Potential influence of Wairau Catchment historical land cover change on Wairau Aquifer levels

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EXECUTIVE SUMMARY

This report, commissioned by the Marlborough District Council (MDC) and prepared by GNS Science with assistance from Manaaki Whenua Landcare Research (MWLR), examines the impact of historical land cover (LC) changes on the groundwater levels of the Wairau Aquifer in the Marlborough District from the 1960s to the present. The Wairau Aquifer, which is crucial both ecologically and economically, has experienced a notable decline in groundwater levels, raising concerns about the sustainability of water resources in the region.

Historical LC data for the Wairau Catchment from NZTopo50 maps covering the period from the 1940s to the 1980s were collated and digitised. The Land Cover Database version 5 (LCDB v5.0) covering the period from 1996 to 2018 was also obtained. These data were used to identify and quantify changes in LC within the catchment. River flow, rainfall and groundwater level data from MDC from the 1930s onwards were also collated and assessed using graphical and statistical analyses.

Reduction in groundwater levels in the Wairau Aquifer has been occurring since the 1970s. The largest LC change is a 21,576 ha (5% of the total catchment area) decrease of high-producing grasslands, and an increase in Orchard, Vineyard or Other Perennial Crop (17,234 ha) and exotic forest (10,270 ha) occurring between the 1996 and the 2018 LC surveys. These LC changes are likely to have increased water demand, and so, potentially contributing to groundwater level decline. However, this is unable to be qualified or quantified due to the absence of adequate groundwater abstraction data.

Groundwater elevations at all monitoring sites exhibit regular seasonal fluctuations in response to high- and low-flow events in the Wairau River. Despite these fluctuations, a significant long-term declining trend is evident across four of the six groundwater sites over the monitoring period 1958–2023..

River flow and groundwater elevation data between 2012 and 2015 support findings of earlier studies that showed changes in the Wairau River's morphology, such as riverbed erosion and incision, and reduced groundwater recharge rates, contributing to the decline in groundwater levels. Increased groundwater abstraction for irrigation, particularly for vineyards, has likely impacted groundwater levels; however, the lack of adequate water use data limits meaningful quantification of this volume.

The results from this study do not provide conclusive evidence that LC changes have directly contributed to the reduction in groundwater levels in the Wairau Aquifer. The impact of LC change may be relatively small compared with abstraction.

To address this issue, it is recommended that MDC implement more comprehensive monitoring and data collection of groundwater abstraction. This will allow a more conclusive assessment of the abstraction effects on groundwater level; and provide an important dataset, such as for numerical models, for future water management.

It is suggested MDC acquire useful datasets, in addition to those already available, for future studies on the groundwater system response. These datasets include, but are not limited to, climate variability, sediment supply, evapotranspiration and greater specificity within some LC types. Assessment and modelling of these datasets will help understanding of system dynamics and inform effective water management strategies.

1.0 INTRODUCTION

The Wairau Aquifer groundwater levels and spring flows have declined since the mid-1970s. Groundwater level monitoring by Marlborough District Council (MDC) has been conducted since the 1930s and shows that groundwater levels were the highest during the 1960s.

Due to lack of data, it could not be confirmed if this groundwater level peak correlates to a maximum grassland area land coverage and the start of the Wairau Valley flood protection scheme (Davidson and Wilson 2011). The onset of groundwater level decline coincides with an increase in vegetated hill country area, and the planting of exotic forests on the North Bank foothills. Finding the causes of the decline has been a priority for MDC for the past decade, with a particular emphasis placed on the factors leading to decreased Wairau River flow, which is the primary recharge mechanism for the Wairau Aquifer (Wöhling et al. 2018).

Establishing how catchment Land cover (LC) has changed and the subsequent effect on groundwater is needed by MDC to understand the dynamics of the hydrological systems and what can be controlled, versus what are largely natural processes. Therefore, MDC commissioned GNS Science (GNS) and Manaaki Whenua Landcare Research (MWLR) to find whether changes in LC in the Wairau Catchment have contributed to variations in the Wairau Aquifer groundwater levels from the 1960s to the present.

This report first summarises historical and recent LC data within the Wairau Catchment, then describes the data processing techniques applied. Insights obtained from trend analysis and key LC changes are later described. Finally, future research and management recommendations are provided.

This study was funded by the Ministry of Business, Innovation and Employment (MBIE) via an Envirolink Grant (2414-MLDC168) and GNS's Groundwater Strategic Science Investment Fund (SSIF) Programme.

2.0 BACKGROUND

The Wairau Catchment study area (Figure 2.1) encompasses an area of 413,888 ha in northern Marlborough, New Zealand. The Wairau River drains this catchment, which includes steep mountain terrain of the south-bank tributaries of the Wye, Waihopai and Branch rivers, the St Arnaud Range in the headwaters and the north-bank tributaries in the Richmond Range (Basher et al. 1995).

The Wairau Aquifer, located in the northern Wairau Plain (Figure 2.1 inset), hosts the largest groundwater resource in the region, both economically and ecologically (MDC 2023). The aquifer extends from the confluence of the Waihopai and Wairau rivers, and fans eastwards to the sea.

Wairau Aquifer Recharge

The Wairau Aquifer is divided into four sectors by location and or aquifer confinement status (Figure 2.1 inset):

- Coastal sector: near the coast.
- Lower Wairau sector: lower catchment.
- Springs sector: confined section.
- Recharge sector: unconfined section.

The boundaries of these sectors is not physically marked but are designated for description purposes. Groundwater monitoring sites used in this study lie within the recharge or springs sector (Table 2.1).

The Wairau River is the primary recharge source for the Wairau Aquifer, identified by oxygen isotope, temperature, hydraulic gradient and Lidar data (Close 2014; Wilson and Wöhling 2015; Wöhling et al. 2018; Morgenstern et al. 2019). Infiltration of precipitation and irrigation is a secondary recharge source (Davidson and Wilson 2011).

Recharge occurs mainly (95%) through the Wairau River channel, particularly within the recharge sector, which extends downstream from the Waihopai River confluence to approximately Wratts Road.

Table 2.1 Groundwater monitoring sites used in this study and their respective sector location within the Wairau Aquifer.

Groundwater Monitoring Site	Location in the Wairau Aquifer
Conders	Recharge sector / unconfined section
Wratts Road	
John Fairhall	
Selmes Road	Springs sector / confined section
Mills & Ford	
Spring Creek	

Wairau Aquifer Groundwater Level

Finding the underlying causes of the Wairau Aquifer groundwater level decline has been a priority for MDC over the past decade. Several studies have been undertaken on understanding the hydraulic connection between surface and groundwater within the Wairau Plain (Close 2014; Wilson and Wöhling 2015; Wöhling et al. 2018; Morgenstern et al. 2019; Wöhling et al. 2020).

Importantly, there has been an absence of investigation into the relationship between LC and Wairau Aquifer levels, with digital historical map data (pre-1996) being previously unavailable to MDC. This was a critical knowledge gap that inhibited understanding of the aquifer and river's natural state prior to intensified land use practices within the catchment.

Climate oscillations over 10–30-year cycle cause alternating wetter and drier conditions in the Wairau Catchment (Wöhling et al. 2018). Recent shifts towards wetter conditions are not yet reflected in the hydrological record.

Groundwater monitoring wells indicate a peak in groundwater levels occurred around 1960, followed by a persistent, aquifer wide, declining trend in groundwater level and spring flow. (Davidson and Wilson 2011). This decline pre-dates the establishment of the Wairau Plains vineyard and orchard industry.

Aquifer recharge decreases rapidly when Wairau River flow at SH1 Tuamarina drops below 20 m^3/s. The occurrence and duration of low-flow periods are linked to climate phases, with an overall increase in low-flow days contributing significantly to declining groundwater levels. These effects are worsened by groundwater abstraction (Wöhling et al. 2018). Individual and cumulative groundwater abstraction volumes are not accurately known, which is an important information gap for understanding of the system and this study.

Impact of Single Events and Engineering Activity on Groundwater Level

The previous studies mentioned above found that weather and climate alone do not fully explain the observed trends groundwater level. While events like floods and earthquakes can alter the hydrological regime, changes in river-bed geometry due to erosion during major floods and engineered river channel modifications also potentially cause lasting decreases in groundwater levels and spring flows.

The Wairau River experienced several large flood events between 2010 and 2012. The largest flood event, in May 2011, peaked at 2,918 m3/s. This flood event was large enough to erode and incise the riverbed and cause lower recharge rates as a result (Wöhling et al. 2020). Longer-term events, such as river training measures, have impacted river morphology, flow regime and aquifer recharge. These measures began over 150 years ago, restricting the braided channels of the Wairau River.

The construction of the Benhopai Dam in 1928 altered the morphology of the Waihopai and Wairau rivers. The Waihopai River previously contributed a large amount of gravel and sediment to the Wairau River, but the dam disrupted this supply, leading to gravel accumulation upstream of the dam (MDC 2016).

Since the 1970s, river training measures (stop banks) have increased sediment deposition and reduced river-channel capacity, raised flood risks and prompted gravel extraction to remove excess sediment. From 1994 to 2016, gravel extraction averaged about 150,000 m^3 per year (MDC 2016), exceeding the natural supply and causing erosion and riverbed level decline.

Observations from 1969 to 2012 show a decrease in riverbed levels in most sections from Conders to SH1 (MDC 2016). The decrease in riverbed levels has reduced river flow and groundwater recharge (Wöhling et al. 2018). The Gravel Bed Rivers (GBR) Endeavour project identified a 1 m drop in the Wairau River riverbed levels as a major factor in groundwater level decline, alongside reduced summer flows (Wöhling et al. 2020). This decline in river flow resulted from riverbed modification, local gravel extraction and decreased sediment input from upstream catchments.

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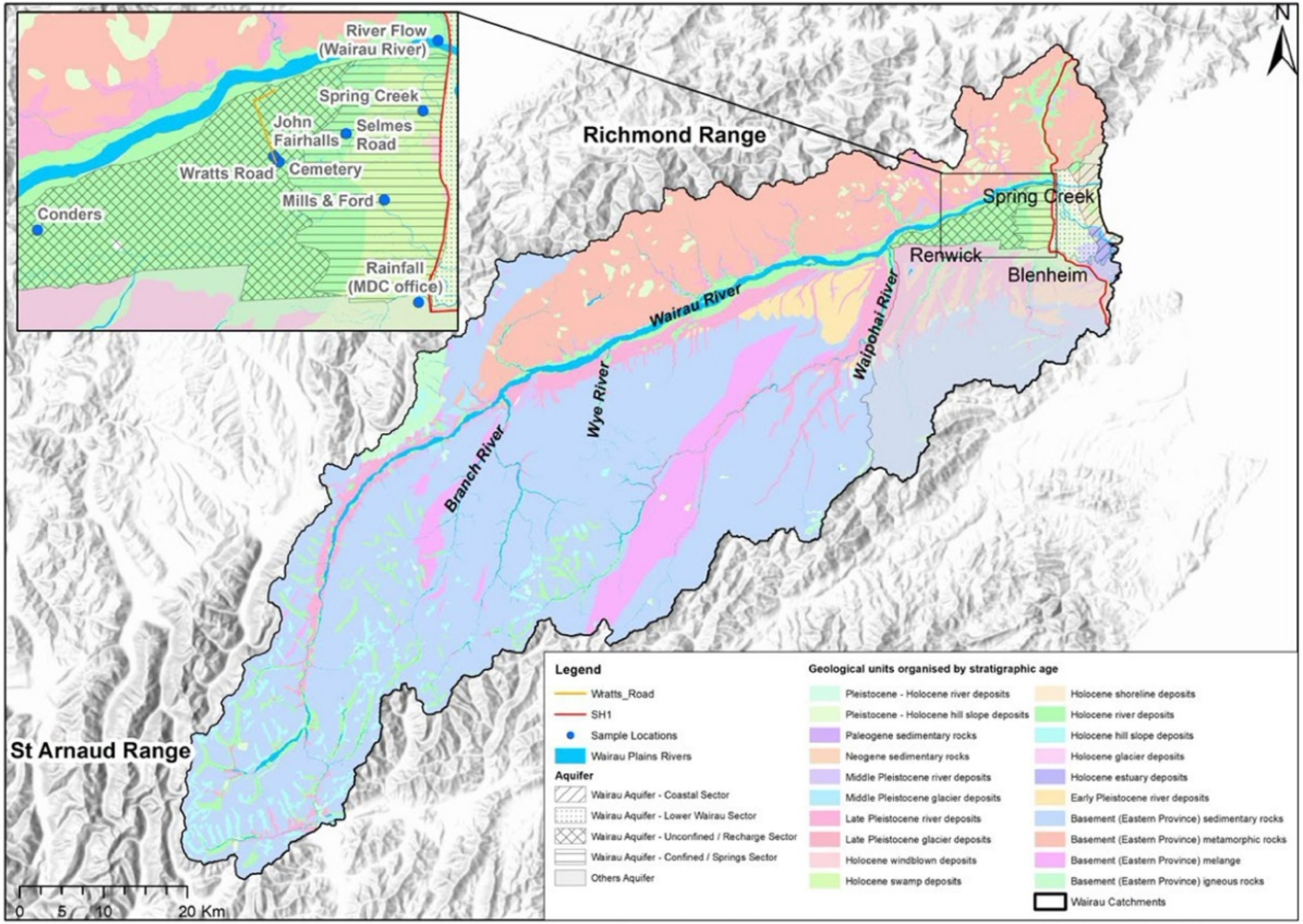

Figure 2.1 Wairau River catchment geology and key geographic locations along with Wairau Aquifer (shaded areas) and monitoring locations (blue circles) used for this study (inset).

3.0 METHODS

3.1 Wairau Catchment Input Datasets

3.1.1 Input Datasets

The Wairau LC dataset was compiled by first aggregating and digitising paper topographical maps for the earlier time intervals, 1940s decade through to the 1980s with the most recent LC digital maps (1996–2018) (Table 3.1 [and references therein]). Historical and current topographic and LC maps, and associated metadata, are provided in Appendix 1.

Table 3.1 Topographic and land cover datasets used in this study.

Dataset Name	In-Text Reference	Description	Temporal Coverage	Reference
Land Cover Database	LCDB/ LCDB v5.0	Multi-temporal thematic classification of New Zealand's LC, which includes 33 LC classes for New Zealand's mainland. Features of this database are described by a polygon boundary, a LC code and a LC name at five-yearly intervals. Version 5.0 (LCDB v5.0), released in January 2020, was utilised for our analysis.	1996–2018	Landcare Research (2020)
LINZ 1:50,000	-	Spatial data for 1980s vegetation as points, lines and polygons were downloaded and vector data clipped from a repository held by MWLR.	1980–1989	
New Zealand Topographic Maps at 1:50,000 scale	NZTopo50	High-resolution scans of historical maps from 1899 to 2009. These maps are not georeferenced but do have all the standard information in the legend and ancillary details, such as date of publication, map series and scale. A full time series of georeferenced topographical maps for New Zealand, collated by decade of publication (1899–2009) accessed via the website www.mapspast.org.nz. These maps are based on and include data from Toitū Te Whenua Land Information New Zealand (LINZ).	1960–1989	Mapspast (2023); University of Auckland (2023); LINZ (2022)
New Zealand Topographic Vegetation Data at 1:50,000 scale	-	Topographic vegetation data for the more recent time interval.	2017–2022	LINZ (2022)
Forest Service Mapping Series 6 1997, 1:250,000	FSMS6	Topographic vegetation data for the catchment.	1997	Ollivier & Co (2008)
Freshwater Ecosystems of New Zealand (FENZ) v1.0 geodatabase	FENZ v1.0	Catchments that would provide surface runoff to the Wairau Aquifer or were in the immediate area of the Wairau Aquifer. Data obtained provides the catchment boundary.	2019	Ministry for the Environment (2019)

3.1.2 Assembly of a Seamless Land Cover Mosaic

In this study, the Wairau Valley Catchment boundaries were defined as the outer boundaries of five Sea Draining Catchments from the Fresh Water Ecosystems of New Zealand (FENZ) v1.0 (Figure 3.1; Table 3.2; Ministry for the Environment 2019). FENZ catchments were derived from hydrological analysis of a digital elevation model based on 20 m contour lines.

In total, 34 historical topographical maps were utilised for the decade time-periods 1940 to 1980 (1940s = 12 maps at the scale of one inch to mile scale, 1960s = 12 maps at the scale of one inch to mile scale, 1980s = 10 maps at the scale of 1:50,000). Maps were found from the Mapspast (2023) website, then downloaded and georeferenced to produce a seamless mosaic using ESRI ArcPro.

While NZTopo50 maps supply valuable historical data, their coverage is limited to pre-1996. For ongoing and recent analysis, more current data sources like the LCDB are necessary to understand contemporary trends and changes in land use. Advances in geographic information systems (GIS) and remote sensing technologies have led to the development of more accurate and detailed datasets, such as the LCDB, which supplies more recent and detailed information on LC changes from 1996 to 2018.

These modern datasets are preferred for their precision and relevance to current environmental and land use studies. The transition from NZTopo50 maps to more modern datasets like LCDB v5.0 reflects the need for up-to-date, accurate and comprehensive data to analyse and manage LC changes and their impacts effectively.

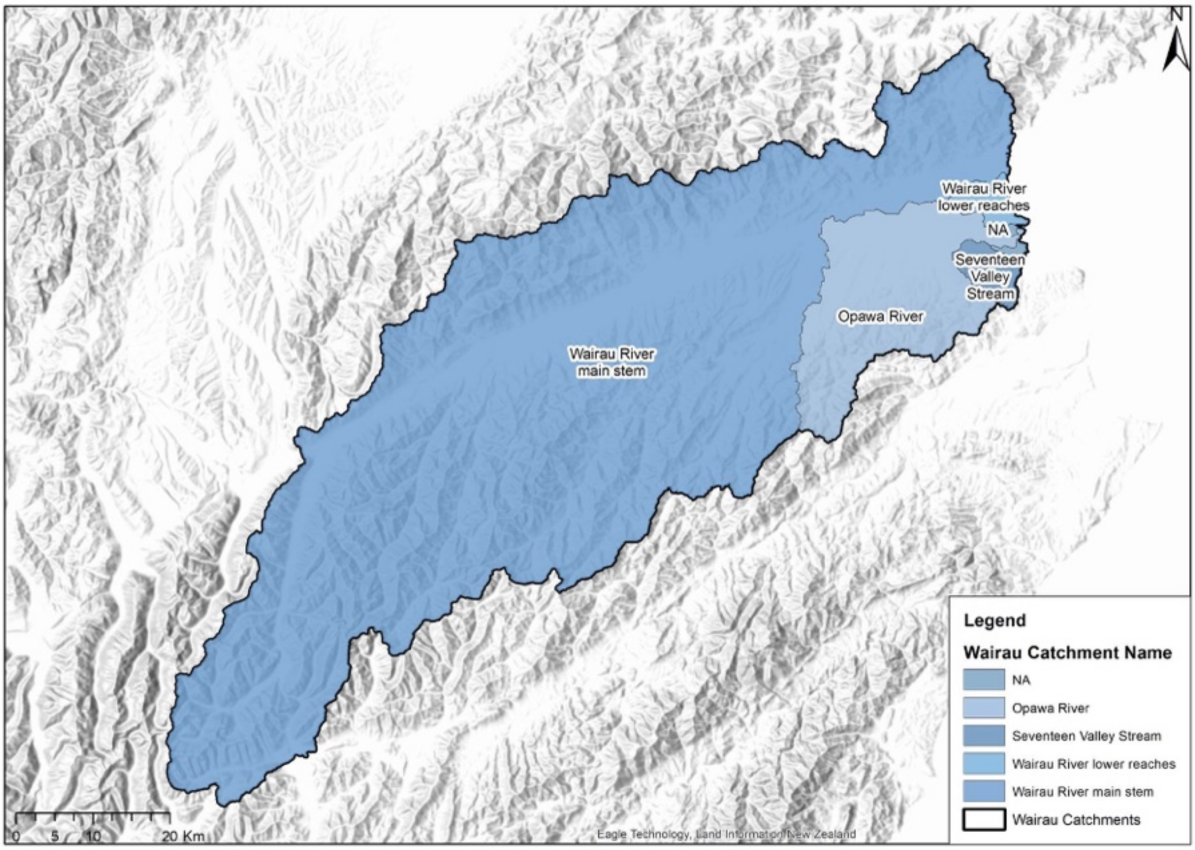

Figure 3.1 FENZ v1.0 catchment boundaries defining the extent for vegetation identification for the entire Wairau Catchment (Ministry for the Environment 2019).

Table 3.2 Names of catchments defining the study area.

Catchment ID	Catchment Name	Area (ha)
1838	Wairau River main stem	358,264
1749	Omaka River	46,509
1737	Seventeen Valley Stream	4,722
1738	Wairau River lower reaches	3,470
1719	N/A	532
1662	N/A	391

3.1.3 Historic Topographical Maps Spatial Accuracy Assessment

Horizontal offset between historic topographical map mosaics and the current digital layer was identified, as well as the potential for discrepancy in how areas of forest or bush features were digitised.

An assessment of the horizontal offset between historic topographical map mosaics and the current digital layer was done by comparing the location of surveyed triangulation stations (trig points) in the Wairau Catchment (Curwen 2023) between datasets.

Trig locations were digitised from historic maps, and distance to the corresponding trig in contemporary datasets calculated using ArcGIS. Trig points features depicted on maps dating back to the 1940s consistently appeared positioned to the north and slightly west of their current locations. Calculated horizontal displacement range from 13 to 174 m, with larger values for the older datasets (Table 3.3).

Table 3.3 Horizontal offset of historic topographical map mosaics compared with 2019 NZTopo50 location.

Dataset Temporal Coverages Grouped by Decade	Distance Between Trig Point in Previous Decades and Current NZTopo50 Trig Location (m)				Number of Trig Points Compared
	Min	Max	Mean	Median	
1940s	92	332	169	174	59
1960s	7	67	26	22	59
1980s	1	35	13	13	56

Scanned historical NZTopo50 maps have the outlines of features, such as patches of bush and exotic forests, represented as lines with a width of around 16 m. Thus, there is a measurable difference if digitising the line following the inner or outer position of the line. Lines were digitised in streaming mode at a zoom scale of between 1:10,000 and 1:25,000, depending on the complexity of features.

Table 3.4 summarises the potential impact on overall area of LC classes from the 1940s and 1960s if the digitised boundary line was shrunk 8 m towards the centre of the area or expanded 8 m towards the outermost extent of the black LC boundary line as printed on the NZTopo50 maps.

Larger LC areas, such as Bush class, are less affected by minor variations in position of the boundary (an overall 3.3% difference between expanded and shrunk boundary in the 1940s and 5% in the 1960s). Smaller areas are more affected by the variation, such as Plantation class, which has an overall 18.1% difference between expanded and shrunk boundary in the 1940s and 20.7% in the 1960s.

Table 3.4 An example of what happens to areas of vegetation classes with an 8 m buffer removed from or added to vegetation boundaries for land cover classes from 1940s and 1960s NZTopo50 Maps.

	Class	Digitised Area (ha)	Digitised Area Shrunk by 8 m	% of Digitised Area Within Boundary	Digitised Area Expanded by 8 m	% of Digitised Area Within Boundary
1940s	Bush	65,270	64,201	98.4	66,348	101.7
	Plantation	498	454	91.1	544	109.2
	Scrub	1,981	1,839	92.9	2,126	107.4
1960s	Bush	79,204	77,204	97.5	81,193	102.5
	Plantation	272	243	89.4	299	110.1
	Scrub	33,503	31,931	95.3	35,099	104.8
	Trees shelterbelts	84	65	77.1	104	124.0

3.1.4 Comparison of Classes in Different Iterations of Land Cover Mapping

The LCDB is a digital database that supplies nationwide, consistent LC maps derived from satellite imagery analysis. These maps depict the distribution of 33 specific LC types, measured in metres squared (m^2) or hectares (ha). Land cover across the country is mapped at five intervals: 1996/97, 2001/02, 2008/09, 2012/13 and 2018/19.

Each interval was released as an updated version of the LCDB (versions 1 through 5), and although the classification system evolved between versions 1 and 3, it remained consistent thereafter. Table A2.1 details how LCDB classifications have evolved over the time intervals. Crucial for LC analysis, there is backwards compatibility of the LCDB across each version.

The LCDB is suitable for national and regional environmental monitoring, biodiversity assessments and forest inventory. The latest version (5.0), developed by Manaaki Whenua – Landcare Research with the Ministry for the Environment and other government agencies' support, was released in January 2020 and included updates to all earlier time intervals.

The classification of vegetation types has undergone changes over time, posing challenges in comparing the extent of bush areas defined in the 1940s with those found through satellite remote sensing within the LCDB program. The delineation of bush, plantation, scrub and orchard polygons in NZTopo50 maps featured distinct boundaries (Figure 3.2).

However, the delineation of scattered scrub areas lacked clear outer boundaries, making digitisation of its extent unfeasible. Thus, it is not possible to define and calculate the area of scattered scrub from 1940s to 1960s NZTopo50 maps, as it is unclear where to find where scattered scrub grades to no scrub at all.

The method and level of detail in mapping underwent significant evolution from 1940 to 1980. Notably, the 1940s NzTopo50 maps depicted three LC classes, expanding to four by the 1960s and then further to six in the 1980s. The earlier maps featured broad LC classes encompassing various categories, such as scrub, bush, plantation and orchard. Artificial surfaces were not mapped in NZTopo50.

Refinement of the classification system occurred with the introduction of LCDB, enhancing precision in land use classification. The area of different LC classes mapped between the 1940s and the 1980s changed largely due to the integration of satellite technology for mapping purposes in the latter decade. This advancement enhanced accuracy in LC classification and enabled the mapping of larger geographical areas that were previously inaccessible.

The 1980s and later digital mapping uses vector polygon features as supplied by Toitū Te Whenua Land Information New Zealand (LINZ) to map vegetation patches. The outlines go to an infinitely narrow width with continuous zooming in – so no assessment of the accuracy of calculated area was applied as there was no grey area around the position of the linework.

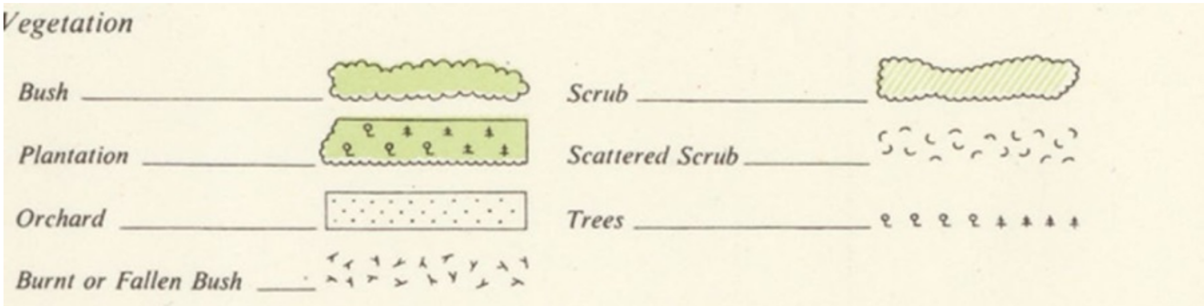

Figure 3.2 Vegetation classes from historical topographic maps in the 1940s and 1960s datasets (Mapspast 2023).

There has been no effort to correlate vegetation classes derived from NZTopo50 maps with those of the LCDB by MWLR, as the task of aligning LC classes from the LCDB to match the rudimentary classification in NZTopo50 maps is beyond the scope of this project, owing to time and technical difficulty.

Table 3.5 illustrates the different vegetation classes within the NZTopo50 datasets. Table A2.2 details the different LC classes for the LDCB over the 1996–2018 time interval. Scattered scrub areas in the NZTopo50 could correspond to LCDB categories, such as Manuka/Kanuka, Matagouri and/or Grey Scrub, making meaningful comparisons about area and actual ground vegetation challenging.

Table 3.5 Land cover classification evolution of NZTopo50 maps from the 1940s to 2023.

1940s NZTopo50	1960s NZTopo50	1980s NZTopo50	2017–2023 NZTopo50
Bush	Bush	Exotic, Native	Exotic, Native
Plantation	Plantation	Orchard, Vineyard	Orchard, Vineyard
Scrub	Scrub	Scrub	Scrub, Scattered scrub
-	Trees shelterbelts	Trees shelterbelts	-

3.2 Data Processing

3.2.1 Land Cover Change Analysis

Visual and calculated area change analysis of the NZTopo50 and LCDB LC changes were done separately, owing to disparities in mapping precision and accuracy for the following time periods: 1940s, 1960s and 1980s (NZTopo50) and 1996, 2001, 2008, 2012 and 2018 (LCDB). Land cover changes were calculated by subtracting areas from one dataset to the more recent one. The result is either positive (area increase) or negative (area decrease).

Additionally, the overall LC changes between the oldest and the youngest dataset were calculated. Area changes greater than 100 ha (18 classes) were selected for graphical analysis and correlation assessment. Spatial changes in LC maps were visually assessed between each time interval to discern changes and interpret the nature of the land use transformations.

3.2.2 Water Quantity Time Series Analysis

The time series datasets consisted of groundwater elevation, metres above sea level (m asl), at six sites (1958–2023), rainfall at one site (1991–2023) and river flow at two sites (1960–2023) (Table 3.6). Missing data flags (i.e. null or 99999 values) were removed from the dataset. Average quarterly groundwater elevations and average monthly rainfall and river flow were used to make the data clearer to interpret. Data for Cemetery well were not graphed as the data had many gaps making graphing and interpretation difficult.

Trend analysis was performed using the R software (version 4.3.3) (RStudio Team 2024) using the LWP-Trends (version 2101) library (Snelder and Fraser 2018) to compute the Mann-Kendall trend test Sen's slope estimations and Kruskall-Wallis seasonality tests (Helsel et al. 2020). In this assessment, a decreasing or increasing trend diagnostic was not informed by the sole comparison of the trend test p-value to an arbitrarily defined confidence level.

Instead, a symmetric confidence interval around the trend was calculated. If this interval contained a zero value, the trend was described as "uncertain". If this interval did not contain a zero value, this interval was "established with confidence" and assigned either a "decreasing" or "increasing" descriptor. This method was recently developed and applied to river quality and groundwater state and trend assessments (Larned et al. 2016; McBride 2018).

Two seasonality settings were used: monthly for cumulative rainfall and monthly average river flows and quarterly for groundwater elevations (Autumn, Winter, Spring and Summer), starting from the 60th Julian day (1 March). The Sen's slope estimator and Mann-Kendall test were seasonality adjusted where seasonality was detected. The following time periods were used for trend analysis: pre-1996, 1996–2008, 2009–2018 and the full length of the record. Shorter time periods were based on the largest LC changes.

The datasets were plotted using R software (version 4.3.3) (RStudio Team 2024). Vertical lines on each graph at the intervals of 1960, 1980, 1996, 2001, 2008, 2012 and 2018 correspond to the NZTopo50 and LCDB v5.0 LC time intervals.

Trend analysis and comparison of groundwater elevations and LC change was done visually.

Table 3.6 Water quantity monitoring datasets used in this study (sourced by MDC).

Dataset Type	In-Text Reference	MDC Reference	Temporal Coverage
Rainfall	Rainfall at MDC Office	Blenheim at MDC Office	1991–2023
River flow	Wairau River	Wairau River flow at SH1 Tuamarina	1960–2023
	Spring Creek	P28w/2226	1996–2023
Groundwater elevation	Wratts Road	P28w/3009	1996–2023
	John Fairhall	P28w/0238	1958–1997
	Cemetery well	P28w/1613	1936–2023
	Mills & Ford	P28w/4404	2009–2023
	Selmes Road	P28w/4577	2010–2023
	Conders	P28w/0398 and P28w/3831	1973–2023

4.0 RESULTS

4.1 Wairau Catchment Land Cover Dataset

Historical maps of Wairau Catchment LC from the 1940s, 1960s and 1980s are provided in this subsection. The coordinate reference system for digitised polygons is NZGD 2000 New Zealand Transverse Mercator.

NZTopo50 data for Wairau Catchment Land Cover is presented in three figures from GIS shape files:

- *Wairau_Catchment_LC_(1940s)* (Figure 4.1).
- *Wairau_Catchment_LC_(1960s)* (Figure 4.2).
- *Wairau_Catchment_LC_(1980s)* (Figure 4.3).

The *Wairau_Catchment_LC_*shape file attributes provide NZTopo50 map attributes as follows (attribute name as it appears in the dataset shown in brackets):

- Count of polygon/polyline/point (FID).
- Feature type – polygon/polyline/point (Shape).
- Unique LC (vegetation) class – Bush/Exotic/Native/Scrub/Plantation/Orchard/Vineyard/Trees shelterbelts/unmapped (Class).
- Unique coverage area of class in metres squared (Area_m^2).
- Unique coverage area of class in hectares (Area_ha) (Table 4.1).

Only one polygon is associated with a named class. Attribute names, descriptions and values are provided in Table 3.6.

The disclaimer and licence for these datasets are provided in Appendix A1.2.

4.2 Spatial and Temporal Land Cover Changes

Between the 1940s NZTopo50 and 2018 LCDB v5.0, the number of LC classes increased from three classes to 31 classes. Some classes only cover a small area (e.g. Flaxland, 1 ha) so were omitted; and only changes in area >100 ha (>1% of total catchment area) are described below.

Figures 4.1 to 4.3 show NZTopo50 maps from the 1940s to the 1980s.

Figures 4.4 to 4.11 show key areas of LCDB class changes between 1996 and 2018, with additional detail provided in Appendix 2.

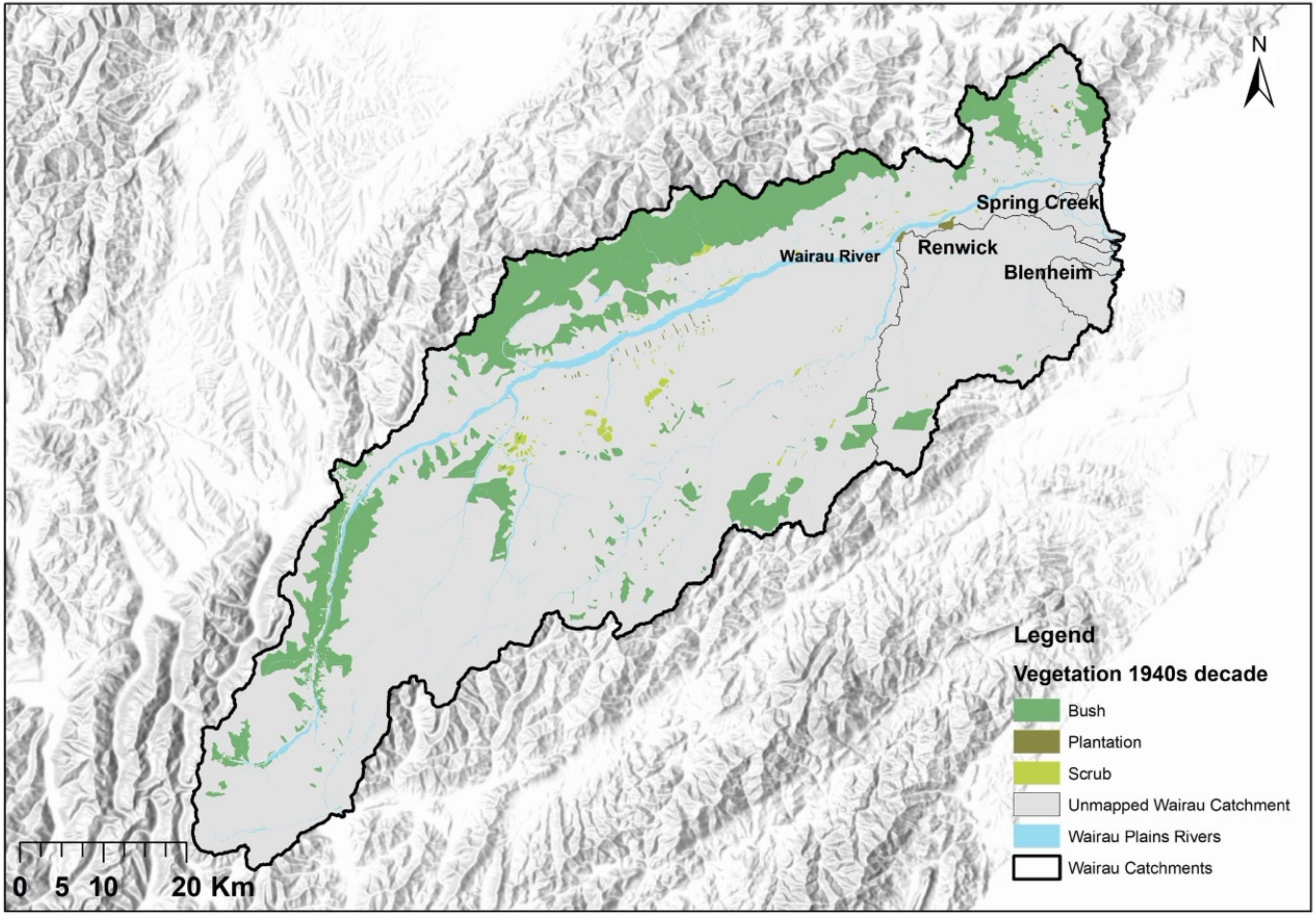

Figure 4.1 1940s NZTopo50 vegetation map (Mapspast 2023; University of Auckland 2023; LINZ 2022; Ministry for the Environment 2019).

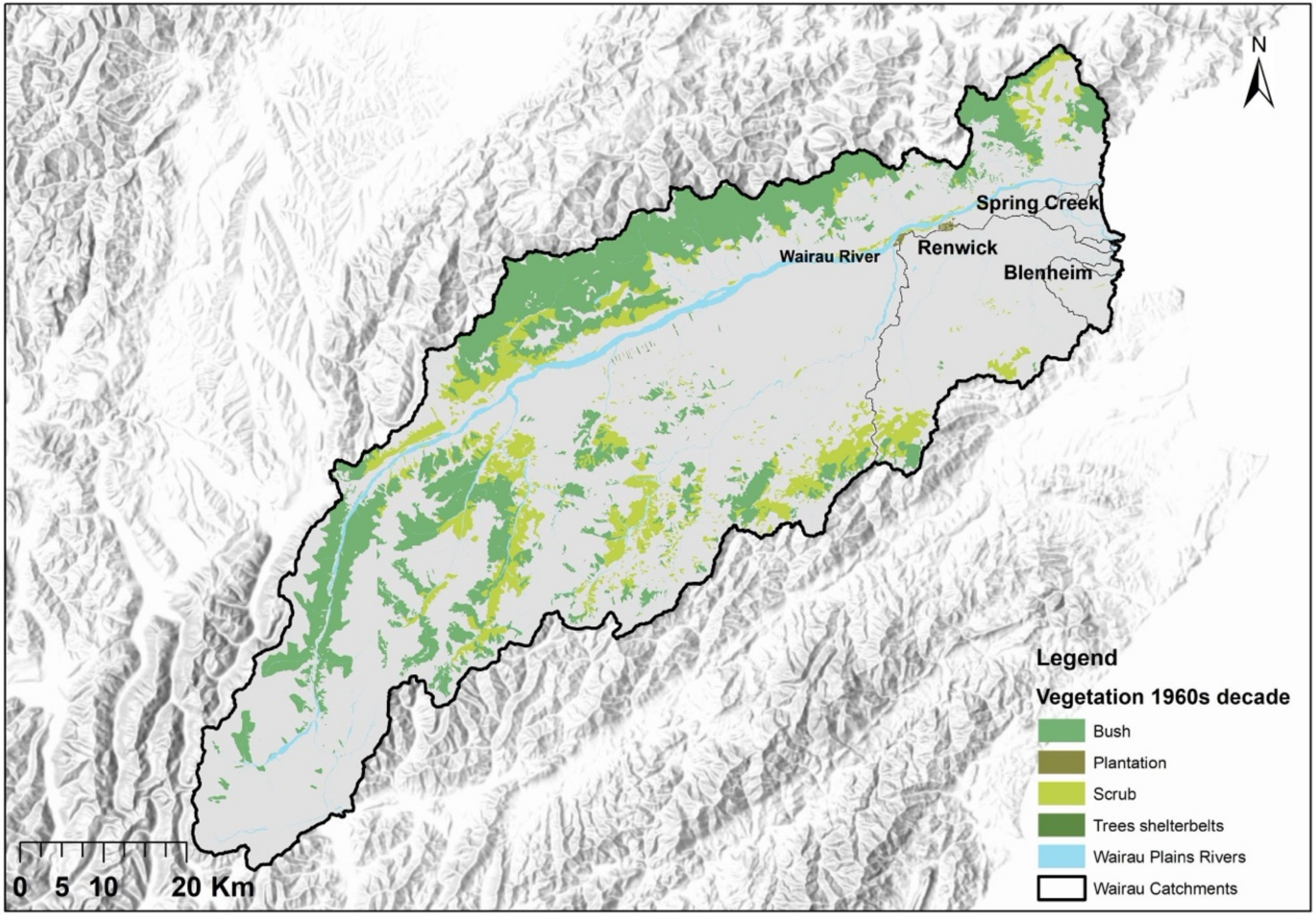

Figure 4.2 1960s NZTopo50 vegetation map (Mapspast 2023; University of Auckland 2023; LINZ 2022; Ministry for the Environment 2019).

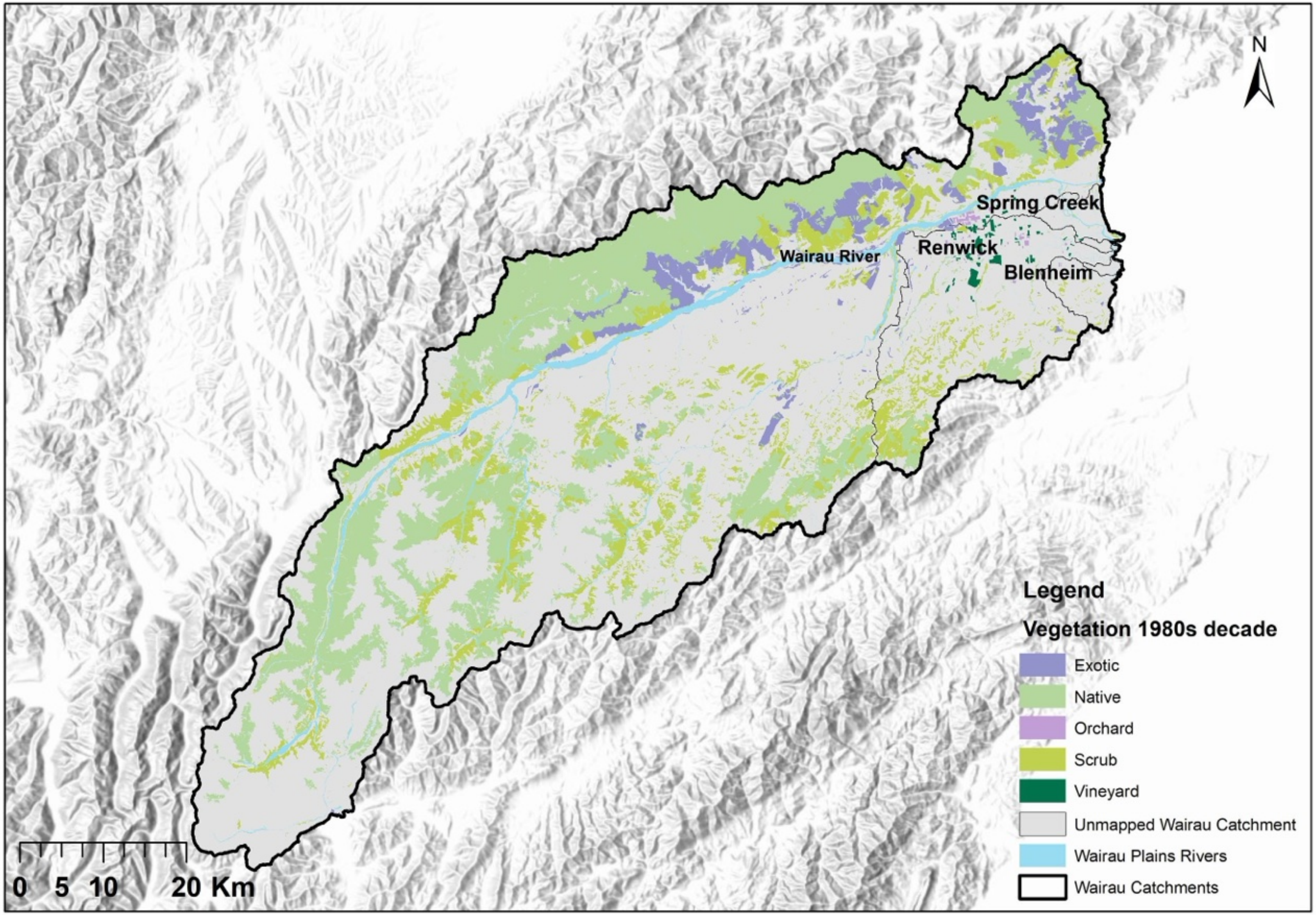

Figure 4.3 1980s NZTopo50 vegetation map without treetops or shelterbelts (Mapspast 2023; University of Auckland 2023; LINZ 2022; Ministry for the Environment 2019).

4.2.1 1940s to 1980s

In the 1940s NZTopo50 map, the Wairau Catchment was mapped mainly as Bush, 65,270 ha (21% of the total catchment area), with much of the catchment not mapped or LC “Not Designated”. (Table 4.1). Between the 1940s and 1980s, five more LC classes were introduced and mapped. Scrub class area increased gradually by 36,589 ha (12% of the total catchment area) over this period. This is likely due to advancements in mapping techniques rather than physical increase in area.

The Bush class increased by 13,934 ha (4% of the total catchment area) between 1940 and 1960. In the 1980s, Bush class was recategorised into Native Forest covering 102,489 ha and Plantation was recategorised to Exotic Forest covering 16,540 ha.

Between the 1940s and 1980s, Bush class increased by 37,219 ha (12% of the total catchment area) and Plantation class increased by 16,268 ha. The decrease of 922 ha in the Not Designated class can be attributed to improved mapping techniques over time, allowing for the better classification to other LC classes.

Notably, by the 1980s, there was the emergence of Vineyards class, at 1207 ha reflecting both a land use change since the 1960s (MDC 2023) and improved mapping techniques. Improved techniques allowed for this LC class to be distinguished from Not Designated and mapped where it was not previously. Land conversion from Not Designated to Orchard class began in the 1980s, encompassing 494 ha.

Table 4.1 Catchment area and their change per land cover classes between 1940 and 1980.

Class (1940–1960s)	1940 Area (ha)	1960 Area (ha)	Change 1940–1960 Area (ha)	Class Equivalent 1980	1980 Area (ha)	Change 1960–1980 Area (ha)	Total Change Area (ha)
Bush	65,270	79,204	13,934	**Native**	102,489	23,285	37,219
Plantation	497	272	-225	**Exotic Forest**	16,540	16,765	16,540
Scrub	1,981	33,503	31,522	-	38,570	5,067	36,589
Trees shelterbelts	-	84	84	-	-	-	84
-	-	-	-	**Orchard**	494	494	494
-	-	-	-	**Vineyard**	1,207	1,207	1,207
Not Designated	249,528	204,213	-45,315	-	157,976	-46,237	-922
Total mapped area	**317,276**	**317,276**	-	-	**317,276**	-	-

4.2.2 1996 to 2001

Between 1996 and 2001 (Figure 4.4; Table A2.2), the following classes decreased by the following area: High-Producing Exotic Grassland (9,519 ha, 2% of the total catchment area), Manuka and/or Kanuka (1,612 ha), Broadleaved Indigenous Hardwoods (1,032 ha), Low-Producing Grassland (699 ha), Short-rotation Cropland (493 ha), and Gorse and/or Broom (336 ha).

Conversely, the following classes increased by the following area: Orchard, Vineyard or Other Perennial Crop (6,791 ha), Exotic Forest (6,609 ha) and Matagouri or Grey Scrub (332 ha).

Near Blenheim, High-Producing Exotic Grassland and Short-rotation Cropland were converted into Orchard, Vineyard or Other Perennial Crop during this time interval. Along the north bank of the Wairau River, Broad Indigenous Hardwoods, Gorse and/or Broom, and Manuka and/or Kanuka were converted to Exotic Forest (Figures 4.9 to 4.11).

Exotic Forest is defined by Landcare Research (2020) as planted or naturalised forest, predominantly of Radiata pine but including any other pine species. Production forestry is the main land use in this class. Forest – Harvested is defined as being predominantly bare ground arising from the harvesting of Exotic Forest.

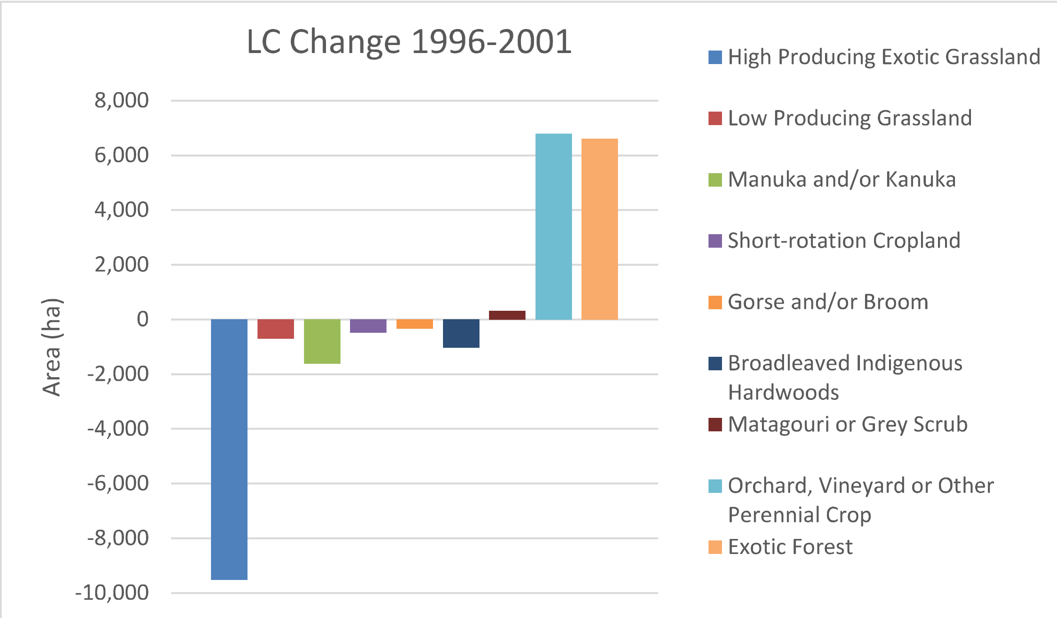

Figure 4.4 Changes in area per land cover class above 100 ha in the 1996–2001 LCDB interval.

4.2.3 2001 to 2008

Between 2001 and 2008 (Figure 4.5; Table A2.2), the following classes decreased: High-Producing Exotic Grassland (10,139 ha, 2% of the total catchment area), Low-Producing Grassland (1,157 ha), Tall-Tussock Grassland (515 ha) and Short-rotation Cropland (305 ha), among others detailed in Table A2.2.

Conversely, the following classes increased in area: Orchard, Vineyard or Other Perennial Crop (8,192 ha), Exotic Forest (3,846 ha) and Forest – Harvested (866 ha).

High-Producing Exotic Grassland and Tall-Tussock Grassland conversion into Orchard, Vineyard or Other Perennial Crop continued. On the north bank of the Wairau River, Gorse and/or Broom were replaced by High-Producing Exotic Grassland. In the same location, the conversion of Exotic Forest into Forest – Harvested continued, but not as strongly as between 1996 and 2001, (Figures 4.9 and 4.11), potentially attributed to certain forests reaching maturity (around 29 years old) and ready for harvest (Eastland Wood Council 2018).

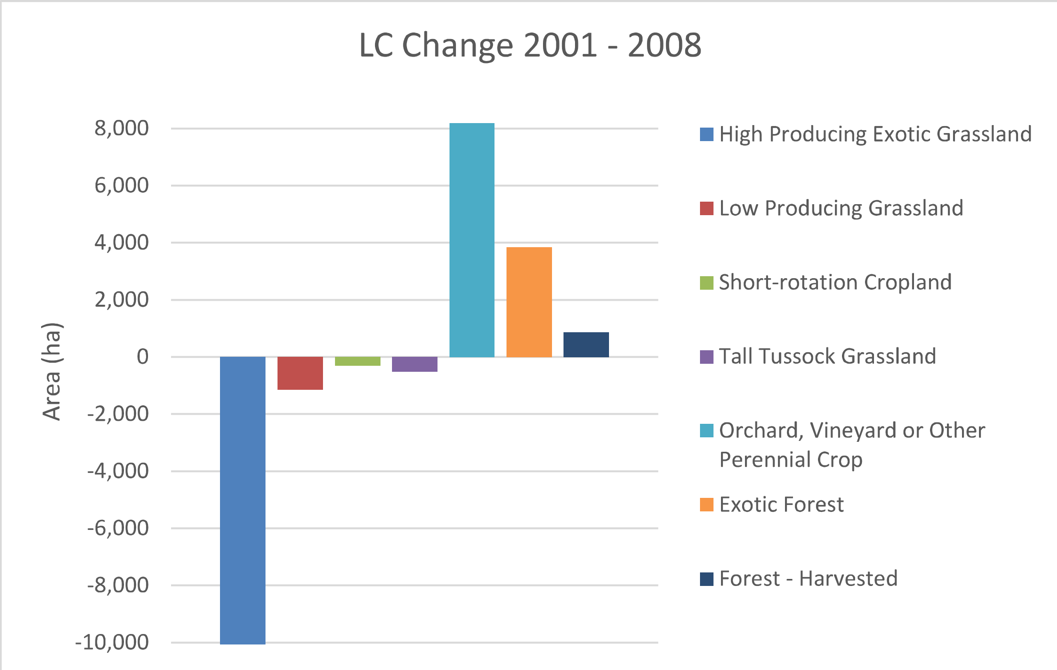

Figure 4.5 Comparison of key land covers and their changes in hectares in the 2001–2008 LCDB interval.

4.2.4 2008 to 2012

Between 2008 and 2012 (Figure 4.6; Table A2.2), the following classes decreased by the following area: Exotic Forest (2,369 ha), Low-Producing Grassland (1,061 ha), High-Producing Exotic Grassland (972 ha), and Short-rotation Cropland (272 ha).

During the same time interval, the following classes increased by the following area: Forest – Harvested (3,489 ha), Orchard, Vineyard or Other Perennial Crop (1,189 ha), Broadleaved Indigenous Hardwoods (327 ha) and Manuka and/or Kanuka (282 ha).

On the north bank of the Wairau River and on the Wairau Plains more Exotic Forest land was converted into Forest – Harvested, on a larger scale than earlier time intervals, potentially due to Exotic Forests reaching maturity and ready for harvest. During this time interval, the growth of Orchard, Vineyard and Other Perennial Crop class was lower than earlier time intervals (Figures 4.9 and 4.10).

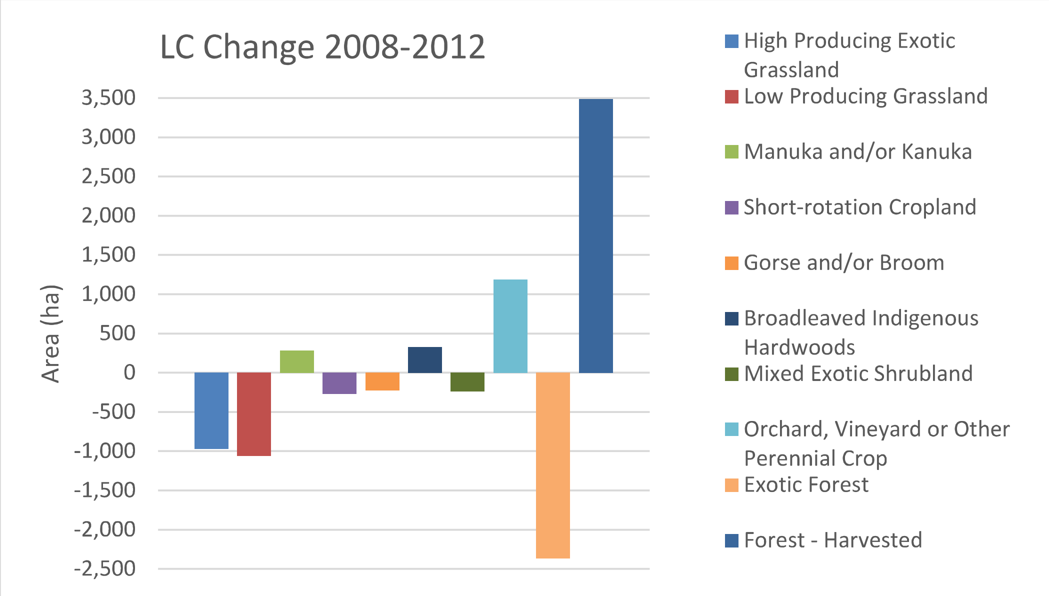

Figure 4.6 Comparison of key land covers and their changes in hectares in the 2008–2012 LCDB interval.

4.2.5 2012 to 2018

Between 2012 and 2018 (Figure 4.7; Table A2.2), the following classes decreased by the following area: Low-Producing Grassland (2,881 ha), High-Producing Exotic Grassland (946 ha), Gorse and/or Broom (591 ha), Matagouri and/or Grey Scrub (-670 ha), and Tall Tussock Grassland (240 ha).

The following classes had increases by the following area: Exotic Forest (2,184 ha), Forest – Harvested (1,565 ha) and Orchard, Vineyard or Other Perennial Crop (1,062 ha).

On the north bank of the Wairau River, Exotic Forest land was converted to Forest – Harvested and later replanted in Exotic Forest. Again, the growth of the Orchard, Vineyard or Other Perennial Crop class was less than earlier time intervals (Figures 4.9 and 4.11).

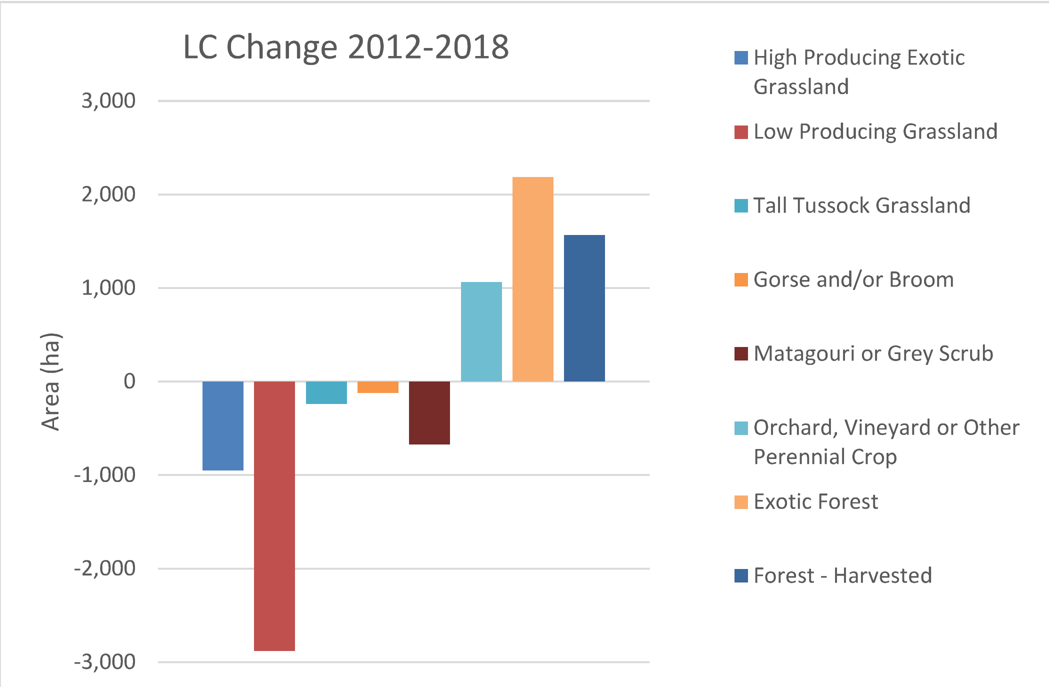

Figure 4.7 Comparison of key land covers and their changes in hectares in the 2012–2018 LCDB interval.

4.2.6 Land Cover Changes Summary

Over the period 1940s to 2018, 32 classes were recorded, with half decreasing in area, 10 increasing, and five remaining unchanged (Table 3.5; Table A2.2). Notable changes occurred between the 1960s and 1980s, and 1996 and 2008.

The conversion of grasslands to forests and vineyards peaked around 2008 (Figure 4.8). Significant conversions included High-Producing Exotic Grassland and Low-Producing Grassland into Exotic Forest, Orchards, Vineyards or Other Perennial Crop and Forest – Harvested classes. After 2008, LC changes were less than in earlier time intervals.

From 1996 to 2018, the most significant LC changes included the decrease of High-Producing Exotic Grassland (21,576 ha, 5% of the catchment) and Low-Producing Grassland (4,640 ha), and the increase of Orchard, Vineyard or Other Perennial Crop (17,234 ha), Exotic Forest (10,270 ha) and Forest – Harvested (6,270 ha).

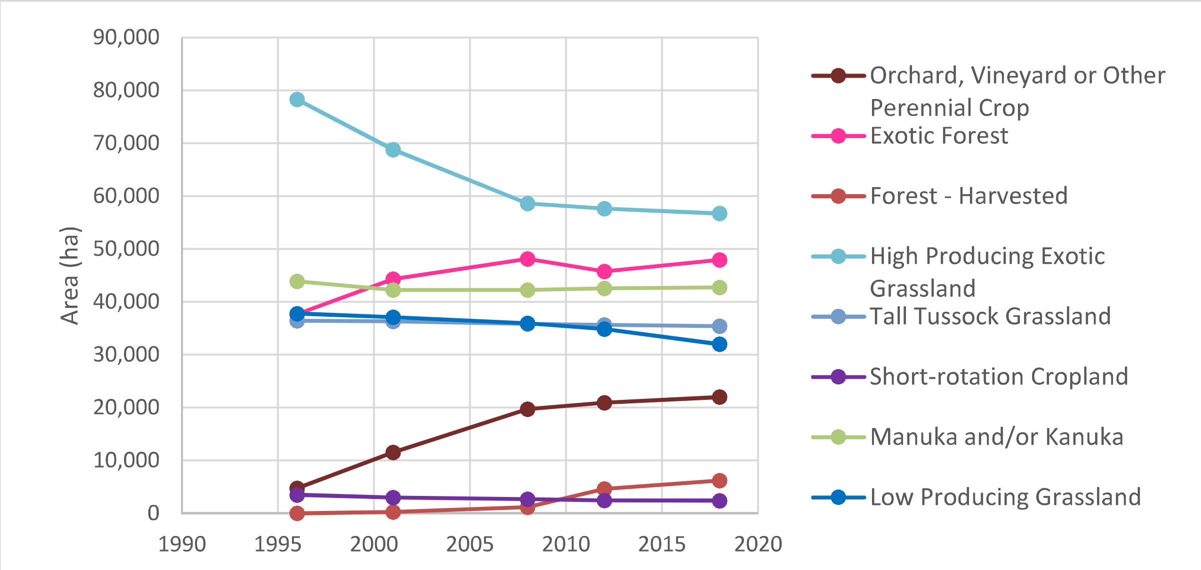

Figure 4.8 Land cover class changes greater than 1000 ha in area between 1996 and 2018.

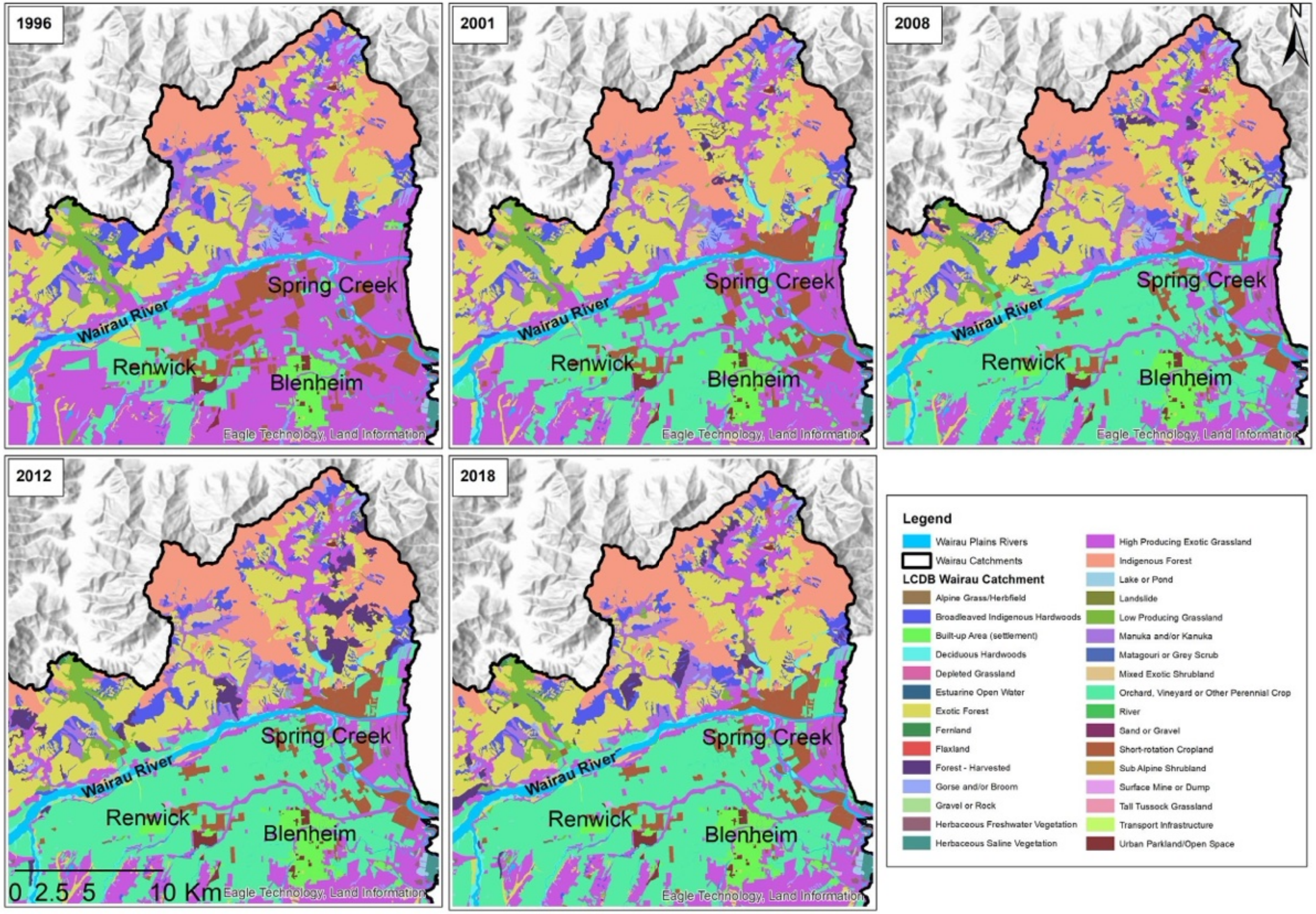

Figure 4.9 Land cover maps of the lower Wairau Plain catchment (1996–2018). This composite map shows the expansion of Vineyard, Orchard or Other Perennial Crop (bright green) surrounding Blenheim and other townships. LC change from Forest – Harvested (deep purple) to Exotic Forest (yellow) on the north bank of the Wairau River (Landcare Research 2020).

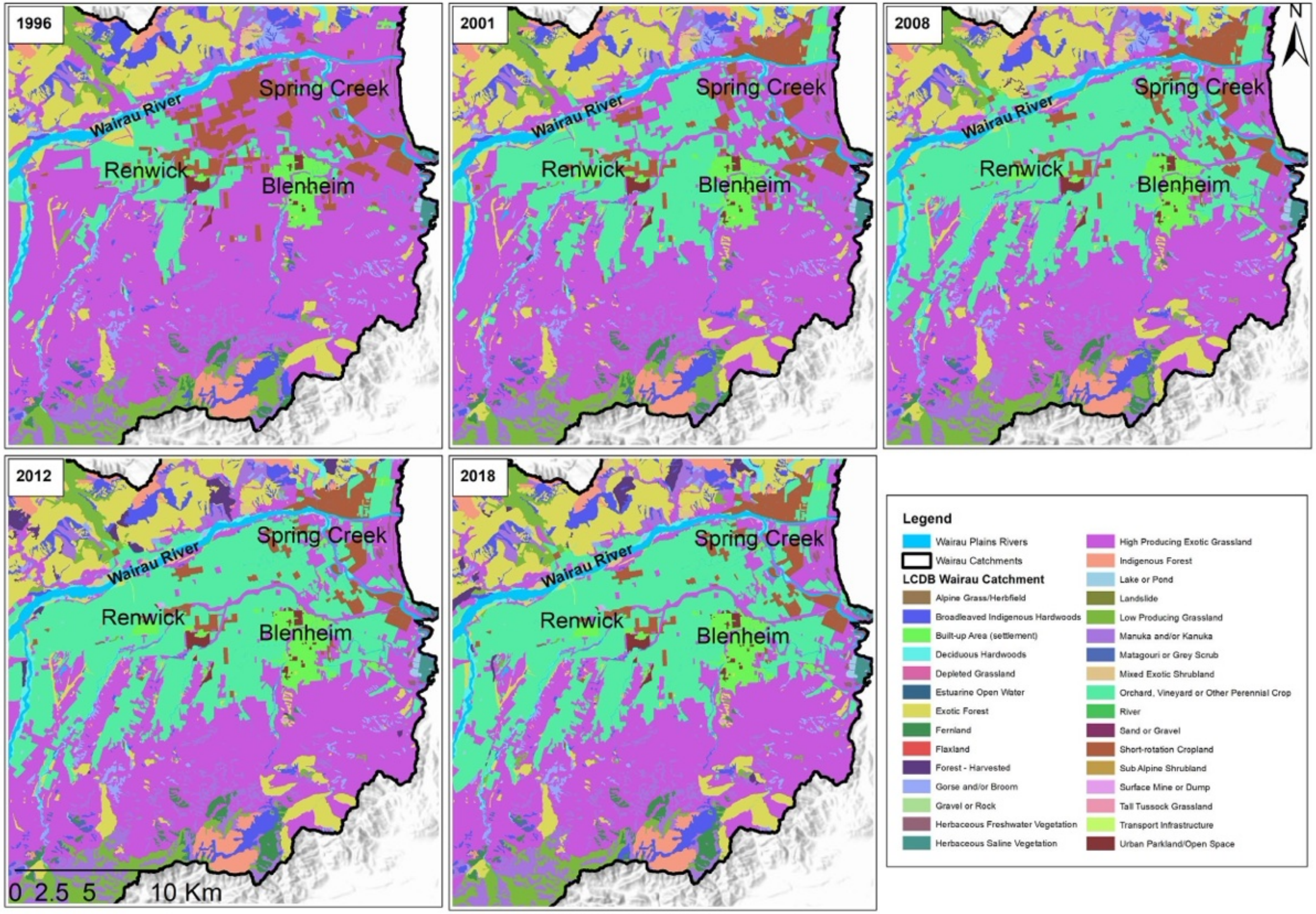

Figure 4.10 Land cover maps of the lower Wairau Plain catchment (1996–2018). This composite map again displays a rapid change in Orchard, Vineyard or Other Perennial Crop (bright green) around Blenheim, Spring Creek and Renwick until 2008, when change appears to have slowed. Forest – Harvested (deep purple) to Exotic Forest (yellow) activity is seen on the north bank of the Wairau River and near the south catchment boundary (Landcare Research 2020).

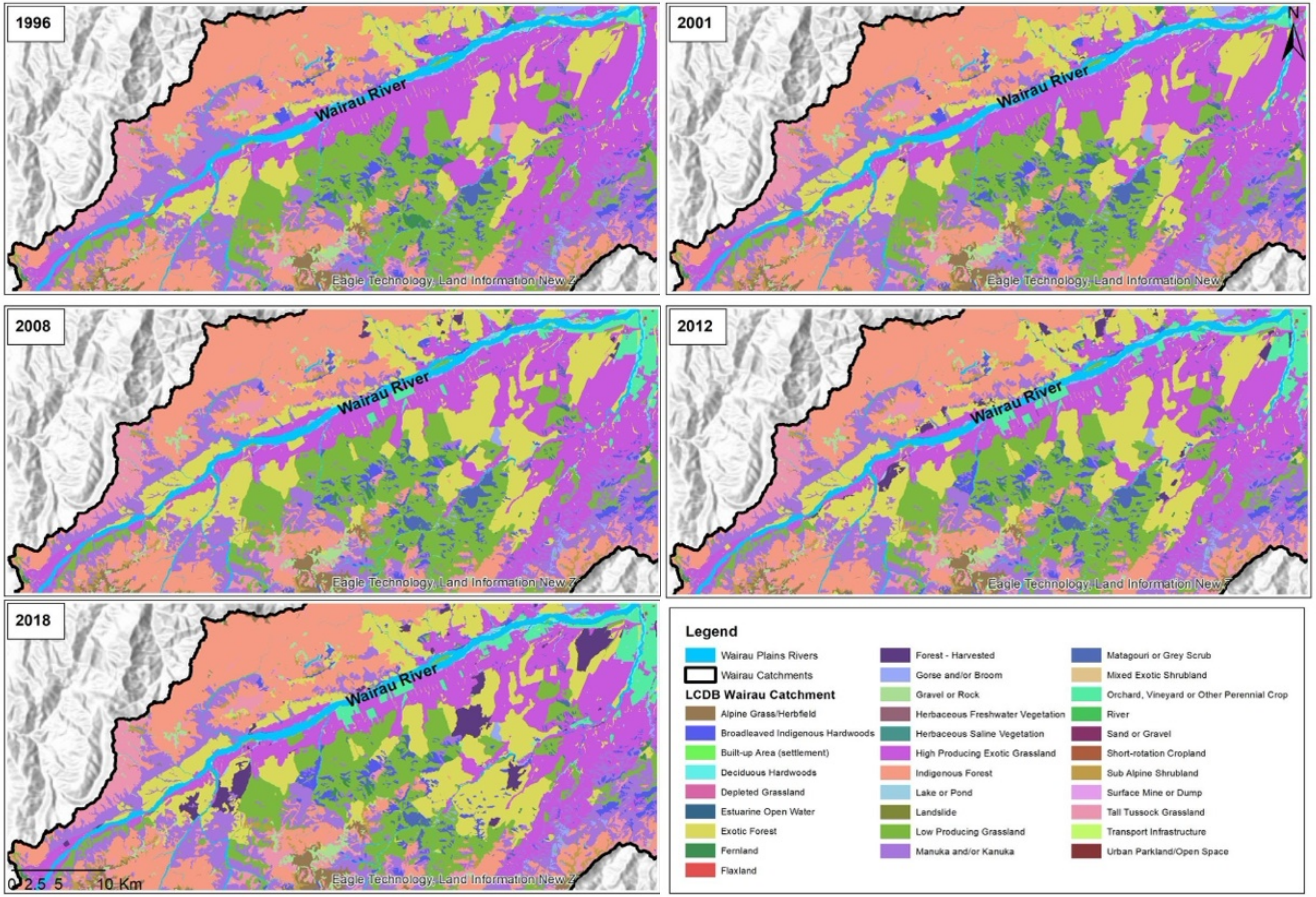

Figure 4.11 Land cover maps of the lower Wairau Plain catchment (1996–2018). On either side of the Wairau River, LC changes from Exotic Forest (yellow) to Forest – Harvested (deep purple). Between 1996 and 2001, Manuka and/or Kanuka (pale purple) is replaced by Exotic Forest (yellow) on the north side of the river with further change to small areas of Forest – Harvested (deep purple) from 2012 (Landcare Research 2020).

4.3 Hydrological Time Series

Time series data is described below by data type. Table 4.2 summarises the trend analysis results at all sites. Trends are discussed on a site-by-site basis in the section below.

Table 4.2 Trend magnitudes for selected time intervals are only shown where the trend was detected with confidence. The number in brackets indicates p-value, where applicable. “Uncertain” denotes instances where trend magnitude confidence intervals included zero and therefore it is not possible to identify a decline or a rise. “NA” indicates time periods during which there is no record and therefore trend analysis was not performed.

		Trend Magnitude (unit per year)			
Data Type	**Site**	**Pre-1996**	**1996–2008**	**2009–2018**	**Full Record**
Rainfall (mm)	MDC Office	Uncertain	Uncertain	Uncertain	Uncertain
River flow (m3/s)	Wairau River	Uncertain	Uncertain	Uncertain	-0.28 (0.002)
	Spring Creek	NA	Uncertain	-0.130 (<0.005)	-0.024 (<0.005)
Groundwater elevation (m ASL)	Mills & Ford	NA	NA	-0.012 (0.12)	-0.078 (0.009)
	Selmes Road	NA	NA	Uncertain	-0.083 (<0.005)
	John Fairhalls	Uncertain	NA	NA	-0.063 (0.001)
	Conders	-0.030 (0.004)	Uncertain	-0.066 (0.036)	-0.026 (<0.005)
	Wratts Road	NA	Uncertain	-0.037 (0.054)	-0.014 (<0.005)

4.3.1 Rainfall and River Flow Time Series

MDC Office Rainfall (1991–2023)

Rainfall at the MDC Office site (Figure 4.12) has high monthly variability and no long-term increasing or decreasing trend from 1991 to 2023 (Table 4.2). High monthly totals occur throughout the 1990s, between 2010 and 2012, and in 2022.

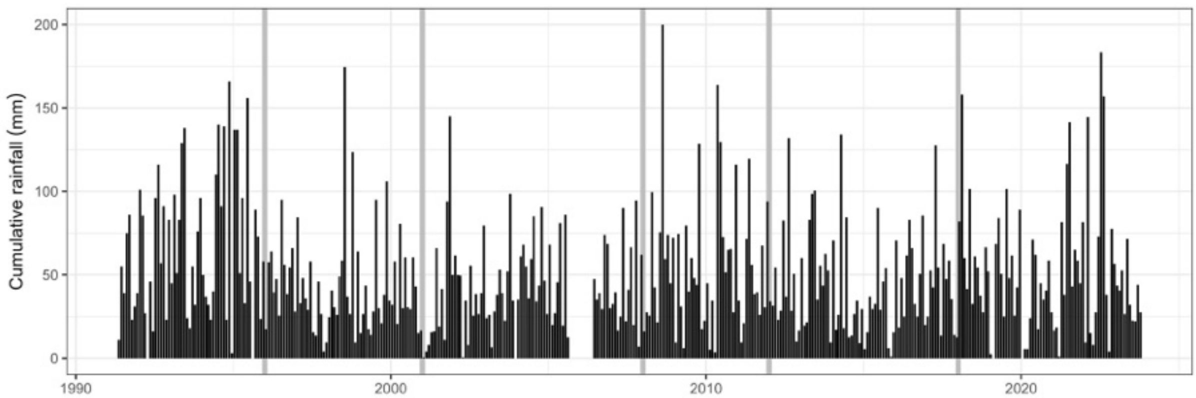

Figure 4.12 Monthly cumulative rainfall (mm) at the MDC Office site in Blenheim, from 1991 to 2023. The darker grey, vertical lines correspond to LCDB v5.0 version years.

Wairau River Flow (1960–2023)

The Wairau River daily average flow record at SH1 (Figure 4.13) spans a period of more than 60 years from 1960 to present. Average daily flow rate varies from close to 0 m³/s to over 500 m³/s.

A long-term decline of the Wairau River flow was detected with statistical confidence for the 1960-2023 time period at a rates of 0.28 m^3/s per year (Table 4.2).

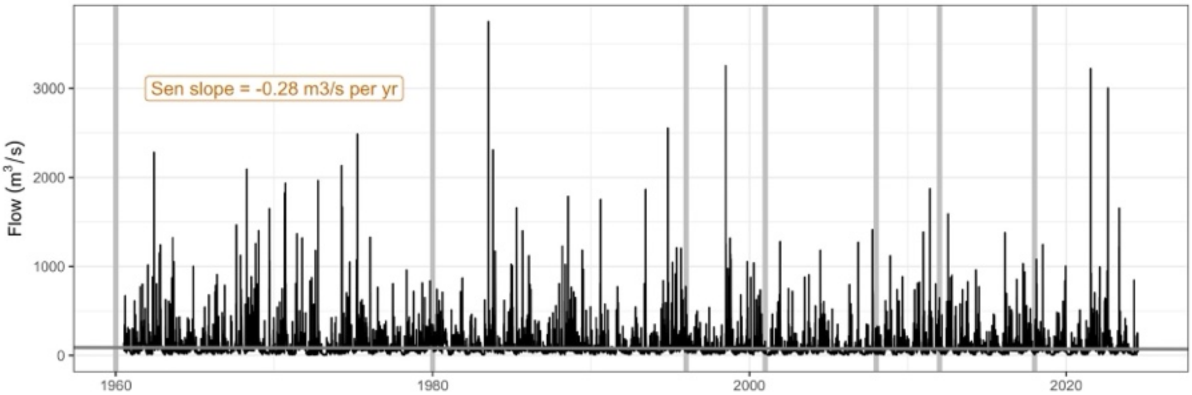

Figure 4.13 Wairau River flow in m^3/s at SH1 near Tuamarina from 1960 to 2023. The darker grey, vertical lines indicate high rainfall events post-1991. Darker grey, vertical lines correspond to LCDB V5.0 version years.

Spring Creek (1996–2023)

The Spring Creek flow record varies from monthly to quarterly intervals from 1996 to 2023 (Figure 4.14). This groundwater-fed creek's monthly average flows range from about 3 m^3/s to 6 m^3/s. High flows are generally consistent with high flows of the Wairau River.

Two statistically significant trends were detected: a short-term rise of 0.016 m^3/s per year between 1996 and 2008, and a long-term decline at a rate of 0.028 m^3/s per year between 1996 and 2023 (Table 4.2).

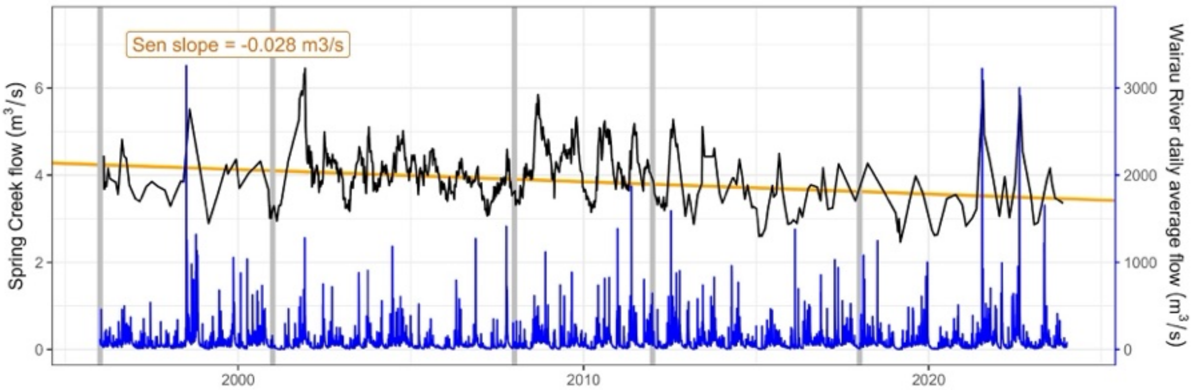

Figure 4.14 Monthly average flow in m^3/s at Spring Creek (black line) and Wairau River daily average flow in m^3/s from 1996 to 2023. Darker grey, vertical lines correspond to LCDB V5.0 version years. The orange line indicates the statistically significant decrease over the 1996–2023 time period.

4.3.2 Groundwater Elevation Time Series

Groundwater elevation at recorded intervals for Mills & Ford, Selmes Road, John Fairhalls, Conders and Wratts Road are shown in Figures 4.15 to 4.19. The recorded interval varies between sites but is consistent over the period of record. The record for Cemetery well spans from 1936 to 1942, which predates our landuse information, so was not included.

4.3.2.1 Springs Sector: Confined Section

Mills & Ford (2009–2023)

The Mills & Ford (Figure 4.15) groundwater elevation record is at a daily interval from 2009 to 2023. Groundwater elevations range from approximately 6.1 m asl to 8.1 m asl. Variations in Wairau River flow rate generally correspond to groundwater elevation fluctuations.

Two statistically significant declines were detected: 0.012 m^3/s per year between 2009 and 2018, and a long-term decline at a rate of 0.008 m^3/s per year between 2009 and 2023 (Table 4.2).

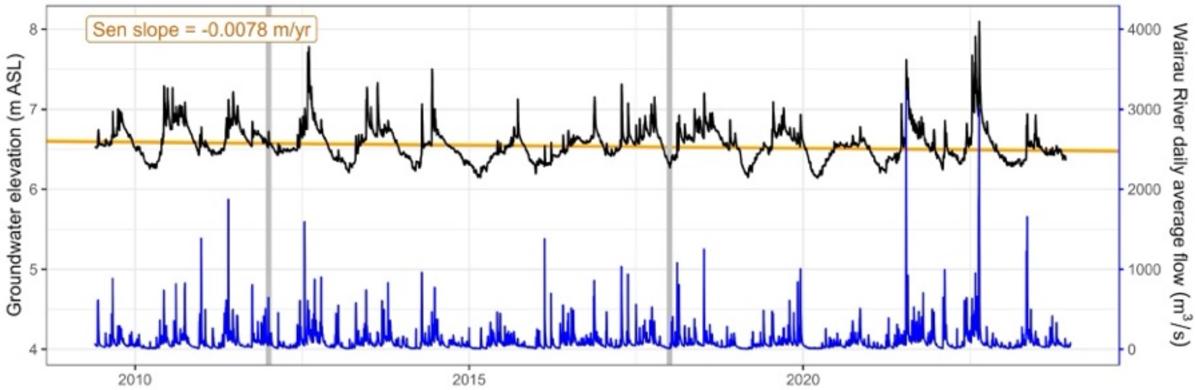

Figure 4.15 Daily groundwater elevation in m asl at the Mills & Ford well (black line) and Wairau River daily average flow (blue line) from 2009 to 2023. Darker grey, vertical lines correspond to LCDB V5.0 version years. The orange line indicates a statistically significant decrease over the full time period.

Selmes Road (2010–2023)

The groundwater elevation record at Selmes Road is at a daily interval from 2010 to 2023 (Figure 4.16). Groundwater elevations range from approximately 7.5 m asl to 8.6 m asl. Variations in Wairau River flow rate generally correspond to groundwater elevation fluctuations.

A statistically significant long-term decline of 0.008 m per year was detected over the period of record (Table 4.2).

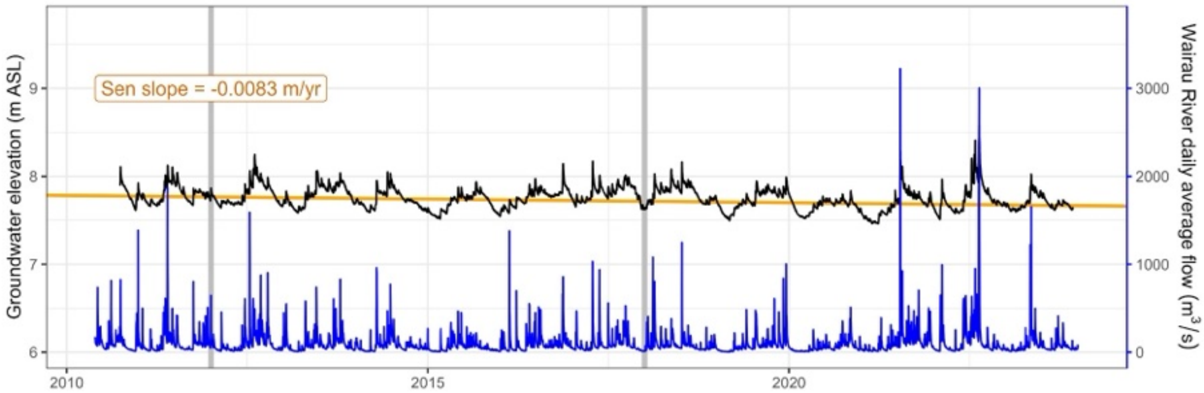

Figure 4.16 Daily groundwater elevation in m asl at the Selmes Road well (black line) and Wairau River daily average flow in m^3/s (blue line) from 2010 to 2023. Darker grey, vertical lines correspond to LCDB V5.0 version years. The orange line indicates a statistically significant decrease over the full time period.

4.3.2.2 Recharge Sector: Unconfined Section

John Fairhalls (1958–1997)

The groundwater elevation record at John Fairhalls is at weekly interval from 1958 to 1997. Groundwater elevations range between approximately 11.5 m asl and 14.4 m asl (Figure 4.17). Variations in Wairau River flow rate generally correspond to groundwater elevation fluctuations.

A decline in groundwater elevation around 1972 and subsequent recovery the following year corresponds to a drought in the Marlborough Region in that year (Chappell 2016). A statistically significant long-term decline of 0.006 m per year was detected over the period of the record (Table 4.2).

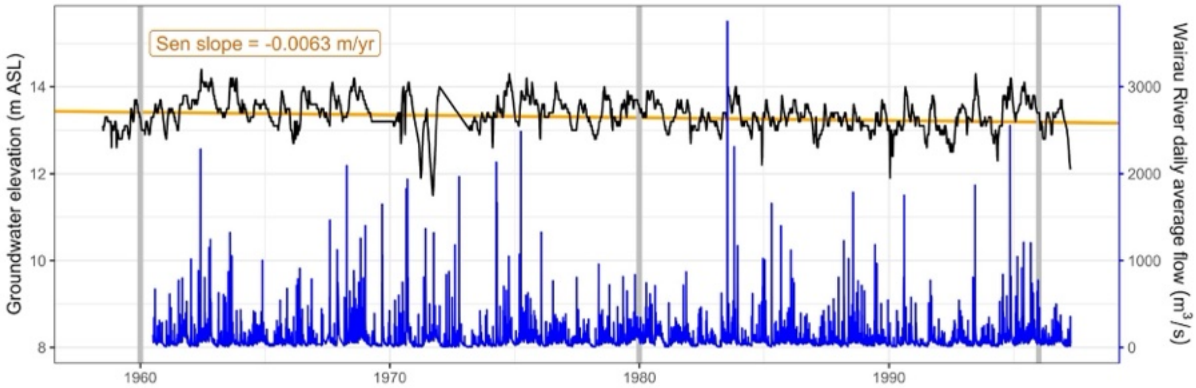

Figure 4.17 Weekly groundwater elevation in m asl at the John Fairhalls well (black line) from 1958 to 1997 and Wairau River daily average flow in m^3/s (blue line) from 1960 to 1997. Darker grey, vertical lines correspond to NZTopo50 and LCDB V5.0 version years. The orange line indicates a statistically significant decrease over the 1958–1997 time period.

Conders (1973–2023)

The groundwater elevation record at Conders is at a daily interval from 1973 to 2023 (Figure 4.18). Groundwater elevations range from about 33.9 m asl to 38.4 m asl. Variations in Wairau River flow rate generally correspond to groundwater level fluctuations.

A period of low groundwater elevations occurred between 2012 and 2016, which corresponds to an extended low-flow period in the Wairau River. Groundwater elevation fluctuations are larger than those at Wratts Road, possibly due to Conders' location further up catchment, closer to the Wairau River.

Three statistically significant declines in groundwater level of 0.03, 0.066 and 0.026 m per year were detected for the pre-1996, 2009–2018 and 1973–2023 periods, respectively (Table 4.2).

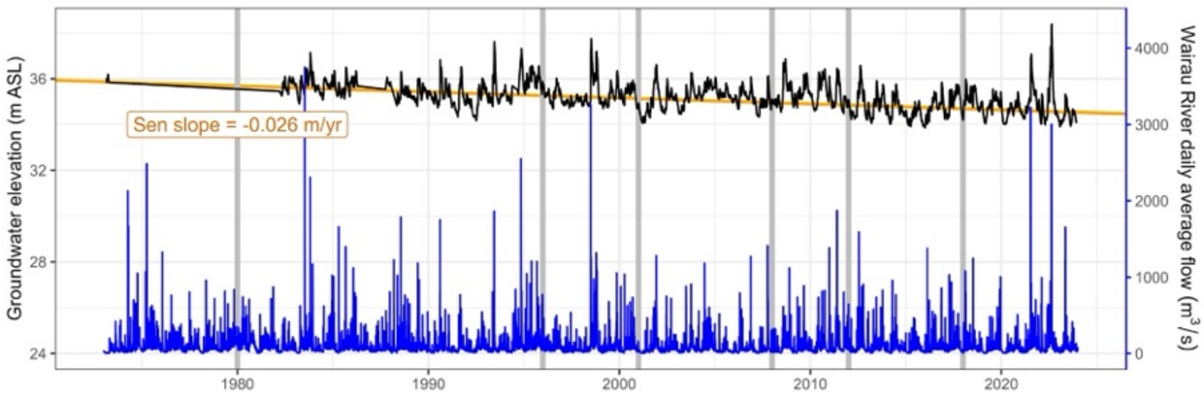

Figure 4.18 Daily groundwater elevation in m asl at the Conders well (black line) and Wairau River daily average flow in m^3/s (blue line) from 1973 to 2023. Darker grey, vertical lines correspond to NZTopo50 and LCDB V5.0 version years. The orange line indicates a statistically significant decrease over the 1973–2023 time period.

Wratts Road (1996–2023)

The groundwater elevation record for Wratts Road is at a weekly interval from 1996 to 2023 (Figure 4.19). Groundwater elevations range from about 12 m asl to 14 m asl. Variations in Wairau River flow rate generally correspond to groundwater level fluctuations.

Two statistically significant declines in groundwater level were detected: 0.037 m^3/s per year between 2009 and 2018, and a longer-term decline of 0.014 m^3/s per year between 1996 and 2023 (Table 4.2).

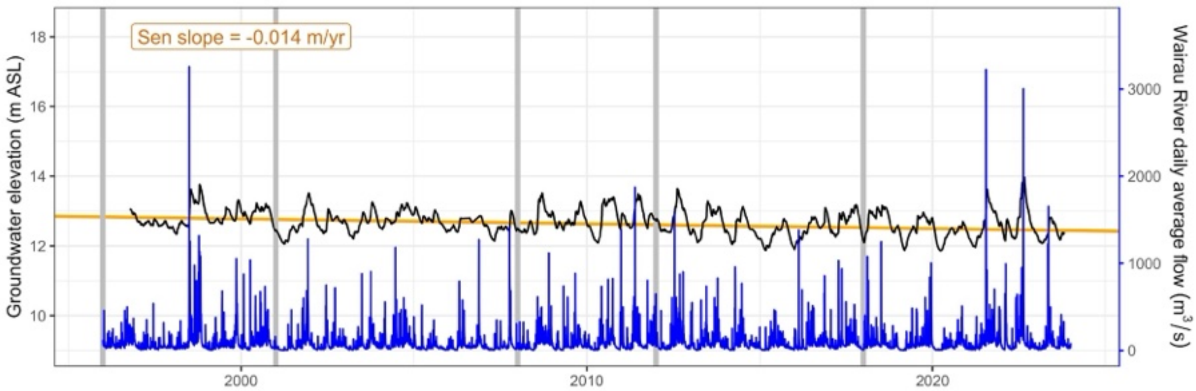

Figure 4.19 Groundwater elevations in m asl at the Wratts Road well (black line) and Wairau River average daily flow in m^3/s (blue line) from 1996 to 2023. Darker grey, vertical lines correspond to LCDB V5.0 version years. The orange line indicates a statistically significant decrease over the 1996–2023 time period.

4.4 Summary of Groundwater Elevation Decline and Land Cover Changes

Declining groundwater elevations occur at all the groundwater sites during dry periods. Dry periods are defined by the Wairau River flow rate of <20 m^3/s and periods of 15 days or longer with <1 mm of rain on any day (Chappell 2016). Groundwater elevations nearly recover in the following wet period. In both the confined and unconfined aquifer, a significant decline in groundwater elevation is observed.

All locations show regular seasonal groundwater elevation variations, and peaks and troughs that generally correspond to high- and low-flow events from the Wairau River. Flood events and higher groundwater elevations between 2010 and 2012 were followed by a prolonged low-flow and subsequent low-groundwater elevation period.

Wöhling et al. (2020) found that higher than average runoff from tributaries into the Wairau River occurred in the Wairau Catchment between 2010 and 2015, based on streamflow data. However, this increase in runoff did not result in a corresponding rise in groundwater elevations. Subsequently, the catchment experienced very dry summers.

The wells in the recharge/unconfined sector have more pronounced groundwater elevation fluctuations than wells in the springs/confined sector, potentially due to the unconfined aquifer hydraulic properties or their locations further up the Wairau Catchment.

4.4.1 1940s–1980s: Initial Mapping and Land Cover Changes

The Wairau Catchment LC was largely unmapped in the 1940s, with Bush covering 21% of the total catchment area. As mapping techniques advanced, LC classifications increased from three classes to six classes by the 1980s. The primary LC increase between the 1940s and 1980s was in Orchard, Vineyard or Other Perennial Crop, with vineyard plantations starting in the mid-1970s. Gravel Extraction in the Wairau River started in 1969, influencing river morphology and potentially groundwater recharge.

The John Fairhalls site is the only groundwater elevation record that covers this time period, and no trends were established with confidence pre-1980s. The lowest groundwater elevation at this well occurred in 1972, with level recovering the following year. Gradual declines in groundwater elevation at John Fairhalls and Conders corresponded with a slight decrease in Wairau River flow and low-flow period due to drought in 1972. Decreases in groundwater elevations between the 1940s and 1980s may be linked to LC changes, higher water demand, drier weather and/or gravel extraction.

4.4.2 1996–2008: Peak Conversion of Grasslands

The conversion of grasslands to forests and vineyards in the Wairau Catchment peaked around 2008. Conversions during the period 1996–2008 included High-Producing Exotic Grassland and Low-Producing Grassland into Exotic Forest, Orchards, Vineyards or Other Perennial Crop, and Forest – Harvested area. During this period, groundwater elevations declined, but not significantly. A rise in flow was observed at Spring Creek.

4.4.3 2009–2018: Post-Peak Land Cover Conversion

No large LC changes occurred between 2009 and 2018. A decline in groundwater elevations occurred in three of the five wells included in this study and at the groundwater-fed Spring Creek. The groundwater elevation decline during this period was greater than in earlier time intervals. Conders had the most pronounced decline with 0.066 m per year.

Wairau River flow slightly increased in 2012, followed by a prolonged low river flow period. A series of floods between 2010 and 2012 potentially led to river erosion and reduced groundwater recharge rates (Wöhling et al. 2020) until around 2021. A decline in flow was also measured at Spring Creek.

4.4.4 2019–Present: Present Land Cover and Groundwater Levels

Higher groundwater elevations occurred in recent years (2021–2023) compared with pre-2021 time periods. Land cover changes levelled off with no significant occurrence. In March 2024, a drought was declared in Marlborough with the region receiving its lowest total rainfall (206.8 mm) in a nine-month period (June 2023–February 2024) in 94 years (1930–2024) (Tomlinson 2024). Groundwater elevations from the latter part of 2023 decreased, corresponding to a reduction in river flow and rainfall.

5.0 CONCLUSION AND RECOMMENDATIONS

This study examined the potential impacts of historical LC changes on the groundwater levels of the Wairau Aquifer. Historical LC data from NZTopo50 maps (1940s–1980s) were digitised and integrated with the Land Cover Database version 5 (1996–2018).

These datasets allowed changes in LC to be tracked and quantified. The largest changes in LC were from High-Producing Grasslands to Vineyards, Orchards and Exotic Forests. This transformation was most pronounced between 1996 and 2008.

Long-term decline in groundwater elevations across the period 1958–2023 were identified within statistical confidence at three of the five wells as well as the groundwater-fed Spring Creek included in this study. This long-term decline in groundwater elevations coincides with increased horticultural activities since the mid-1970s. The increase in Vineyards and Exotic Forest LC likely caused an increase in water demand relative to previous LC, and may be associated with groundwater level decline.

From 1996 to 2008, LC changes may have impacted groundwater elevations; however, other factors, such as abstraction rates, river morphology, climatic variations and regional hydrological conditions, may also have contributed.

From 2009 onwards, LC changes slowed, but groundwater elevations continued to decrease, suggesting that ongoing or increasing water demand associated with these LC changes could be a key contributor to the groundwater decline.

While this study identifies a potential link between LC changes and groundwater level decline, it is not conclusive. Multiple factors may have contributed to the groundwater level decline, and the absence of groundwater abstraction totals by Fresh Water Management Unit (FMU) and season is an important information gap.

To better understand the decline in groundwater levels of the Wairau Aquifer, we recommend MDC implement more comprehensive monitoring and data collection of water abstraction as soon as possible. This will provide quantifiable data to assess the impact of abstraction on groundwater level. Good quality abstraction data will also be an important dataset for water management tools such as numerical models.

There are several other useful datasets that MDC should acquire and use in addition to those already available for future studies on the groundwater system response. These include but are not limited to climate variability, sediment supply, evapotranspiration and greater specificity within some LC types. These datasets will help to gain a deeper understanding of system dynamics and to inform effective water management strategies.

6.0 ACKNOWLEDGEMENTS

This work was supported by Envirolink funding (2414-MLDC168) and Groundwater SSIF funding. Firstly, thanks go to the contributors of this study: Graeme Curwen for the compilation, digitisation and georeferencing of the historical maps and for providing LCDB data, Magali Moreau and Stewart Cameron for their invaluable assistance and review comments, Maria Narvaiza for finalising the maps and Pete Davidson for his support and providing key data.

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APPENDICES

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APPENDIX 1 WAIRAU PLAIN LAND COVER MAPS (NZTOPO50)

A1.1 Illustrations and Tables of Historical Topographic Data

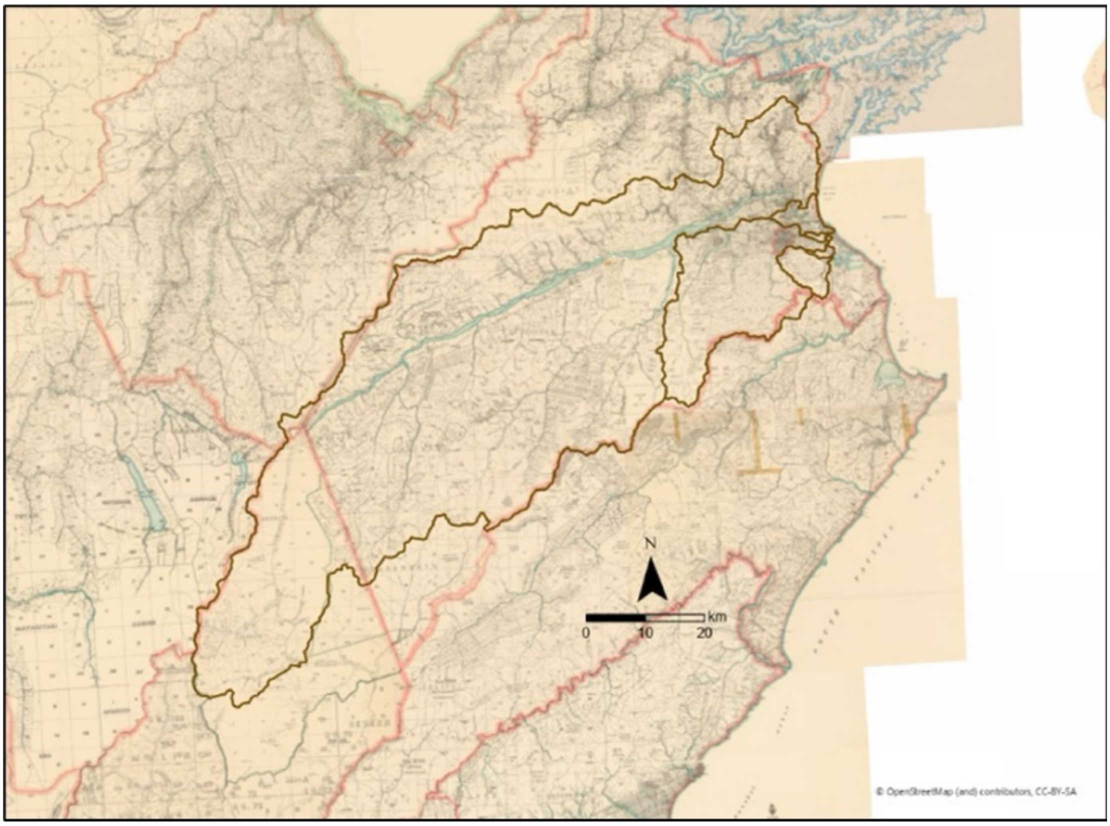

Figure A1.1 1st edition series map of the Wairau Plain published at the end of 1939. This map highlights the advancement of mapping ability over time. (Mapspast 2023).

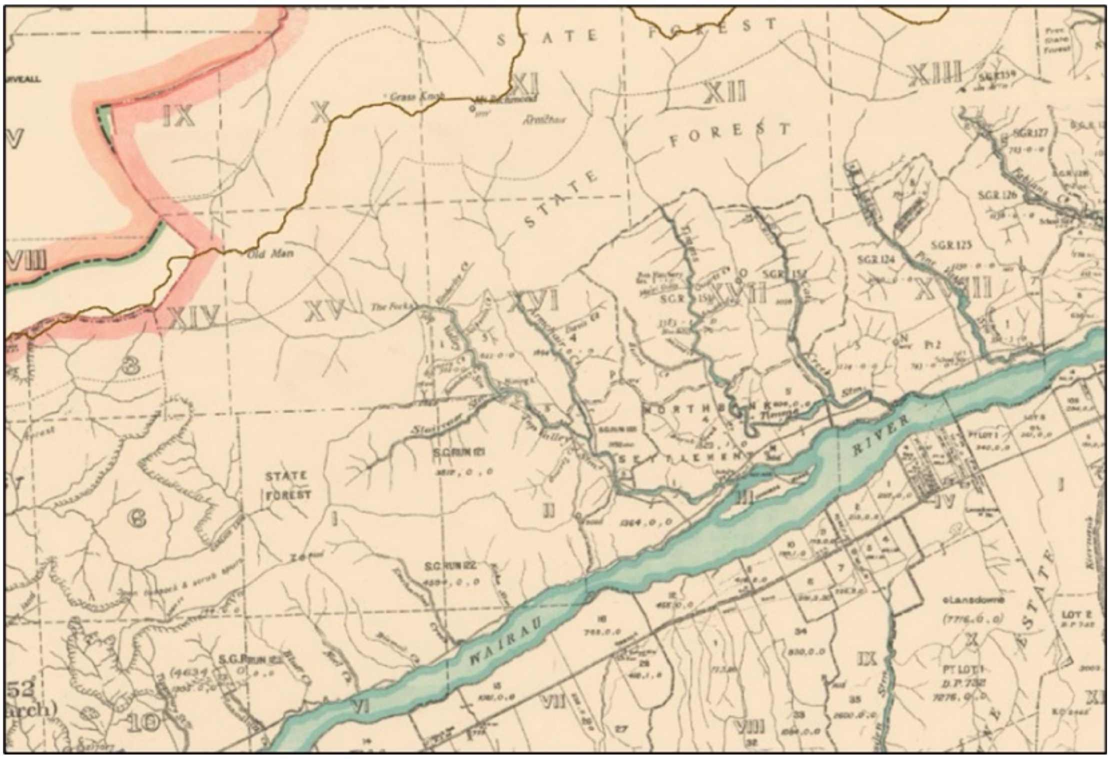

Figure A1.2 Detail of the 1939 topographic map, showing the hills to the north of the Wairau River (Mapspast 2023).

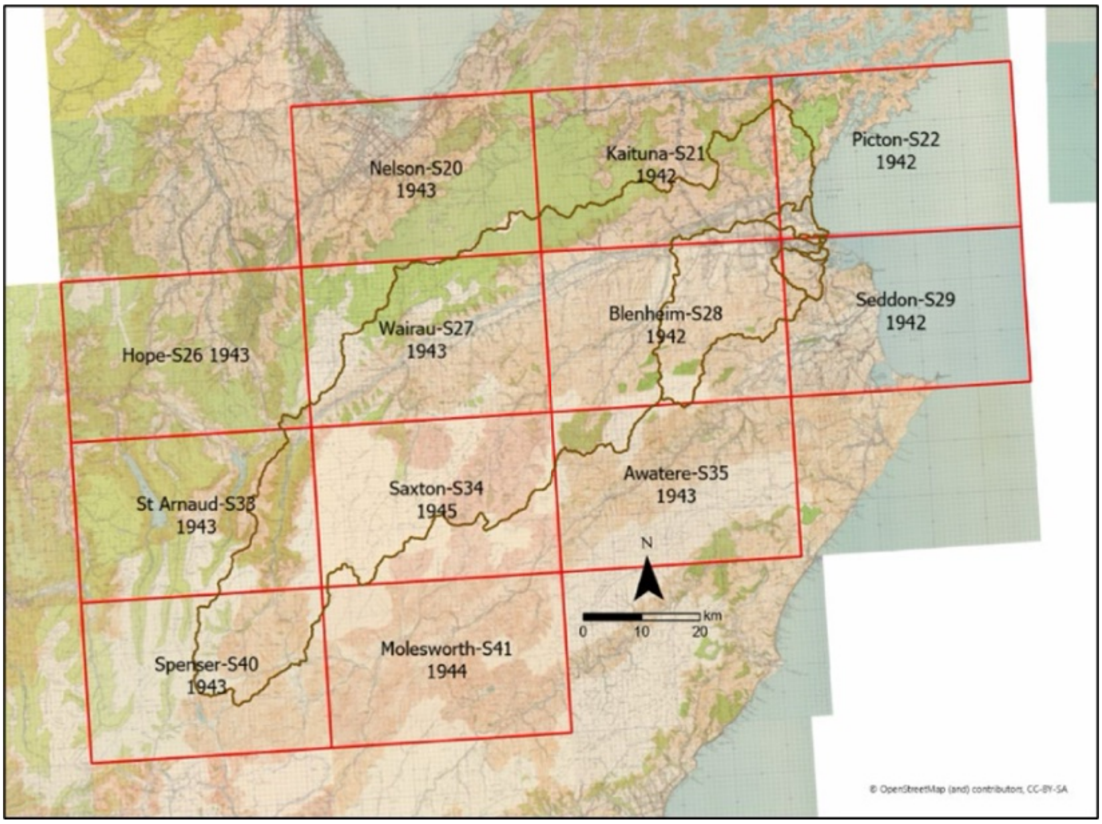

Figure A1.3 Topographic map index for the Wairau Plain 1942–1944. The names, sheet number and dates of the NZMS 1 inch to the mile (1:63360) 1st edition series (Mapspast 2023).

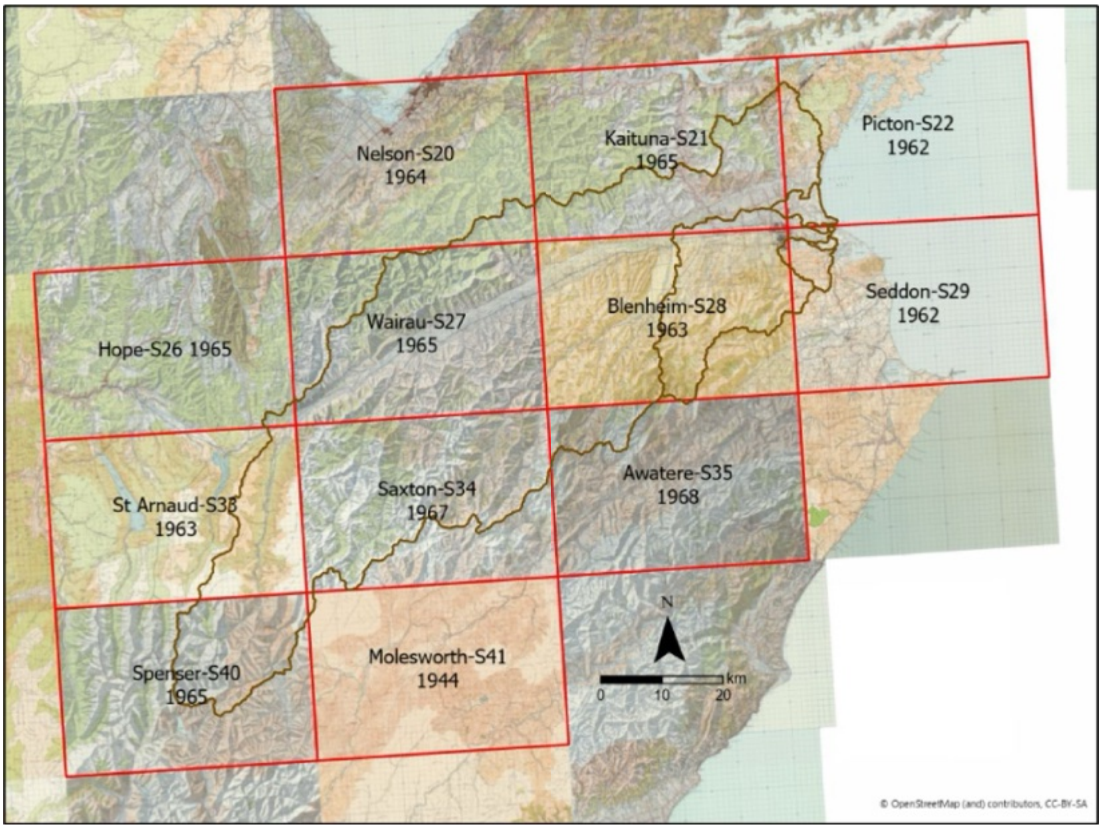

Figure A1.4 Topographic map index for the Wairau Plain 1944–1968. The names, sheet number and dates of the NZMS 1 inch to the mile (1:63360) 2nd edition series (Mapspast 2023).

Figure A1.5 Topographic map index for the Wairau Plain 1981–1989¶The names, sheet number and dates of the NZMS260 (1:50,000) 1st edition series (Mapspast 2023).

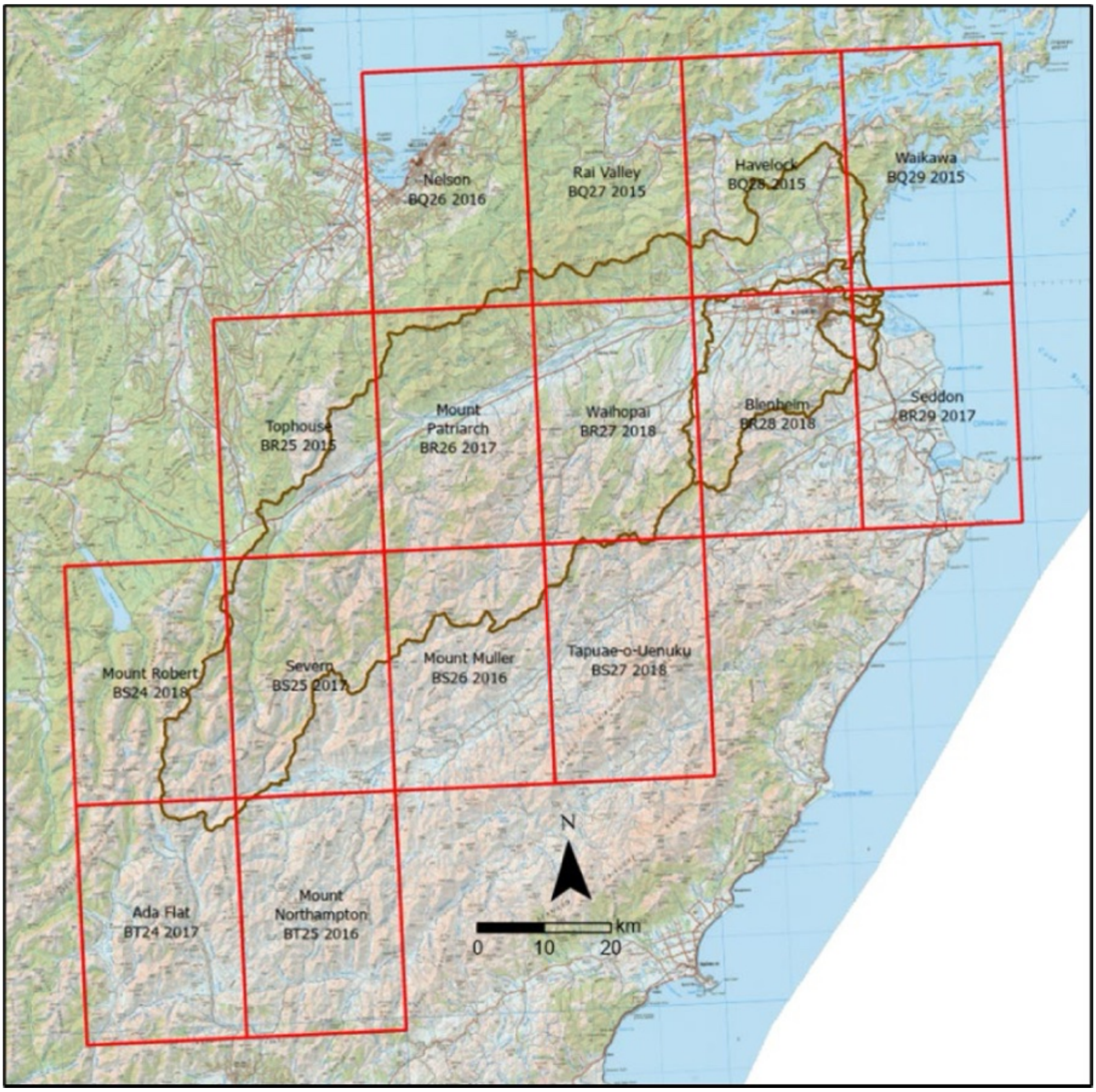

Figure A1.6 Current topographic map index for the Wairau Plain 2015–2018. The names, sheet number and dates of the NZTopo50 (1:50,000) series (Mapspast 2023).

A1.2 Topographical Map Metadata

Table A1.1 Metadata for the topographical maps used in this study (Mapspast 2023).

Sheet Name	Sheet No.	Year Print	Series	Scale	Projection	Published By	Copyright	Edition	Year Surveyed
Metadata for 1940s Topographical Maps									
Wairau	S27	1943	NZMS1	1:63360	SIMG (yard grid)	LINZ / Lands and Survey	CC (Attribution)	No data	No data
Molesworth	S41	1944							
Picton	S22	1942							
Kaituna	S21	1942							
Spenser	S40	1943							
Saxton	S34	1945							
St Arnaud	S33	1943							
Awatere	S35	1943							
Nelson	S20	1943							
Hope	S26	1943							
Seddon	S29	1942							
Blenheim	S28	1942							
Metadata for 1960s Topographical Maps									
Wairau	S27	1965	NZMS1	1:63360	SIMG (yard grid)	LINZ / Lands and Survey	CC (Attribution)	No data	No data
Molesworth	S41	1944							
Picton	S22	1962							
Kaituna	S21	1965							
Spenser	S40	1965							
Saxton	S34	1967							
St Arnaud	S33	1963							
Awatere	S35	1968							
Nelson	S20	1964							
Hope	S26	1965							
Seddon	S29	1962							
Blenheim	S28	1963							

Sheet Name	Sheet No.	Year Print	Series	Scale	Projection	Published By	Copyright	Edition	Year Surveyed
Metadata for 1980s Topographical Maps									
Awatere	O30	1988	NZMS260	1:50,000	NZMG49 (metre grid)	LINZ / Lands and Survey	CC (Attribution)	No data	No data
Blenheim	P28	1985							
Golden Downs	N28	1987							
Grassmere	P29-Q29	1985							
Matakitaki	M30	1989							
Picton	P27	1981							
St Arnaud	N29	1984							
Tarndale	N30	1987							
Waihopai	O29	1986							
Wairau	O28	1985							
Metadata for 2019 Topographical Maps									
Ada Flat	BT24	2017	NZTopo50	1:50,000	NZTM2000 (metre grid)	LINZ / Lands and Survey	CC (Attribution)	No data	No data
Blenheim	BR28	2018							
Havelock	BQ28	2015							
Mount Muller	BS26	2016							
Mount Northampton	BT25	2016							
Mount Patriach	BR26	2017							
Mount Robert	BS24	2018							
Nelson	BQ26	2016							
Rai Valley	BQ27	2015							
Seddon	BR29	2017							
Severn	BS25	2017							
Tapuae-o-Uenuku	BS27	2018							
Tophouse	BR25	2015							
Waihopai	BR27	2018							
Waikawa	BQ29	2015							

APPENDIX 2 WAIRAU PLAIN LAND COVER MAPS (LCDB V5.0)

A2.1 LCDB v5.0 Maps from 1996 to 2018

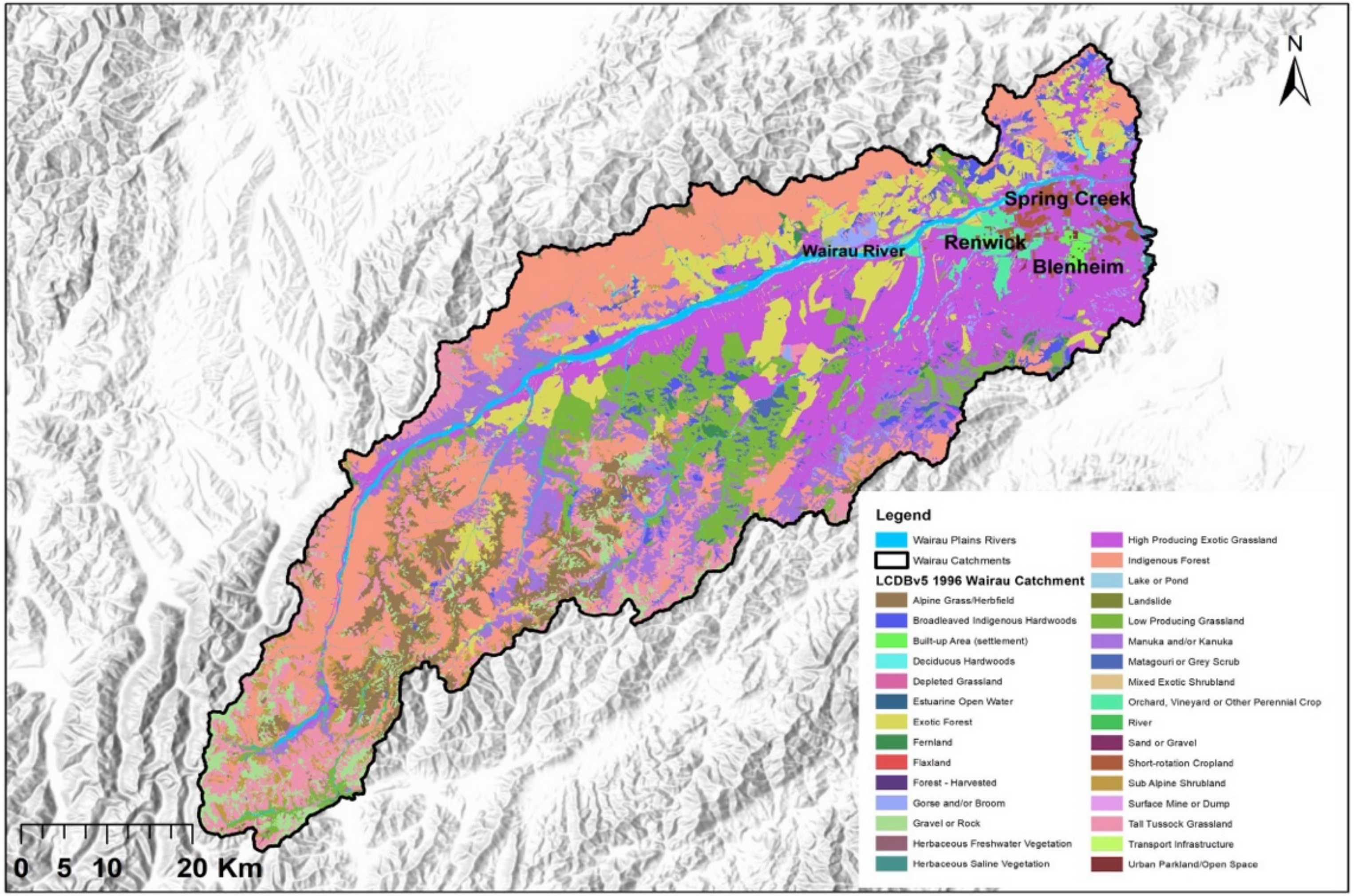

Figure A2.1 Land cover in the Wairau Catchment published in 1996 (Landcare Research 2020).

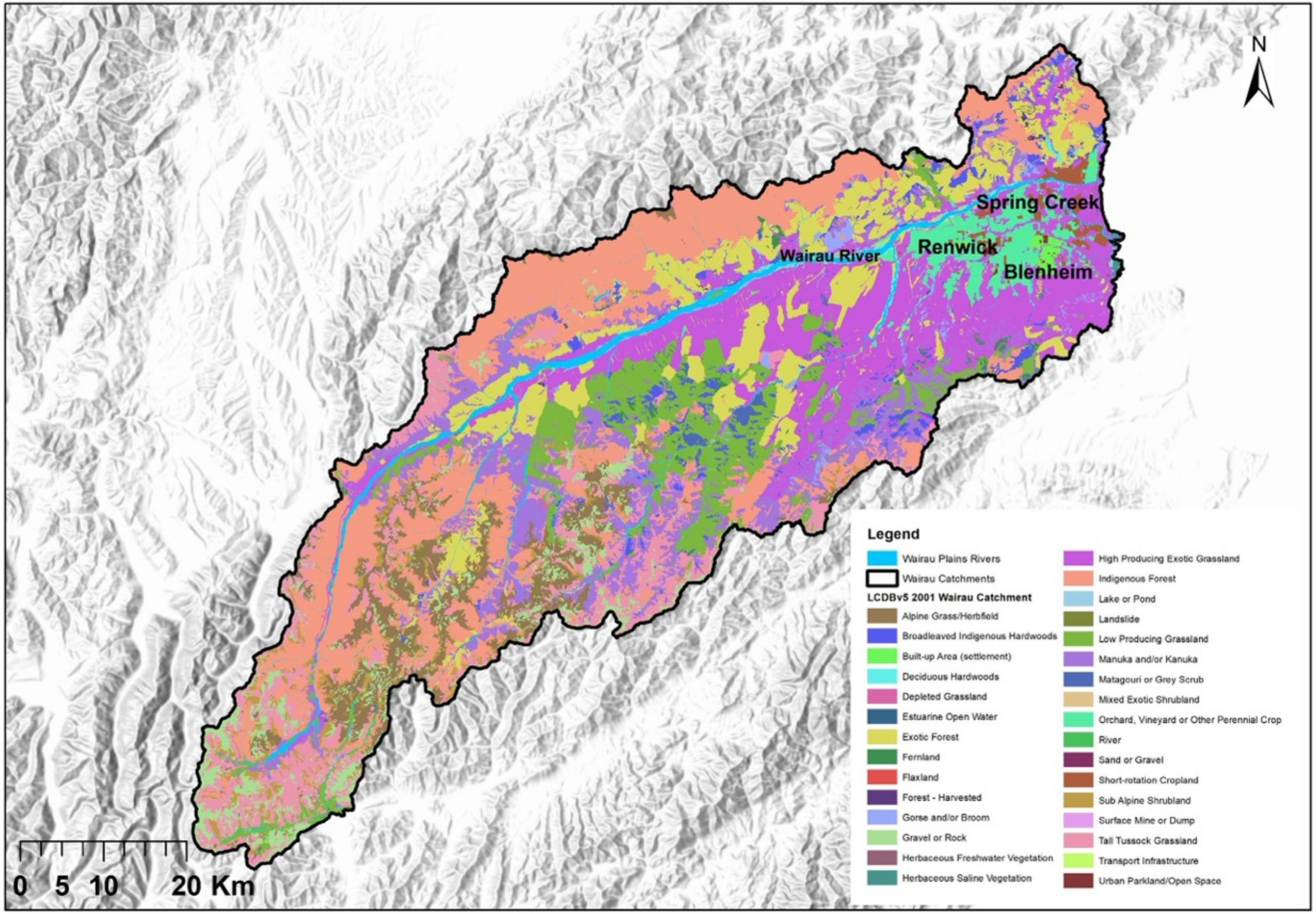

Figure A2.2 Land cover in the Wairau Catchment published in 2001 (Landcare Research, 2020).

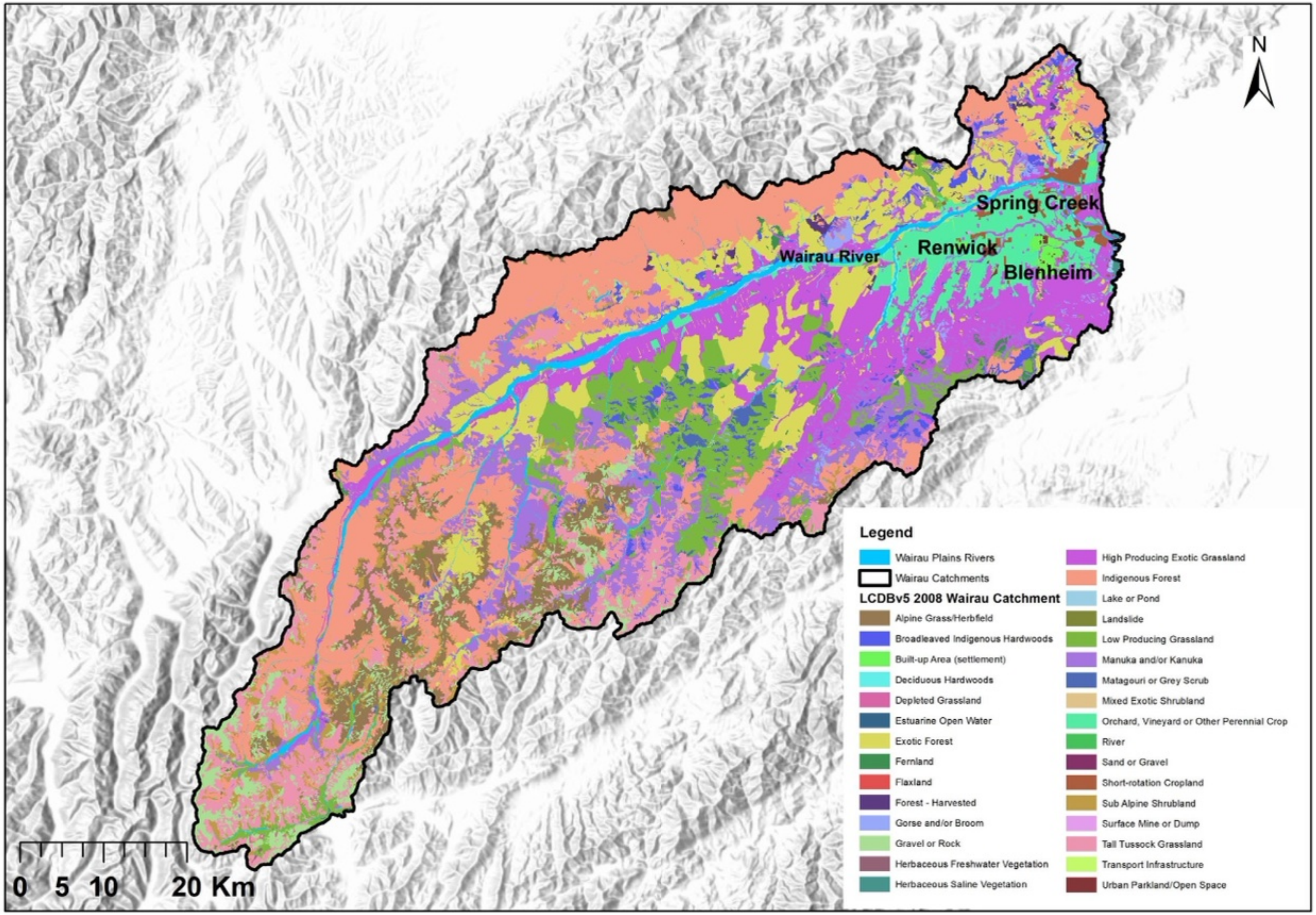

Figure A2.3 Land cover in the Wairau Catchment published in 2008 (Landcare Research 2020).

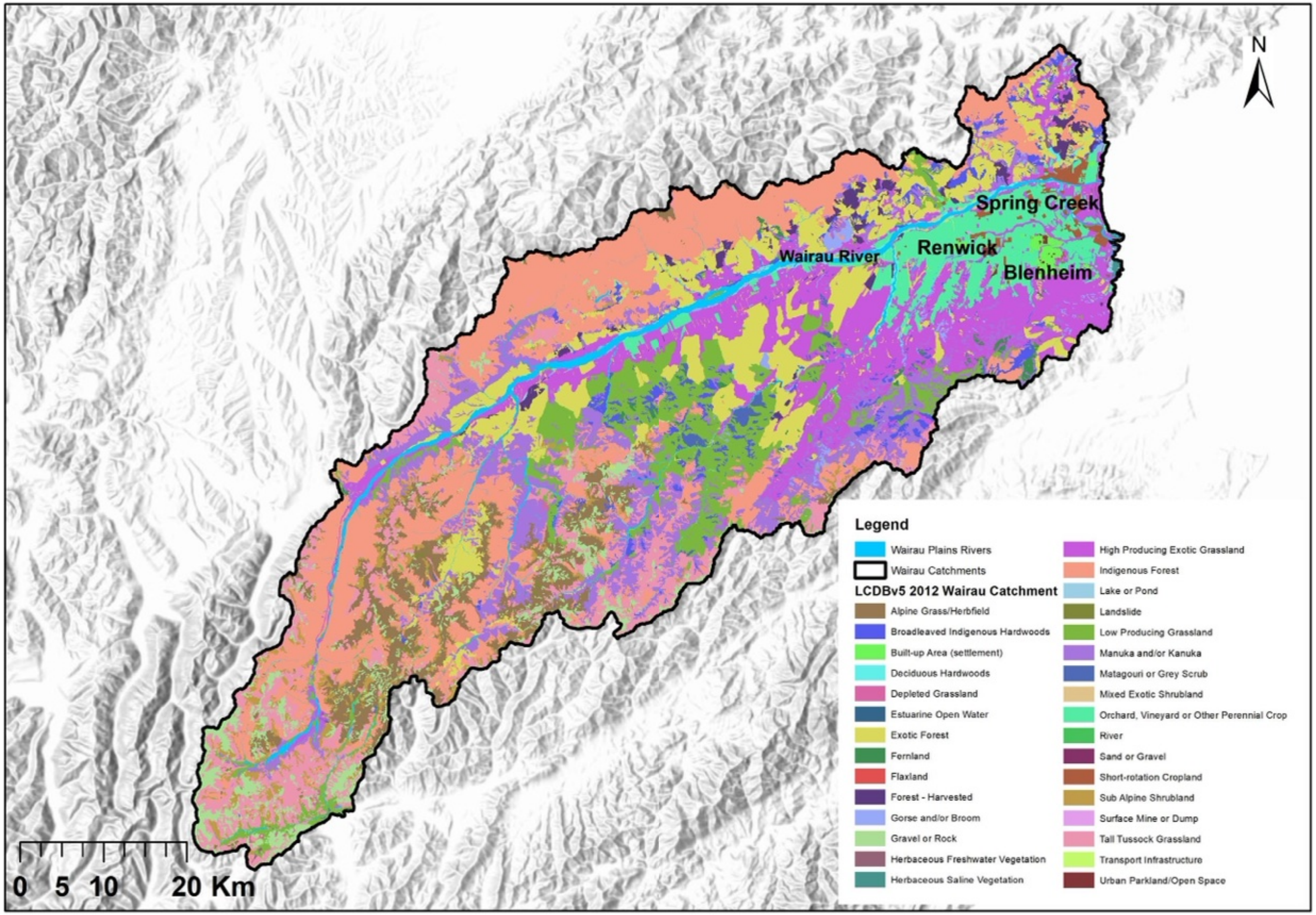

Figure A2.4 Land cover map of the Wairau Catchment published in 2012 (Landcare Research 2020).

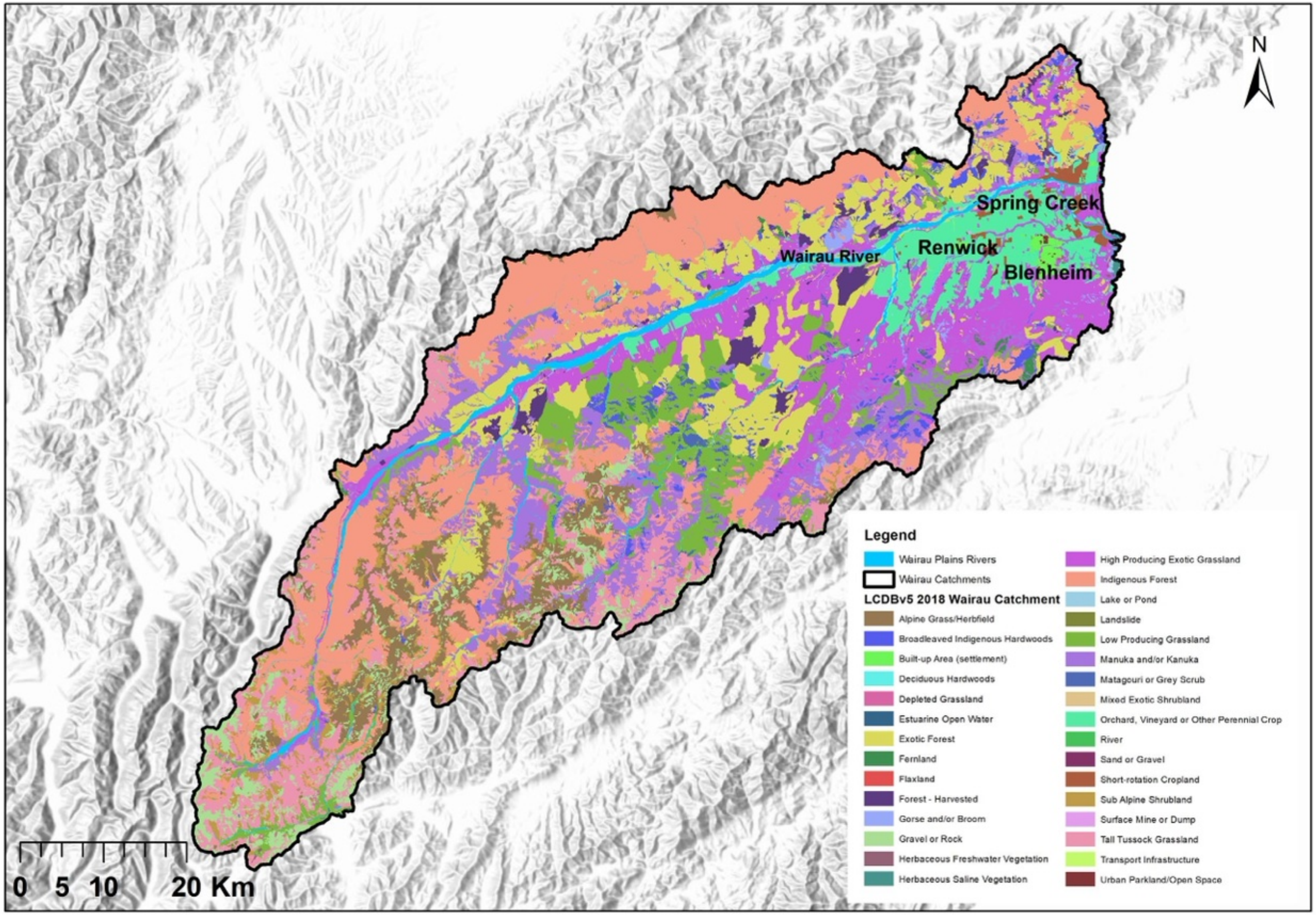

Figure A2.5 Current land cover map of the Wairau Catchment published in 2018 (Landcare Research, 2020).

Table A2.1 Evolution of land cover classes between LCDB versions. As technology has advanced, more detailed classifications have been made (Landcare Research 2020)

	LCDB v1	LCDB v2		LCDB v3		LCDB v4 onward	
	Class Name	Class Code	Class Name	Class Code	Class Name	Class Code	Class Name
Other						0	Not land (used in Version 5.0 onwards)
Artificial Surfaces	Urban Area	1	Built-up Area (settlement)	1	Built-up Area (settlement)	1	Built-up Area (settlement)
	Urban Open Space	2	Urban Parkland / Open Space	2	Urban Parkland / Open Space	2	Urban Parkland / Open Space
	Mines and Dumps	3	Surface Mine	6	Surface Mines and Dumps	6	Surface Mines and Dumps
		4	Dump				
		5	Transport Infrastructure	5	Transport Infrastructure	5	Transport Infrastructure
Bare or Lightly-vegetated Surfaces	Coastal Sand	10	Coastal Sand and Gravel	10	Sand and Gravel	10	Sand and Gravel
	Bare Ground	11	River and Lakeshore Gravel and Rock	16	Gravel and Rock	16	Gravel and Rock
		13	Alpine Gravel and Rock				
		12	Landslide	12	Landslide	12	Landslide
		14	Permanent Snow and Ice	14	Permanent Snow and Ice	14	Permanent Snow and Ice
		15	Alpine Grass / Herb field	15	Alpine Grass / Herb field	15	Alpine Grass / Herb field
Water Bodies	Inland Water	20	Lake and Pond	20	Lake or Pond	20	Lake or Pond
		21	River	21	River	21	River
		22	Estuarine Open Water	22	Estuarine Open Water	22	Estuarine Open Water
Cropland		30	Short-rotation Cropland	30	Short-rotation Cropland	30	Short-rotation Cropland
	Primarily Horticulture	31	Vineyard	33	Orchard Vineyard and Other Perennial Crops	33	Orchard Vineyard and Other Perennial Crops
		32	Orchard and Other Perennial Crops				
Grassland, Sedgeland and Marshland	Primarily Pastoral	40	High-Producing Exotic Grassland	40	High-Producing Exotic Grassland	40	High-Producing Exotic Grassland
		41	Low-Producing Grassland	41	Low-Producing Grassland	41	Low-Producing Grassland
	Tussock Grassland	43	Tall Tussock Grassland	43	Tall Tussock Grassland	43	Tall Tussock Grassland
		44	Depleted Grassland	44	Depleted Grassland	44	Depleted Grassland
	Inland Wetland	45	Herbaceous Freshwater Vegetation	45	Herbaceous Freshwater Vegetation	45	Herbaceous Freshwater Vegetation
	Coastal Wetland	46	Herbaceous Saline Vegetation	46	Herbaceous Saline Vegetation	46	Herbaceous Saline Vegetation
		47	Flaxland	47	Flaxland	47	Flaxland
Scrub and Shrubland	Scrub	50	Fernland	50	Fernland	50	Fernland
		51	Gorse and/or Broom	51	Gorse and/or Broom	51	Gorse and/or Broom
		52	Manuka and/or Kanuka	52	Manuka and/or Kanuka	52	Manuka and/or Kanuka
		53	Matagouri	58	Matagouri or Grey Scrub	58	Matagouri or Grey Scrub
		57	Grey Scrub				
		54	Broadleaved Indigenous Hardwoods	54	Broadleaved Indigenous Hardwoods	54	Broadleaved Indigenous Hardwoods
		55	Sub-Alpine Shrubland	55	Sub-Alpine Shrubland	55	Sub-Alpine Shrubland
		56	Mixed Exotic Shrubland	56	Mixed Exotic Shrubland	56	Mixed Exotic Shrubland
		55[1]	Peat Shrubland (Chatham Islands only)			80	Peat Shrubland (Chatham Islands only)
		56[1]	Dune Shrubland (Chatham Islands only)			81	Dune Shrubland (Chatham Islands only)
Forest		60	Minor Shelterbelts	71	Exotic Forest	71	Exotic Forest
	Major Shelterbelts Planted Forest	61	Major Shelterbelts				
		62	Afforestation (not imaged)				
		63	Afforestation (imaged, post LCDB1)				
		65	Pine Forest – Open Canopy				
		66	Pine Forest – Closed Canopy				
		67	Other Exotic Forest				
		64	Forest – Harvested	64	Forest – Harvested	64	Forest – Harvested
	Willows and Poplars	68	Deciduous Hardwoods	68	Deciduous Hardwoods	68	Deciduous Hardwoods
	Indigenous Forest	69	Indigenous Forest	69	Indigenous Forest	69	Indigenous Forest
		70	Mangrove	70	Mangrove	70	Mangrove

[1] Class Codes 55 and 56 were re-used in LCDB v2 when new classes were created for “Peat Shrubland” and “Dune Shrubland” for Chatham Islands mapping. Unique codes (80 and 81) were assigned to these classes when Chatham Islands were remapped at LCDB v4

Table A2.2 LCDB land cover classes and their respective area in hectares (ha). Change in ha between time intervals is calculated in the light grey columns. The LC has been sorted into loss and then gain in order of largest to smallest. Total loss of over 100 ha is highlighted in red; total gain over 1000 ha is highlighted in green and total gain over 100 ha highlighted in yellow.

Land Cover Classification (LCDB v5.0)	1996 Hectares (ha)	2001 Hectares (ha)	Change 1996–2001 Hectares (ha)	2008 Hectares (ha)	Change 2001–2008 Hectares (ha)	2012 Hectares (ha)	Change 2008–2012 Hectares (ha)	2018 Hectares (ha)	Change 2012–2018 Hectares (ha)	Total Change Hectares (ha)
High-Producing Exotic Grassland	78,292	68,773	-9,519	58,634	-10,139	57,662	-972	56,715	-946	-21,576
Low-Producing Grassland	37,798	37,100	-699	35,942	-1,157	34,882	-1,061	32,000	-2,881	-5,798
Manuka and/or Kanuka	43,893	42,279	-1,615	42,261	-17	42,544	282	42,718	174	-1,176
Short-rotation Cropland	3,515	3,022	-493	2,717	-305	2,445	-272	2,415	-30	-1,101
Tall-Tussock Grassland	36,457	36,327	-130	35,812	-515	35,670	-141	35,430	-240	-1,027
Gorse and/or Broom	3,765	3,430	-336	3,161	-268	2,939	-223	2,818	-121	-947
Broadleaved Indigenous Hardwoods	10,309	9,277	-1,032	9,083	-194	9,410	327	9,385	-25	-924
Matagouri or Grey Scrub	1,612	1,944	332	1,897	-47	1,811	-86	1,141	-670	-470
Mixed Exotic Shrubland	969	993	24	942	-51	704	-238	662	-42	-307
Alpine Grass / Herb field	23,167	23,097	-70	22,902	-195	22,899	-3	22,885	-15	-282
Deciduous Hardwoods	2,001	1,988	-13	1,830	-158	1,759	-71	1,721	-38	-280
Fernland	1,730	1,469	-261	1,465	-4	1,507	42	1,481	-26	-249
Gravel or Rock	24,396	24,338	-58	24,297	-41	24,290	-6	24,274	-17	-122
Sub-Alpine Shrubland	9,654	9,636	-18	9,581	-55	9,588	6	9,570	-18	-84
Indigenous Forest	88,625	88,619	-6	88,599	-20	88,575	-24	88,560	-14	-65
Sand or Gravel	48	48	0	48	0	48	0	47	-2	-2
Orchard, Vineyard or Other Perennial Crop	4,769	11,561	6,791	19,752	8,192	20,942	1,189	22,003	1,062	17,234
Exotic Forest	37,685	44,294	6,609	48,139	3,846	45,770	-2,369	47,954	2,184	10,270
Forest – Harvested	11	298	287	1,165	866	4,654	3,489	6,218	1,565	6,207
Built-up Area (settlement)	1,441	1,539	98	1,702	163	1,736	34	1,777	41	336
Lake or Pond	241	247	5	340	94	363	23	408	45	167
Landslide	714	784	70	784	0	787	3	787	0	73
Herbaceous Freshwater Vegetation	274	275	1	275	0	336	61	331	-4	57
Urban Parkland / Open Space	298	328	30	330	2	331	1	331	0	32
Surface Mine or Dump	48	48	0	54	6	61	7	78	17	30
River	1,656	1,656	1	1,656	0	1,659	3	1,659	0	3
Flaxland	1	1	0	1	0	1	0	1	0	0
Depleted Grassland	270	270	0	270	0	270	0	270	0	0
Herbaceous Saline Vegetation	228	228	0	228	0	228	0	228	0	0
Estuarine Open Water	1	1	0	1	0	1	0	1	0	0
Transport Infrastructure	19	19	0	19	0	19	0	19	0	0
Area total (ha)	413,888	413,888		**413,888**		**413,888**		**413,888**		

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