buried forests illustrates that some areas of the plain were free from flooding for periods long enough to permit establishment of forests. However, the podocarp forest indicated by the buried logs and early-European forest remnants would have coped with inundation, provided that it was not very frequent and if it only resulted in the deposition of fine alluvium and not thick gravel. Most of the floodplain aggradation has occurred during times when the Wairau Plains were heavily forested.

A series of near-surface dates was also obtained from the areas mapped as older terraces with Renwick-age soils. These are the oldest deposits and surfaces on the Wairau Plains, and have been correlated with the Speargrass Formation deposited before about 14 000 years. However, the radiocarbon dates indicate that at least parts of the land surfaces are considerably younger than this.

The dates come from the base of the peat in the former Fairhall Swamp and from buried soils in fine-textured alluvium surrounding the swamp. The Fairhall Swamp was remote from the main rivers, and development of peat in this area resulted from low rates of alluvial sedimentation and poor drainage. Poor drainage was due to the low-lying nature of the land relative to the surrounding areas, and the inflow of creeks with no defined outlet. However, despite this stability, the peat (mapped as Burleigh series) is surprisingly young. The stratigraphy of the site shows an early phase of sedimentation of silt and clay, followed by development of an A horizon, and progressive worsening of the drainage status and development of an organic soil (peat). Gravel lies at an unknown depth below the silt and clay but is found adjacent to the swamp at depths of 2–4 m. The buried A horizon is dated at 3750±70 years and the base of the peat at 3410±70 years, indicating that the land surface is late Holocene rather than Otiran in age.

Extensive areas of buried woody debris were also located in and around the Fairhall Swamp. North of the swamp, *in situ* stumps in silty alluvium were a similar age to the base of the peat (WK1953, 3620±70 years). The remainder of the dates were, however, considerably younger than this, ranging from 1670±50 years (WK1952) to 590±55 years (WK1948) – essentially the same as dates obtained from the Wairau-age soils of the younger terraces. All the dates were associated with minor stream channels and indicate the activity of these creeks (e.g. Doctors Creek, Golf Course Creek). Attempts were made to determine whether the buried soils were widespread, but coring failed to locate them at sites remote from the creeks.

The surface soils adjacent to the creeks, however, appear to be the same as those on the surrounding terrace lands, suggesting that much of the landscape has been subject to flooding and sedimentation within the last 500–1000 years. The advanced stage of profile development in the soil may be due to the fine-textured parent materials and heavy gleying induced by poor drainage, rather than an indication of greater age. The dates indicate that flooding and sedimentation have been active as recently as 600 years ago in at least parts of the surfaces mapped by Brown (1981a,b) as late Otiran. All the dates from the older terraces, especially those from the Fairhall Swamp, imply that these surfaces are considerably younger than has been previously thought, and suggest a dynamic and rapidly aggrading floodplain.

Beach deposits

The beach deposits comprise discontinuous sand dune arcs with continuous gravel ridges to seaward. The innermost and largest sand dune arc running from Spring Creek to Riverlands, about 5.5 km from the coast, is undated. However, based on a radiocarbon date of 6600±80 years (NZ3125) from subsurface marine deposits slightly inland of these dune remnants, Brown (1981a) suggests that these arcs represent the coastline about 6000 years ago.

The gravel ridges began forming once the Boulder Bank enclosed Cloudy Bay, which Pickrill (1976) suggests occurred after 4630±100 years (NZ1955), based on the change from higher to lower salinity recorded by fossil assemblages in subsurface deposits near the present lagoon. However, one of the older beach ridges is dated at 1950±80 years (WK1571), determined from totara stumps (in growth position) in sand overlying a gravel ridge. This ridge is blanketed by alluvial sediments and landward of the ridges still exposed at the surface, suggesting that the ridges are considerably younger than 4000 years. Two of the youngest ridges have minimum ages of 400±45 years (WK2182) and 720±50 years (WK2181), based on the age of the base of the peats found between the ridges. The ridge dated at 400±45 years may overlie an older ridge, since wood in a gravelly sand overlying a gravel ridge was dated at 1450±50 years (WK1858) at a site slightly upstream. The stratigraphic relationship of the two sites is unclear, since vegetation covers the area between the two sites, and the wood dated by WK1858 was a small fragment of totara that could have a considerable inbuilt age. If two ridges are dated here it suggests the coastline may have oscillated in position through time, perhaps in response to tectonic subsidence, rather than simply progressively prograding.

Flood hazard on the Wairau Plains inferred from surface ages

In combination, the soil pattern, topography and radiocarbon dates from near-surface material allow interpretation of land surface age, and hence a broad indication of flood hazard. Four age groups of land surfaces were recognised (Map 1):

1. Unprotected floodplains and river channels; flooded in historical times and unprotected from current flooding. They are highly susceptible to flooding and deposition and lie within the active floodways of the major rivers (Wairau, Opawa, Omaka, Fairhall and Taylor Rivers).

2. Protected and higher floodplains; flooded in historical times but now protected by stopbanking and channel protection works. Flooding and deposition are likely to occur only during major flood events once every 20–50 years. Awatere-age soils are developed on these surfaces adjacent to the present-day river channels and major streams. Buried soils are a feature adjacent to the Opawa River, near the Opawa Breach and Grovetown where large floods have deposited recent alluvium over soils of the Wairau series in historical times. Radiocarbon dates from these buried soils suggest surfaces ages of <250 years.

3. Young terraces and levees with Wairau-age soils; formed in post-glacial alluvium older than that on which the Awatere-age soils occur. This surface is 2–3 m above the floodplain of the Wairau River and adjacent to the Opawa River, and has been overtopped by large historic floods. Flooding and deposition during these events have been most extensive in the lower-lying areas. Between the Wairau River and the Opawa overflow buried soils are common. Near Spring Creek and Grovetown, buried soils, overlain by thin (<50 cm) recent deposits, record major floods in historical time. Radiocarbon dates from these buried soils suggest surfaces ages of between 300 and 3500 years.

4. Undissected higher terraces with Renwick-age soils; formed on late Pleistocene Speargrass Formation alluvium comprising the southern margin of the plain from the Waihopai junction to Blenheim. Radiocarbon dates suggest a considerably younger age (<4000 years) for some of the near-surface deposits and indicate that flooding and sedimentation have been active as recently as 600 years ago on at least parts of these surfaces.

Geomorphic history of the Wairau Plains

Overview

The Wairau River lies in the fault-angle depression formed along the Wairau Fault. This has been filled with at least 300 m of sediments deposited during successive glacial and interglacial periods by alluvial, lagoonal and marine sedimentation. Glacial outwash deposits are buried by post-glacial alluvial, lagoonal and marine sediments in the lower Plains, while in the upper Plains and Plains margins they form high terraces. The present-day land surfaces comprise post-glacial floodplains and terraces flanked by sand dunes and gravel ridges near the coast, and by older terraces along the southern margin of the Plains.

During the last glaciation, Speargrass Formation glacial outwash was laid down with the aggradation surface steeper than the present surface of the Plains since sea level was more than 100 m lower. Changes in river gradient, possibly combined with reduced sediment loads from the upper catchment as a result of improved vegetation cover during the post-glacial (Brown 1981a), caused entrenchment of the Wairau River into the aggradation terrace in the upper part of the Plains, and burial of Speargrass Formation in the lower part. Rising sea level in the post-glacial reduced the river gradient and caused sedimentation in the lower part of the Plains. It also caused migration of the shoreline inland and deposition of marine and lagoonal sediments along the coast. The sea level rose rapidly from about 35 m below the present at 10 000 years ago, to reach its present position by about 6500 years. Between 6500 and 2000 years ago, the sea level has fluctuated by –0.4 to +0.6–0.9 m, but since 2000 years it has remained within a few decimetres of the present level (Gibb 1986). The post-glacial history is one of progressive aggradation and infilling, with all early post-glacial land surfaces apparently buried below the Plains.

Northwest tilting of the block between the Wairau and Awatere Faults has been sufficiently rapid to maintain the main channel of the Wairau River on the north side of the Plains throughout this time.

The formation of erosion-resistant gravel ridges on the northern side of Cloudy Bay has forced the Wairau River to swing to the southeast for at least the last 2000 years and perhaps for as much as 4000 years.

Alluvial deposition

The oldest terraces on the Plains are underlain by Speargrass Formation glacial outwash laid down 14 000 to >20 000 years ago (Suggate 1988). This forms a prominent aggradation terrace in the upper part of the Plains. A series of gently sloping fans from southern tributaries of the Wairau River is also mapped as Speargrass Formation, although it appears from this study that they also received sediment during the post-glacial. Over most of the Plains, Speargrass Formation has been buried by Rapaura Formation deposits.

Most of the Plains are underlain by post-glacial sediments of the Rapaura Formation which range from coarse gravels in the upper part of the Plains to fine-textured silt and sand in the lower part. Aggradation throughout the post-glacial period has progressively filled the Wairau valley and buried older surfaces. All the early Rapaura Formation sediments are buried below the Plains with no surface features older than about 3500 years. Brown (1981a) suggests that the early Rapaura Formation deposits (14 000 to 7000 years old) were laid down when the sea level was rising and this is why they are all buried. However, the older late-Rapaura Formation deposits, laid down when the sea level was about its present level, are also buried, suggesting that subsidence of the Wairau Plains is more important in controlling aggradation in the long term.

Two age groups of surface features make up the present-day landforms. The low terrace, with Wairau-age soils, was formed between 300 and 3500 years ago, although parts of this surface near the Wairau and Opawa Rivers have been subject to more recent deposition. Soil development on this surface has been sufficient to mask near-surface alluvial stratification. The unprotected and protected floodplains, with Awatere-age soils, formed over the last 250 years, were subject to frequent flooding before river control measures. Alluvial stratification is still very obvious in these soils.

Throughout this time the Wairau has flowed in its main channel on the northern side of the

Plains. In major floods, however, water and sediment were regularly carried by a major distributary channel that left the Wairau in the vicinity of Conders Bend and flowed down the Opawa River. This was a relatively common occurrence when the first settlers arrived on the Plains (Rae 1987). Gravel was carried down both channels as far as Tuamarina and the vicinity of Thomsons Ford respectively. In major floods, breakouts would also have occurred from the main Wairau River channel below Conders Bend, but these flows were nowhere near the scale of the Opawa overflow and have mainly served to fill the swales occupied by the spring-fed streams with silt. Normal flow of these spring-fed streams would have removed much of the sediment in the floors of the swales but not in the adjacent interfluve areas. Widespread silt deposition also occurred adjacent to the main Wairau River channel and the Opawa overflow. Extensive fine-sediment deposition occurred in the low-lying area behind the beach ridges on the coast side of the Wairau River. This deposition is slowly covering the older beach ridges with alluvial silt. Extensive deposition has also occurred in the low-lying swampy areas in the lower Opawa River above the lagoons. The fairly uniform infilling of the entire plain and the spatial complexity of the radiocarbon dated deposits suggest that, in its uncontrolled state, the locus of deposition of the Wairau would have changed frequently. The young age of many of the surface deposits indicates a dynamic and rapidly aggrading floodplain. It appears entirely conceivable that floods such as that in 1868 covered the entire valley.

Parts of the fans of the south-bank tributaries on Speargrass Formation were also affected throughout the late post-glacial by alluvial deposition. Sedimentation from these tributaries was slower than from the Wairau River, resulting in a relatively low-lying area where the two sources intersected. A swamp developed where the Fairhall and smaller creeks (Doctors Creek, Golf Course Creek) lost their flow to groundwater. The beginning of peat growth in this swamp is dated at about 3500 years ago. The most recent sedimentation in Doctors Creek and Golf Course Creek is dated at about 600 and 1700 years respectively. Doctors Creek has a very small channel in relation to the size of the catchment that it drains, and it is likely that in major storms overbank flooding and sedimentation would cover a very wide area. While the deposits underlying the fans at depth may well be Speargrass Formation in age, the surface deposits are very recent.

Coastal progradation

Rapidly rising sea level in the post-glacial caused migration of the shoreline inland and deposition of marine and lagoonal sediments along the coast. Sea level reached its present height by about 6000–6500 years ago, at which time the coastline was about 7 km inland of its present position and the lower Wairau valley was a shallow arm of the sea (Pickrill 1976). At this time sand dunes were formed at the coast, and at the south end of Cloudy Bay a spit began to form (the Boulder Bank). The northern part of the Plains initially prograded as a series of sand dunes, while still exposed to the open ocean. In the south the spit acted as a littoral conveyor for sediment supplied from southern sources (White Bluffs and the Awatere River) and grew to form a barrier enclosing the Wairau Bay, perhaps by about 4000 years ago. Following this, the northern part of the coast prograded rapidly as a series of gravel ridges that were large enough to divert the course of the Wairau River to the southeast. Historically, progradation was measured (Pickrill 1976) at 1.2±0.21 m/year (1924–70), and this rate appears to have held over the last 1500 years. The shoreline position may have oscillated, perhaps in response to tectonic-induced subsidence, rather than prograded progressively. In the south an extensive estuary formed behind the spit and, over time, this has infilled with sediment from the Wairau and Opawa river systems. For at least the last 1500 years the Wairau River appears to have entered the sea through the Boulder Bank, although the exact position varied with tidal and storm flows, and littoral drift. Until permanently controlled by a training wall, the position of the Wairau Bar varied by as much as 1.6 km and it also varied greatly in size – in the 1868 flood for example, 100 m was washed away. Pickrill (1976) suggests, from wave diffraction patterns, trends in sediment size and sorting, and the presence of a strong northerly littoral current, that virtually all the sediment for coastal progradation comes from the south. The presence of common limestone and igneous rock fragments in the beach deposits, and the lack of coarse sediment in the lower 10 km of the river, also suggest that the Wairau is unimportant as a source for coastal progradation. The northern end of Cloudy Bay has been a sink for sediments supplied by littoral drift from the south and has progressively reoriented itself as Cloudy Bay has been infilled.

Factors determining floodplain development

River gradient variation

River gradient is a major control of bed-load transport capacity and determines, for a given regime of runoff and sediment supply, whether a river bed aggrades or degrades. Long-term changes in the Wairau gradient occurred between glacial and interglacial periods because of changes in the relative elevation of downstream (sea level) and upstream (height of aggradation terraces) control points. Since the last glacial, changes in these controls have seen a progressive reduction in gradient across the Wairau Plains. The gradient of the Speargrass Formation surface is about 1:300 compared to 1:400 for the present surface of the Plains (Brown 1981a).

The progressive down-valley reduction in gradient is the major control on the change in surface sediments from gravels to sand/silt. The very low gradient below Tuamarina marks the threshold beyond which the river is unable to transport large quantities of gravelly sediments. The gradient halves below Tuamarina, from 1:526 to 1:1192. Water well logs and field evidence show that gravels underlie the fine-textured sediments at generally shallow depths. These depths, often only 1–5 m, indicate that gravels were transported to the coast in the fairly recent past when the gradient was presumably greater. Sites of contemporary gravel aggradation are where the river gradient lessens.

River control measures have locally changed the river gradient and transport capacity. As part of these control measures, the Wairau River channel has been shortened and constricted. This has shortened the river and steepened its gradient but appears to have had little influence on the extent of gravel movement down the channel. Although gravel aggradation has halved since the Wairau River control scheme was completed, Noell and Williman (1992) suggest this is due to natural variation in gravel supply rather than the impact of control measures. Deposition remains well in excess of gravel extraction.

Subsidence and uplift, both regional and local, also influence river gradient and hence sediment transport capacity. Regional tilting determines the course of the Wairau across the northern margin of the Plains. Regional uplift may also be a factor affecting the upstream control on river gradient (i.e. in the upper part of the Plains and above the Waihopai). Locally on the Plains both uplift and subsidence are occurring. Lensen (1976) notes that the upthrown side of the Wairau Fault changes repeatedly throughout its length. Near Renwick the recent trace shows uplift up to 3 m, but the upthrown side varies from the southeast to the northwest along the fault trace. On the trace near the coast the northwest side of the fault is upthrown by about 2 m (Grapes and Wellman 1986). Subsidence of the coastal sediments induced by earthquake shaking and direct tectonic movement is a major influence on river gradient. Ota et al. (in press) estimate subsidence of the lower Wairau Plains at more than 4 mm/year, of which half is tectonic and half is due to compaction.

Sediment sources

Two sources are possible for the sediment on the Wairau floodplain: the hilly and mountainous catchment upstream, and entrenchment of the upper floodplain and reworking of sediment within the river bed. No studies have looked at this in detail, but the burial of former surfaces rather than entrenchment of the upper fan suggests that most of the sediment is contributed from sources above the Waihopai confluence. Brown (1981a) suggests entrenchment of the river into Speargrass Formation fluvioglacial sediments in the upper Wairau was the main source for the sediments on the floodplain. Within the Wairau mountainlands, Simpson (1980) suggests that natural phenomena are more important than induced erosion in supplying sediment to the river system, and identifies streambank erosion of post-glacial terrace gravels and scree, and gullying of solifluction deposits as the most important sources. Loss of riparian protection following vegetation removal is also important.

Because of the far greater rainfall in the upper Wairau, this area is likely to be the ultimate source of much of the sediment deposited on the floodplain. However, there may be a long time lag for transport of sediment from the upper

Wairau, and the immediate source of sediment may have more to do with reworking of the bed in the lower reaches of the Wairau. A sediment budget for the lower Wairau, including the relative influence of sediment sources from the upper catchment and the Plains, remains to be resolved.

Clearly, it is difficult to predict accurately either the past or likely future rates of gravel movement from current knowledge, but redistribution and accumulation of this gravel within the channel will largely determine the sites of future river avulsion. Development of a comprehensive sediment budget and an improved understanding of the impact of upstream works in reducing sediment supply to the Wairau are needed to predict likely future rates of gravel movement.

Sediment load variation

Long-term variation in a river's sediment load results from variation in sediment supply and/or the hydraulic regime. Major changes in sediment supply are likely to have occurred in times of glacial advance and recession. During glacial advances, sediment yield may increase (Brown 1981a), through a lack of vegetation in the mountains and foothills and an increase in mechanical weathering accompanying colder temperatures. This results in the formation of aggradation surfaces. Brown (1981a) suggests that fluvioglacial deposits laid down during times of glacial advance in the inland mountain ranges have been eroded and redeposited during warmer interglacial periods.

Within the Wairau catchment, geological and induced erosion are frequently associated but Simpson (1980) suggests that vegetation disturbance, especially forest removal, is the major factor accelerating instability. Without a sediment budget to determine the importance of upper catchment sources in controlling deposition on the Wairau floodplain, it is difficult to assess the relative importance of factors affecting variation in delivery of sediment from the upper catchment and those directly affecting in-channel processes.

Short-term variation in the Wairau River sediment load is likely to be primarily related to sediment production and transport during episodic periods of storminess. A large proportion of the total sediment load is likely to be carried in extreme events, which can have long-lasting impacts on sediment production, storage and transport.

Gravel waves

Little is known of the transport of gravel by the Wairau River but it is likely that much of the gravel transport is associated with the migration of large, low-amplitude, long-wavelength 'gravel waves' as observed in similar rivers such as the Waimakariri (Griffiths 1979). The analysis of bed level changes provides some evidence for the passage of gravel waves, with the aggradation zones showing local aggradation or degradation. Noell and Williman (1992) suggest that gravel is deposited in the lower Wairau where the gradient reduces, and in moving lobes that are activated with major floodflows. This process produces a feedback effect that readjusts the gradient and shifts the sites of deposition. Because gravel is not transported to the coast, the channel would be filled eventually, causing the river to avulse to another course. In its uncontrolled state this was a normal part of Wairau floodplain development and would have occurred regularly, thus uniformly filling the entire valley. Since river control measures have been implemented, aggradation has largely been confined to the stopbanked channels. It is expected in the long term that aggradation will continue, thus reducing the channel capacity. The actual sites of aggradation will change through time, associated with the passage of gravel waves and episodic major floods. The location of sites where overtopping or erosion of the stopbanks occurs will in part be controlled by the passage of gravel waves.

Coastal progradation

Coastal processes have influenced the course and gradient of the river across the lower Plains. Changes in sea level associated with glacial advance and retreat have provided a long-term control on the river gradient and thus sediment transport capacity. Since sea level has been at about its present level, the major impact of coastal processes has been the formation of the gravel ridges that have diverted the river to the southeast and lengthened its course, thus reducing the gradient and sediment transport capacity.

In addition, the progressive progradation of the coast has further lengthened the course and reduced river gradient. The size of the exit of the Wairau through the barrier spit will have influenced flood flows across the Plains and associated sedimentation by backing up floodwaters in large-magnitude events.

Tectonism

Tectonic activity influences river gradient and sediment transport capacity, as outlined on page 34, while regional tilting determines the course of the Wairau across the northern margin of the Plains. Subsidence of the coastal sediments induced by earthquake shaking and direct tectonic movement affects both river gradient and the size of the Wairau Lagoons. The size of the lagoons and the tidal prism contained within them have a secondary effect on the stability and scour of the Wairau Bar.

Future influences on the floodplain and coast

It is expected that the broad geomorphic trends of the last few thousand years will continue. Thus continued aggradation of the river channel, especially of gravel above Tuamarina, is certain, and coastal progradation will continue. In detail, some change is likely as a result of changing environmental conditions, river channel management, and extreme events. Changes or events that are likely to influence the behaviour of the Wairau River and its floodplain include possible climate change and sea level rise associated with the 'greenhouse effect', changes in the rate of gravel extraction from the river bed, earthquakes and associated land instability on the floodplain or in the basin headwaters, and stopbank failure during extreme flows.

Climate change

There is worldwide, but by no means unanimous (Bryant 1987), concern that increases in the concentration of greenhouse gases such as carbon dioxide and methane in the atmosphere are leading to global warming. Temperatures are likely to be 1.5°C higher by 2050, but may be as much as 3°C higher (Royal Society of New Zealand 1988). Warming may change weather patterns and lead to a rise in sea level, although at present the magnitude and, in the case of climate, even the direction of possible changes are only vaguely appreciated.

An increase in global temperature may change the atmospheric circulation pattern in the vicinity of New Zealand and affect precipitation, since warmer air can hold more water vapour. Regional climate-change scenarios for Marlborough (Salinger and Hicks 1990) suggest a precipitation increase of 5–10% by AD 2050, higher intensities, and a greater number of extreme rainfall events. This may increase the runoff and sediment yield of the Wairau River, thereby exacerbating flooding on the Wairau Plains. Griffiths (1990) predicts an increase in runoff of 10–40% by AD 2050, and an increase in suspended sediment supply to the Wairau River. Impacts of individual storm events will probably be within the present natural variability, with an increase in the frequency rather than magnitude of major storms and floods.

Sea level rise

Global warming is likely to lead to a general rise in sea level as a result of the thermal expansion of sea water and the melting of glaciers (Gibb 1988a). Locally, the sea level may rise or fall depending on tectonic activity. Predictions of change to the global sea level range from a slight fall to a rise of 1.4 m (Hicks 1990). For coastal planning and management, Gibb (1988b) recommends that it would be prudent to anticipate a rise of 0.5 m by 2050, and 1.5 m by AD 2100. For coastal Marlborough, Salinger and Hicks (1990) predict a sea level rise of between 20 and 60 cm by AD 2050.

The potential effects of a rise in sea level on the Wairau coast are (Burns et al. 1990; Hicks 1990):

- Enhanced aggradation of the lower reaches of the river bed, with an associated decrease in the effectiveness of flood protection works. The river bottom will tend to rise with the river water level. As the sea level rises it will decrease the gradient in the lower reaches of the river and lead to greater aggradation of sand and silt between Tuamarina and the coast. The direct impact on gravel aggradation is likely to be less severe, although lessening of the river gradient will exacerbate gravel aggradation.
- Greater frequency of flooding on the low-lying coastal areas by the individual or combined effects of extreme tides, storm surges and river floods.
- Greater likelihood of storm waves overtopping low-lying areas of beach ridge or spit, although the beach ridges may build higher to match the higher level of the storm waves.
- A change towards a predominantly northerly wave climate would initiate a realignment of the northern end of Cloudy Bay and possibly change the littoral drift regime.
- More frequent and greater episodes of erosion of the shore while beach profiles adjust. Shoreline change can be estimated from Bruun's (1962) model. This assumes that as sea level rises, the beach profile translates landward and upward. This will induce beach erosion and retreat. However, since the coastline is prograding, it is likely that the net effect would be for progradation to slow rather than for the coast to retreat. Since

the coast is mainly gravel it is also likely that it may not retreat much. The net impact will depend on any changes to littoral drift and sediment supply from the south. Precise estimations of changes to coastline shape and dynamics are difficult to predict and require further research.

- More frequent changes in the tidal reaches and river mouth areas, including the Wairau Lagoons, caused by changes in the volume of the tidal prism and therefore tidal velocities and scour. The main effect on the Wairau Lagoons is likely to be an increase in their size as well as flooding of the surrounding land, and instability of the estuary entrance and training wall. The training wall at the entrance will be less effective in deepening water, and an increased frequency of northerly gales could see greater wave attack on it. Sedimentation in the estuary is unlikely to change significantly unless there are changes to sediment load in the Wairau and Opawa river systems, since most of the sediment supplied from the south bypasses the estuary.
- Higher groundwater levels, and saline intrusion into the coastal water table aquifer in areas where wells pump large quantities of water.

For most of these, a quantitative assessment for a given sea level rise requires detailed data on coastal topography, ocean wave climate, and groundwater features, combined with hydraulic studies of river flood and tidal flows. However, in general terms it can be expected that the major changes will be greater aggradation of sand and silt between Tuamarina and the coast, changes to beach profiles and stability, to the entrance to the Wairau Lagoons, and to the stability of the training wall at the entrance to the lagoons.

Gravel aggradation

Predictions on the likely magnitude of gravel aggradation are difficult to make in the absence of both a sediment budget for the Wairau catchment and a clear understanding of the long-term significance of the measured short-term rates of aggradation. However, it must be assumed that gravel extraction will continue at least at the present rate.

The measured rate of gravel aggradation should be regarded as a minimum; thus it is likely that, in the long term, rates of gravel supply will increase and lead to increased gravel aggradation. As at present, the aggradation will not be uniform but will occur at specific locations that will change through time as gravel waves pass through the river system, and as major floods deposit gravel. Even at present, rates of gravel extraction do not match the supply of gravel, except at specific sites. This imbalance is likely to increase in the future, resulting in increased aggradation. Regular monitoring of riverbed levels is essential to determine changes to riverbed aggradation and waterway capacity. Extraction may be necessary at specific points which show long-term aggradation (e.g. between Wratts and Jefferies Roads).

Earthquake effects

The lower Wairau is a seismically active area with recent fault traces. Large historical earthquakes have also occurred. While transcurrent movements predominate, both uplift and down-warping can occur locally (Lensen 1968, 1976). In addition, tectonically induced subsidence is a significant factor in the coastal area underlain by fine-grained, saturated sediments. The 4 mm/year subsidence rate has had, and will continue to have, a major influence on river gradient and thus sediment transport capacity. Subsidence is likely to continue into the future at a similar rate.

Large earthquakes may also endanger the stopbanks of the river, although most mechanically compacted embankments or fills of earth and rock have performed well under shaking (Earthquake Engineering Research Institute 1986). Exceptions are embankments and fills of loose, fine-grained cohesionless material, or locations where foundations have failed. Most foundation failure results from liquefaction or from slope failure of the sloping margins of fills where compaction is commonly poor. Liquefaction is most common in poorly compacted fine sand, silty sand, or sandy silt that has been deposited in the last few hundred years (Earthquake Engineering Research Institute 1986). Such deposits are common in the lower Wairau Plains where Awatere-age soils occur. Stopbank failure is possible in this area in a major (MMVII or greater) earthquake.

The Earthquake Engineering Research Institute (1986) indicates that penetration resistance is a useful indicator of liquefaction susceptibility.

Where stopbanks are constructed on sandy or silty material such tests should be carried out to assess likely foundation stability in a major earthquake, since it is certain in the long term that the Wairau Plains will be subject to major earthquakes.

The upper Wairau catchment has many active faults (Lensen 1976, Simpson 1980, Johnston 1990). Smith and Berryman (1986) estimate that earthquakes of intensities MMVI, MMVII, MMVIII, and MMIX have recurrence intervals of about 5, 17, 58, and 210 years respectively at Blenheim. Rock avalanches are present (e.g. at Lake Chalice, in the upper Wairau near Island Pass, the Branch near Scotts Stream) and these were probably triggered by earthquakes of at least MMVII (Whitehouse and Griffiths 1983; Earthquake Engineering Research Institute 1986). The frequency of large rock avalanches in the Wairau is unknown, but such events provide a potential mechanism for a supra-design flood event through the formation and breaching of a landslide dam on the Wairau River above the Waihopai confluence. The probability of such an event is very low (probably <0.0005) but it would cause major geomorphological changes on the Wairau Plains, with widespread aggradation and the likelihood of river avulsion.

Stopbank failure/overtopping

The stopbanks along the Wairau were originally designed to contain a flood of 5100 m^3/s, with a recurrence interval of 100–200 years (Marlborough Catchment Board 1959). More recently, Williman (1992) has recommended that the July 1983 flood (estimated at about 5800 m^3/s and with a recurrence interval of about 150 years) be used as the design flood for current works.

The 1983 flood provides a good model should stopbanks be overtopped by floods slightly in excess of design discharge. Floodwaters will be carried via Conders Bend to the Opawa River, and there will be substantial flooding of low-lying areas adjacent to the original course of the Wairau below Tuamarina, and between Tuamarina and the Pukaka drain. Overtopping is also likely above Wratts Road. The areas likely to be flooded are those delineated as Awatere-age soils on Map 1. Some areas of Wairau-age soils may also be flooded.

The existing flood scheme considers flooding from overtopping associated with a design discharge (associated with a hydrological event), and assumes no vertical movement of the river bed or base level over the design life. However, there are several possible scenarios where these assumptions could fail and lead to more frequent flooding in the area beyond the stopbanks. These scenarios include the stopbanks being breached by river scour, the capacity of the floodway being diminished (by aggradation, progradation and possibly sea level rise), and a supra-design event.

Breaching by scour of the stopbanks would be local and, as with stopbank overtopping, floodwater would flow down the nearest available relict channel. Local overtopping of stopbanks or enhanced frequency of breaching by scour could occur with the passage of gravel waves. Gravel waves probably migrate on a time-scale of decades, so there should be sufficient time to discern the local aggradation from repeated channel surveys and to undertake remedial gravel extraction.

Widespread flooding, and massive aggradation and scour, could occur during a supra-event, for example from a dam burst upstream. In such an event, flooding of all the Wairau Plains – the Awatere, Wairau and Renwick-age surfaces – including Blenheim, is likely.

Future trends

From our understanding of the behaviour and history of the Wairau River, and our interpretation of the effects of predicted environmental changes, we believe the future evolution of the Wairau floodplain will follow a similar pattern to the recent past:

- Gravel waves will continue to migrate down the river. These will reduce flood freeboard, and ultimately lead to channel avulsion, unless enough gravel is extracted.
- There will be an increased frequency of flooding below Tuamarina and adjacent low-lying areas because of a reduction in river gradient by coastal progradation and a possible rise in sea level. By AD 2050, the sea level may be 0.5 m above its present level.
- Aggradation and sediment transport rates will be at least as high as over the last 100 years.

Gravel aggradation may be significantly higher if the river is able to transport its theoretical bed load. Gravel deposition will be restricted to within the vicinity of the main channel as dispersing flood flows from flood breakouts rapidly lose velocity. Fine sediments will be deposited at the margins of such flows and continue to accumulate in topographic lows and pondage areas, especially behind obstructions such as the Pukaka Stream embankment and the lower Wairau River stopbanks. Aggradation of sand and silt may increase in the lower reaches below Tuamarina as sea level rises.

- The Opawa overflow from the vicinity of Conders Bend will continue to serve as a major distributary of Wairau floodwaters and sediment. Sites of long-term channel aggradation, such as those currently occurring between Wratts and Jefferies Roads, and between Hillocks and Cravens Roads, may also cause river avulsion by reducing waterway capacity and threatening stopbank stability.

- Strong northward longshore drift will continue to maintain coastal progradation, although the rate may be reduced as a result of sea level rise. The bar will stay much in the same position as it is now, although there will be increasing instability of the river mouth and training wall as a result of sea level rise and increased tidal outflow. However, if the wave climate becomes more northerly the effects on longshore drift and coastal progradation will be more complex.

- Long-term subsidence is projected to be greatest for the area of fine-grained wet sediments dominant in the southeastern part of the Wairau Plains.

- Development of the Wairau Diversion to handle a greater proportion of the flood flows will reduce flood levels and potential ponding in the old course below Tuamarina, provided that upstream flood flows are contained within the main channel.

- In the absence of a solution to the longer-term problems arising from gravel aggradation, continuing progradation of the coastline and lengthening of the lower river channel, it is inevitable that the river will attempt to adopt a new course. It is within engineering capacity to control the location of that course.

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