Examining the spatial and temporal variability of historical drought events to inform future climate risk in Canterbury

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Abstract

Droughts are severe and unpredictable climate hazards that are challenging to predict and quantify. They are widely regarded as one of the most destructive natural hazards due to their unpredictability and far-reaching impacts, which extend across both time and space. Droughts affect socioeconomic and environmental systems, with their impacts often cascading beyond the initially impacted areas and systems. With climate change projected to increase the frequency and intensity of drought events globally, there is a growing need to further knowledge and understanding of drought characteristics to mitigate their impacts and develop effective adaptation strategies. Canterbury, a key agricultural region in New Zealand, is particularly vulnerable to drought.

This study explores the spatiotemporal variability of historical summer droughts in Canterbury using long-term rainfall records from 1950–2022 at twenty five weather stations. The analysis reveals significant spatial and temporal variability in drought rarity and severity, identifying five sub-regional clusters with similar rainfall experiences. Further investigation of the temporal characteristics of Canterbury droughts at weather stations with at least one hundred years of rainfall data highlighted the extreme 1897/98 drought, which affected much of the region.

Using a storyline approach, a worst-case drought scenario was developed. The 1897/98 drought was compared with more recent known high impact droughts in 1988/89, 1997/98, and 2000/01 using rainfall and, where available, soil moisture data from two stations situated in the intensive dairying area of the Canterbury Plains. Each drought exhibited unique characteristics: the 1988/89 event had the driest March–November period on record, while the 2000/01 drought experienced the driest December–May. However, the most severe 15-month rainfall deficits occurred during the 1897/98 drought, marking it as an unprecedented event in Canterbury's climate history. The findings highlight an increased risk of severe and prolonged droughts in Canterbury under climate change.

Understanding historical drought spatiotemporal patterns and constructing a worst-case scenario provide valuable insights for assessing future drought risk, supporting the development of targeted mitigation and adaptation strategies in a changing climate.

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1 Introduction

The primary sector is one of New Zealand's major industries and employers and accounts for approximately 7% of New Zealand's gross domestic product (GDP) (Stats NZ, 2020). For the year ending March 2024, dairy exports were valued at NZD 23.7 billion, accounting for 24% of total exports (Te Tai Ōhanga, The Treasury (Treasury), 2024). Between 2000 and 2021, agriculture contributed between 7 and 8% to the GDP of Canterbury. (Environment Canterbury Regional Council, Kaunihere Taiao ki Waitaha (ECAN), 2024). Not only is the primary sector crucial for the Canterbury economy, it is also essential for sustaining rural communities, is a major employer, and has flow-on economic benefits to other businesses and industries (Ministry of Business Innovation & Employment, Hīkina Whakatutuki (MBIE), 2023).

The reliance of New Zealand's economy on agriculture makes it vulnerable to droughts, a common occurrence in many of New Zealand's agricultural areas. The dairy sector depends on reliable water supply for pasture growth and livestock water, which makes it particularly susceptible to drought. This dependence on water is especially the case in Canterbury, where there is a significant reliance on irrigation water in the agricultural sector due to the region's naturally dry climate (Grout et al., 2022; Smith & Montgomery, 2004; MacLeod & Moller, 2006). As of 2022, approximately 63% of irrigated land in New Zealand was in Canterbury. (Stats NZ, 2024). Overall, 19% of Canterbury's agricultural land in 2022 was irrigated, the highest percentage in New Zealand. In some areas of the Canterbury Plains, where dairy farming is intensive, over 50% of agricultural land is irrigated. In 2022, Canterbury dairy farms accounted for 70% of dairy farming irrigation in New Zealand (Stats NZ, 2024). The irrigated land in New Zealand has significantly increased since the early 2000s and correlates well to the increase in dairy farming in Canterbury (Stats NZ, 2024).

Droughts can directly and indirectly impact the agricultural sector (Ramsay, 1998; Agriculture New Zealand (ANZ) & Butchers Partners Limited (BPL). These impacts can include reduced crop yields, loss of pasture for livestock, high costs to farmers, loss of livestock, loss of jobs, and soil erosion (e.g. ANZ & BPL, 2000; Elvidge, 1987; Burton & Peoples, 2014). These impacts can be short-term (lasting while the drought is in progress) and long term (lasting well after the drought has ended). (e.g. McPherson, 1989; Lucas, 1989;

Smith & Montgomery, 2004; Wilhite et al., 2000). The recent 2024 North Canterbury drought centred in the Hurunui district has had significant direct and indirect impacts on this rural community. This district is adapted to dry conditions, particularly over summer. However, the dry weather continued into autumn and winter, with one farmer indicating that their farm near Greta Valley had had only 220 mm of rain between December 2023 and August 2024 (Burns & McKinnon, 2024). Low product prices and high interest rates have exacerbated the impacts, limiting farmers' ability to relocate stock and bring in feed (Burns & McKinnon, 2024). Money has been very tight for farmers, and this has had a knock-on effect on other rural services and businesses. For example, the local vets have noted a decline in business during this time (Burns & McKinnon, 2024). Mental health issues have also been highlighted as an ongoing impact of the drought in the area (Connolly, 2024).

Due to the reliance on the primary sector for New Zealand's export economy and its vulnerability to drought, understanding droughts, their impacts, and risks is essential for helping New Zealand remain resilient in a warming climate and to inform adaptation and management requirements. Understanding drought characteristics and potential impacts is particularly important in Canterbury as one of New Zealand's primary agricultural and dairy production areas reliant on irrigation and highly susceptible to significant droughts (e.g. Maraca, 2016; Waimakariri Irrigation Limited (WIL), 2024; Grout et al., 2022) , including the droughts of 1988/89, 1997/99, and more recently 2014/15, and 2024 (e.g. Burton & Peoples, 2014; Brackebush, 2015; Kenny, 2001; Horrell et al., 1998; Underhill, 2015; Burns & McKinnon, 2024).

Canterbury is complex in terms of drought occurrence, spatial and temporal variations in drought severity, and impacts experienced. This complexity is partially due to the diverse terrain over short distances, orographic features, and climate, as well as where rain falls and how this impacts important sources of irrigation, the rivers and aquifers (Sturman, 1986). To understand the potential impacts of climate change on the primary sector in Canterbury and inform adaptation and mitigation efforts, a good understanding of the regional variations in how droughts are experienced is essential. Another essential requirement for successful adaptation is understanding what has happened in the past, especially extreme events that may have happened before living memory. This is because adaptation often only occurs to the worst event in living memory rather than what is physically plausible (e.g. Wilhite, 2019;

Carrão et al., 2016; Wilhite & Pulwarty, 2018). To date, limited studies have addressed these issues in the Canterbury region.

1.1 Thesis aims

This thesis has two aims:

1. To investigate the spatiotemporal characteristics of droughts in the Canterbury region.
2. To identify what a plausible worst-case drought scenario in the future look like in the intensive dairy farming areas of the Canterbury Plains.

These questions will be answered by systematically analysing historical rainfall data. These questions are important in order to develop effective adaptation plans in a warming climate for future drought events in Canterbury, a region that is vulnerable to the impacts of drought.

1.2 Thesis outline

Chapter 2 consists of a literature review that gives an overview of droughts and their complexities, looks into the spatiotemporal characteristics of droughts, drought impacts and management, the effects of climate change on droughts, and the use of a storyline approach to help understand risk and plausibility of potential extreme drought events. Chapter 3 briefly describes the Canterbury region and drought issues in the area, including how climate change may influence droughts in the future. Drought impacts and the use of irrigation are discussed. The climate data used and how it was selected and processed is outlined in Chapter 4. The specific methodology for each chapter is outlined at the beginning of the relevant chapter.

Chapter 5 identifies five meteorological drought events in the Canterbury region that occurred post-1950 and analyses their spatiotemporal characteristics. Some drivers of these droughts are also discussed, including the influence of the El Niño Southern Oscillation (ENSO). Chapter 6 looks further into the temporal and spatial variations of post-1950 meteorological droughts in Canterbury and identifies different Canterbury sub-regions with similar rainfall experiences. Chapter 7 identifies significant historical meteorological droughts pre-1950. Chapter 8 uses a storyline approach to identify a plausible worst case

drought scenario for the intensive dairy farming area of the Canterbury Plains. Chapter 9 gives a qualitative assessment of the implications of climate change on plausible drought scenarios. Chapter 10 is a brief summary of the thesis.

2 Literature Review

2.1 Overview of droughts

Droughts are a complex natural phenomenon and are considered among the most damaging natural hazards globally (e.g. Caloiero, 2017; Palmer et al., 2015; Pendergrass et al., 2020). They can cause severe adverse impacts on economic, social, and ecological systems (e.g. Tirivarombo et al., 2018; Reyniers et al., 2023; Caloiero, 2017; Carrão et al., 2016; Wilhite et al., 2000). Droughts are challenging to predict and quantify. They can vary both spatially and temporally, and their impacts depend on the exposure to the drought (e.g. duration, intensity, spatial extent) and the vulnerability to the drought (e.g., economic stability, health, poverty, inequalities, politics, mitigation measures in place) (e.g. Quiring & Papakryiakou, 2003; Carrão et al., 2016; Zargar et al., 2011; Wilhite et al., 2007). Droughts are often termed a creeping hazard and usually develop gradually, increasing in both intensity and duration over months (e.g. Mukherjee et al., 2018; Schwartz et al., 2023; Mol et al., 2017). However, this is not always the case. Flash droughts, where drought conditions develop very quickly (within the space of days to weeks), are becoming more commonly recognised, though their definition is still disputed (e.g. Ji et al., 2024; Yang et al., 2023; Ford & Labosier, 2017; Schwartz et al., 2023). For both fast and slow onset droughts, the impacts can be severe and extremely costly (Ford & Labosier, 2017; Ji et al., 2024; Yang et al., 2023). The development of droughts is generally non-linear and can have unequal impacts on the environment and society, which adds to the complexity and difficulty of predicting them and their impacts (Mukherjee et al., 2018; NIWA, n.d.).

Due to the complexity of droughts, including how they start, their varying impacts, and spatial and temporal scales, there is no universal definition of a drought (e.g. Koster et al., 2019; Wilhite et al., 2007; Mukherjee et al., 2018). Simplistically, droughts can be defined as significant periods where rainfall or moisture is below normal relative to the long-term average climatic conditions at a particular location (e.g. Wilhite & Glantz, 1985; Intergovernmental Panel on Climate Change (IPCC), 2023; Lloyd-Hughes, 2014; Sheffield & Wood, 2011; Carrão et al., 2016). This definition implies that the duration and location of a moisture deficit are important factors in determining a drought's severity (Lloyd-Hughes, 2014). It also highlights the spatiotemporal variations that occur with droughts. Droughts

should therefore be defined based on local or regional climatic conditions and the resulting impacts (Wilhite et al., 2007; Trivarombo et al., 2018; Mol et al., 2017).

Droughts are classified into different types of droughts, with the three most common being:

- Meteorological drought - significant rainfall deficits relative to normal.
- Agricultural droughts - significant soil moisture deficits impacting water availability to crops.
- Hydrological droughts - a deficit in water supply to groundwater, rivers, and other hydrological systems (e.g. Sheffield & Wood, 2011; Caloiero, 2017; AghaKouchak et al., 2023; Carrão et al., 2016; Yang et al., 2023; Mol et al., 2017).

These different types of droughts can co-exist or exist independently and propagate from one type to another (Tirivarombo et al., 2018). For example, a drought may start as a meteorological drought and then progress to an agricultural drought, and then a hydrological drought where river and/or groundwater levels are impacted by low rainfall and low soil moisture levels (Sheffield & Wood, 2011).

There are multiple drivers of drought, including both global and local climate phenomena (e.g. ENSO), low rainfall, temperature, wind, and evapotranspiration (e.g. Tirivarombo et al., 2018; Harrington et al., 2016; Koutroulis et al., 2011; Yang et al., 2023). Other factors, such as topography and land cover, can influence drought severity, likelihood, and resulting impacts (Vishwanathan et al., 2024). Two thirds of the rainfall deficit during the 2001 to 2009 *Millenium* drought in southeast Australia was attributed to the prevailing El Niño conditions (van Dijk et al., 2013). On a large scale, the climate and rainfall of the Western United States is impacted by large scale climatic patterns. These result in either dry summers and wet winters along the western edge of the United States or wet summers and dry winters from the southwest United States to the southern Rocky Mountains and Great Plains (Whitlock & Bartlein, 1993; Sheppard et al., 2002). On a regional scale, topography has a greater influence, and on a local scale, orography significantly influences precipitation (Whitlock & Bartlein, 1993).

Often, a combination of a number of these drivers can create the environment for more severe droughts. For example, the 1988/89 Canterbury drought was one of the droughts with the greatest impact on record. Along with low rainfall, persistent severe northwesterly gales (and associated high temperatures and high evapotranspiration) were a significant factor in the severity of the drought (McGann, 1991; Lucas, 1988; Malthus, 1988).

Declaring a drought is often subjective and can be highly specific to the area in question, the type of drought, and the impacts that the drought may have on the social, economic, and environmental systems of the area (Cronshaw, 2004; Gorman, 2003; NIWA, n.d.). This drought specificity highlights the need to understand droughts in a local context. For example, if there is an extended dry period, this may technically be a meteorological drought. However, a drought may not be declared as little to no social, economic, or environmental impacts exist. This local requirement is evident in the Canterbury region, where dry spells are not uncommon (Gorman, 2003; Macara, 2016), and if droughts were declared solely based on a dry spell, there would be droughts almost every year (Gorman, 2003). Instead, drought is often only declared once there are more severe impacts on the socioeconomic and environmental systems, particularly when livelihoods are impacted (Cronshaw, 2004), which can be a function of the dry period's length, intensity, and extent. In New Zealand, there can also be caution about declaring a region in drought due to compensatory issues (Cronshaw, 2004; Burton & Peoples, 2014).

2.2 Spatiotemporal characteristics of droughts

The spatiotemporal characteristics of droughts are key factors influencing their complexity and, hence, the prediction and management of these phenomena. Droughts can develop and persist over various time scales (e.g. Quiring and Papakryiakou, 2003; Pendergrass et al., 2020). Droughts are a creeping hazard that can take months to reach their full spatial extent and intensity (Yang et al., 2023). They can also last for years or decades (megadroughts) (van Dijk et al., 2013; Neelam & Hain, 2024). The Millennium drought in southeast Australia lasted from 2001–2009 (van Dijk et al., 2013), and during the 1930s, the Central Plains of the United States were hit with multiple severe droughts, commonly grouped as the "Dust Bowl" drought (Cook et al., 2009). The typical slow-developing droughts can remain hidden until they start to impact people or the environment. and the risk and potential impacts of the

drought can often be underestimated as a consequence (Pendergrass et al., 2020; United Nations Office for Disaster Risk Reduction (UNDRR), 2019; UNDRR, 2021).

Droughts can also develop rapidly, as in the case of flash droughts. (Yang et al., 2023; Ford & Labosier, 2017). The United States Midwestern drought flash drought of 2012 started developing in May, rapidly intensifying to a peak in July. The aerial extent of the dry areas over continental United States went from 30% to 60% in that time (Pendergrass et al., 2020; Jin et al., 2019). Flash droughts can be difficult to recognise and are challenging to mitigate and manage as they develop very quickly (Neelam & Hain, 2024; Pendergrass et al., 2020). The impacts are often severe due in part to the minimal time available to mitigate the impacts (Ford & Labosier, 2017). For example, the flash droughts in the Dakotas and Montana in 2017 resulted in approximately USD 2.6 billion in agricultural losses (Neelam & Hain, 2024).

The time scales over which droughts can develop make it challenging to define their start and end dates (Tirivarombo et al., 2018; Vicente-Serrano & Lopez-Moreno, 2005), complicating mitigation and management efforts. In comparison, other natural hazards, such as fires or floods, have clear start and end dates, which makes management and response to these events simpler (NIWA, n.d). The type of drought can also have different response times (i.e. how long it takes for drought conditions to be present). For example, meteorological droughts may have a response time of as little as one month, whereas for a hydrological drought, this may be over twelve months (Vicente-Serrano & Lopez-Moreno, 2005; Mol et al., 2017). The impacts of droughts can also linger for long periods after the end of the drought (Pendergrass et al., 2020; Wilhite & Vanyarkho, 2000). These temporal uncertainties can make managing droughts difficult, increasing the potential for adverse impacts to occur (Ford & Labosier, 2017; Wilhite & Vanyarkho, 2000).

Droughts can occur almost anywhere globally, including wet and humid areas. The only exception is deserts, where the term drought has little meaning (Carrão et al., 2016). Spatial variations in drivers of drought over both large and small areas can result in substantial local and regional variations in the intensity and severity of droughts (e.g. Tirivarombo et al., 2018; Vicente-Serrano & Lopez-Moreno, 2005; Vishwanathan et al., 2024; Quiring & Papakryiakou, 2003). Geographically diverse areas can exhibit different weather patterns over short spatial scales, influencing important drivers of drought such as

precipitation, temperature, and wind (Koster et al., 2019; Vishwanathan et al., 2024). For example, the Iberian Peninsula in Spain has a diverse geography, impacting the resulting atmospheric circulation patterns. In the north, the mean annual precipitation is more than 1000 mm, whereas in the south, the mean annual precipitation is less than 400 mm (Vicente-Serrano, 2006).

Due to the complex and diverse topography and weather patterns experienced in New Zealand, there is marked local and regional environmental variability and changes in the climate over small distances (Sturman et al., 1999; Sturman, 1986; Vishwanathan et al., 2024). Consequently, it is rare to have nationwide droughts; most droughts tend to be either local or regional (Salinger & Porteous, 2014; Cronshaw, 2004). The South Island of New Zealand has diverse topography over a small area. The primary rain-bearing airflows come from the west, and most of the rain falls as it hits the Southern Alps, meaning there is less moisture in the air as it goes east. This results in the west coast of the South Island being very wet. Annual rainfall is typically between 2,000 mm and 3,000 mm in low-lying areas and up to 11,500 mm in mountainous areas (Macara, 2016a; Vishwanathan et al., 2024). On the other hand, the east coast of the South Island is dry and more susceptible to droughts. Typically, annual rainfall is less than 1000 mm east of the Southern Alps (Macara, 2016; Vishwanathan et al., 2024).

Understanding the spatiotemporal characteristics of droughts can help understand what areas are potentially more susceptible to drought and determine if changes are happening over time, particularly with respect to climate change (i.e. is climate change changing the severity and/or the frequency of droughts or their spatial extent) (Ullah et al., 2023). Understanding these variations also helps with planning for adaptation and mitigation to protect economic, social, and environmental systems (Cao et al., 2021; Wilhite et al., 2007; Ullah et al., 2023).

2.3 Drought impacts

Not all droughts result in severe impacts; they become impactful when water demands are no longer met, and there is an increased risk of the system being unable to cope with this lack of water (UNDRR, 2021). This risk can seriously impact social, economic, and environmental systems (e.g. AghaKouchak et al., 2023; Caloiero, 2017; Ford & Labosier, 2017; UNDRR, 2021). The risk of a drought having serious impacts is a function of the hazard, exposure to

the hazard, and vulnerability (UNDRR, 2021). Vulnerability refers to the susceptibility to impacts, coping capacity, and adaptive capacity. The higher the susceptibility, the lower the coping and adaptive capacity, and the more likely that impacts from drought will increase (UNDRR, 2021).

Drought impacts are context specific and can vary over both spatial and temporal scales due to changes in the system such as societal characteristics and the ability of the systems to adapt. (Burton & Peoples, 2014; NIWA, n.d.). The impact of a drought isn't just caused by the natural event itself, but also by how it interacts with the wider system, including how resilient or vulnerable that system is. For example, drought effects depend on things like water use, crop production, and how well-prepared a community is (Wilhite et al., 2007; Wilhite & Vanyarkho, 2000; UNDRR, 2021). For example, the impacts of a similar scale drought may be different at different times due to societal conditions present at the time. The Canterbury droughts of 1988/89 and 1997/98 demonstrate this. These droughts were meteorologically similar. However, the impacts of the 1988/89 drought were far worse (Burton & Peoples, 2014). There were multiple reasons for this including a lack of adaptability of farmers at the time, the restructuring of the New Zealand economy in the 1980s, and the debt held by the farmers (Burton & Peoples, 2014; Smith & Montgomery, 2004). In comparison, in 1997/98, farmers had become more adaptable and resilient to drought (partly from lessons learned from the 1988/89 drought) and had made changes to their farming systems (e.g. diversified). They were also financially better off, enabling them to cope much better with this drought, reducing the impacts (Burton & Peoples, 2014).

Droughts and their impacts are often associated with the agricultural sector. The 2011 United States drought centred in Texas was estimated to cost USD 7.62 billion in agriculture losses and USD 800 million in timber losses (Ford & Labosier, 2017; Hoerling et al., 2013). Droughts are well known to contribute to rural stress and psychological well-being (Elvidge, 1987; Turner, 1990). Stress and adverse psychological well-being were evident in Canterbury during the 1980s. The economic situation in New Zealand and the change of government and their policies were already causing significant stress to the agricultural sector (Elvidge, 1987; Turner, 1990; Burton & Peoples, 2014). Multiple droughts during the decade exacerbated these stresses, decreasing psychological well-being and mental health (Elvidge, 1987; Turner, 1990).

However, agriculture is not the only sector negatively impacted by droughts. Droughts can have far-reaching socioeconomic and environmental impacts. For example, the 1991/92 (energy crisis) and 2000/01 drought resulted in low levels in the hydro lakes of Central Canterbury, impacting electricity production and increasing the cost of power nationwide (Waugh et al., 1997; Daniels, 2002). The 1991/92 energy crisis was caused by low rainfall in the central Southern Alps, resulting in prolonged periods of low flows into the hydro lakes. The impacts of this event were felt throughout New Zealand, where nationwide electricity shortages were experienced (Waugh et al., 1997). The 2013 North Island drought was one of the most extreme droughts in the last 50 years, resulting in severe soil moisture and rainfall deficit over a large area (Harrington et al., 2016). At the peak of this drought, it was estimated that only 20 days of water was available for Wellington. This drought resulted in approximately USD 1.3 billion in lost revenue and a decrease in the annual GDP of New Zealand by 0.6% (Mol et al., 2017; Harrington et al., 2016). It was estimated that farmers in the North Canterbury area would have a two to three year recovery period due to the 2014/15 drought (Brackebush, 2015). A study by Bell et al. (2021) showed a clear link between soil moisture levels and farm profits; for each very dry day, there was a corresponding loss in annual profit, which could be felt over the corresponding year or longer depending on the farm type.

Droughts have significant impacts on the environment. The 2019/20 Australian bushfires were preceded by a persistent drought, particularly in the Murray-Darling basin, which recorded its hottest and driest summer on record (Kumar et al., 2020; Climate Council, 2019). The drought exacerbated the bushfire risk, drying the soil and fuels (Climate Council, 2019). The bushfires caused significant ecological and environmental impacts, with over 21% of the Australian forests burnt (Kumar et al., 2020). Between 2001–2020, seasonal drought in subtropical China was shown to cause a 31% increase in fire ignition probability and spread rates (Yin et al., 2024). During 2009/10, southwestern China experienced a severe drought. The drought impacted the ability of forests to absorb carbon due to the faster water cycling. This area was a significant carbon sequestration area, so the drought also had impacts on climate change mitigation efforts (Yang et al., 2023).

Whilst the absolute scale of the economic impact of droughts in high income countries is the biggest, the economic impacts of drought can also be severe in low income countries. However, the social impact can often be far more significant than in low income countries

than in high income countries (Carrão et al., 2016). The social impacts may include drinking water shortages, food deficits, political unrest, and conflict (Carrão et al., 2016). The 2009/10 drought in southwestern China resulted in drinking water shortages and crop failure, resulting in approximately USD 3.5 billion in damages (Zhu et al., 2018; Barriopedro et al., 2012). In Syria, severe multi-year droughts between 2006 and 2011 contributed to agricultural failures, water insecurity, and mass rural-to-urban migration (estimated at 1.5 million people), resulting in urban unemployment and increasing social and political unrest in an already unstable region (Carrão et al., 2016; Gleick, 2014).

Droughts are often termed a cascading hazard, where the initial event triggers further hazards and impacts (AghaKouchak, 2023; UNDRR, 2021). For example, as highlighted above, low rainfall can lead to drought and agricultural losses, impacting local economies. The impacts of drought may then sometimes extend to global markets, food shortages, and insecurity, particularly in vulnerable locations (UNDRR, 2021). An example is the Euphrates-Tigris Basin in the Middle East. This area has been affected by multiple droughts, including 1998–2001, and 2006–2010 (UNDRR, 2021). Many areas and people in this region are vulnerable to water shortages (e.g. subsistence farmers, areas where rain is essential for farming). Droughts in this region have contributed to several cascading impacts. The initial exposure has led to social and economic losses, in turn forcing people to migrate to cities due to a loss of livelihood in the rural areas. This migration can lead to further impacts, including increased pressures on cities and a breakdown in food production (UNDRR, 2021). These drought cycles have also had cascading environmental impacts, including land degradation, desertification, and large scale ecosystem impacts (UNDRR, 2021). Cascading impacts underscore the complexity of droughts, their impacts, and their management.

2.4 Drought management

Droughts are one of the most consequential climate-related hazards, partly due to their long-lasting socioeconomic, environmental, and cascading impacts (Carrão et al., 2016). Inadequate management and adaptation to droughts can increase and prolong these impacts (Wilhite, 2019). Drought management can broadly follow two approaches: managing the drought or natural hazard and managing the drought risk (NIWA, n.d.; Wilhite et al., 2000).

Historically, responses to drought have been either to only adapt to the worst drought in memory or being reactive, resulting in a crisis management type of approach to dealing with droughts (i.e. just dealing with the consequences of the drought at the time or managing the drought) (e.g. Wilhite, 2019; Carrão et al., 2016; Wilhite & Pulwarty, 2018). This approach can include repairing damage or loss after or during the event and government support and subsidies (NIWA, n.d.). These management options can result in an increased dependence on governmental or outside assistance and decreased self-reliance (Wilhite, 2019; Wilhite & Pulwarty, 2018; Burton & Peoples, 2014). This management approach could be considered maladaptation, where adaptation/mitigation options increase, rather than decrease, the risks of a particular hazard (e.g. a drought) (Barnett & O'Neill, 2010). This is because a crisis management approach to droughts can reinforce past agricultural and management practices, which helped create the vulnerabilities in the first place (Carrão et al., 2016).

The weaknesses in this approach were highlighted during the 1988/89 Canterbury and Otago drought. Before restructuring the New Zealand economy in 1984, substantial subsidies and government payouts were available to sheep and beef farmers. These subsidies and payouts resulted in a climate with little incentive to adapt to extreme weather conditions (e.g. drought) or improve farming practices (Burton & Peoples, 2014). This lack of adaptability was evident during the 1988/89 drought, which resulted in severe socioeconomic and environmental impacts in Canterbury and North Otago (Burton & Peoples, 2014). The severity of these impacts was partly attributed to the lack of adaptability and resilience of the sheep and beef farmers due to the loss of subsidies and government drought assistance that occurred as part of the economic restructuring (Burton & Peoples, 2014; ANZ & BPL, 2000).

In contrast, proactive adaptation or a risk-based approach to drought management allows for potential impacts and vulnerabilities in the system to be identified in advance and appropriate measures to be taken to mitigate and minimise or eliminate the impacts of drought before they happen (NIWA, n.d). This approach can include modifying farming practices so that they are appropriate for the climate (and predicted climate), diversification, and using indigenous knowledge (NIWA, n.d; Nyong et al., 2007). Whilst the 1997–1999 drought in Canterbury still had significant impacts on the farming community, vulnerabilities in the agricultural systems on the Canterbury Plains were identified as a result of lessons learned from the 1988/89 drought. Adaptations such as farm diversification before the event helped reduce the overall impacts (Burton & Peoples, 2014; ANZ & BPL, 2000) (see Chapter 8).

Good planning for drought requires detailed information about the various drivers of drought and their impacts and the plausible extreme droughts (Tijdeman et al., 2022). For effective drought management and adaptation, a detailed understanding of drought's spatiotemporal variability and characteristics is important. (Van Lanen et al., 2016; Liu et al., 2016; Tijdeman et al., 2022).

2.5 Drought and climate change

Climate change will impact regional climate systems and climate extremes, with some regions receiving more or less rain than and others (e.g. Wilhite, 2019; IPCC, 2023). Globally, meteorological droughts are projected to increase, as are some of their primary drivers, including temperature (UNDRR, 2021; Kenny, 2001). The Intergovernmental Panel on Climate Change (IPCC) predicts that in New Zealand the Droughts Index will increase by 10–20% by 2070–2099 under RCP8.5 (high baseline emissions scenario) (IPCC, 2023; Bodeker et al, 2022).

While it is accepted that drought will get worse in many areas, there has been some uncertainty on the severity and impacts of these changes and how they will vary locally and regionally (Seneviratne, 2012). Some of the uncertainty can be attributed to a lack of data and studies. This uncertainty is particularly the case in New Zealand where the IPCC has stated that lack of data and studies is a reason for the uncertainty associated with drought trends in the country (IPCC, 2023; Bodeker et al., 2022; Naumann et al., 2018). Drivers of drought, such as precipitation deficits, temperature, and high evapotranspiration rates, will increase with climate change, resulting in severe and frequent droughts, especially in areas that are already drought prone. (IPCC, 2023; Reyniers et al., 2023; Paez-Trujillo et al., 2024; Naumann et al., 2018; Kenny, 2001).

Extreme events, including drought and flooding, are expected to increase (Harrington et al., 2024; Paez-Trujillo et al., 2024). This change in rainfall distribution will result in more extreme events including severe droughts. The drought and heat wave in central and northern Europe during the summer of 2018 had a large spatial and temporal footprint, resulting in severe impacts on the environment and community. These types of events are expected to worsen with climate change (Tijdeman et al., 2022).

Due to the lack of studies, drought and rainfall trends in New Zealand are uncertain, with some areas reportedly becoming drier and others wetter due to anthropogenic climate change (Bodeker et al., 2022; Lewis et al., 2023; IPCC, 2023; Mullan et al., 2018; Sood & Mullan, 2020). Despite some uncertainty, studies and IPCC predictions indicate that droughts will become more severe in New Zealand due to climate change (IPCC, 2023; Clark et al., 2011; Caloiero, 2017). Northland, Canterbury, and other eastern coastal areas are expected to be the worst impacted areas (Caloiero, 2017). During this century, even under mild climate change scenarios, Canterbury is expected to be in drought 5–10% more of the time than what is currently experienced (NIWA, n.d.-a). The IPCC predicts that the most significant increase in drought intensity in New Zealand will be in the eastern areas of the South Island and the north and east of the North Island (IPCC, 2023; Bodeker et al., 2022). The IPCC also predicts an increase in the number of days where the potential evapotranspiration deficit (PED) will be severe, with the Canterbury region being particularly affected. This PED will result in long term drying of affected areas (IPCC, 2023; Bodeker et al., 2022) and impact the agricultural sector and beyond. A study by Babylon et al. (2022) on climate change and perennial ryegrass (the primary grass used for dairy pastures) found that in the upper North Island, the suitability of this grass would decline, especially under more severe warming predictions. They also found that the primary growing season would change, and winter would be least impacted by climate change, requiring adaptation to farming practices (Babylon et al., 2022).

Harrington et al. (2014) found that the extreme 2013 drought over the North Island of New Zealand could be attributed to climate change. It was found that the synoptic conditions responsible for the extreme rainfall deficits were more likely to occur in today's climate than in the 1800s (Harrington et al., 2016). Another study by Gibson et al. (2016) had similar findings and showed that circulation systems that cause low rainfall in New Zealand were more likely to occur under the high emission RCP 8.5 scenario. Lewis et al. (2023) used a storyline approach to look at drought risk in both a wetting and drying climate. They found that under wetting conditions, the rainfall partially offset the effects of temperature induced drying, resulting in a modest increase in drought severity (Lewis et al., 2023). In contrast, drought severity significantly increased under a drying scenario with increased temperatures and decreased rainfall. Also, the onset and end of the droughts will be changed, with the onset being earlier and the end later. In this scenario, a mean hydrological year in the future will be comparable to the worst historical years on record (Lewis et al., 2023). Harrington et al.

(2024) found that under a 3°C warming scenario, even with negligible changes in annual mean rainfall, there are likely to be significant changes in the amount of rain falling on the wettest days and the number of dry days, leading to more droughts (and floods).

The likely increase in both severity and frequency of droughts globally and New Zealand, but also their uncertainties, requires further understanding of the drivers of drought, including their spatial and temporal characteristics. The literature highlights the importance of understanding droughts and their complexities and identifying plausible scenarios for droughts in New Zealand and Canterbury. Understanding droughts will help inform adaptation challenges and strategies, enabling proactive adaptation, mitigation, and management of droughts. This understanding will increase resilience and decrease vulnerability to droughts, which do not occur when adopting event-specific responses (Wilhite, 2019; Lewis et al., 2023).

2.6 Storyline approaches

Probabilistic climate change projections have been the focus of climate science for some time; however, understanding risk and plausibility provides more information for decision-makers and the public (Sillmann et al., 2020). Climate modelling has, in the past, assigned probabilities to future scenarios or events that may occur under climate change. However, this approach is becoming limited (Shepherd et al., 2018). Models are only a simplification of the real system (Maraun et al., 2017) and have limitations such as biases, scale and resolution, and quality of the data input (Maraun et al., 2017; Gibson et al., 2023). These limitations increase the uncertainties associated with these models and limit the reliability of their predictions (Shepherd et al., 2018; Gibson et al., 2023). These uncertainties can escalate to a point where the predictions made by the models are less reliable and no longer support decision making and adaptation efforts (Gibson et al., 2023). This uncertainty is especially true for extreme or rare events, as outliers occur and are often dismissed as an error in the model rather than something that could plausibly happen (Sillman et al., 2017).

An alternative approach is to create storylines about future climate scenarios. Storylines emphasise understanding and plausibility rather than probabilistic predictions (Gibson et al., 2023; Chan et al., 2022; Shepherd et al., 2018). They emphasise a qualitative rather than a quantitative understanding of droughts. A storyline can be a logical sequence of past or

possible future events, including long-term trends (Shepherd et al., 2018). They do not assign probabilities but focus on understanding the factors driving these events, helping manage uncertainty and informing local and regional decision-making (Chan et al., 2022; Shepherd et al., 2018). Multiple storylines can be explored to consider various possible futures. Historical events can also be used as case studies to explore rare or extreme scenarios without waiting for them to occur again (Shepherd et al., 2018). Storylines can complement probabilistic methods, creating a more comprehensive view of potential outcomes (Shepherd, 2019).

Storylines are particularly valuable for examining uncertainty, understanding extreme events, and developing scenarios that can be used to adapt and manage these events before they happen (Shepherd et al., 2018; Lewis et al., 2023). Typically, humans find it difficult to adapt or respond to potential events they have no experience with, even when presented with reliable quantitative data on the probability of such an event (Shepherd et al., 2018). This means people only adapt to events within their living memory and often only after an event has occurred (Shepherd et al., 2018). This delayed adaptation can result in much higher impacts than if adaptation had occurred earlier or to a plausible event that may occur. It is difficult to comprehend numbers or probabilities and what they may look like (i.e. what does a 1 in 1000-year drought look like?) (Shepherd et al., 2018).

In comparison, storylines allow people to see or understand an event that has already occurred using episodic memory. Storylines enable complex and uncertain events or situations (e.g. droughts and climate change) to be effectively communicated, uncertainties identified, and risks assessed (Shepherd et al., 2018). Because storylines focus on physically plausible events, they effectively capture extreme events, which models can often miss. They can also provide a flexible method to investigate climate risks and are effective tools for communicating these risks (Chan et al., 2022; Shepherd et al., 2018). These characteristics make storylines an ideal tool to help inform decisions in high uncertainty situations such as climate change and drought assessment and management. Their use is becoming more widespread in climate science (Shepherd et al., 2018; Baldissera Pacchetti et al., 2024).

An example of how storyline approaches have been applied in climate studies include Zappa and Shepherd (2017). They used a storyline approach to analyse how regional climate impacts in parts of Europe depend on different plausible changes in the atmospheric circulation under climate change (Zappa & Sheppard, 2017). Dessai et al. (2018) used a

storyline approach to describe how future rainfall in India will change and the climate processes and anthropogenic factors that may influence this. As described in Chapter 2.5, Lewis et al. (2023) used a storyline approach to assess future drought risk under both wetting and drying climate scenarios in New Zealand. These examples highlight the usefulness of a storyline approach in studying climate change, its uncertainty, and possible impacts. A storyline approach will be used in Chapter 8 to assess a plausible worst case drought scenario for the Canterbury region.

3 Study Area

3.1 Canterbury

Canterbury covers an area of over 45,000 square kilometres and is located on the eastern side of the South Island of New Zealand. It is bounded to the west by the Southern Alps and to the east by the Pacific Ocean. To the north, it is bounded by the Clarence River catchment, and to the south by the Waitaki River catchment (Figure 3-1). Rivers drain to the east (except on Banks Peninsula) and can run high due to rain or snow melt in the Southern Alps, even when dry on the Plains (Maraca, 2016).

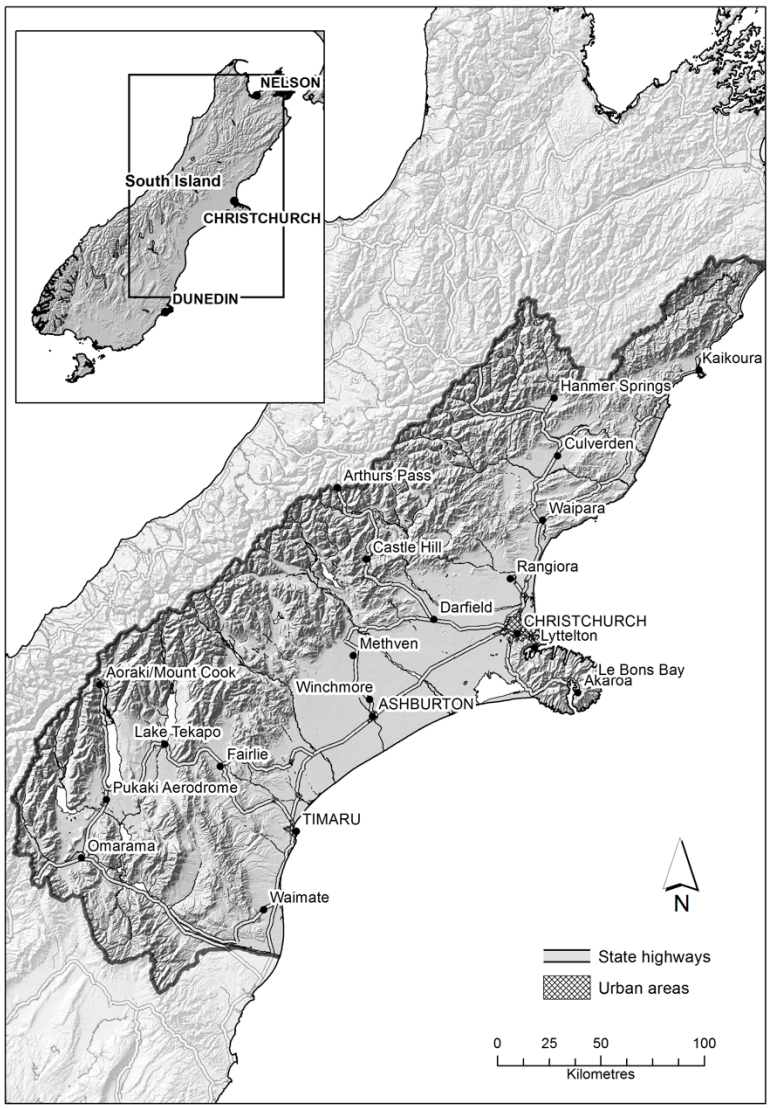

Figure 3-1. Map of the South Island of New Zealand and the Canterbury boundaries. The west is bounded by the Southern Alps and the east by the Pacific Ocean. To the north, it is bounded by the Clarence River catchment, and the south by the Waitaki River catchment. From The climate and weather of Canterbury (p.6), by G.R. Macara, 2016, NIWA. (https://niwa.co.nz/climate-and-weather/regional-climatologies/canterbury). Copyright 2016 by NIWA. Reprinted with permission.

The Southern Alps significantly impact the Canterbury climate and act as a barrier to prevailing westerly winds, causing most rain to fall on the west coast, making the east very dry (Maraca, 2016; Vishwanathan, 2024). The main divide receives the highest amount of rain, and the inland basins (such as the Mackenzie Basin) are extremely dry, often receiving less than 500mm/year (Figure 3-2). Most Canterbury locations have higher rainfall in autumn and winter (Maraca, 2016). Maraca (2016) describes the five main climatic zones of Canterbury in Table 3-1.

Table 3-1. Climatic Zones of Canterbury (Macara, 2016).

Climate Zone	Where	Description
1	Coastal Plains	– The plains slope from the coast to the foothills, with a maximum elevation between 200m and 400m . – Prevailing northeast and southeast winds, low rainfall, and a large annual temperature range. – Northwest winds are less common but can result in extreme evapotranspiration, making them important for agriculture.
2	Banks Peninsula and coastal strip north of Amberly	– Banks Peninsula has a maximum altitude of 919 m. – Winters are mild and can experience relatively high annual rainfall. Rainfall is generally higher in winter.
3	Eastern foothills and southern Kaikoura	– Cooler and wetter relative to other parts of Canterbury. – Prevailing winds are northwest.
4	High country	– Near the main divide and receives abundant precipitation and winter snow. – Prevailing winds are northwest.
5	Inland basins	– Low rainfall, with a maximum in summer. – Both diurnal and annual temperature ranges are large.

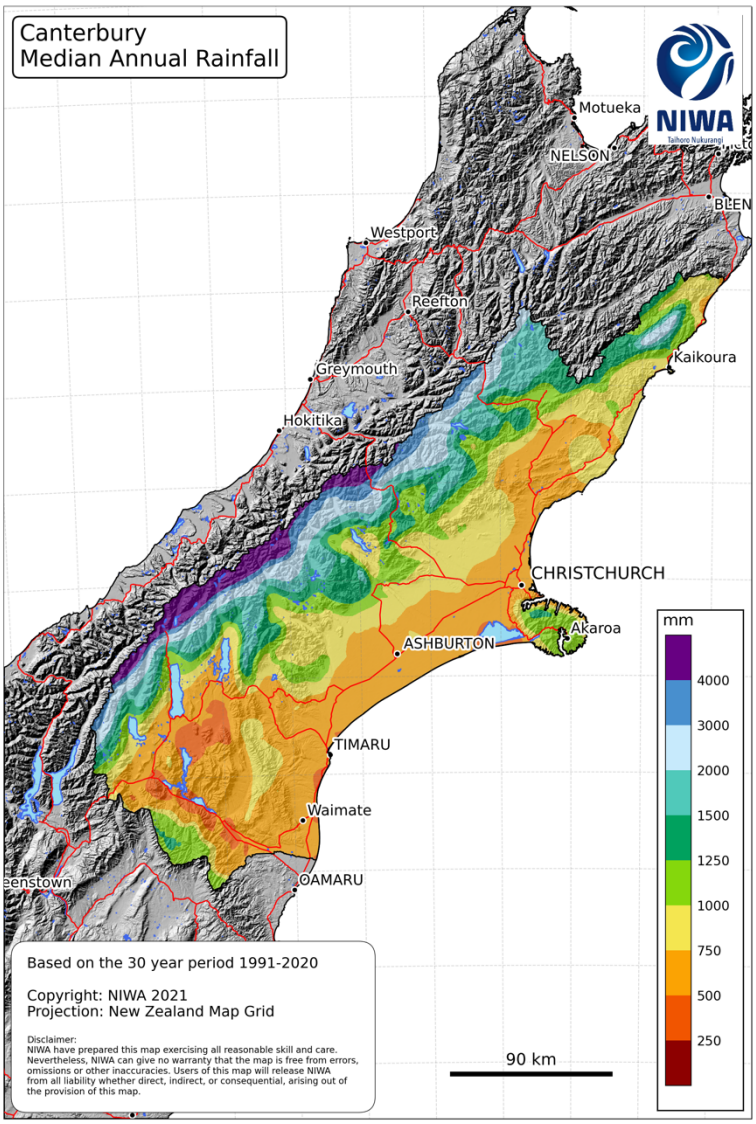

Figure 3-2. Map showing the median annual rainfall in the Canterbury region. This shows that the Southern Alps are the wettest areas and the plains and inland lake areas are the driest. Banks Peninsula is wetter than the surrounding plains area. From "The climate and weather of Canterbury" (p.16), by G.R. Macara, 2016, NIWA. (https://niwa.co.nz/climate-and-weather/regional-climatologies/canterbury). Copyright 2016 by NIWA. Reprinted with permission, figure updated by G.R. Macara.

3.2 Drought in Canterbury

Due to the complex terrain in Canterbury, the eastern parts are highly susceptible to droughts and dry spells (Sturman, 1986). Dry spells (defined as <1 mm, rain for periods of 15 days or more) are very common in Canterbury, occurring about every four months in Christchurch. These dry spells often occur when persistent (blocking) anticyclones become established over the South Island (Macara, 2016). Between 2013–2022, four to six droughts were declared in the Canterbury region (depending on area and type of drought) (Stats NZ, 2023).

Over the next century some areas of Canterbury are expected to become wetter (e.g. the east) and others dryer (e.g. the inland areas and Banks Peninsula) (Macara et al., 2020). Generally, the east will become significantly wetter in winter (in some places, up to 40% wetter), but many areas, such as Banks Peninsula, will be drier in summer (Macara et al., 2020). Despite the potential for an increase in rainfall in many areas of Canterbury, droughts are projected to increase (Macara et al., 2020; Clark et al., 2011; IPCC, 2023; Bodeker et al., 2022). Potential evaporation deficit (PED) is the difference between the amount of water that could evaporate and the amount that evaporates due to water availability. Essentially, the amount of rainfall that is missing for optimal pasture growth (Macara et al., 2020). PED is expected to increase over most of the Canterbury region, increasing drought risk (Macara et al., 2020; IPCC, 2023; Bodeker et al., 2022; Lewis et al., 2023). In addition, other drivers of drought, including temperatures, hot days, and extreme winds, are all expected to increase over the next century (Macara et al., 2020; Lewis et al., 2023). Farmers have already reported that the air and temperatures are hotter, increasing the impacts of dry spells (such as increased runoff due to hard, impenetrable soils) (The New Zealand Herald, 2021). Other issues, such as decreased runoff (into rivers and groundwater), will also contribute to drought impacts (Kenny, 2001).

3.2.1 Canterbury drought impacts and irrigation

Historically, droughts in Canterbury have had significant impacts, primarily in rural areas and on the agricultural sector. Not only are the impacts felt during the events but they can also be long lasting. The 1997/98 drought was one of the worst in memory, causing significant negative impacts on the Canterbury region. This drought negatively affected the agricultural sector, including farming and non-farming businesses that support farming communities, employment, and rural townships. (Ramsay, 1998; ANZ & BPL, 2000). Over the entire drought, which spanned from 1997–1999, the economic cost to the agricultural sector was estimated to be over NZD 425 million (over NZD 800 today) (Kenny, 2001). Ongoing impacts included loss of employment and decreased spending in the rural towns and Christchurch (ANZ & BPL, 2000).

Since the late 1990s, drought risk has been mitigated to some extent by increased irrigation in the Canterbury region. During the 1997–1999 drought, farmers who irrigated viewed the drought as less severe than those who did not (ANZ & BPL, 2000). Since the 1990s, dairy cow numbers have rapidly increased on the Canterbury plains (Joy et al., 2022; Grout et al., 2022; MacLeod & Moller, 2006). There were multiple drivers behind this rapid increase in

dairy farming on the plains (see Chapter 8), but irrigation is essential to this change. Canterbury is a naturally dry region previously considered unsuitable for dairy farming due to the requirements for high-quality pastures and water (Joy et al., 2022; Grout et al., 2022). Between 1985–2005, irrigated land in Canterbury increased by approximately 260% (Baskaran et al., 2009).

With the potential increase in drought conditions, the reliability of irrigation will be an important issue for Canterbury in the future. Canterbury is complex as irrigation water is taken from both surface and groundwater (both deep and shallow aquifers) sources. Irrigation taken from surface water has trigger levels, where if the river is below a minimum flow, water cannot be abstracted (ECAN, 2025). However, just because a drought may be present on the Canterbury plains does not mean the river is necessarily running low. Many of the rivers, especially the larger rivers such as the Rangitata or Rakaia Rivers, which are major sources of water for irrigation, have their headwaters in the Southern Alps. The location of their headwaters means they may still be running at normal to high levels due to rain in the Southern Alps, when the plains are very dry, allowing irrigation to occur still (Macara, 2016). Likewise, for groundwater, where water can be obtained from both the shallow and deep aquifers, water is often still available even when the region is experiencing very dry weather. This ability to take water when it is dry is especially the case for the deep aquifers in the Central Plains area, north of Ashburton, where the depth to the groundwater is large (Horrell et al., 1998). There have been occasions where the shallow groundwater aquifers have become unviable for irrigation. Water in these aquifers can become unavailable when the groundwater levels fall below the wellheads, meaning water cannot be pumped or when the well becomes dry (White, 1997). During the 1997–1999 drought record low groundwater levels were recorded in the Ashley-Waimakariri plains area, and some shallow wells became dry (Sanders, 2000; Horrell et al., 1998).

Occasionally, groundwater abstraction can be prohibited when it is very dry. For example, when an aquifer is hydraulically connected to local rivers/streams, abstraction can impact water levels in these rivers/streams. Groundwater abstraction in these areas may have restrictions when water levels in the river/stream fall below a certain level (WIL, 2000; ECAN, 2025).

Even though irrigation can be available to farmers during drought events, there have been cases where bans on irrigation have impacted farmers. During the 1988/89 Canterbury drought, irrigation bans were placed on most North Canterbury farmers for the first time due to newly implemented rules around irrigation. These irrigation bans resulted in prosecutions due to non-compliance, feed running out for livestock, and low milk production (McPherson, 1989; WIL, 2024). In 2000/01, irrigation bans in Canterbury meant grass did not grow, and supplementary feed was required, increasing costs to farmers (Kenny, 2001). Some areas have limited irrigation options, such as Banks Peninsula, where there is no connection to the aquifer systems, limiting irrigation options when the surface water flows become too low (The New Zealand Herald, 2021). Banks Peninsula is predicted to get drier under all climate change scenarios, which may seriously impact agriculture due to limited irrigation options (Macara et al., 2016). The reliability of irrigation in the future is likely to be one factor in the continued success of dairy farming on the Canterbury plains in a warming climate (Kenny, 2001). There are concerns over the vulnerability of the dairy industry, particularly to extreme events, due to high water demands. This vulnerability is likely to increase with the impacts of climate change (Kenny, 2001). Increased environmental concerns over the dairying industry, including high nitrate levels in the ground and surface water, methane emissions, and insufficient water for irrigation, may also lead to restrictions on the dairying industry in the future (Baskaran et al., 2009; Radio New Zealand (RNZ), 2022; Federated Farmers, 2024; Williams, 2024).

The uncertainties with future drought scenarios and the reliability and/or availability of irrigation water in Canterbury demonstrate the usefulness of a storyline approach to determining plausible drought events in the region.

4 Rainfall Data

Rainfall data were chosen to analyse the spatiotemporal characteristics of drought and plausible worst-case dry periods in the Canterbury region as longer observational records exist (in some cases over 100 years) for rainfall, and there is reasonable spatial coverage. These data allow both spatial and temporal characteristics to be analysed and extreme events to be identified. Equally long records do not exist for other variables, such as temperature, soil moisture or potential evapotranspiration, which places constraints on the analysis which can be performed. For example, soil moisture recordings generally only began at a few weather stations in the late 1990s. Temperature readings can go back prior to the 1950s; however, the spatial coverage is poor, with only two weather stations with records this long (neither of which are in rural areas). Drought indices were not used due to the requirement for observational records from multiple variables.

The National Climate Database of New Zealand holds data from historical and current climate stations around New Zealand. The database was accessed using NIWA's free web system, Cliflo (Note that the climate data previously accessed through Cliflo has been transferred to NIWA DataHub since 31 October 2024 (NIWA, n.d-i).

4.1 Climate station selection

Climate stations within the Canterbury region of New Zealand that had rainfall data from at least 1950 to at least 2023 were identified using Cliflo (Table 4-1 and Figure 4-1). This period ensured a large selection of weather stations with complete or almost complete rainfall records over a wide spatial area of Canterbury. The selected locations covered Canterbury's main climatic regions, including North Canterbury, Banks Peninsula, Christchurch, the Canterbury Plains, South Canterbury, and the inland lakes (Table 3-1). Daily rainfall data were extracted for each station's entire record.

Table 4-1. Canterbury climate stations with rainfall recorded from at least 1950–2023 or longer. Note that stations with an end date of present have data available to at least September 2024.

Station Number	Station Name	Start Date	End Date	Latitude	Longitude	Height above MSL (m)
4843	Christchurch Aero	02/09/1943	present	-43.493	172.537	37
4925	Okuti	02/09/1915	present	-43.78952	172.80958	61
4809	Glentui 1	02/12/1947	present	-43.235	172.248	235
4701	Hororata West	02/01/1948	present	-43.53306	171.85676	213
4702	Hororata	02/07/1890	present	-43.546	171.898	287
4525	Riverside	02/04/1916	present	-42.719	172.885	217
4778	Ashburton Council	02/01/1927	present	-43.89658	171.7472	101
4560	Hawkswood	02/01/1931	present	-42.654	173.329	152
4711	Springburn	02/09/1913	present	-43.68984	171.48338	312
4920	McQueens Valley	01/02/1947	present	-43.733	172.633	17
4720	Rakaia, Greenfields	02/01/1949	present	-43.60857	171.7323	305
4740	Lyndhurst, Limewood Farm	12/05/1934	present	-43.703	171.717	243
4548	Whalesback Station	02/01/1937	present	-42.491	173.183	463
4958	Little Akaloa, Brockworth	02/10/1911	present	-43.6645	172.99511	244
4796	Waipara, Wattle Grove	02/03/1923	present	-43.05294	172.972	74
4556	Keinton Combe	02/01/1912	01/01/2024	-42.608	173.108	213
4970	Lake Tekapo, Air Safaris	02/05/1925	present	-44.002	170.441	762
5061	Orari Estate	02/10/1897	present	-44.127	171.308	81

Station Number	Station Name	Start Date	End Date	Latitude	Longitude	Height above MSL (m)
4629	Lake Pukaki, Braemar	02/01/1914	01/01/2024	-43.989	170.198	550
5053	Kakahu Bush	02/07/1909	01/07/2024	-44.159	171.096	179
5110	Lake Ohau Station	02/05/1948	01/01/2024	-44.168	169.82224	533
4559	Ferniehurst	02/03/1949	present	-42.6039	173.324	137
4495	Hapuku, Grange Hill	02/12/1915	present	-42.312	173.692	140
4858	Christchurch Gardens	02/01/1873	present	-43.531	172.619	7
4939	Magnet Bay	02/02/1917	01/05/2023	-43.844	172.744	6

Figure 4-1. Location map of the selected Canterbury climate stations with rainfall records pre-1950s until 2023.

4.2 Data processing

Raw data from each station was processed to account for missing data. The World Meteorological Organisation (WMO) guidelines (WMO, 2017) were used as a guideline for the data processing. Years or summers were eliminated if the following applied:

1. More than three consecutive days of rainfall data, or a total of five days, was missing throughout the period of interest. The start year of interest was then deleted. Note that sometimes rainfall data were not recorded daily, but if it was accounted for, the data were not eliminated (see point 2). For example, rainfall data may have been recorded on 10 December, but the data on 11 and 12 December were missing, but 72 hours of data were then recorded on 13 December. Therefore the data had been accounted for and kept.

2. If daily data was not recorded but accounted for on the first day of the month at the start of the period of interest or the 1st of the first month after the period of interest, years were eliminated if that rainfall amounted to more than 5 mm. For example, if rainfall was not recorded on 30 and 31 of March 1991, but 15.1mm was recorded on 1 April 1991, data for the start year of 1990 for September-March, October-March, and January-March periods were deleted. Likewise, if rainfall for the 30 and 31 August 1990 was not recorded, but 15.2 mm of rain was recorded on the 1st September, then data for the start year of 1990 for September-March was deleted.

5 Spatiotemporal characteristics of Canterbury droughts

5.1 Introduction

The Canterbury region of New Zealand is one of the most important agricultural areas in the country and is highly susceptible to drought (Millner & Roskruge, 2013; Srinivasan & Duncan, 2012). The agricultural sector is adapted to dry conditions in the Canterbury region, and farmers tend to manage their farms to cope with these dry periods (e.g. keeping stock numbers low) (Keen & Rotorua, 1996). In Canterbury, droughts and dry spells can occur in both summer and winter; typically, the east is more susceptible than the west (Salinger & Porteous, 2014; Macara, 2016). The most severe drought impacts tend to occur if drought extends across autumn or spring, which are crucial periods for pasture growth (Keen & Rotorua, 1996).

Apart from low rainfall, a significant driver of drought in the Canterbury region is wind, particularly the hot dry northwesterly winds, which also contribute to high evapotranspiration rates, depleting the soil of moisture (McGann, 1991). ENSO is a naturally occurring climate cycle that has a global influence on weather (NIWA, n.d-e). It oscillates between its two phases, El Niño and La Niña, typically every few years (NIWA, n.d-e) and can influence weather features such as temperature, rainfall, and winds, which are all drivers of droughts (e.g. NIWA, n.d-e.; McGann, 1991; Horrell et al., 1998; Collen, 1983). The Southern Oscillation Index (SOI) quantifies the pressure difference between eastern and western areas of the South Pacific (Darwin and Tahiti) (NIWA, n.d-e). When the SOI is below -1, the El Niño phase is present, and above 1.0, the La Niña is present (NIWA, n.d-e). Between -0.5 and 0.5, it is neutral (neither El Niño nor La Niña).

On average, El Niño events in New Zealand can result in more frequent winds from the west in summer, the western areas being wetter and the east being dryer (NIWA, n.d-e). Due to the potential dryer conditions, the El Niño phase is often associated with droughts and dry spells in the eastern areas of New Zealand (The Country, 2023; Ministry for Primary Industries: Manatū Ahu Matua (MPI), n.d; Morton, 2023). Despite the association of El Niño with dry weather and droughts, it is accepted that this ENSO phase does not always result in drought conditions (NIWA, n.d-f; NIWA, n.d-e). In contrast, La Niña events have less impact on New

Zealand's climate. Northeasterly winds are more common, bringing rain to northeastern areas of the North Island and less rain in the south and west of the South Island (NIWA, n.d-e). Droughts are not as often associated with La Niña compared to El Niño, however, they can occur in both La Niña and El Niño ENSO phases in the Canterbury region (NIWA, n.d-f). Whilst these are the average outcomes of El Niño and La Niña events in New Zealand, there can be significant variations year to year, and these events do not have a large impact on the overall rainfall and temperature variations in New Zealand (NIWA, n.d-e). In comparison, the ENSO state impact on rainfall in eastern Australia is well documented. La Niña events can increase the likelihood of a wet spring and El Niño a dry spring (Tozer et al., 2023). However, like New Zealand, there is variability in this pattern, with many locations along the eastern seaboard of Australia (e.g. Sydney) being largely unaffected by the ENSO state (Tozer et al., 2023).

Managing drought risk through proactive management and mitigation measures, rather than crisis managing the drought, requires understanding the spatiotemporal characteristics of droughts in the Canterbury region. Previous spatiotemporal drought studies in New Zealand have primarily focused on drought characteristics on a national scale. Salinger and Porteous (2014) recognised that droughts in New Zealand tended to be regional in extent due to the interaction between large-scale climatic patterns, persistent synoptic weather, and topography. They identified five regions over New Zealand where droughts appeared spatially coherent. One distinct region was the east of the South Island (which would include much of Canterbury). Caloiero (2014) looked into the spatiotemporal distribution of drought over New Zealand using the standardised precipitation index (SPI). Areas vulnerable to drought were identified, including Canterbury and other eastern areas of New Zealand. There have been other studies on a national scale, that have primarily looked into changing drought risk with climate change, which have identified regional differences to drought vulnerability (e.g. Mullan et al., 2005; Clarke et al., 2011, Sood & Mullan, 2020). Whilst these studies provide a good starting point, they do not highlight the local scale variations in drought occurrence within a specific region.

There have been few studies on the spatial and temporal characteristics of drought carried out on a regional scale in the Canterbury region. One study by McGann (1991) looked at the spatial and temporal distribution of the 1988/89 Otago and Canterbury drought and factors that influenced the drought (e.g. northwest winds and ENSO conditions at the time).

Given the complex topography and weather systems of the Canterbury region and the different climatic zones present, further research is required to fully understand the spatiotemporal drought characteristics to manage and mitigate the impacts of drought effectively. This chapter uses long-term historical rainfall data to explore the spatiotemporal characteristics of droughts in the Canterbury region and whether the ENSO state influences their occurrence at the time.

5.2 Methodology

Using the stations and data identified in Chapter 4, an initial scan of six randomly selected stations (Keinton Combe, Waipara, Okuti, Hororata, Christchurch Aero, and Kakahu Bush) covering most of the Canterbury region (except the inland lakes) was carried out to determine dry periods of interest between 1950–2022 and the approximate months that a dry period occurred over. This was done by graphing the rainfall record between 1950–2022 in MATLAB and qualitatively identifying five dry periods where there was low rainfall. Note that there were more periods in these records with low rainfall; however, the study was limited to five seasons. The cumulative rainfall from 1 June–31 May was then plotted in MATLAB against the entire rainfall record between 1950–2022 to estimate the dry periods (for example Okuti, Figure 5-1) (see Appendix A for the other cumulative rainfall graphs). The dry periods of interest (the months of the year that were analysed) identified during this process are shown in Table 5-1. Note that the dry periods were not the same for each randomly selected station. This was due to the large geographical area. A 'best-fit' type approach was used, meaning that the periods used covered most of the stations. The dry periods chosen were over the spring-autumn periods (“summer”) as this is during the main growing and milk production season and are when droughts in Canterbury (New Zealand) typically have the biggest impact on the agricultural sector (NIWA, n.d-h; MPI, n.d-a).

For each station (Table 4-1), the climate normals were calculated for the dry periods of interest (Table 5-1) over thirty years from 1991–2020, and basic statistics were calculated (e.g. mean, maximum and minimum rainfall) (see Appendix B). The total rainfall was calculated for each dry period of interest (Table 5-1), and the ratio of rainfall to the climatic mean was calculated to determine the percent anomaly of rainfall for a particular period to the mean. The rainfalls for each year from 1950–2022 and the periods of interest were ranked, with 1 being the driest year.

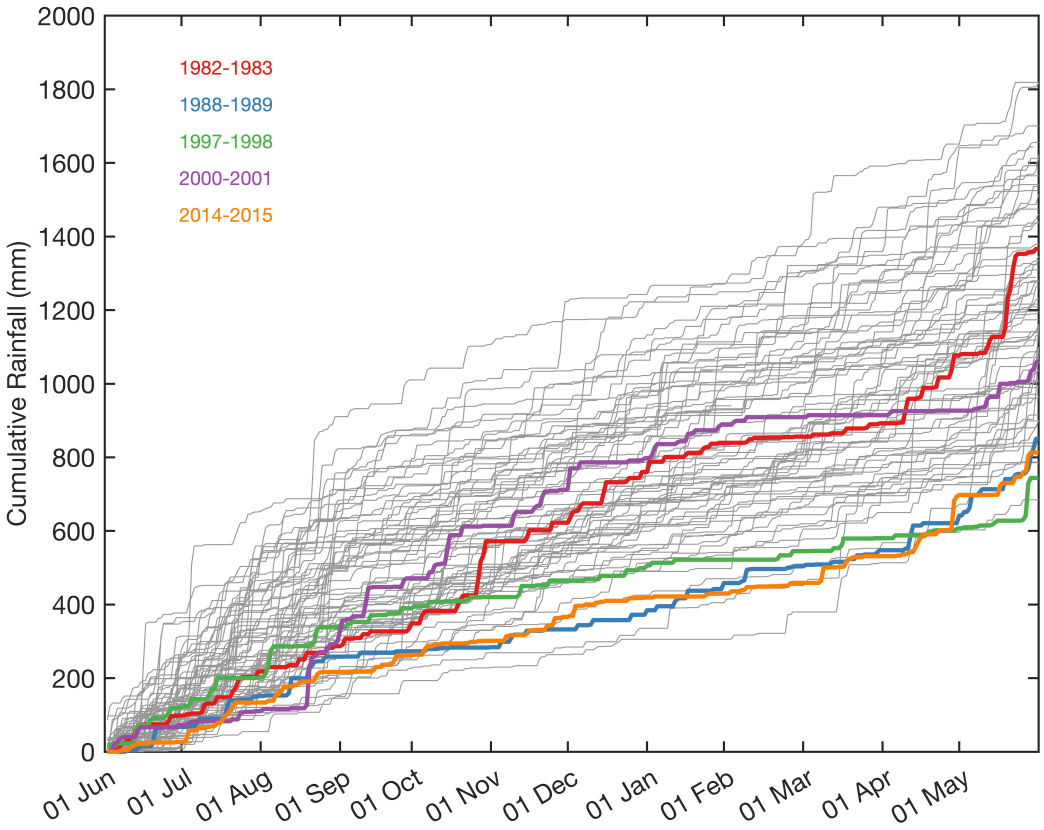

Figure 5-1. Cumulative rainfall at Okuti. Highlighted years are the years of interest. The grey lines are all other years between 1950–2022. This is an example of the figure used to estimate the dry period for the years of interest. For example, during 2000/01 there appears to have been minimal rain between the beginning of December and the end of April.

Table 5-1. Years that were selected to analyse further.

Years of interest	Dry months
1982 - 1983	1 January 1983–31 March 1983
1988 - 1989	1 September 1988–31 March 1989
1997 - 1998	1 October 1997–31 March 1998
2000- 2001	1 December 2000–30 April 2001
2014 - 2015	1 October 2014–31 March 2015

5.3 Results

5.3.1 January 1983–March 1983

Rainfall rankings and percent anomalies between 1 January 1983–31 March 1983 did not indicate that this was an exceptionally dry year in Canterbury (Figure 5-2a). The exceptions were Magnet Bay, Christchurch Aero, and Whalesback Station, which were all in the driest 3 years between 1950-2022. Magnet Bay (47%), Christchurch Aero (43%), Whalesback Station (44%), Ashburton Council (47%), Waipara (44%), and Keinton Combe (44%) all had rainfall less than 50% of normal (Figure 5-2b). Whilst this year may not have been exceptionally dry, the data shows that low rainfall was still experienced over most of the Central Plains, North Canterbury, and Banks Peninsula, with most of these stations recording precipitation totals in the lowest 15 years between 1950–2022 (Figure 5-2a). In contrast, rainfall was slightly below normal in the Canterbury high country, Mackenzie Basin, and the Southern Plains (Figure 5-2b).

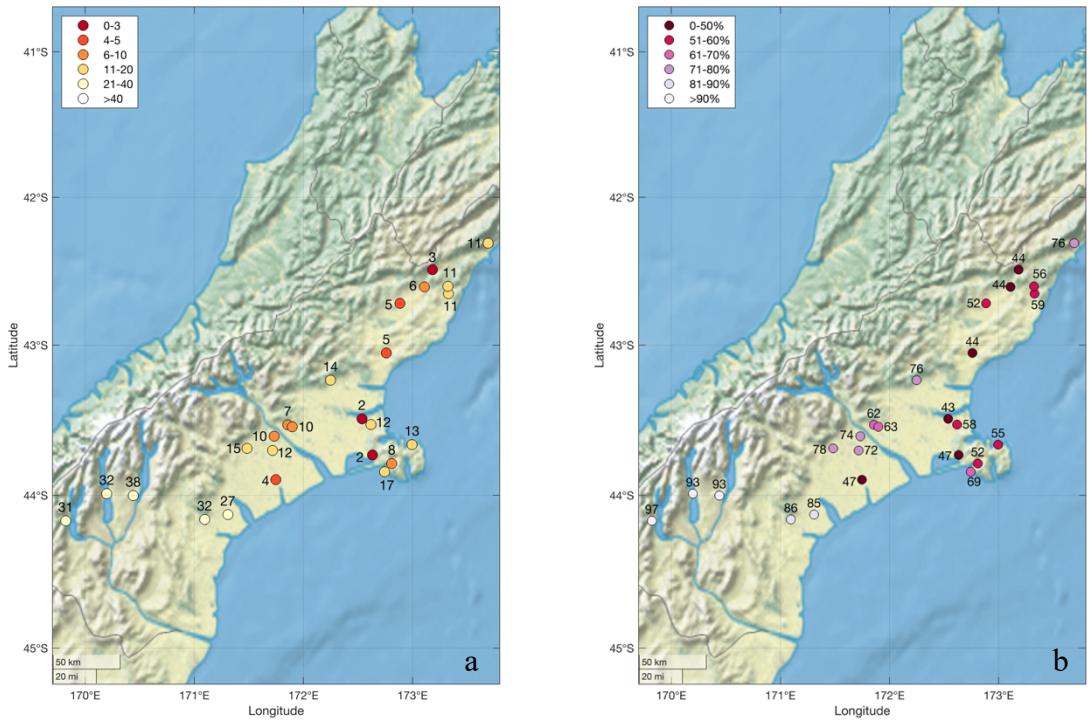

Figure 5-2. Rainfall rankings and percent anomalies between 1 January 1983–31 March 1983 from 25 Canterbury weather stations covering different climatic regions. (a) Ranking of rainfall totals between 1950–2022. 1 indicates the driest or least rainfall recorded between these dates at that particular weather station. (b) The percent rainfall anomaly relative to the 1991–2020 climatology. Anomaly values below 100% indicate less than the mean rainfall total for this period.

5.3.2 September 1988–March 1989

Rainfall rankings and percent anomalies between 1 September 1988–31 March 1989 was very low compared to normal in Banks Peninsula, North Canterbury, and the Central Plains areas, with some of the stations recording their lowest rainfall on record (Whalesback, Keinton Combe, Christchurch Gardens, Ashburton Council, McQueens Valley) (Figure 5-3a). In contrast, Lake Ohau, in the Canterbury high country, was very wet, with it being one of the wettest years (67 out of 70 years) between 1950 and 2022 (Figure 5-3a). Even though the rainfall was low, most stations had rainfall of more than 50% of the mean (Figure 5-3b). Only McQueens Valley (50%), Christchurch Gardens (49%), and Keinton Combe (50%) had rainfall 50% or lower than the mean. Rainfall at Lake Ohau was 114% of the mean, and at Lake Tekapo, 104% of the mean.

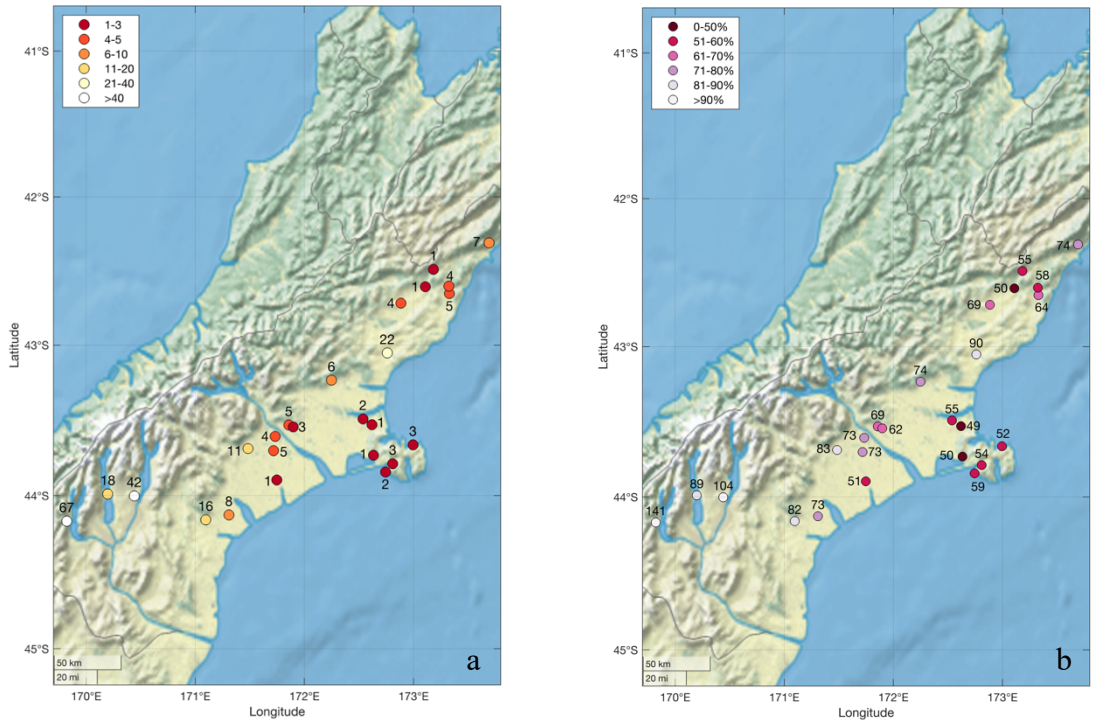

Figure 5-3. Rainfall rankings and percent anomalies between 1 September 1988–31 March 1989 from 25 Canterbury weather stations covering different climatic regions. (a) Ranking of rainfall totals between 1950–2022. 1 indicates the driest or least rainfall recorded between these dates at that particular weather station. (b) The percent rainfall anomaly relative to the 1991–2020 climatology. Anomaly values below 100% indicate less than the mean rainfall total for this period.

5.3.3 October 1997–March 1998

The rainfall rankings and percent anomalies from 1 October 1997–31 March 1998 was low over much of Canterbury, especially north and central Canterbury and Banks Peninsula (Figure 5-4). Record or near-record low rainfall totals were recorded at all weather stations in these areas, with rainfall below 63% of normal north of the Rakaia River (Figure 5-4b) at all weather stations. Stations on the Canterbury Plains south of the Rakaia River did not experience as extreme dry conditions as those further north (Figure 5-4b). Apart from Rakaia (ranked 2nd worst), these stations ranked between the seventh and thirteenth worst years (Figure 5-4a). The percent anomalies were between 65% and 78% of the mean (Figure 5-4b). In contrast, Lake Ohau, in the Canterbury high country, experienced high rainfall and was one of the wetter years on record (ranked 50 out of 70 years), with rainfall being greater than the mean (114 %) (Figure 5-4b). Lake Pukaki and Lake Tekapo also experienced wetter weather than the rest of Canterbury, though at Lake Tekapo the mean rainfall was still slightly below normal (84%).

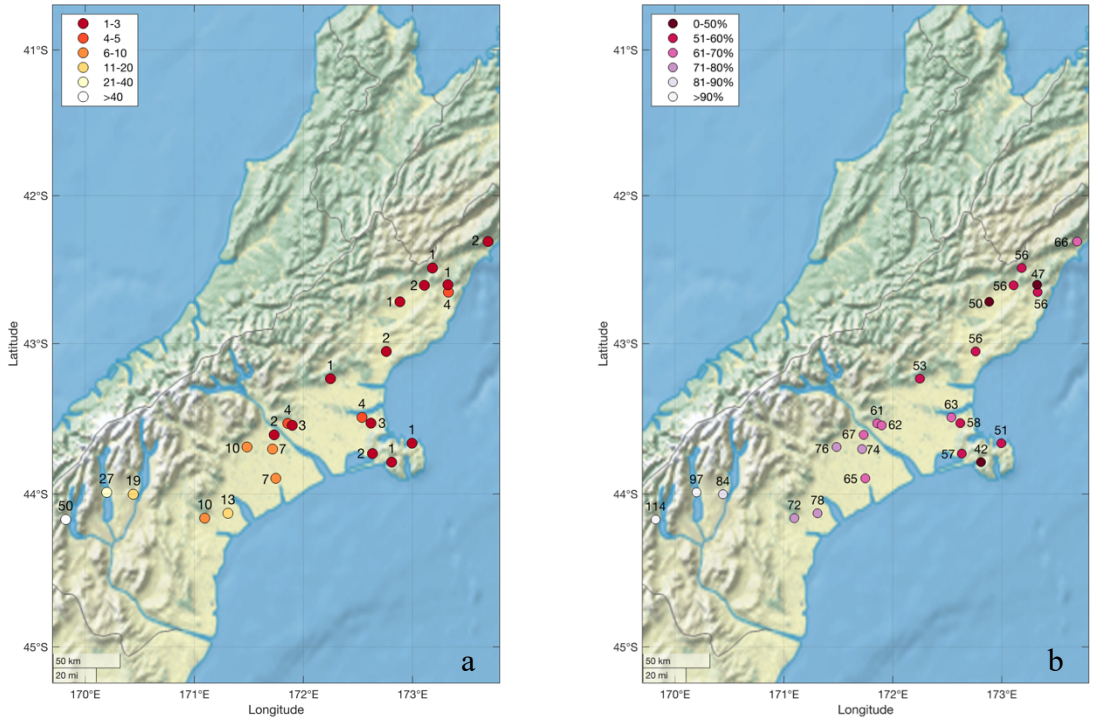

Figure 5-4. Rainfall rankings and percent anomalies between 1 October 1997–31 March 1998 from 25 Canterbury weather stations covering different climatic regions. (a) Ranking of rainfall totals between 1950–2022. 1 indicates the driest or least rainfall recorded between these dates at that particular weather station. (b) The percent rainfall anomaly relative to the 1991–2020 climatology. Anomaly values below 100% indicate less than the mean rainfall total for this period.

5.3.4 December 2000–April 2001

Rainfall rankings and percent anomalies for 1 December 2000–30 April 2001 show record-low or near-record-low rainfall over all of Canterbury except Lake Ohau station (Figure 5-5a). At all stations (except Lake Ohau), the rainfall totals ranked in the lowest three recorded between 1950–2022 for these months and most of these stations (exception being Rakaia, 56%, Kakahu Bush, 54% and Lake Pukaki, 52%) had rainfall totals less than 50% of normal (Figure 5-5b). The spatial extent of this dry period is far greater than the other periods analysed, where extremely dry conditions were not as widespread.

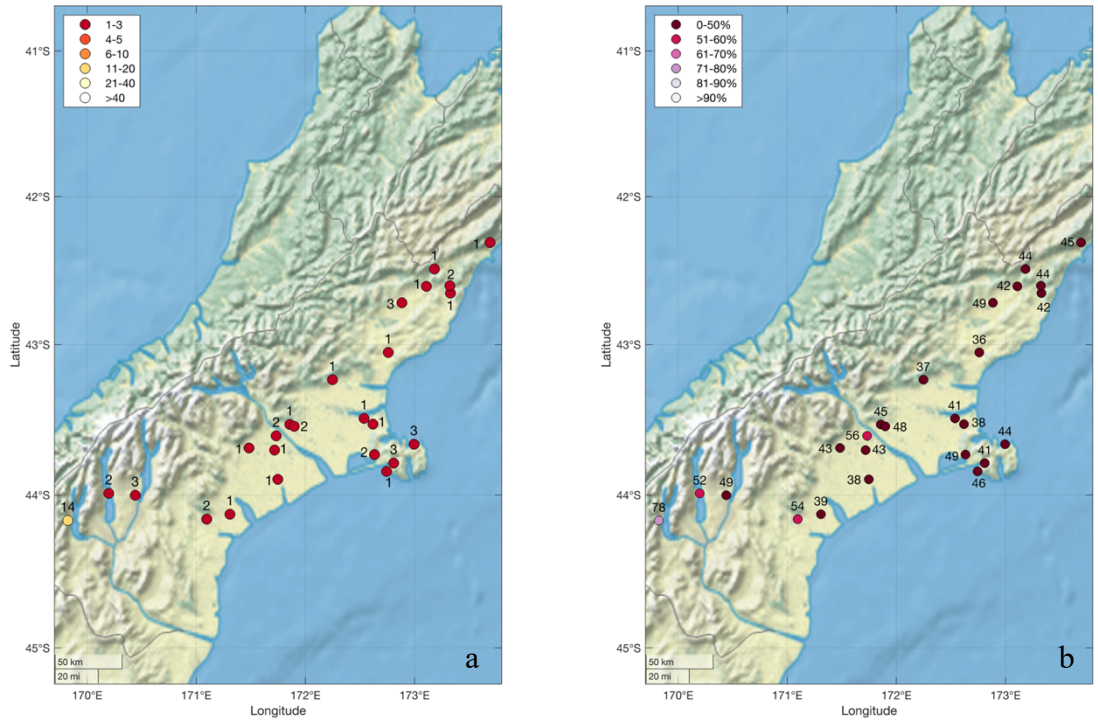

Figure 5-5. Rainfall rankings and percent anomalies between 1 December 2000–30 April 2001 from 25 Canterbury weather stations covering different climatic regions. (a) Ranking of rainfall totals between 1950–2022. 1 indicates the driest or least rainfall recorded between these dates at that particular weather station. (b) The percent rainfall anomaly relative to the 1991–2020 climatology. Anomaly values below 100% indicate less than the mean rainfall total for this period.

5.3.5 October 2014–March 2015

Rainfall rankings and percent anomalies show that dry conditions were widespread over Canterbury between 1 October 2014–31 March 2015 (Figure 5-6), similar to the 2000/01 dry period. Four stations (Kakahu Bush, Orari Estate, Hororata, Magnet Bay) experienced their lowest rainfall; another eight stations were ranked in the lowest three between 1950–2022 (Figure 5-6a). Despite the widespread dry conditions, only two stations, Hororata West (43%) and Kakahu Bush (47%), recorded rainfall less than fifty percent of the mean. Most stations were between 55-70% of the mean (Figure 5-6b).

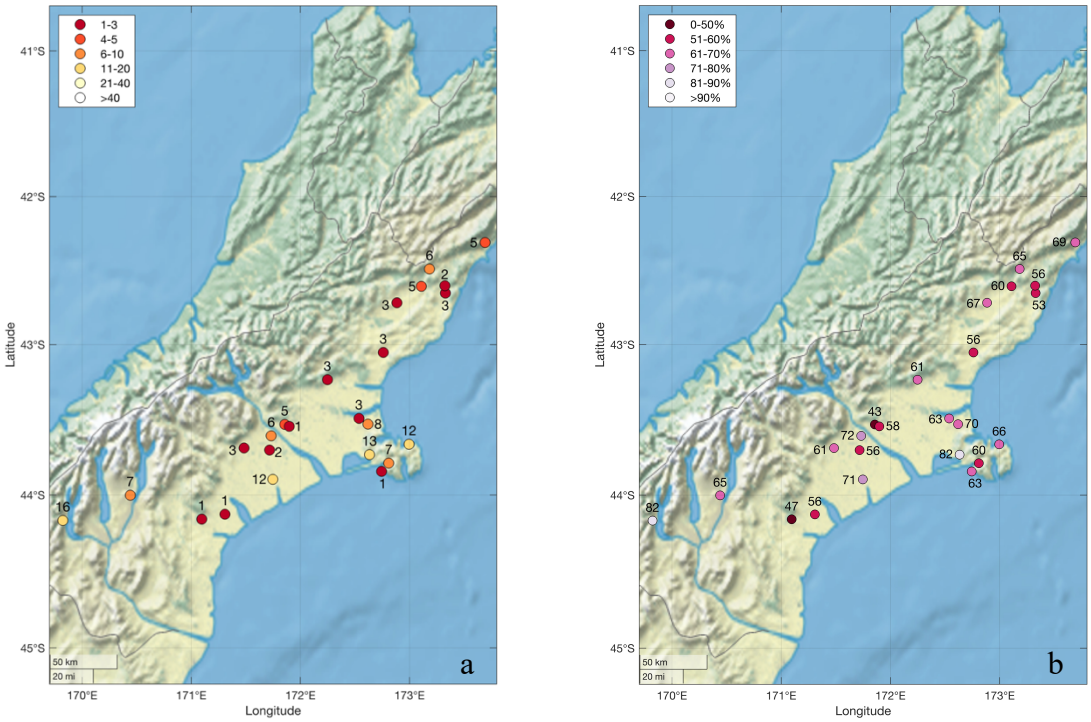

Figure 5-6. Rainfall rankings and percent anomalies between 1 October 2014–31 March 2015 from 25 Canterbury weather stations covering different climatic regions. (a) Ranking of rainfall totals between 1950–2022. 1 indicates the driest or least rainfall recorded between these dates at that particular weather station. (b) The percent rainfall anomaly relative to the 1991–2020 climatology. Anomaly values below 100% indicate less than the mean rainfall total for this period.

5.4 Discussion

The results are consistent with historical accounts of drought in the Canterbury region and show spatial and temporal variations in the occurrence and severity of droughts experienced.

5.4.1 Historic Accounts

The January–March 1983 results show that the lowest rainfalls were mainly experienced in parts of North Canterbury and Banks Peninsula (Figure 5-2). The results are consistent with the historical observations that describe drought conditions in both the north and east of Canterbury. A severe drought was recorded between Blenheim and Kaikoura (Collen, 1983), and parts of Nelson and Marlborough recorded no rainfall during February 1983 (Stats NZ, 1984). Dry conditions in the north and east of the South Island were experienced for four months from December 1982–March 1983. This drought extended into the North Island, including the Hawkes Bay and East Cape, where a severe drought was recorded (Collen, 1983). By the autumn of 1983, most of the South Island had received significant rain, breaking the drought; however, the drought lasted longer in the North Island (Collen, 1983).

While this event overall did not come up as an exceptionally severe drought event based on the rainfall rankings (Figure 5-2a), the percent rainfall anomalies were very low, with many stations recording rainfall less than 50% of normal (Figure 5-2b). The number of stations recording such low rainfall was more than in periods with severe drought (e.g. 1988/89, Figure 5-3b). These low rainfall percentages suggest that extremely low rainfall between January and March is not uncommon in many parts of Canterbury. It also shows that the rankings better indicate a severe dry event than percent anomalies. For example, Waipara and Keinton Combe recorded 44% of normal rainfall, yet this year was only the fifth and sixth worst year between 1950–2022 despite the very low rainfall. For this drought, the historical accounts detailed that December was a dry month. This month was not analysed, as it did not meet the selection criteria, which may have changed the severity of the drought/dry period had this been included.

The 1988/89 Canterbury drought has been well documented as having severe impacts over extensive areas of Canterbury and costing the economy millions of dollars (Turner, 1990). The main areas affected ranged from North Otago to North Canterbury. It was one of the severest droughts recorded in these regions (McGann, 1991). The rainfall analysis confirms these observations, with rain being particularly low in Central and Northern Canterbury and Banks Peninsula (Figure 5-3). Many stations recorded rainfall in the lowest five years between 1950–2022 (Figure 5-3a). The exception was Waipara, where the rainfall was 90% of normal, and the year ranked 22 out of 68 years.

Records show that the dry period started in April 1988 in North Otago and steadily moved northwards. By November 1988, North Canterbury was extremely dry; by December 1988, the Canterbury foothills were very dry (McGann, 1991). For the first eight months of the year, many parts of Canterbury had only 40–50% of their normal rainfall (Harford & Lucas, 1988). During September 1988, many weather stations recorded their lowest recorded rainfall (McGann, 1991) and reports highlighted that Canterbury was on the verge of a severe drought if rain did not fall soon (Harford & Lucas, 1988). Substantial rain finally fell in April 1989, breaking the drought (McGann, 1991).

Even though many stations had rainfall ranking in the lowest five between 1950–2022, the percent anomalies were mainly above 50%. Like 1982/83, this indicates that percent anomalies are less reliable in detecting a dry spell or drought. Historical records (Harford & Lucas, 1988) have shown that rainfall anomalies throughout the drought may have been more severe than the current analysis. This observation is likely due to the periods chosen for the analysis (September to March), as the focus was only on spring to autumn droughts and highlights the effects that a dry winter may have and that droughts are not always a spring to autumn phenomenon. Droughts in the region can be caused by slow moving or "blocking" anticyclones, which are more frequent in winter (Salinger & Porteous, 2014).

Like the 1988/89 drought, the 1997/99 Canterbury drought was well-documented and costly. This drought extended over two summer periods (Sanders, 2000; He, 2000), but only the 1997/98 drought is discussed for this analysis. The 1997/98 drought started in the winter of 1997 and continued throughout the summer (Horrell et al., 1998). Due to low rainfall, there were severe soil moisture deficits; for example, at Lincoln, the worst annual soil moisture deficit was recorded (Horrell et al., 1998). Extremely low river flows in the Canterbury foothills were recorded, though not in rivers where the headwaters are in the Southern Alps. These rivers were generally unaffected by the drought (Horrell et al., 1998). Groundwater levels in the shallow aquifers were also very low in some parts of Canterbury (Horrell et al., 1998; Sanders, 2000). The low flows in the rivers and groundwater levels impacted irrigation. (Horrell et al., 1998).

The drought was widespread, and its effects were felt over much of Canterbury (Horrell et al., 1998). The results show that all the stations analysed north of the Rakaia River were in the driest four years between 1950–2022, indicating that this drought was possibly more severe

north of the Rakaia River. Historic observations confirm that the effects of the drought were most pronounced in North Canterbury (Horrell et al., 1998). Like 1988/89, the onset of this drought was before the period analysed (from 1 October 1997) and continued past the end of the rainfall analysis (31 March 1998), highlighting the impact that a dry winter can have on the establishment or onset of droughts and the importance of looking at dry winters as well as the sprint to autumn periods.

The 2000/01 year was extremely dry in central New Zealand, with the Nelson and Marlborough regions experiencing severe drought and extensive fires (NIWA, n.d-c). Low rainfall was experienced throughout Canterbury except for Lake Ohau. At all stations (except Lake Ohau), the rainfall was in the lowest three years on record, and percent rainfall anomalies were mostly below 50%. The extent and severity of low rainfall experienced over Canterbury differed from those experienced in the other years analysed, where distinct clusters were observed. However, unlike the other years analysed, few historical accounts of this dry spell in Canterbury exist. There are some reports of soil moisture deficiencies and weather stations receiving little rain, such as Winchmore on the Central Canterbury plains (Figure 8-3), where rainfall was in the lowest three years on record (NIWA, n.d-c). During the beginning (and winter) of 2001, the water levels in the hydroelectric lakes in Central Canterbury fell to very low levels due to low inflows into the lakes from rivers and streams, impacting the energy supply in New Zealand (Daniels, 2002).

Historic observations showed that during the 2014/15 dry period, there were dry conditions over much of the country, and rainfall was well below normal in eastern Canterbury, with record or near record low rainfalls being recorded (NIWA, n.d-b). The analysis also shows this, with dry conditions widespread in the east. Many stations between South and North Canterbury had rainfall in the lowest three years between 1950–2022. Despite the low rainfall rankings, the rainfall anomalies were not exceptionally low, again highlighting the reliability of rankings versus anomalies.

Soil moisture at the beginning of March 2015 was well below normal and a medium scale drought was declared on 12 February 2015 (NIWA, n.d-b; Underhill, 2015). The drought persisted until at least May, when most areas of Canterbury started to get some rain (though not all areas – e.g. Cheviot) (Brackebush, 2015). Farmers in North Canterbury were some of the worst affected, with some farmers describing the drought as one of the worst they had

experienced (Brackebush, 2015). This observation by the farmers is interesting. The period analysed for 2014/15 was identical to 1997/98 (1 October–31 March). In North Canterbury, the rainfall rankings were between two to six, and one to four, lowest in 2014/15 and 1997/98, respectively. Based on rainfall only, this would suggest that the 1997/98 drought was more severe than 2014/15, yet many farmers described 2014/15 as one of the worst ever. These observations highlight the complexity of droughts and their impacts and that multiple factors, not just rainfall, can come into play when assessing the severity of a drought event.

5.4.2 ENSO and weather features

The ENSO state is shown in Table 5-2 for the years that were analysed. Even though El Niño events are more commonly associated with dry weather (NIWA, n.d-e; NIWA, n.d-f), drought events can occur during El Niño and La Niña phases (NIWA, n.d-f; Caloiero, 2017). The 1982/83 El Niño event was a super El Niño event and one of the strongest recorded events. Despite this, the drought event in Canterbury was not extreme compared to other years (though it was severe in the North Island). In comparison, the 1988/89 drought was one of the most impactful droughts in Canterbury and was during a La Niña phase. These examples demonstrate that the current ENSO phase is not necessarily a good predictor of potential drought events or conditions in the Canterbury region.

Other weather features (apart from rainfall), such as temperature and wind, contribute to drought conditions influencing their severity (e.g. Tirivarombo et al., 2018; Harrington et al., 2016; Koutroulis et al., 2011; Yang et al., 2023) (also refer to Chapter 2). The ENSO phase can influence these at the time, but like rainfall, the effects can be varied and do not necessarily follow the expected patterns (e.g. NIWA, n.d-e; McGann, 1991 Horrell et al., 1998; Collen, 1983). An example of how the ENSO state may have inconsistent impacts on the weather is the 1988/89 drought (La Niña) event after an El Niño event. By late 1987/88, the SOI was close to zero (i.e. neutral), and extreme weather patterns, such as frequent and strong westerlies, were not expected in the coming year (McGann, 1991). However, a significant contributing factor to the 1988/89 drought was the frequent northwesterly winds experienced over Canterbury. The winds were especially prevalent from June to October 1988; at the time, October 1988 was the windiest October on record (McGann, 1991). A large destructive north westerly gale affected Canterbury on 15 October 1988 (Lucas, 1988; Malthus, 1988), when Canterbury, particularly North Canterbury, was plunged into a severe

drought (Malthus, 1988). From November 1988, an anticyclonic regime predominated, prolonging the drought conditions (McGann, 1991).

In other years, low temperatures were recorded in the summer of 1982/83 (Stats NZ, 1984). The 1997/98 summer drought was thought to be influenced by the El Niño event, which brought hot and dry conditions (Horrell et al., 1998). During the summer of 2000/01, hot and windy conditions were experienced due to frequent highs in the Tasman and ridges east of the Chatham Islands (NIWA, n.d-c). Anticyclones were the predominant weather system during the summer of 2014/15, leading to lower rainfall. Above average temperatures were experienced over most of the South Island (NIWA, n.d-b).

Table 5-2. ENSO phase during the years of interest (NIWA, n.d-e)

Years	ENSO phase
1982–1983	El Niño
1988–1989	La Niña
1997–1998	El Niño
2000–2001	La Niña
2014–2015	El Niño

5.5 Conclusions and limitations

There are clear spatial and temporal variations in the drought events analysed in the Canterbury region. Not all areas were impacted to the same degree by the same events. Some droughts impact only a few areas of Canterbury, whereas others were more extensive. For example, the 1997/98 drought, which, through both the analysis and historical accounts, was more severe north of the Rakaia River. In comparison, the 2000/01 dry period was widespread and impacted most areas of Canterbury.

There was no clear relationship between the ENSO phase and droughts in the region, with droughts occurring in both El Niño and La Niña phases, consistent with the recent literature (Caloiero, 2017). Historical accounts of the analysed droughts highlight temperature, the hot, dry northwesterly wind, large scale weather systems (other than ENSO), and associated high evapotranspiration rates as being some of the drivers of drought in the region (e.g. NIWA, n.d-c; McGann, 1991; Malthus, 1988).

When comparing the event's severity from location to location and over different time scales, the percent anomaly of rainfall from the mean was not as reliable as the rainfall ranking. In some cases, a severe drought still had rainfall more than 50% of normal, and in less severe droughts, the percent anomalies were below 50%. During the 1988/89 drought, anomalies were over 50% between 1 September 1988–31 March 1989, but in the most severely impacted areas, the rankings were in the bottom three. In comparison, during the 1982/83 dry period between 1 January 1983–31 March 1983, many stations had rainfall below 50% of normal but were not ranked in the lowest five rainfall years on record.

A limitation of this analysis was that only five droughts were analysed, which meant that some significant dry/drought years were not analysed. The periods for the analysis were chosen by examining graphs of cumulative rainfall, focusing on the spring to autumn months during the primary growing and milk production season (NIWA, n.d-h). This method may have overlooked important dry periods, potentially skewing the results. Given that drought start and end dates are notoriously difficult to identify (e.g. Tirivarombo et al., 2018; Vicente-Serrano & Lopez-Moreno, 2005), this methodology is a reasonable approach.

The focus on the summer meant that droughts that started in late autumn, winter, or early spring may not have been identified, or the severity of a particular drought lessened due to the analysis period being outside the start or end date of the drought. Winter droughts are known to be common in the Canterbury region due to the prevailing climatic conditions (Salinger & Porteous, 2014). The 1988/89 drought, which started in April 1988, is an example of a severe drought that extended over winter. The above analysis for this drought started in September 1988, meaning that up to five months of drought conditions were omitted at the beginning of this drought.

6 Historic low rainfall years and clustering

6.1 Introduction

Globally and in New Zealand, regional variations in climate and rainfall are common and widely reported (e.g. Vishwanathan et al., 2024; Tijdeman et al., 2022; Salinger & Porteous, 2014; Vicente-Serrano; 2006). For example, in Great Britain, there is a southeast-to-northwest rainfall gradient, with the northwest (e.g. parts of Scotland) receiving almost twice as much rain as the southeast (e.g. the Thames estuary) (Tanguy et al., 2021). In New Zealand, NIWA has identified ten climate zones over the three main Islands of New Zealand, where there are distinct differences in the climate. (NIWA, n.d-d).

On a regional scale, there can be variations in climate within that region. In Canterbury, NIWA has identified five main climatic zones (see Table 3-1). These are areas or zones where there are similarities in the climate that may be experienced. For example, the inland South Canterbury basins (e.g. the Mackenzie Basin) are typically dry and hot in summer and can experience significant day and night temperature variations. In contrast, Banks Peninsula has milder winters but higher rainfall (Macara, 2016). The orographic influence and complex topography of Canterbury significantly impact the climate and, hence, rainfall (Macara, 2016; Vishwanathan et al., 2024; Salinger & Porteous, 2014).

Chapter 5 further demonstrated spatiotemporal variations in rainfall within the Canterbury region. This analysis found that different events had different impacts over different areas of Canterbury and that there appeared to be distinct clusters where the rainfall was low over particular periods and localities. This chapter aims to explore further the Canterbury region's spatial and temporal rainfall variations by identifying the lowest rainfall years over the defined periods between 1950–2022. This information was used to determine any relationship between rainfall events in areas of Canterbury and whether distinct subregions based on rainfall can be defined.

6.2 Methodology

The driest year for each station between 1950–2022 and the period of interest (Table 5-1) were determined using the rankings identified in Chapter 5.2.

A Spearman's rank correlation was performed on all weather stations to explore further the spatial relationship between the dry periods at different stations. Four stations (Keinton Combe, Okuti, Hororata, and Lake Pukaki) were qualitatively selected as representative stations of the different Canterbury climatic areas identified by NIWA (Table 3-1) and were analysed further in the section. It should be noted that there was little difference in the rankings between stations in four of the five different climatic areas, which is why only 4 stations were selected. The Spearman's rank correlation measures the strength of the relationship between two ranked variables. Where there is a strong positive correlation between the variables, the coefficient will be close to 1 (Statstutor, n.d). The rainfall between 1950–2022 during the four selected periods was ranked for each station. A Spearman's rank correlation between each station and the four selected stations was then carried out using MATLAB.

6.3 Results

6.3.1 Lowest rainfall years

The years with the lowest rainfall between 1950–2022 for the dry periods of interest (Table 5-1) were identified (Figure 6-1). For all the dry periods analysed, no one year had the lowest rainfall at all sites in Canterbury (Figure 6-1). The most spatially extensive low rainfall year was from 1 December 2000–30 April 2001 (Figure 6-1d) where it was the lowest rainfall year for 56% of the stations. There is some clustering of record low rainfall years that loosely follows the climatic regions of Canterbury (Table 3-1). For example, for the 1 January–31 March period (Figure 6-1a), there are clusters in the Central Plains (1981/82), South Kaikoura (1963/64), North Canterbury (2014/15), and Lake areas (1972/73). This period also shows the most extensive temporal distribution of the lowest rainfall years from the 1960s to the 2020s.

Except for the 1 January–31 March period (Figure 6-1a), the years of interest identified in Chapter 5.2 registered as the worst on record in at least some parts of Canterbury. For 1

September–31 March, 1988/89 was the lowest rainfall year at some stations along the coastal plains and south of Kaikoura (Figure 6-1b). For the 1 October–31 March period, 1997/98 was the lowest rainfall year at some of the stations in the Banks Peninsula, South Kaikoura, and eastern foothill areas. 2014/15 was the lowest rainfall year for the same period in some Central Plains and southern Plain stations (Figure 6-1c). 2000/2001 was the worst year over much of Canterbury (except for the Canterbury High Country and Mackenzie Basin). (Figure 6-1d).

Over all four time periods, a large number of years recorded the lowest rainfall. There were eleven different lowest rainfall years between 1 January–31 March and 1 October–31 March and nine different years between 1 September– 31 March and 1 December–30 April. The large number of lowest rainfall years shows spatial and temporal variability in low rainfall years in the Canterbury region.

Table 6-1 shows that for the dry periods analysed, there were no record dry spells in the 1950s and only a few in the 1960s and 1970s. The driest decades appear to be the 1980s, 1990s, and 2000s, with multiple weather stations recording record dry spells (since the 1950s).

Table 6-1. Number of lowest rainfall years per decade for each dry period analysed across all sites.

Decade	Jan-Mar	Sep-Mar	Oct-Mar	Dec-Apr
1950s	0	0	0	0
1960s	3	0	1	1
1970s	4	1	2	4
1980s	6	11	7	2
1990s	2	5	7	2
2000s	1	3	3	14
2010s	5	5	5	2
2020s*	4	0	0	0

* Partial decade only

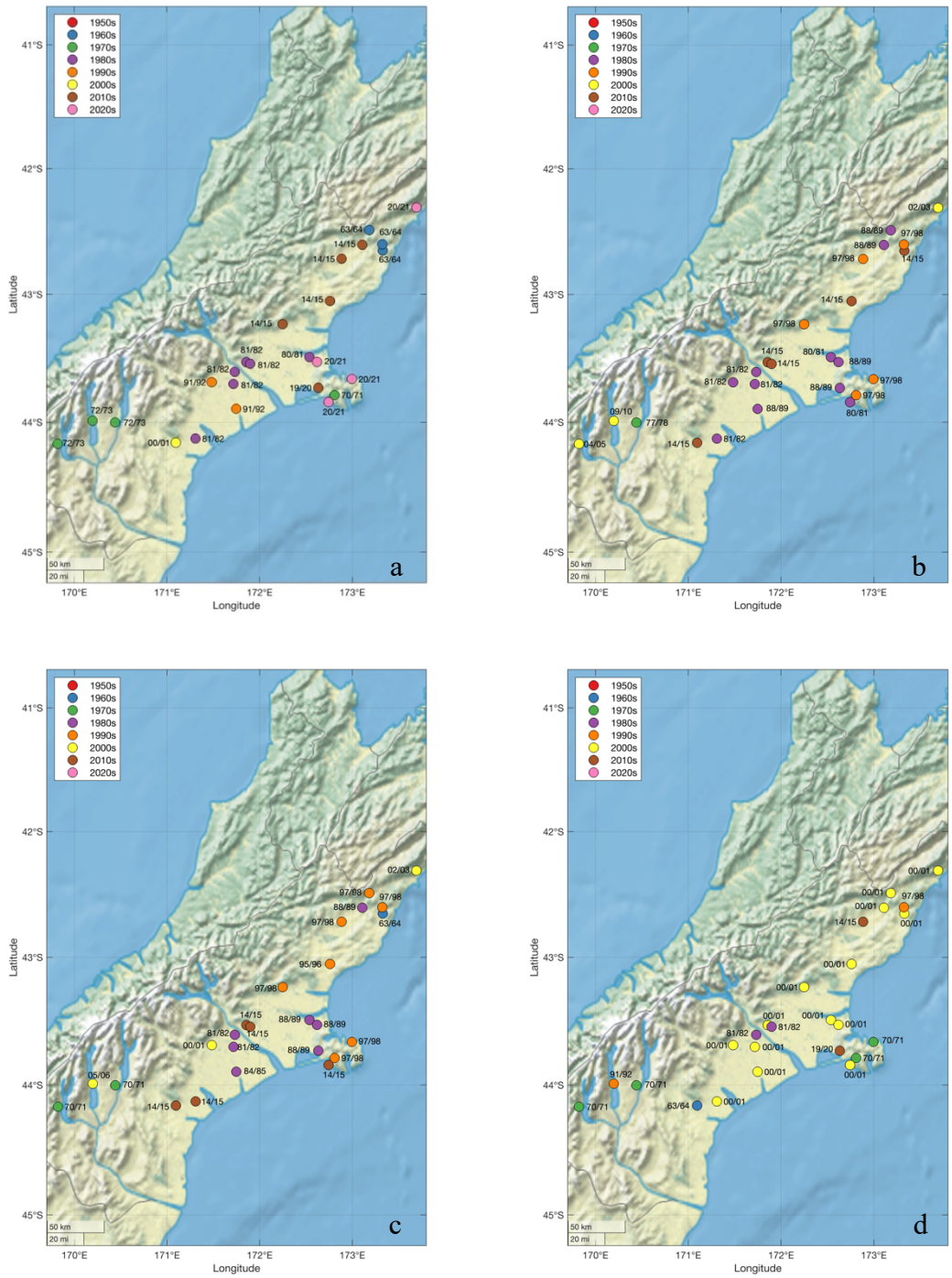

Figure 6-1. Years with the lowest total rainfall between 1950–2022 for a specific dry period in the Canterbury region. (a) 1 January–31 March. (b) 1 September–31 March. (c) 1 October–31 March. (d) 1 December–30 April.

6.3.2 Clustering

The Spearman's rank correlation at Keinton Combe (Figure 6-2a), Okuti (Figure 6-2b), Hororata, and Lake Pukaki between 1950–2022, for 1 December–30 April, relative to the other Canterbury weather stations are shown in Figure 6-2. There were statistically significant ($p<0.05$) positive associations between rainfall rank between all four weather stations and most of the Canterbury weather stations. The exception was Lake Ohau when associated with Keinton Combe, Hororata, and Okuti, there was no statistically significant association ($p>0.05$). Because of this, Lake Ohau's association with these three stations is not discussed further for these stations. For the three other periods studied (Table 5-1), no significant differences in the rainfall associations were observed from the 1 December–30 April periods. As there were minimal differences, only the 1 December–30 April period is discussed below and is considered representative of the other periods. The other three periods are can be found in Appendix C.

Keinton Combe, Hororata, and Okuti generally have very strong rainfall associations with weather stations in the same area. For example, at Keinton Combe, there are very strong associations with other North Canterbury stations (e.g. Whalesback) (Figure 6-2a) or for Hororata, there are very strong associations with other stations on the Central Canterbury Plains (e.g. Rakaia) (Figure 6-2c). These associations indicate that stations close together on the Canterbury Plains, Canterbury foothills, or Banks Peninsula are likely to experience similar relative rainfall. If dry conditions are experienced at Keinton Combe, it may be reasonable to expect similar dry conditions at Riverside or Whalesback stations. For Keinton Combe and Okuti, there are also very strong associations with some weather stations on the Central Canterbury Plains, indicating there is a likelihood that these stations will experience similar relative rainfall (Figure 6-2a and Figure 6-2b).

Hororata had very strong rainfall associations with most South, Central, and North Canterbury, Kaikoura, and Banks Peninsula stations (Figure 6-2c). This strong association is more widespread than the other three stations. These associations indicate that a dry period in the Central Canterbury Plains could be more extensively experienced over the Canterbury region compared to dry spells in other sub-regions of Canterbury.

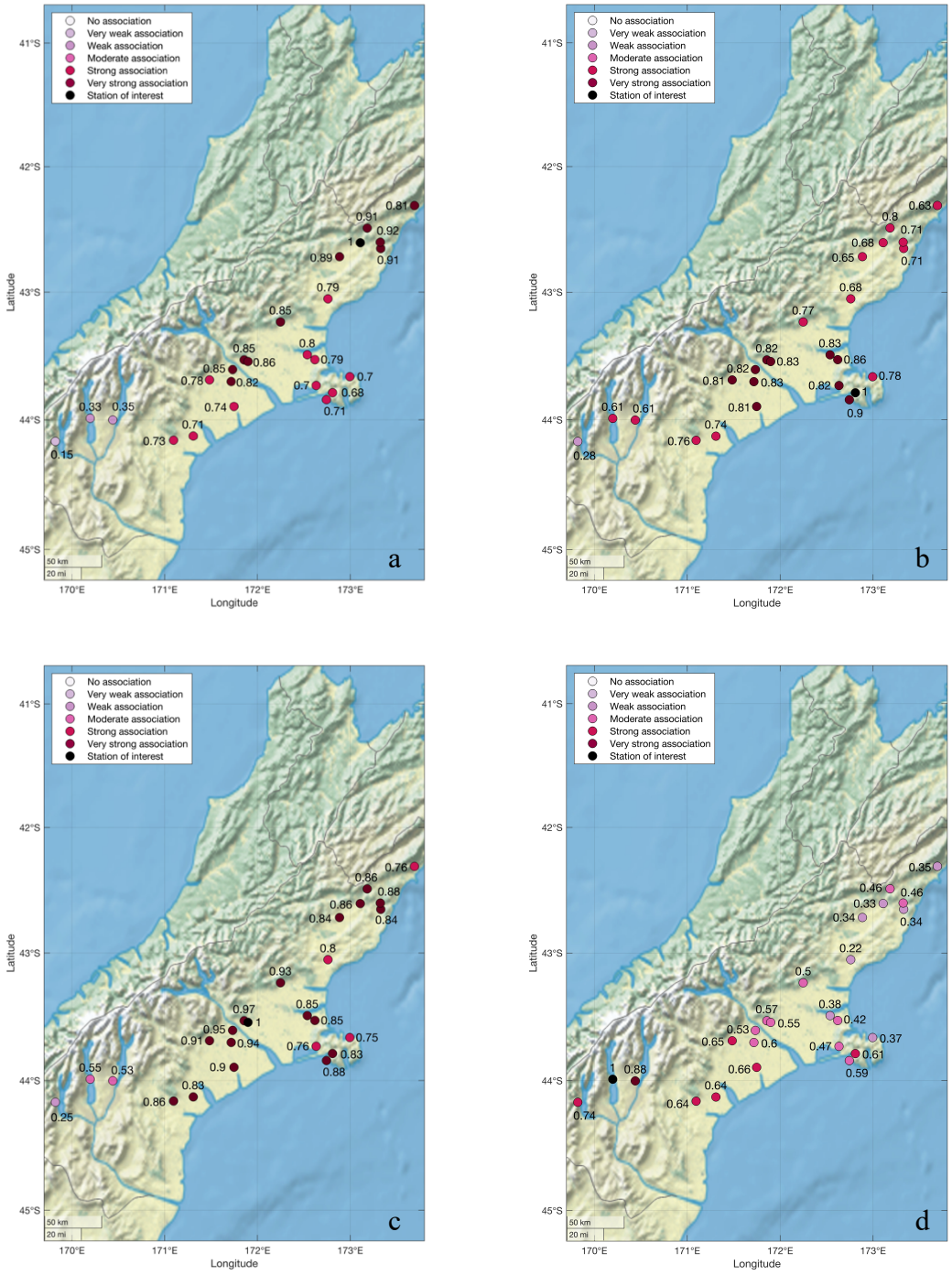

Figure 6-2. Spearman's rank correlation of rainfall between 1 December–30 April for the years 1950–2022 relative to (a) Keinton Combe, (b) Okuti, (c) Hororata, (d) Lake Pukaki. The station of interest is marked 1. Generally the closer to the station of interest, the higher the correlation between rainfall experiences.

The weather stations in the Canterbury inland lakes areas experienced varying rainfall associations with Keinton Combe, Hororata, and Okuti. Lake Pukaki and Tekapo were still strongly associated with Okuti (Figure 6-2b). For Keinton Combe and Hororata, there was a

moderate to weak association with these two stations (Figure 6-2a and Figure 6-2c). For Keinton Combe and Hororata, this suggests a minimal relationship exists with rainfall experienced at these two Canterbury inland lake stations. For example, if it was very dry in Hororata, it could be near normal or wet at these lake stations.

The relative rainfall at Lake Pukaki shows a very strong association with Lake Tekapo and a strong association with Lake Ohau, Kakahu Bush and Orari Estate (southern Canterbury), Ashburton, Springburn (Central and Coastal Canterbury Plains) and Okuti (Banks Peninsula) (Figure 6-2d). For the rest of Canterbury, the association is moderate to weak. These associations indicate that rainfall experienced at Lake Pukaki is not a good indicator of the rainfall that may be experienced over these parts of Canterbury.

From the Spearman's rank correlation, it has been established that there are clear sub-regions where similar rainfall may be experienced. From these correlations, a map estimating sub-regions where the relative rainfall experienced is most similar was created (Figure 6-3 and Table 6-2). The five sub-regions identified broadly align with the NIWA regions (Table 3-1).

Some stations within each sub-region could be aligned with two (or more) regions. For example, Glentui could be in the Canterbury Plains or North Canterbury (Figure 6-2c and Figure 6-2a). Christchurch Gardens and Aero could have been assigned to the Canterbury Plains rather than Banks Peninsula (Figure 6-2c and Figure 6-2b). The two South Canterbury Plains stations (Kakahu Bush and Orari Estate) have been assigned to the Canterbury Plains. Whilst there is generally a strong rainfall association between these two stations and other stations on the Canterbury Plains (Figure 6-2c) there is some variation in the strength of this relationship, particularly when compared with stations further north (Figure 6-2a and Figure 6-2b). These two stations could have had their own sub-region assigned to them.

Table 6-2. Sub-regions where relative rainfall has been identified as similar over the Canterbury region.

Region number	Name
1	North Canterbury and Kaikoura
2	Banks Peninsula and Christchurch
3	Canterbury Plains
4	Canterbury Lakes
5	Canterbury High Country

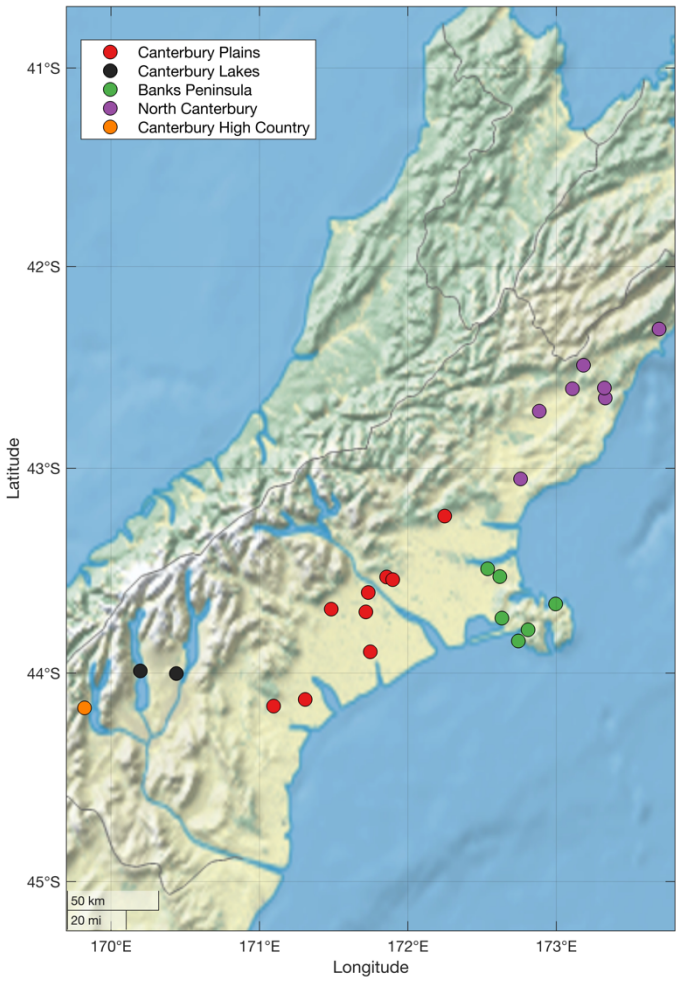

Figure 6-3. Sub-regions identified on the Canterbury plains where similar relative rainfall conditions may be expected. Note that some stations could be in more than one region or have their own distinct region.

6.4 Summary

In Chapter 5 spatial variation in drought occurrences was analysed by looking at individual events (e.g. 1 September 1988–31 March 1989). This analysis showed a spatial variation in how these events were experienced over the Canterbury region. This chapter (Chapter 6) has focused on systematically looking at dry periods in all years between 1950–2022 and seeing how different years are experienced over the Canterbury region. The analysis showed a wide spatial and temporal variation in the lowest rainfall years over the region and that dry years are not necessarily experienced uniformly over the whole region.

Using statistical methods (Spearman's rank correlation), subregions with similar rainfall experiences over the defined dry periods were identified in the Canterbury region (Figure 6-3). These sub-regions may indicate areas that may be experiencing similar dry conditions.

There is some overlap in these regions, with some areas on the "borders" that could be aligned with another sub-region or a distinct region. The identified sub-regions (Figure 6-3) align reasonably well with climatic zones previously identified by NIWA (Table 3-1).

7 Past years

7.1 Introduction

In Chapters 5 and 6 rainfall has only been analysed since 1950 to ensure a good density of weather stations with complete records over the Canterbury area. However, the literature indicates that there were significant dry spells and droughts before this date. For example::

> ….the farmers of Canterbury and Southland have been the victims of two extremes in the matter of weather. The Canterbury districts, both North and South, are suffering from the effects of drought, the unfavorable weather giving deficient yields, whilst Southland has had many crops ruined by excessive rain.
> (The Evening Post, 1897, p6).

More dry periods were noted over the next three decades, including 1906/07, 1914/15, and 1921. During the 1930s, multiple droughts were recorded, including 1931/32, 1934/35, 1938/39, and 1939/1940 (Parkhill, 1970; H.A.M., 1939).

On 17 December 1931, The Pahiatua Herald (Manawatu-Wanganui region) reported "The dry spell in South Canterbury has been the worst for many years. All over Canterbury crops have suffered severely from lack of moisture. Oat crops, except in small patches of heavy land, have been a complete failure". (Pahiatua Herald, 1931, p6).

On the 18 of November 1939, The Press reported:

> Anxiety is developing at the long continued stretch of dry weather. In the last two months barely an inch of rain has been recorded in Christchurch, and this may be taken as indicative of the rainfall in most parts of North and Mid-Canterbury.… The position is aggravated this year by the prevalence and ferocity of the nor'-westers, which have made the dry soil still drier. (H.A.M., 1939, p.10).

This evidence indicates that a further investigation of the longer rainfall records is required to identify any notable dry years before 1950. This chapter aims to look into rainfall records of 100 years or longer in the Canterbury region to identify significant droughts that occurred pre-1950, where rainfall was as low or lower than the worst recorded years post-1950.

7.2 Methodology

Historical dry years over the last 100-plus years were identified using the methodology described in Chapters 4 and 5.2. However, only stations with at least 100 years of rainfall records were used (Table 7-1). Whilst this reduced the quantity and density of the stations (15 down from 25), it provided a greater temporal range and allowed the identification of extremely dry years before 1950. Four out of the five identified sub-regions have been included in this analysis. The Canterbury High Country only had one station post-1950 and no suitable stations pre-1950. As such, this area has not been included in this analysis.

Table 7-1. Canterbury climate stations with rainfall records 100 years or longer. Note that stations with an end date of present have data available to at least September 2024.

Station Number	Station Name	Start/End Dates	Record Length (Years)#
4925	Okuti	02/09/1915–present	109
4702	Hororata	02/07/1890–present	134
4525	Riverside	02/04/1916–present	108
4778	Ashburton Council*	02/01/1927–present	97
4711	Springburn	02/09/1913–present	111
4958	Little Akaloa, Brockworth	02/10/1911–present	113
4796	Waipara, Wattle Grove	02/03/1923–present	101
4556	Keinton Combe	02/01/1912–present	112
4970	Lake Tekapo, Air Safaris*	02/05/1925–present	99
5061	Orari Estate	02/10/1897–present	127
4629	Lake Pukaki, Braemar	02/01/1914–01/01/2024	110
5053	Kakahu Bush	02/07/1909–01/07/2024	115
4495	Hapuku, Grange Hill	02/12/1915–present	109
4858	Christchurch Gardens	02/01/1873–present	147
4939	Magnet Bay	02/02/1917–01/04/2023	106

*Added into the analysis to allow for gaps in the spatial coverage, even though they did not have 100 years of records.

This is the record length prior to the data being processed, so in some cases, the record length may be slightly shorter.

7.3 Results

The analysis showed that at most stations with longer records the driest year was experienced post-1950 during the dry periods of interest (Table 5-1), and hence was not changed from the analysis in Chapter 6.3. Out of the fifteen stations analysed, seven stations had at least one

period with a drier year than post-1950 (Table 7-2). The driest year over the four periods was post-1950 at the other eight stations. Magnet Bay was drier during all four periods pre-1950, and Hororata was drier in three out of four periods. Lake Pukaki, Christchurch Gardens, and Little Akaloa had two periods recording the lowest rainfall pre-1950. Interestingly, the four stations in the Banks Peninsula cluster (Figure 6-3) had drier periods pre-1950, whereas none of the North Canterbury stations (Figure 6-3) did. Like post-1950, there appear to be some decades (1890s, 1910s, and 1930s) with clusters of very dry weather.

Table 7-2. Stations with long term rainfall records (greater than 100 years) where the lowest rainfall for a defined period was lower than the post-1950.

	Driest year in the whole record	Driest year from 1950 onwards
1 January-31 March		
Okuti	1938/1939	1970/1971
Little Akaloa, Brockworth	1938/1939	2020/2021
Christchurch Gardens	1938/1939	2020/2021
Magnet Bay	1932/1933	2020/2021
1 September-31 March		
Hororata	1897/1898	2014/2015
Lake Pukaki, Braemar	1914/1915	2009/2010
Magnet Bay	1932/1933	1980/1981
1 October-31 March		
Hororata	1897/1898	2014/2015
Little Akaloa, Brockworth	1934/1935	1997/1998
Lake Pukaki, Braemar	1916/1917	2005/2006
Christchurch Gardens	1934/1935	1988/1989
Magnet Bay	1931/1932	2014/2015
1 December-30 April		
Hororata	1897/1898	1981/1982
Kakahu Bush	1914/1915	1963/1964
Magnet Bay	1932/1933	2000/2001

Further analysis of 1897/98, 1914/15, 1931/32, 1932/33, 1934/35, and 1938/39 was carried out to determine the extent of these dry years.

For 1897/98, only one station (Hororata) had complete data for this summer. Only three stations have data back this far, but missing data has eliminated all the periods from Christchurch Gardens and the September to March period for Orari Estate. At Hororata, this

was the driest year by some margin for all but the 1 January–31 March period. At Orari Estate, 1897/98 was the third driest during the 1 December–30 April period and the 11th and 14th between 1 January–31 March and 1 October– 31 March, respectively. Figure 7-1 shows that from 1 June 1897–31 May 1898, 1897/98 had the lowest cumulative rainfall between 1890–2022 at Hororata. Compared to the five years analysed in Chapter 5, the summer of 1897/98 was notably drier at Hororata. For Orari Estate the records only started in October 1897 so it was not possible to assess the cumulative rainfall relative to other years between 1 July–31 May.

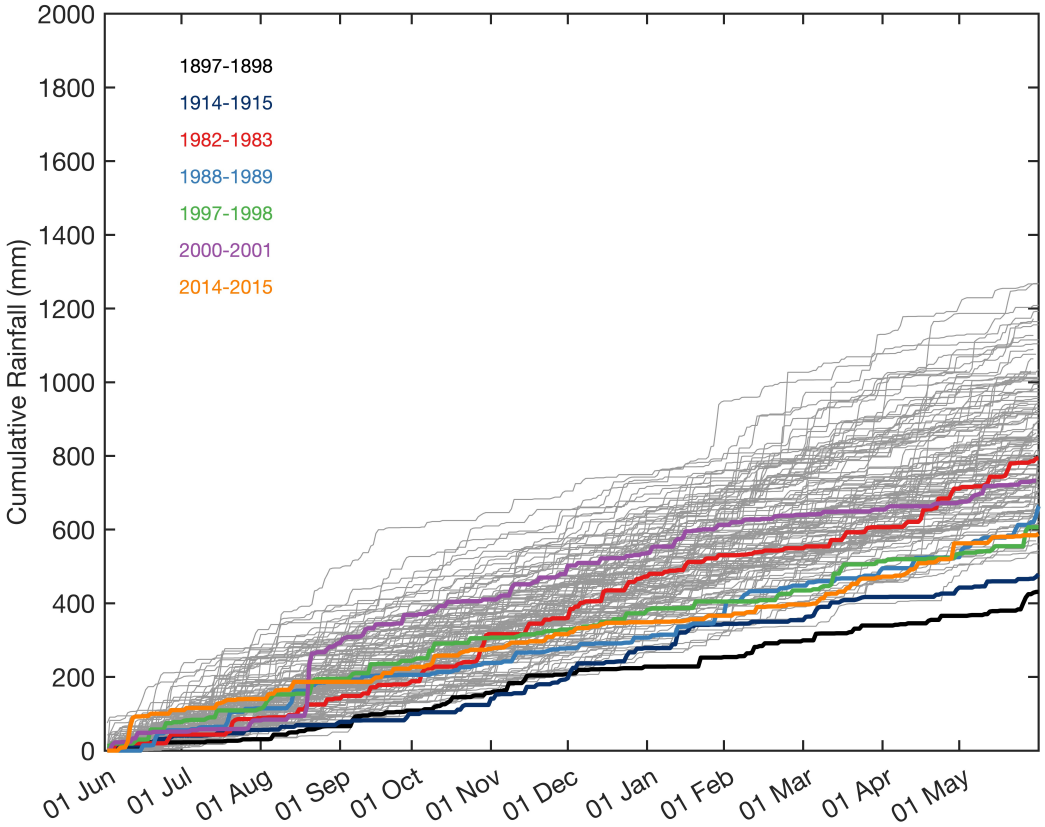

Figure 7-1. Cumulative rainfall at Hororata between 1 June–31 May. Highlighted years are the years of interest, including 1897/98 and 1914/15. The grey lines are all other years between 1890–2022. 1897/98 is the driest overall. However, 1914/15 was also very dry despite it not registering in the analyses.

Newspaper records indicate that the 1897/98 year was extremely dry, with multiple reports of dry conditions impacting the farming sector (e.g. The Press, 1898b; The Press, 1897a). The reports also indicate that dry weather lasted for an extended period. The Press reported on 29 April 1898:

> The reports that have appeared from time to time concerning the effect of the unprecedentedly long spell of dry weather upon the agricultural lands of the province do not appear to have in any way been overdrawn. As we may now be considered to be on the edge of winter, without the hoped for break having occurred, the outlook has become a serious one, especially to owners of stock. (The Press, 1898b, p.3).

Six stations (Hororata, Springburn, Keinton Combe, Orari Estate, Kakahu Bush, and Christchurch Gardens) had complete data for 1914/15. Over the four time periods, only Kakahu Bush recorded rainfall in the lowest five years (September-March, 4th driest, and December-April, driest). Orari Estate, also in South Canterbury, recorded its sixth driest year between December and April. The New Zealand yearbook, 1915, stated that this was a very dry year (Stats NZ, 1915) in New Zealand. On 16 April 1915, The Otago Daily Times reported:

> Mr Massey was reported the other day, after his visit to Canterbury, to have said that the province was suffering from a phenomenal drought….Canterbury has had no rain for quite nine months. Now and again rains have fallen; but, with terrible regularity, they have been followed by fierce nor'-westerly gales, which have quickly dried up the moisture in the land. Probably the country that is feeling the lack of rain most severely is the district round about Waikari and Waipara, and to the north, where there is nothing but an expanse of burnt-up grass….In parts of South Canterbury, too, the situation is distinctly bad… (The Otago Daily Times, 1915, p.2).

The cumulative rainfall at Kakahu Bush between 1 June 1914–31 May 1915 was the lowest recorded, confirming that it was particularly dry in South Canterbury (Figure 7-2). Figure 7-2 shows that the winter, summer, and autumn appeared very dry, but the spring was not as dry. The wet spring may be why this year did not register as particularly dry over some of the periods chosen (e.g. September to March) despite the reports of a particularly dry year. At Hororata (Figure 7-1) 1914/15 had the second lowest cumulative rainfall between 1 June–31

May. However, the ranking for the periods chosen was between 9th to 25th. Further indicating that the periods chosen influence which years come out as dry. The cumulative rainfall during 1914/15 at Keinton Combe, in North Canterbury, where it was reported that the drought was particularly dry, was in the lowest three on record, similar to 1988/89 and 2014/15 (Appendix A). These more recent events were known to have significant adverse impacts in North Canterbury.

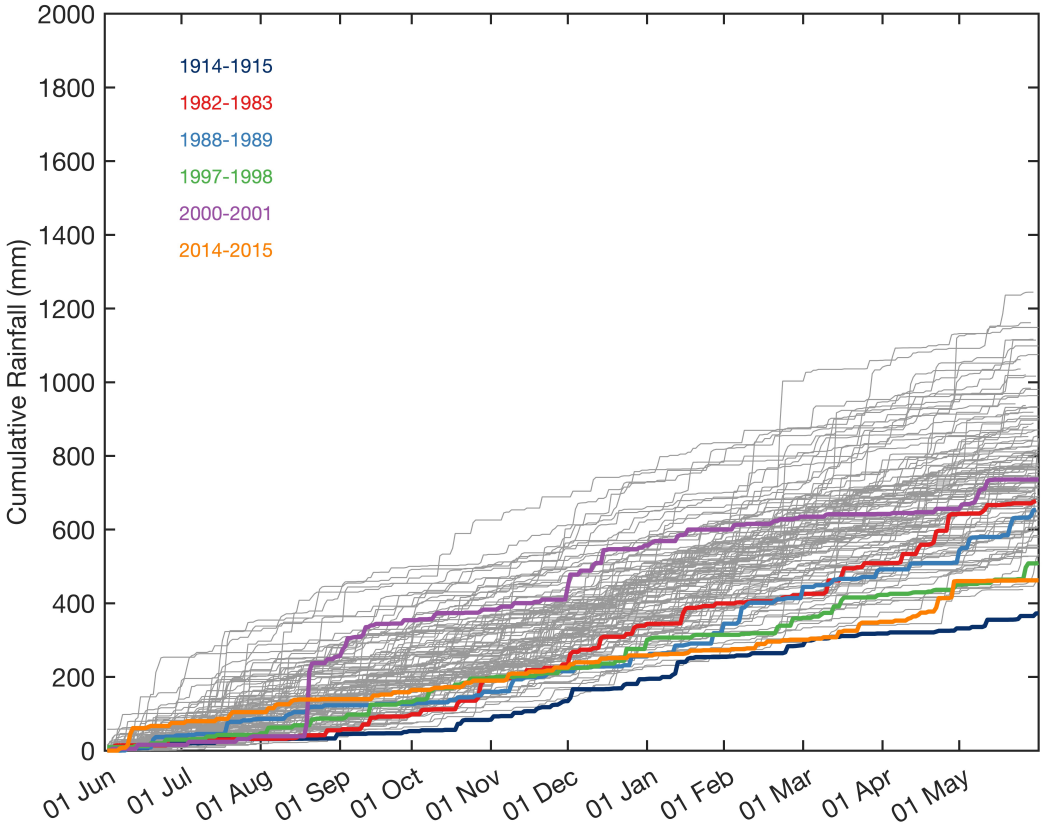

Figure 7-2. Cumulative rainfall at Kakahu Bush between 1 June–31 May. Highlighted years are the years of interest, including 1914/15. The grey lines are all other years between 1910–2022. 1914/15 is notably drier overall than all the other years, including the years previously analysed.

Between 1931–1935, three dry periods had at least one station recording its lowest rainfall. All fifteen stations had complete records during this time. During 1931/32, Magnet Bay recorded its lowest rainfall between 1 October and 31 March. During the same period, Ashburton Council (second driest), Riverside (fifth driest,) and Springburn (fifth driest) also had rainfall totals in the lowest five on record. Lake Tekapo recorded its second driest year between 1 September and 31 March. As noted in Chapter 7.1, 1931/32 was described as a dry year with significant impacts on the agricultural sector.

Between 1 September 1932–31 March 1933, only Hapuku (fifth driest year) recorded rainfall in the lowest five on record. From 1 December 1932 to 30 April 1933 , Hapuku (second driest) and Magnet Bay (driest) had rainfall in the lowest five years on record. From 1 January 1933–31 March 1933, Okuti (fourth driest), Hapuku (fourth driest), and Magnet Bay (driest) recorded rainfall in the lowest five years on record. Overall, this did not appear to be a significant dry year over much of Canterbury, with only two other stations (Ashburton Council and Little Akaloa) recording rainfall in the lowest ten years over any of the periods analysed.

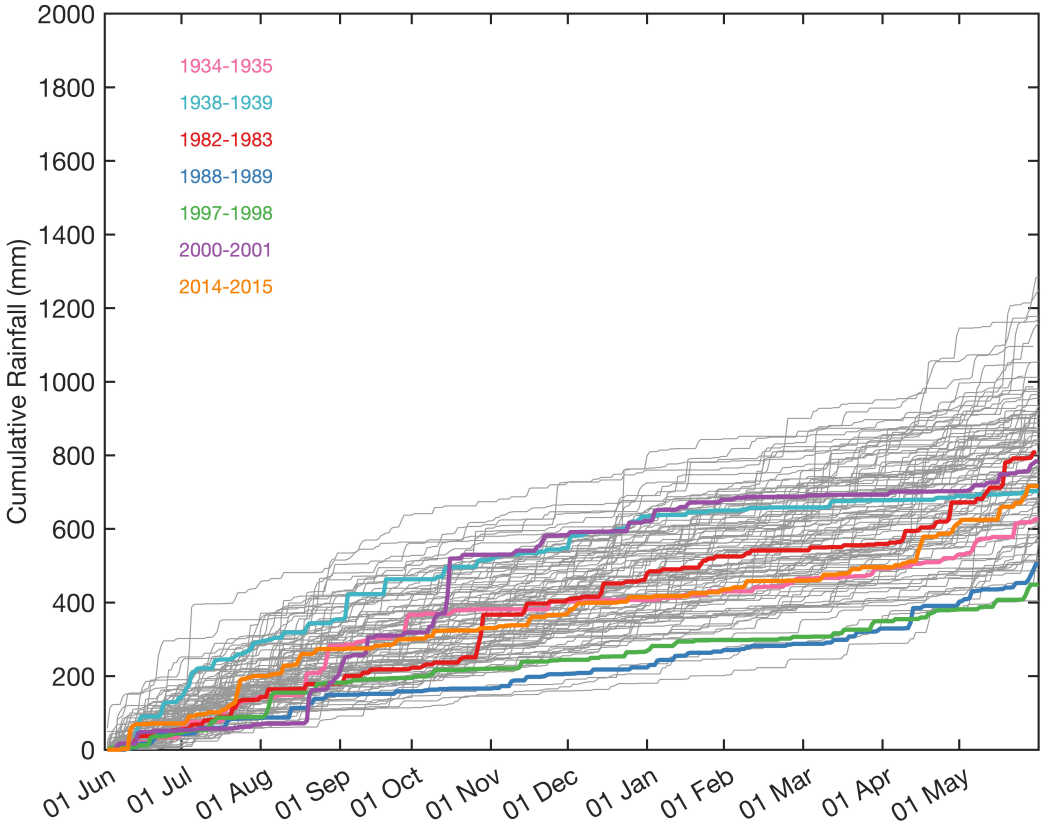

Figure 7-3. Cumulative rainfall at Little Akaloa between 1 June–31 May. Highlighted years are the years of interest, including 1934/35 and 1938/39. The grey lines are all other years between 1912–2022.

During 1934/35, Christchurch Gardens (driest), Little Akaloa (driest), Magnet Bay (third driest), and Okuti (fifth driest) had rainfall in the lowest five on record between October and March. This period appears to have been very dry, but when looking at the overall cumulative rainfall for this year (Figure 7-3) it did not register as a particularly dry year. Christchurch Gardens (third driest) and Magnet Bay (fourth driest) also had rainfall in the

lowest five on record between 1 December–30 April. This dry spell is concentrated around the Banks Peninsula area. Some historical reports confirm that 1934/35 was a severely dry year in Canterbury and, in particular, South Canterbury (Parkhill, 1970). There are reports that this drought was progressively broken from February 1935, with the Queensland Times reporting on 26 February 1935 that "The drought broke in Canterbury last night after the driest summer for 40 years." (Queensland Times, 1935, p.7).

During 1938/39, Okuti, Christchurch Gardens, and Little Akaloa experienced their driest 1 January–31 March on record. Four other stations, Riverside (second driest), Ashburton Council (third driest), Lake Tekapo (fourth driest), and Magnet Bay (third driest), had rainfall in the lowest five years during the same period. Between December and April, Okuti (fifth driest), Little Akaloa (third driest), and Lake Tekapo (fifth driest) were the only stations recording rainfall in the lowest five years on record. No stations recorded rainfall in the lowest five during the other two periods. This year has similarities to 2000/01, with the spring being very wet, followed by a very dry summer/autumn (Figure 7-3). The wet spring may explain why no stations recorded extremely dry weather between 1 September–31 March and October to March. Like 1931/32, 1938/39 has been noted as a particularly dry year with significant impacts on the agricultural sector (Chapter 7.1).

7.4 Discussion

Overall, there is a wide variation in the spatial and temporal distribution of the driest years in Canterbury over the last 100-plus years. Since the 1890s, there were nine different decades (1890s, 1910s, 1930s, 1970s, 1980s, 1990s, 2000s, 2010s, and 2020s) where over the four different periods analysed, the driest year was recorded in at least one of the fifteen stations analysed pre-1950. Between 1 October–31 March, five out of fifteen stations recorded their lowest rainfall pre-1950. Whereas, over the other three periods, only three out of fifteen stations had their lowest rainfall pre-1950s. There are multiple possible reasons for the apparent drying conditions, including climate change. There have been multiple studies on the role of climate change on drought severity and frequency, with some conflicting conclusions (Trenberth et al., 2014; Seneviratne, 2012). However, many studies have suggested there are links between drought frequency and/or severity and climate change (e.g. Mullan et al., 2005; Harrington et al., 2014; Ullah et al., 2023).

However, the apparent increase in drought frequency post-1950 could be due to insufficient data or the reliability of the rainfall data, particularly pre-1940s, where there were significant gaps in the available data. There are some accounts that the older station data could be inaccurate due to issues such as poorly mounted rain gauges (e.g. gauges loosely mounted or not level) and exposure at the site affecting measurements (e.g. shelter belts impacting wind/rain recordings) (Larsen, 2005).

There were some distinct clusters where the driest periods occurred. For example, in the Banks Peninsula sub-region between 1 January–31 March, all of the lowest rainfall years were during the 1930s, yet in no other Canterbury sub-region were any years in this decade recorded as the lowest rainfall year for this period. A lack of dry years at other locations during the 1930s could be limited by data availability (e.g. some of the stations not analysed pre-1950s may have had extremely dry years in the 1930s) but could also highlight the distinct climate of the Banks Peninsula area. In the Canterbury Lakes sub-region, over all periods, the 1970s was at least one of the worst decades. Only the Banks Peninsula sub-region had a lowest rainfall year in the 1970s, and only from 1 December–30 April. The Canterbury Lakes sub-region had the strongest association with Banks Peninsula compared to the other sub-regions (Canterbury Plains and North Canterbury). However, the association is still comparatively low (Chapter 6.3.2 and Figure 6-2). These results highlight the lack of alignment of dry years in the Canterbury lakes area compared to the other Canterbury sub-regions. The decade with the largest spatial extent was the dry period recorded in the 2000s (specifically 2000/01) between 1 December–30 April, where this was the driest year in seven of the fifteen stations, encompassing three of the four sub-regions analysed.

Of the years identified before 1950, both 1897/98 and 1914/15 stand out as significant dry years, with the cumulative rainfall being either the lowest or close to the lowest on record at some of the stations. McGann (1991) also noted that both these years were extremely dry in the Canterbury region. An issue with both of these years is the limited rainfall data available. Only one station in all of Canterbury had complete data for 1897/98 through to 2022 (note two other stations have data this far back, but the data was not complete for 1897/98 and hence omitted). The lack of data makes it difficult to assess the severity of this event. Similar data completeness issues were experienced in 1914/15, with only six of the fifteen stations having data. The driest years are also dependent on the period chosen to be analysed. The choice of the period is demonstrated in 1914/15, where it barely registered as a

dry year during the periods chosen. However, closer analysis and historical reports confirmed this was a dry year. The 1897/98 and 1914/15 droughts started during winter (Figure 7-1), highlighting the importance of considering winter droughts in the Canterbury region.

7.5 Conclusions and limitations

There was a wide variation in the spatial and temporal distribution of the driest years (over the periods analysed) among stations with over 100 years of rainfall data. Nine different decades (and nineteen different years) recorded the lowest rainfall at one or more stations. There were more lowest rainfall years recorded post-1950 (out of a total of 59 years, 43 were post-1950 and 16 pre-1950) than pre-1950 over the four periods analysed. This apparent increasing dryness in more recent decades could be due to changes in the climate and rainfall patterns due to anthropogenic climate change. However, data completeness and reliability could also be factors. As demonstrated in Chapter 6 there were clear clusters where similar dry weather was experienced. For example, between 1 January 1939 and 31 March 1939 (1938/39 years), all four Banks Peninsula stations (Okuti, Christchurch Gardens, Magnet Bay, and Little Akaloa) recorded their driest year. No other stations analysed had this year as the driest for this period, though some did record rainfall in the lowest five for this year.

Analysing rainfall pre-1950 has significant limitations, including data completeness, reliability, and spatial coverage. There were significant gaps in the completeness of some data records, with many years omitted from the analysis. Previous studies have highlighted that old weather stations may have data reliability issues (Larsen, 2005). The spatial coverage in weather stations was reduced from 25 post-1950 to 15 for stations with 100 years or more of data (note that two stations were included here that had just under 100 years of data to improve spatial coverage). This reduction in weather stations may have meant significant events may have been missed or overrepresented. Also, there was no even spatial distribution of stations with these long term rainfall records. Banks Peninsula, for example, was represented by four out of the original six stations (post-1950), versus the Canterbury High Country which had no stations with 100- plus years of records.

As highlighted in Chapter 5, another limitation was the periods chosen to be analysed, which missed the potential winter droughts. In this case, the 1914/15 drought, which historical reports highlight as a significant drought, barely registered in the initial analysis due to the

primary dry spell being during the winter months. Two years were identified as being potentially significant droughts pre-1950, 1897/98, and 1914/15. Both droughts started before winter, with the 1897/98 drought continuing over the summer months. There was limited data available for both years, but both of these years may have had dry spells or droughts as significant (in terms of rainfall deficits) as more recent droughts.

8 What could an extreme drought in Canterbury look like?

8.1 Introduction

Over the last three decades, there has been a rapid intensification in dairy farming on the Canterbury Plains (Joy et al., 2022; Grout et al., 2022; MacLeod & Moller, 2006). Before 1990 sheep and beef farming dominated the Canterbury Plains and there were relatively few dairy farms. The rapid change that occurred was partly brought on by the change to neoliberal policies that were implemented by the Government of the time. Before 1984, when these changes started to be implemented, the Government supported a lot of the agricultural sector via subsidies (Burton & Peoples, 2014). From 1984, the Government removed many of the subsidies for farming, which in some cases made up to 40% of a farm's income (Smith & Montgomery, 2004; MacLeod & Moller, 2006; Burton & Peoples, 2014). The removal of the subsidies also coincided with other changes including deregulation of the markets, lifting wage freezes, high interest rates and inflation, reduction in land values, floating the New Zealand dollar, and phasing out assistance for land development (Burton & Peoples, 2014; Smith & Montgomery, 2004). The Government also made drought assistance harder to obtain to decrease reliance on the Government and move the responsibility of drought from the Government to individuals and communities (Smith & Montgomery, 2004; Burton & Peoples, 2014).

In 1988/89, Canterbury was affected by a severe drought. Partly due to the neoliberal policies implemented in the mid-1980s, many farms were in debt and were ill-prepared for this drought, forcing them to cut spending and take out more debt (with interest rates as high as 30%). There was a limited ability to mitigate the impacts of this drought and just a general hope that it would just start to rain (Burton & Peoples, 2014). The severity of this drought combined with the changes in New Zealand's economic policies, forced change in the farming practices on the Canterbury Plains (Burton & Peoples, 2014; Smith & Montgomery, 2004). This was one of the first times farmers realised that sheep farming alone may not provide a sustainable or reliable future and that changes to farming practices, whether conversion to dairying or other diversification options were required (Burton & Peoples, 2014). Before this, there had been a reluctance to change, which may have been influenced by several factors including culturally based reluctance (i.e. my family and I have always farmed sheep) and reluctance from the Government Rural Bank (who loaned most money) to

fund dairy farms in areas they deemed unsuitable for dairy farming (e.g. North Otago and the Canterbury Plains) (Burton & Peoples, 2014).

Whilst these changes hit the agricultural sector hard, dairy farming (also horticulture and viticulture) was not impacted as much as sheep and beef farming as this farming sector did not receive significant subsidies from the Government before the economic restructuring (Smith & Montgomery, 2004; Burton & Peoples, 2014). As the Government had not propped up dairying, the withdrawal of subsidies and the changes that occurred allowed dairy farming to be able to compete with sheep and beef farming, which until 1984 had been artificially profitable due to the significant subsidies sheep and beef received (Smith & Montgomery, 2004; Burton & Peoples, 2014). It also meant that the dairy sector emerged from these market changes in a better condition than the sheep and beef sectors (Burton & Peoples, 2014). The dairy industry had established an effective marketing program (this had occurred since the 1960s), targeting nontraditional markets and consolidating its European markets, which meant that the dairy industry was well placed to cope with the demands of this new market when these reforms came (Burton & Peoples, 2014). The implementation of the Resource Management Act (RMA) in 1991 signalled changes to environmental policies, which shifted the responsibility of environmental management from central to local Government (Burton & Peoples, 2014).

The market changes, the need for diversification to combat the impacts of drought, and the increased ability to irrigate made dairy farming an attractive option for many struggling farmers (Burton & Peoples, 2014; Smith & Montgomery, 2004). There was a rapid increase in dairy farming over all of New Zealand from 1990, particularly the Canterbury Plains. Between 1990–2002 there was over a 350% increase in the dairy cow numbers in Canterbury (Grout et al., 2022; Smith & Montgomery, 2004). By 2017 there were approximately 1.3 million dairy cows in the Canterbury region, up from approximately 113,000 in 1990 (Joy et al., 2022) (see Figure 8-1 and Figure 8-2). By the end of the 2000s, almost no specialised sheep and beef farms were left in Canterbury (Burton & Peoples, 2014).

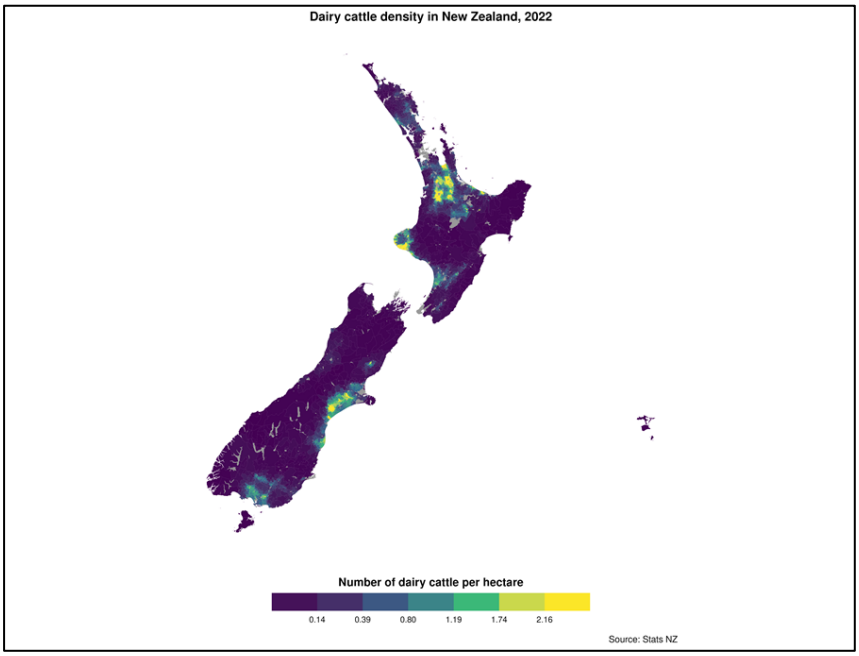

Figure 8-1. Dairy cow density in New Zealand, 2022. This figure shows that on the Canterbury Plains the dairy cow density is one of the highest in New Zealand. From *Livestock numbers: Data to 2023,* by Stats NZ, 2024a, (https://www.stats.govt.nz/indicators/livestock-numbers-data-to-2023/). Creative Commons Attribution 4.0 International License.

Irrigation is a key factor in the intensification of land use and the viability of dairy farming on the drought prone Canterbury Plains (Grout et al., 2022; Smith & Montgomery, 2004; MacLeod & Moller, 2006; Joy et al., 2022) (Figure 8-2). Significant areas of the agricultural land of the Canterbury Plains is irrigated, with water taken from rivers, irrigation schemes (e.g. the Rangitata Diversion Race), and groundwater. When it is dry, irrigation restrictions can apply, though it depends on the water source (ECAN, 2024a) (see also Chapters 3.2.1). To combat any irrigation restrictions and to ensure water when it is dry, many farms have water storage systems on their farms (e.g. storage dams or tanks) (ECAN, 2024a).

Despite some resilience in the system, intensive dairy farming, the reliance on irrigation, and the predicted increases in drought intensity and frequency on the Canterbury Plains as a result of climate change make this region extremely vulnerable to the impacts of droughts especially when extreme droughts occur. Even as far back as 2001, this vulnerability was noted by Kenny (2001):

> The vulnerability of the dairy industry to drought could increase if the planned expansion into Canterbury occurs. In the 2000/01 season Canterbury dairy farmers faced irrigation bans, which led to high supplementary feed costs. The situation could be repeated with greater frequency in the future because of increased water demands for expanding and more productive farms, even without considering the effects of climate change. (p.7).

Figure 8-2. A typical dairy herd and irrigation near Lincoln, Canterbury. (a) Large dairy herds are common on the Canterbury plains and dairy cow numbers have significantly increased on the Canterbury Plains in the last three decades. (b) The dairy industry in Canterbury is reliant on irrigation. Large center pivot irrigators, such as the one shown in this photo, are common on the Canterbury Plains.

Understanding a plausible worst case drought scenario in the Canterbury region will enable an informed proactive risk based approach to mitigating and minimising drought impacts. Using a storyline approach (see Chapter 2.6) this chapter aims to identify and understand what a plausible worst case drought scenario might look like in the intensive dairy farming areas of the Canterbury Plains.

8.2 Methodology

To understand what a plausible worst case drought scenario might look like in the intensive dairy areas of the Canterbury Plains, rainfall and soil moisture data (where available) were analysed. Analysing both types of data enabled meteorological and agricultural droughts to be assessed. Agricultural droughts are more relevant for the agricultural sector as crops, pasture agricultural productions and support industries can be impacted. They can also have far ranging impacts on the wider society (ANZ & BPL, 2000). The 1897/98 dry period identified in Chapter 7 was chosen to analyse further. It stood out as a potentially very dry year with rainfall well below other years with complete data for the period chosen. To compare this year with more recent known droughts or dry spells, rainfall data from 1988/89 and 1997/98 were analysed further, and both rainfall and soil moisture data from 2000/01.

A examination of weather stations on the Canterbury Plains, via the Cliflo database, was carried out to identify any stations or localities that had both soil moisture data and rainfall data from at least 1897 to the present. Two localities that fit these criteria were identified, Lincoln and Winchmore (Figure 8-3). Both of these locations are located in the Canterbury Plains sub-region, although Lincoln could also have some alignment with Banks Peninsula (Figure 6-3). Five weather stations were in the Lincoln area and six in the Winchmore area (Table 8-1). At both locations, no single station had complete rainfall data from pre-1897 to the present. Following the WMO guidelines, which required that stations be sufficiently close together in distance and elevation and are sufficiently well correlated (WMO, 2017), records at both locations were combined to obtain a complete record at each site from pre-1897 to the present (Table 8-2). Rainfall data was processed as per the methodology described in Chapters 4 and 5.2.

Limited soil moisture data were available, with records only from 2000 and 1999 at Lincoln and Winchmore respectively. At Lincoln data from one station were used and at Winchmore data were combined for two stations as per WMO guidelines (WMO, 2017) (Table 3-1). The

raw soil moisture data were recorded hourly. A daily average was calculated and then processed following the methodology used for rainfall outlined in Chapters 4 and 5.2.

Neither of these locations were analysed in Chapters 5 to 7 as no one weather station met the criteria for those analyses (i.e. complete data between 1950–2022 at an individual weather station). However, these localities and weather stations are ideal for this case study as they have suitable rainfall and soil moisture data (once combined). They are also located on the Canterbury Plains in the intensive dairy farming areas, which is an area of interest given the rapid intensification of dairy farming on the Canterbury Plains. Hororata was not analysed even though it has rainfall data for the required period as no soil moisture data were available.

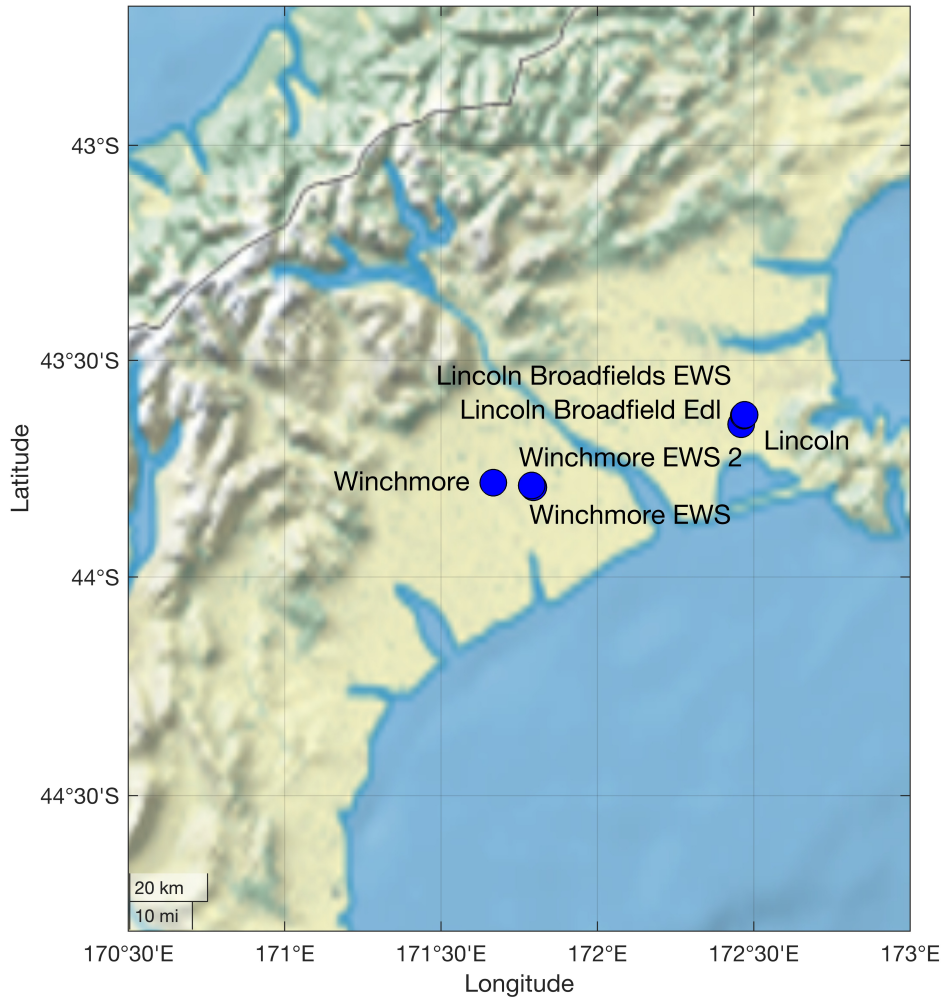

Figure 8-3. Location map of Lincoln and Winchmore weather stations that were used in the rainfall and soil moisture analyses. These weather stations are located on the Canterbury plains in intensive dairy farming areas.

Table 8-1. Canterbury weather stations at Lincoln and Winchmore locations.

Station Name/Number	Rainfall data available	Soil moisture data available	Latitude	Longitude	Height above MSL (m)
Lincoln (4881)	2/1/1881–1/1/1988	-	-43.648	172.463	11
Lincoln Broadfield Edl (4882)	2/3/1972–4/5/2000	-	-43.628	172.468	12
Lincoln Broadfields EWS (17603)	30/6/1999–present	24/2/2000–present	-43.62622	172.4704	18
Lincoln Broadfields EWS 2 (45751)	27/6/2023–present	27/6/2023–present	-43.62285	172.46918	17
Lincoln Broadfield Raine EWS	15/2/2018–present	-	-43.62622	172.4704	18
Winchmore (4739)	2/5/1885–1/8/1954		-43.783	171.667	137
Winchmore EWS (4764)	2/1/1947–22/5/2018	15/12/1999 – 22/5/2018	-43.79346	171.79512	160
Winchmore EWS 2 (42899)	30/6/2017–present	30/6/2017–22/1/2022	-43.78935	171.79032	164
Winchmore 2, Raine EWS (44001)	5/8/1919–present		-43.78935	171.79032	164
Winchmore Mixed Farm (4760)	2/1/194–1/3/1953		-43.833	171.717	191
Winchmore M.W.D (4761)	16/5/34–7/10/59		-43.833	171.717	142

Table 8-2. Lincoln and Winchmore weather stations that were used in rainfall and soil moisture analysis.

Station Name/Number	Rainfall data used	Soil moisture data used
Lincoln (4881)	2/1/1881–31/12/1987	-
Lincoln Broadfield Edl (4882)	1/1/1988–3/5/2000	-
Lincoln Broadfields EWS (17603)	4/5/2000–16/7/2024	24/2/2000–16/7/2024
Winchmore (4739)	2/5/1885–31/7/1954	
Winchmore EWS (4764)	1/8/1954–27/8/2017	15/12/1999–27/8/2017
Winchmore EWS 2 (4289)	28/8/2017-14/6/2024	28/8/2017–22/1/2022

The dry periods of interest for 1897/98 and 2000/01 were identified using the methodology outlined in Chapter 5.2 (see Figure 8-4, Figure 8-5 and Table 8-3). The drought was known to extend over both winter and summer periods. To capture both the winter and summer, three time periods were chosen to be analysed. The first covered autumn through to the beginning of summer (1 March–30 November). Figure 8-4 and Figure 8-5 show that there was little rainfall at both locations during this period in 1897/98. The second period covered summer and Autumn the following year (1 December–31 May (year 2). Figure 8-4 and Figure 8-5 show slightly more rainfall during this period in 1897/98. The overall period from 1 March–31 May (year 2) was also analysed.

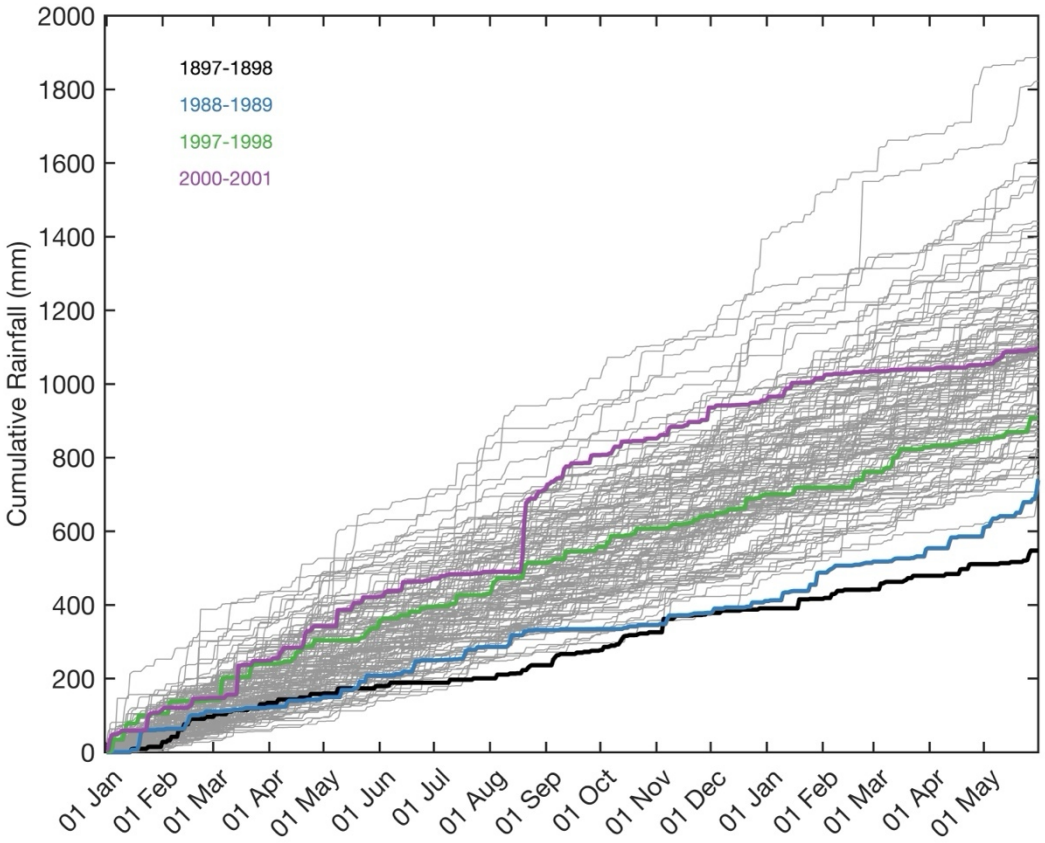

Figure 8-4. Cumulative rainfall at Winchmore. Highlighted years are the years of interest. The grey lines are all other years between 1886–2022. This figure was used to estimate the driest months for the years of interest. Note that an extended period was used to identify the driest months due to historical evidence that indicated that the 1897/98 drought spanned both winter and summer.

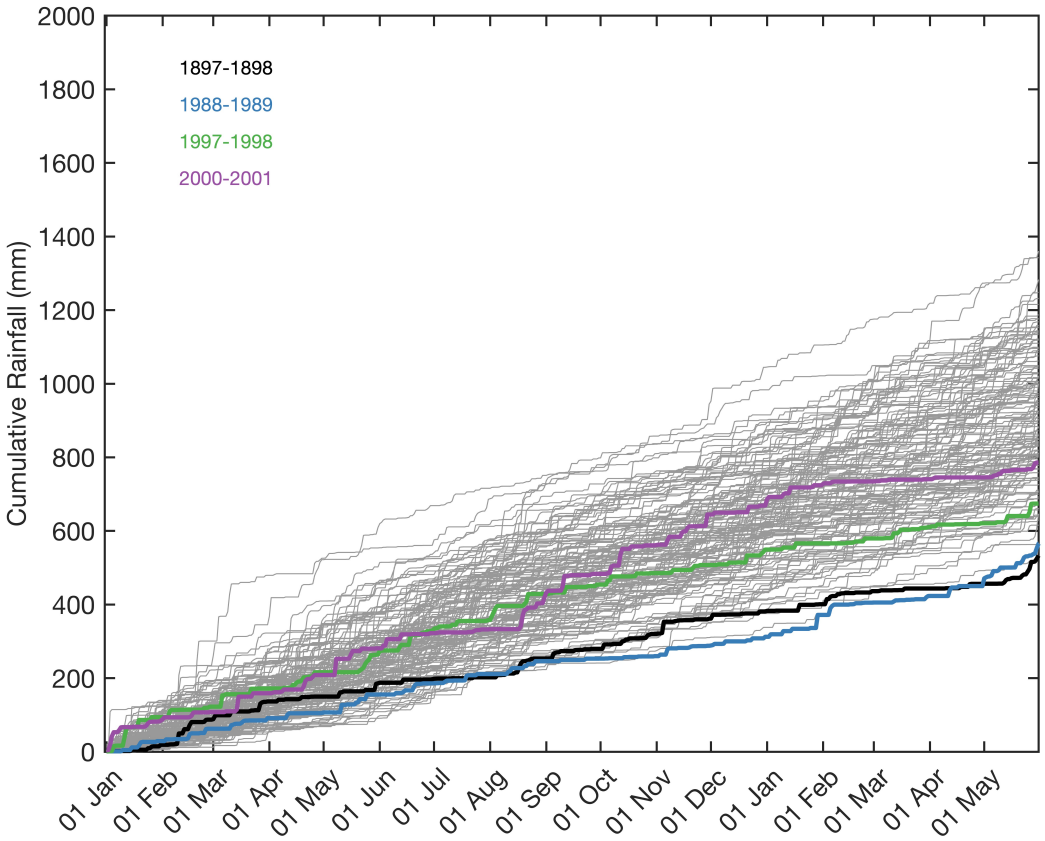

Figure 8-5. Cumulative rainfall at Lincoln. Highlighted years are the years of interest. The grey lines are all other years between 1881–2022. This figure was used to estimate the driest months for the years of interest. Note that an extended period was used to identify the driest months due to historical evidence that indicated that the 1897/98 drought spanned both winter and summer.

Table 8-3. Periods of interest.

Period of interest	Period name
1 March–30 November	Winter
1 December–31 May	Summer
1 March (year 1)–31 May (year 2)	Overall

For Winchmore and Lincoln, the climate rainfall normals were calculated for the periods of interest (Table 8-3) over a thirty-year period from 1991–2020 (Appendix D). The total rainfall was calculated for each period of interest (Table 8-3) (Appendix D) and the ratio of rainfall to the 1991- 2020 climatic mean was calculated to determine the percent anomaly of rainfall for a particular period to the mean.

To estimate the duration and severity of any agricultural drought present during the 2000/01 periods, soil moisture percentiles were calculated. Calculating the percentiles allows the soil moisture recorded on a particular day to be compared to what has been seen previously at a particular location (Yang et al., 2023) (i.e. 10% means the soil moisture is at the 10th percentile for a given day, in other words, likely to be very dry relative to normal conditions). Calculating soil moisture percentiles was done as Canterbury is a naturally dry area so absolute soil moisture values may not indicate an agricultural drought. Using soil moisture percentiles can indicate whether or not an agricultural drought may be present in the area and can be particularly useful in determining if a drought is present during the winter months (Yang et al., 2023; Koster et al., 2019; Neelam & Hain, 2024).

The following methodology was used to determine the soil moisture percentiles for the 2000/01 period. (Koster et al., 2019; Neelam & Hain, 2024):

- On a given day of the year, k, a cumulative distribution function (CDF) of soil moisture was created using the data from 2000–2024.
- A CDF was created by taking 5 sampling dates for each day of each year in the data series, k-6, k-3, k, k+3, and k+6. This essentially smooths the data, reducing noise.
- The percentile for each day in the time series of interest was calculated from the CDF.

According to the United States Drought Monitor (USDM), below the 20th percentile is considered a moderate drought (Koster et al., 2019; U.S Drought Monitor, 2025;)

8.3 Results

8.3.1 Rainfall

Figure 8-6 shows the percent rainfall anomaly relative to the current climatology (1991–2020) over all years, with complete records at Winchmore and Lincoln. The highlighted years are four identified years (1897/98, 1988/89, 1997/98, and 2000/01) with significant dry spells or known droughts. The grey lines are all other years and the black line is the mean rainfall (based on the 1991–2020 climatology). Two different periods were analysed. The first is from 1 March–30 November, which is considered winter (Figure 8-6a) ("winter period"). The second was from 1 December–31 May, considered the summer period (Figure 8-6b)

("summer period"). Lastly, the overall time ("overall period") was analysed from 1 March (year 1)–31 May (year 2), this took into account both summer and winter periods (Figure 8-6c).

For the winter period (Figure 8-6a), the lowest rainfall of the four years analysed was recorded during 1988/89 at Lincoln and Winchmore. Rainfall during this year was 49.6% and 48.4% of normal respectively and was the lowest on record at both stations for this time period. 1897/98 was the second lowest precipitation at Winchmore (51.1% of normal) and the third lowest at Lincoln (60.2% of normal). In contrast, this period's 2000/01 rainfall was well above normal at 117.8% (96th out of 139 years) and 142.7% (117th out of 124 years) above normal at Lincoln and Winchmore respectively. The relatively high rainfall in 2000/01 can be attributed to a storm between 18–20 August 2000 where more than 200 mm of rain fell on parts of the Canterbury plains and foothills (The New Zealand Herald, 2000). At both stations, rainfall in 1997/98 was just below normal at 84.4% (26th out of 139 years) and 90.3% (41th out of 124 years) at Lincoln and Winchmore respectively.

Over the summer period, rainfall was very low in 2000/01, 1897/98, and 1997/98 (Figure 8-6b). At Lincoln, all three years were in the lowest 10 recorded out of a total of 139 analysed. 2000/01 was the second lowest rainfall (50.7 % of normal), 1997/98, was sixth (59.9% of normal) and 1897/98 was eighth (61.4% of normal). At Winchmore, precipitation during 2000/01 was the lowest recorded out of 126 years analysed (44.2% of normal), and during 1897/98 the second lowest (46.2% of normal). Precipitation was 72.8% (17th out of 124 years) of normal during 1997/98. At both stations, rainfall for 1988/89 was close to normal at 99.5% (51 out of 139 years) and 98.8% (57 out of 126 years) of normal at Lincoln and Winchmore respectively.

Over both the winter and summer periods, rainfall was very low during 1897/98. This low rainfall is highlighted in (Figure 8-6c) where precipitation during the overall period was well below any other year at Lincoln and Winchmore (60.8% and 49.1% of normal at Lincoln and Winchmore respectively). Despite a relatively wetter summer, the overall rainfall during 1988/89 was also very low compared to other years at 68.7% (second out of 137 years) and 68.5% (second out of 119 years) of normal at Lincoln and Winchmore respectively. For 1997/98, the overall rainfall was the sixth lowest at Lincoln (75.3% of normal) and 21st lowest at Winchmore (83.2% of normal). Even though the summer of 2000/01 was

extremely dry, the overall rainfall was near or just above normal at both stations at 92.5% (31st out of 137 years) and 103.4% (66th out of 119 years) of normal at Lincoln and Winchmore respectively. This higher overall rainfall is because of the storm on 18–20 August 2000, which brought significant rainfall to many parts of Canterbury (The New Zealand Herald, 2000).

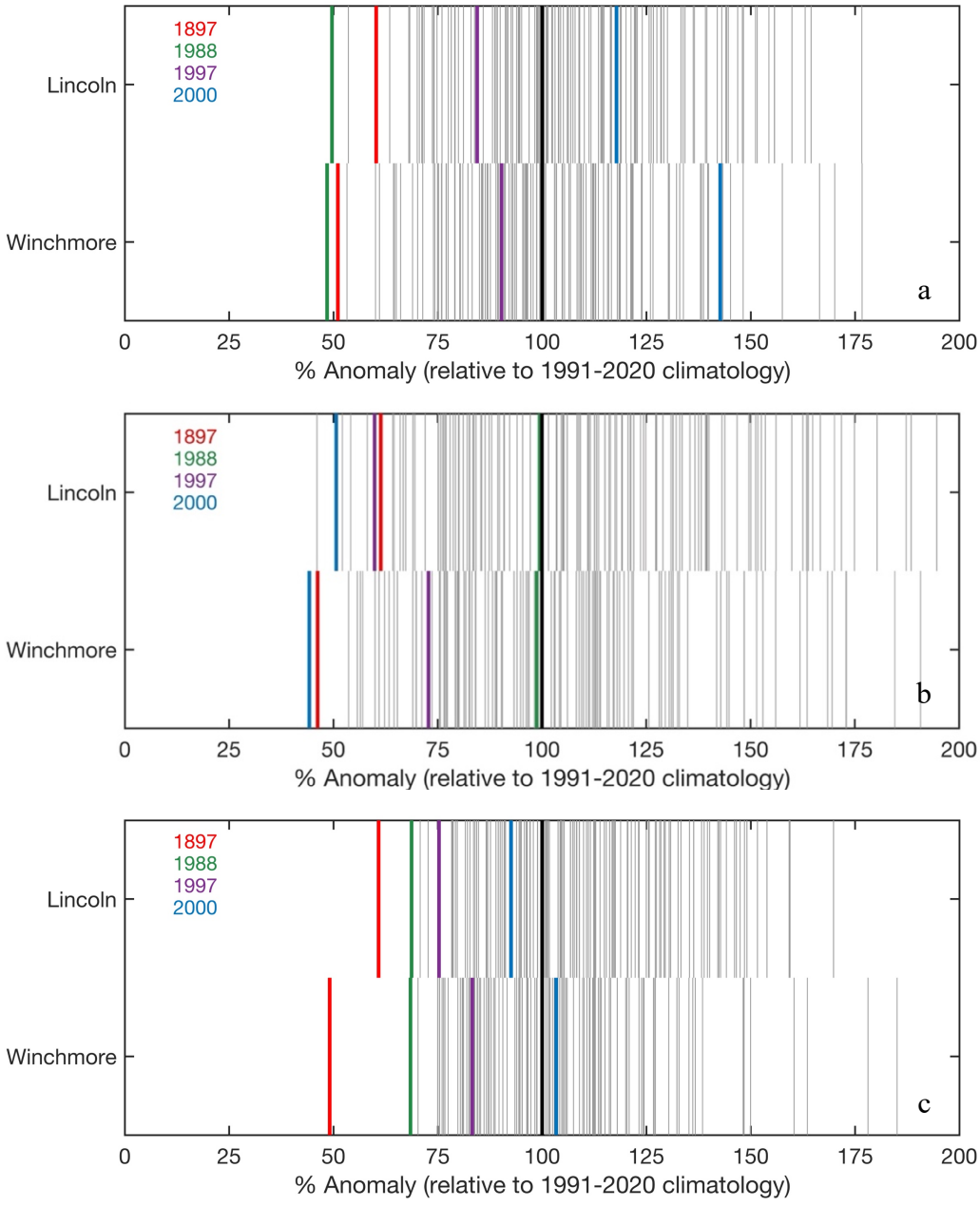

Figure 8-6. Rainfall anomalies relative to the 1991–2020 climatology at Winchmore and Lincoln over different time periods. Coloured lines are for 1897, 1988, 1997 and 2000 (years of interest) and grey lines are all other years that had data available. The black line is the mean rainfall for the specified period based on the 1991-2020 climatology. (a) 1 March (year 1)–30 November (year 1). (b) 1 December (year 1)–31 May (Year 2). (c) 1 March (Year 1)–31 May (year 2).

8.3.2 Soil moisture

Soil moisture data were available from early-2000 and late 1999 at Lincoln and Winchmore. The soil moisture and rainfall were averaged over 5-day periods (pentad scale) to smooth the data and reduce noise. Agricultural droughts, or soil moisture droughts are important for agriculture as they result in a deficit in the water available for crops and pasture, which can impact the whole agricultural system (Seneviratne, 2012). The USDM is commonly used to identify soil moisture droughts, and defines a moderate drought when it is below the 20th soil moisture percentile and an extreme drought is below the fifth soil moisture percentile (U.S Drought Monitor, 2025). NIWA has a similar drought monitor for New Zealand that uses various drought indices to assess drought risk in the country (NIWA, n.d-g; Mol et al., 2017).

8.3.2.1 Lincoln

The five-day average soil moisture percentiles for 2000/01 at Lincoln are shown in Figure 8-7. This figure shows that from the beginning of January 2001, the soil moisture rapidly decreased below the 20th percentile, indicating drought conditions were likely present from late February or earlier. The spring of 2000 was wet, and soil moisture percentiles were generally very high.

The five-day averaged raw soil moisture percentage for 2000/01 versus the five-day averaged rainfall for 2000/01 and 1897/98 were analysed and compared (Figure 8-8). In general, the soil moisture drops when there has been little to no rain and increases with significant rainfall. For example, in mid-August 2000 there was a large rainfall event on 18–20 August that increased the soil moisture percentage (Figure 8-7 and Figure 8-8). Likewise, between mid-January–May 2001, there was little rain recorded. The soil moisture during this period steadily dropped before increasing again in May when there were more significant rainfall events (Figure 8-7 and Figure 8-8).

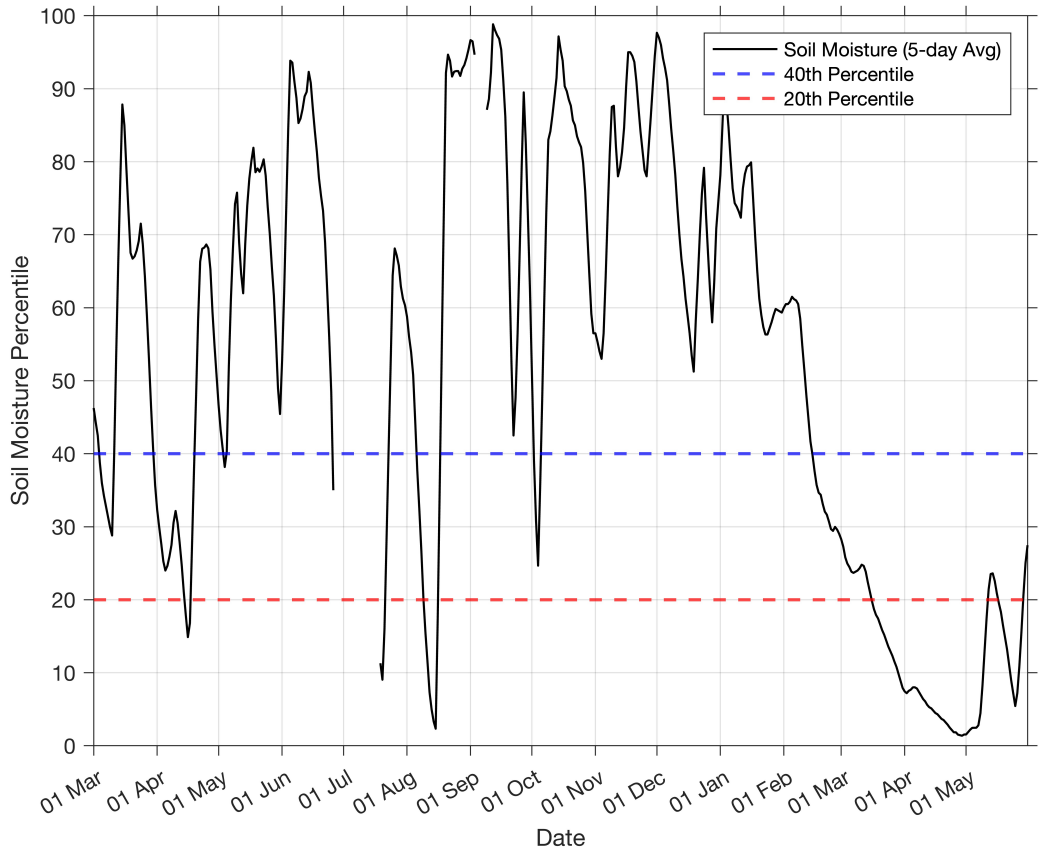

Figure 8-7. Five-day averaged soil moisture percentiles between 1 March 2000–31 May 2001 at Lincoln. A rapid decrease in soil moisture was observed from February 2001. Above the 40th percentile lines represents normal to near normal conditions (i.e. no drought) and below the 20th percentile line represents moderate to exceptional droughts (U.S Drought Monitor, 2025; Neelam et al., 2024). Note that there is a gap in the data from late June to early July due to missing data.

Figure 8-8 shows the five-day average soil moisture for 2000/01 against the five-day average rainfall for 2000/01 and 1897/98 between 1 March (year 1)–31 May (year 2) at Lincoln. Between March and mid-June, there was more rainfall and more frequent rainfall events in 2000/01 compared to 1897/98. The soil moisture recorded during 2000/01 steadily increased during this period. Given there was both lower rainfall and less frequent rainfall events in 1897/98, it would have been likely that the soil moisture would have either remained low or possibly decreased further, especially between mid-April to the end of April when there was little rain recorded.

From mid-June to mid-August, only small rainfall events occurred during 2000/01. There is some missing soil moisture data, but the soil moisture did drop especially in early August

when no rainfall was recorded between 2 August 2000–18 August 2000. 1897/98 recorded similar rainfall to 2000/01 from mid-June to early July, however, there was some rainfall in early August, therefore it is likely that the soil moisture would have increased. From mid-August to mid-January 2000/01 was reasonably wet, with a storm bringing 52.2 mm rain between 18–20 August 2000. Soil moisture was above the 80th percentile during much of this period (Figure 8-7) In comparison 1897/98 was much drier, except for a rainfall event at the end of October. Overall it would be expected that soil moisture would have decreased or remained relatively low during this period (except for a short increase in October that would have been related to the rainfall event). The soil moisture would likely have been low enough for an agricultural drought to have been present (i.e. below the 20th percentile line).

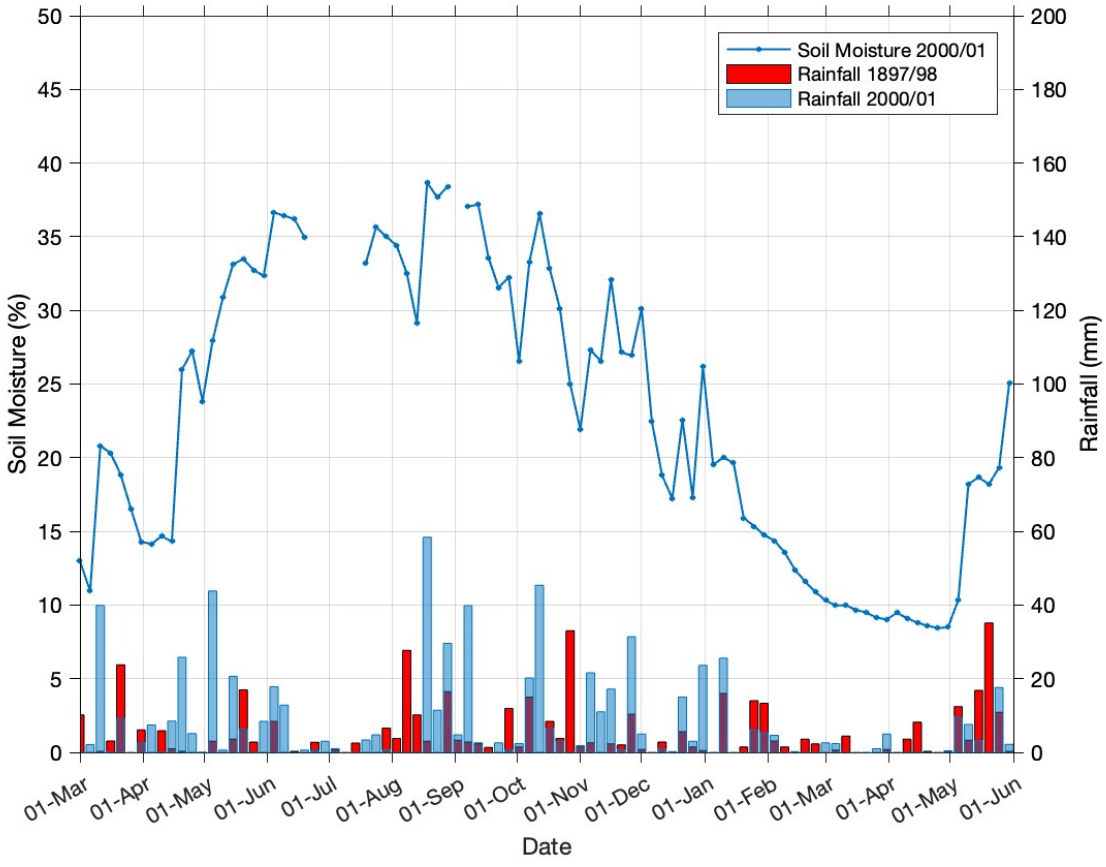

Figure 8-8. Five-day averaged soil moisture from 2000/01 and five-day averaged rainfall from 1897/98 and 2000/01 at Lincoln between 1 March (year 1)–31 May (year 2). Very low soil moisture percentiles and rainfall were experienced between late December 2000–early May 2001.

From mid-January to the beginning of May (year 2), very little rainfall was recorded in 2000/01. The soil moisture percentage (and percentile) rapidly decreased to extremely low levels (below the 10th percentile). In comparison, more rainfall was recorded during 1897/98, especially at the end of January and mid-April, though it was still very dry. The soil moisture may have increased slightly at the end of January. However, it would have likely remained low for most of this period, with some possible temporary increases in mid-April when there was some rainfall. Both years had some rainfall from May, though the rainfall appeared to be greater in 1897/98. The soil moisture during this period would likely have increased more rapidly in 1897/98 than in 2000/01. Whilst the soil moisture levels may have improved during this period in 1897/98, drought conditions persisted as described in April 1898:

> Mr William Bishop has been thirty five years farming in Canterbury, and has never experienced so dry a time as the present season. He had never seen crops so poor, or feed of every kind so scarce. He looked on the coming winter as a very serious time indeed, and was certain that a large number of farmers would not be able to carry their stock through without starving some of them. (The Press, 1898b, p.3).

8.3.2.2 Winchmore

The five-day average soil moisture percentiles for 2000/01 at Winchmore are shown in Figure 8-9. This figure shows that from approximately mid-October 2000, the soil moisture rapidly decreased and drought conditions were likely from November. This decrease was earlier than at Lincoln and the soil moisture percentiles were typically lower than at Lincoln indicating that the conditions at Winchmore were relatively drier. The difference between Winchmore and Lincoln demonstrates the variation in the Canterbury region's temporal and spatial characteristics of droughts.

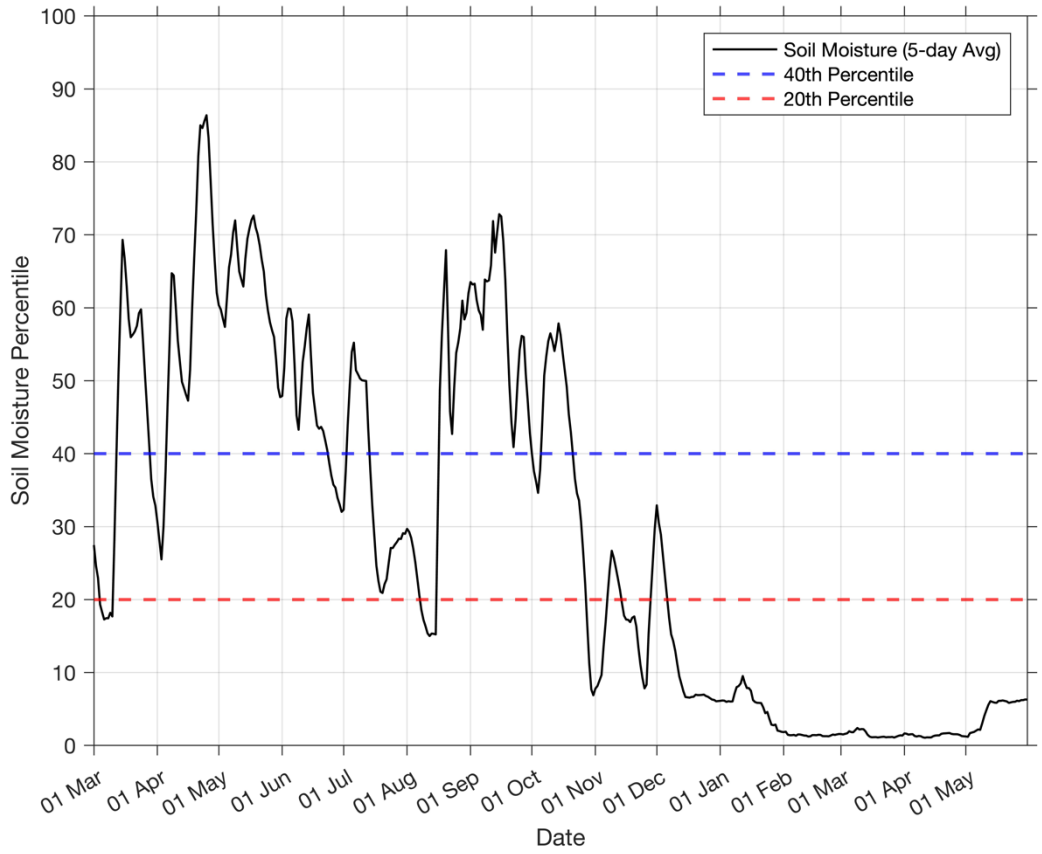

Figure 8-9. Five-day averaged soil moisture percentiles between 1 March 2000–31 May 2001 at Winchmore. A rapid decrease in soil moisture was observed from October 2000. Above the 40th percentile lines represents normal to near normal conditions (i.e. no drought) and below the 20th percentile line represents moderate to exceptional droughts (U.S Drought Monitor, 2025; Neelam et al., 2024). From February to the end of April, the soil moisture percentile extreme to exceptional drought range (U.S. Drought Monitor, 2025).

Figure 8-10 shows the five-day average soil moisture for 2000/01 against the five-day average rainfall for 2000/01 and 1897/98 between 1 March (year 1)–31 May (year 2) at Winchmore. Like Lincoln, between March and mid-June, there was overall more rainfall and more frequent rainfall events in 2000/01 compared to 1897/98. During this period, the soil moisture recorded during 2000/01 steadily increased. Given there were both lower rainfall and less frequent rainfall events in 1897/98, it would have been likely that the soil moisture would have either remained low or possibly decreased further, especially in May when little rain was recorded.

From mid-June to mid-August there were only small rainfall events during 2000/01 and the soil moisture levels slowly dropped. Figure 8-9 shows that the soil moisture percentile

dropped below the 20th percentile during this time, indicating that it was relatively dry. 1897/98 reordered similar rainfall to 2000/01 from mid-June to early July, however, there was some rainfall in early August, therefore it would be likely that the soil moisture would have increased at this time, but overall it is likely that they would have been very low. From mid-August to November 2000/01 was reasonably wet, with a storm bringing 187.6 mm of rain between 18–20 August 2000. Soil moisture was generally above the 50th percentile during this period (Figure 8-9). The relative soil moisture percentile was lower overall at Winchmore than Lincoln (Figure 8-9 and Figure 8-10). In comparison 1897/98 was overall drier, though October appears to be slightly wetter, with a significant rainfall of 36.3 mm recorded on 5 November 1897 (Figure 8-10). Overall it would be expected that soil moisture would have remained relatively low during this period (except for a short increase in October that would have been related to the rainfall event and slightly wetter weather).

From November to mid-January, rainfall was still recorded during 2000/01 at Winchmore. There were some reasonable rainfall events at the end of November and mid-January (Figure 8-10), but overall the rainfall was low. The soil moisture steadily dropped, except for a temporary increase in mid-January, coinciding with the rainfall event. By mid-December, the soil moisture was typically below the 10th percentile (Figure 8-9). In 1897/98 rainfall was also very low during this period, so it is likely that overall the soil moisture levels would have been extremely low.

From mid-January to the end of May (year 2), very little rainfall was recorded in 2000/01 until the beginning of May. Almost no rainfall was recorded in March and April (a total of 12.4 mm, of which over half fell after 20 April 2001). The soil moisture percentage was extremely low, remaining below two from late February to early May. Between 20 March 2001–5 May 2001, the soil moisture percentile was below one, falling to a low of 0.046 between 18-20 April (Figure 8-10) Figure 8-9 shows that the soil moisture percentile was below the fifth percentile for this period. Between 27 January 2000–10 May 2001, the soil moisture was below the fourth percentile the entire time.

The soil moisture levels did start to increase slightly in May when a rainfall event occurred. In comparison, more rainfall was recorded during 1897/98, though it was still very dry. The soil moisture may have increased slightly but likely remained low for most of this period, with possible temporary increases when rainfall events were recorded. Both years had some

rainfall from May, though the rainfall appeared to be greater in 1897/98. The soil moisture during this period would likely have increased more rapidly in 1897/98 than in 2000/01. While soil moisture levels may have improved during this period in 1897/98, drought conditions persisted as described in Chapters 7, 8.3.2 and 8.4.

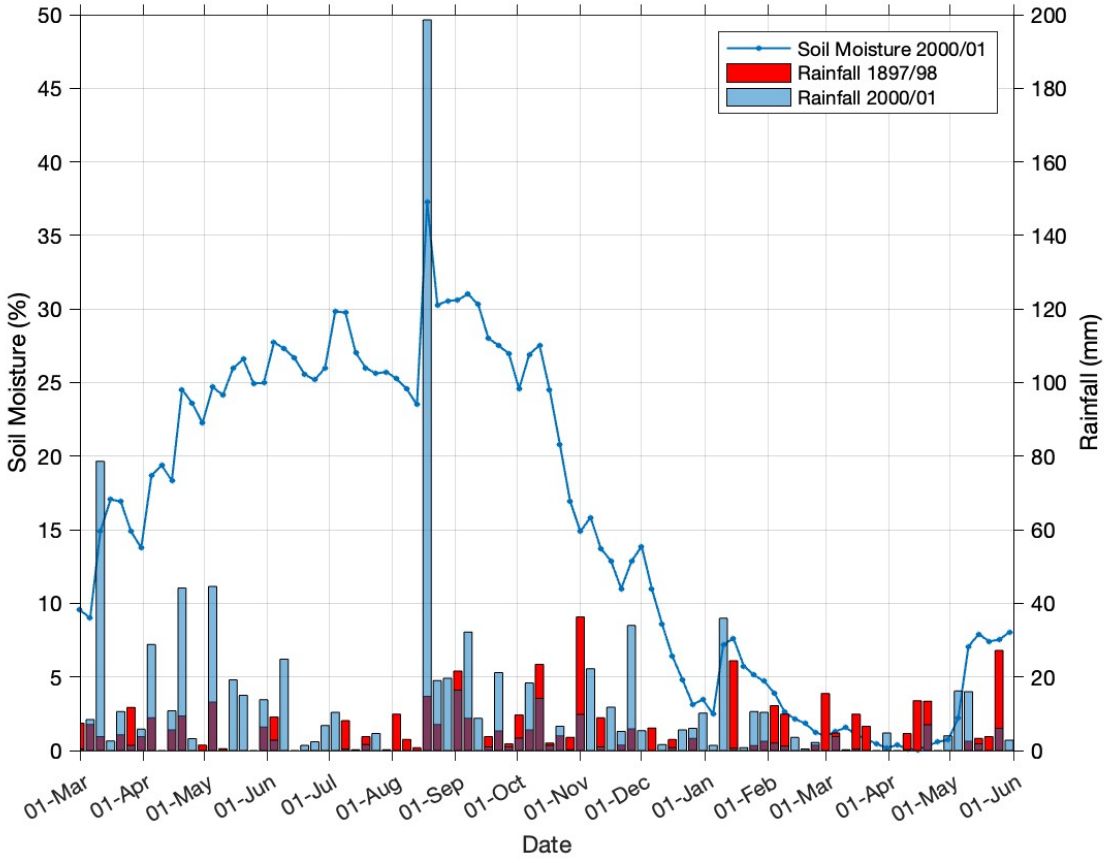

Figure 8-10. Five-day averaged soil moisture from 2000/01 and five-day averaged rainfall from 1897/98 and 2000/01 at Winchmore between 1 March (year 1)–31 May (year 2). Very low soil moisture percentiles and rainfall were experienced between late December 2000–early May 2001.

8.4 Discussion

At Lincoln and Winchmore, the 1897/98 year over the overall period analysed had the lowest rainfall, lower than the recent high-impact droughts of 1988/89 (second at both locations) and 1997/98 (sixth and 21st at Lincoln and Winchmore respectively). Whilst only the summer period of 2000/01 recorded extremely low rainfall, substantial impacts were still recorded despite the wetter winter and spring. The soil moisture records for 2000/01 also show that an agricultural drought was present. Then comparing rainfall data from 2000/01 and 1897/98, it is likely that during 1897/98 severe soil moisture deficits would likely have occurred. The

presence of an agricultural drought in 1897/98 can be substantiated by newspaper reports at the time, which describe low crop yields and challenging conditions for farmers:

> The rain of Thursday last spoilt the holiday and has done no real good for the crops in the North Canterbury district. There was not enough of it in the first place, and in the second place the return of the hot sun and dry wind makes matters just as bad as ever they were….Grass lands are looking browner and more burned up than we remember to have seen them since the memorable season of 1863…North Canterbury it is at present making a struggle for existence on lands from which there is no moisture to be drawn from the subsoil. (The Press, 1897a, p.2).

> …There is very little pasture for the wind to affect…but the paddocks are for the most part a deplorable sight, and the scarcity of last year's hay, which was given out early in the season, is being felt…..On all hands the land is too hard to operate upon. (The Press, 1898b, p.3).

The 1897/98 meteorological (and likely agricultural) drought event could occur again, making it a plausible worst-case scenario for the Canterbury region. The impacts of an event this scale in today's world are difficult to predict due to factors such as changes in farming practice, adaptation that has already occurred in the region (e.g. diversification), economics and political systems at the time, and irrigation and how that may buffer drought impacts. Looking back on the more recent large scale droughts in the region that have been analysed (1997/98, 1988/89, and to a lesser extent 2000/01) gives insight into the potential impacts that may occur.

The impacts of the 1988/89 and 1997/98 droughts were substantial. The 1988/89 drought was one of the worst droughts recorded at the time, with Christchurch City recording its lowest rainfall years since 1894 (McGann, 1991). Though less impactful, the 1997/98 drought was considered meteorologically similar to the 1998/89 drought (Burton & Peoples, 2014). The lower impacts in 1997/98 was partly due to changes in farming systems since the 1988/89

drought and fewer structural changes to the economic systems of New Zealand that played a significant role in the impacts of the 1988/89 drought (Chapter 8.1).

Impacts from both droughts included extremely low river levels, irrigation bans, requirement for supplementary feedstock, and damage to pasture (Burton & Peoples, 2014; ANZ & BPL, 2000; Smith & Montgomery, 2004). During the 1988/89 drought, impacts included cows drying up, impacts on milk supply to Christchurch, and poor stock conditions (McPherson, 1989). Near-record low groundwater levels in the shallow aquifers were reported in 1997/98 (Horrell et al., 1998; Sanders et al., 2000). However, the deep aquifers in this drought were not impacted, nor were the flows in the large Canterbury rivers, such as the Rakaia, with headwaters in the Southern Alps (Horrell et al., 1998). The droughts also contributed to substantial socioeconomic impacts, particularly to the rural sector including debt, loss of employment, impacts on rural retail, processing plants, mental health, and suicide (e.g. Ramsay, 1998; ANZ & BPL, 2000; McPherson, 1989; Lucas, 1989; Turner, 1990). In South Canterbury alone, it is estimated that the 1988/89 drought cost the economy approximately NZD 124 million (approximately NZD 200 million today) (Turner, 1990). The cost to the whole of the Canterbury economy would have been significantly higher. It is estimated that the 1997/98 drought farm gate cost and loss of revenue was over NZD 260 million (just under NZD 500 million today) (Chalmers, 1998). The total cost to the economy was greater due to flow on impacts such as loss of businesses to retailers and jobs losses (Ramsay, 1998). The impacts of the 1997/98 drought were somewhat buffered by the increased irrigation in Canterbury (ANZ & BPL, 2000). Whilst there were fewer documented impacts from the 2000/01 drought, irrigation bans occurred (Kenny, 2001) and the hydro lakes in Central Canterbury were extremely low, impacting energy supply over the country (Daniels, 2002).

The impacts from the 1897/98 drought have not been published academically, however newspaper reports from the time detail crop losses and low yields, loss of stock and poor stock conditions, and generally difficult conditions for farmers in much of the Canterbury region, with the year being described as the worst ever seen (The Press, 1898b). From historical newspaper reports the 1897/98 drought was severe and long lasting:

> The first break in the drought which held the lands of South Canterbury in its embrace for over eighteen months occurred on Thursday…The dry spring had a most disastrous effect on all crops… The outlook early in the year was gloomy in the extreme….(The Press, 1898b, p.3).

Like the 1988/89 drought, it started before winter and was made worse by hot temperatures and persistent northwest gales, as reported in The Press newspaper on multiple occasions, for example:

> Our correspondents write that a howling nor'-west gale, carrying clouds of dust high into the air, passed over the North Canterbury district yesterday…..the hot, dry wind must have done a great deal to bring on the grain prematurely.... Rain is very greatly needed. (The Press, 1897, p.5).

> A strong nor'-west wind sprang up in Ashburton yesterday morning and, increasing to a gale, blew with great fury all day. There is very little pasture for the wind to affect, but it will be terribly severe on the standing crops. (The Press, 1898a, p.3).

From the analysed rainfall data at Lincoln and Winchmore and historic newspaper reports, the 1897/98 drought and its impacts varied spatially within the Canterbury region, adding weight to the conclusion that there are regional variations in drought and drought impacts within the Canterbury region. Whilst the percent abnormality was greater at Winchmore (less than 50%), compared to Lincoln (61%), both locations recorded their lowest rainfall over the entire period between the 1880s and 2022. Reports detail significant impacts on the coastal

and lower parts of the Canterbury Plains south to Otago, and North Canterbury. The impacts of the drought appeared to be less significant in the Canterbury foothills and Banks Peninsula These observations align well with the cluster analysis from Chapter 6 which showed that there was a very strong association between rainfall on the Canterbury Plains and North Canterbury and slightly weaker associations with Banks Peninsula. (Figure 6-2a). Newspaper articles from The Press detail some of these spatial variations in the drought:

> The Little River and Peninsula districts have been specifically favoured with a sufficient rainfall to keep the grass growing. Feed is generally in good condition, and is a long way in advance of the plains. The hill tops and valleys all present refreshingly green appearance…..generally the Peninsula farmers have had a satisfactory year….. Nearer the hills, in the Malvern and Greendale districts, where a much heavier rainfall was experienced all through the summer, both the cereal and root crop are a long way ahead of those lower down on the plains..... The effects of the drought throughout the whole of Canterbury and away south to below Palmerston are most disastrous….To deal more especially with the country south of the Rakaia, from the hills to the sea, the season has been the worst ever experienced since the turning over of the first tussock. The Ashburton county is one of the chief grain-growing centers of New Zealand, but the returns for the past season are phenomenally low….Along the foothills they have had nice showers at frequent intervals all through summer, with the result that feed has been plentiful, roots have flourished, and what little grain was sown gave satisfactory yields. (The Press, 1898b, p.3).

It is clear from the impacts of the more recent Canterbury droughts and the 1897/98 event that extreme drought events can have significant and long lasting impacts on the region and that adaptation to these events is crucial for the agricultural sector. Even as far back as 1897/98, it was recognised that adaptation and irrigation was extremely important for the continued success of agriculture in the region:

> In the Oxford district the water supply system aided the farmers to a large extent. In the Cust, Swannanoa and West Eyreton districts the water supply, so far as it reached, was of great value to the northern producers, and the crops varied from 10 to 51 bushels per acre. (The Press, 1898b, p.3).

> …The very lengthy drought has again revived the question of irrigation, and if a vote were taken just now it would be very largely in favour of some scheme whereby farmers would be able to at least irrigate some of the paddocks of their homesteads. That it would pay, and most handsomely, scarcely needs argument, and in a district so admirably adapted as Ashburton is for irrigation it seems almost incredible that the millions of gallons of water daily running down our rivers into the sea should not be utilised to an infinitely better and immensely more profitable purpose. The farmers have the matter in their own hands, and the present season causes them to think very seriously about making use of the bountiful supply of water Nature has provided for one of the best districts in New Zealand. (The Press, 1898, p.8).

Whilst the 1897/98 drought event is plausible, some factors may minimise or increase its overall impact today, these may include:

- How widespread the drought is. Given the limited data, it was not possible to fully assess this in this analysis. If the drought was more localised, the impacts may be

minimised as local droughts are typically easier to manage (e.g. stock can be relocated easily), and the overall economic cost is not as great (Cronshaw, 2004; Burton & Peoples, 2014). In contrast, if the drought had the spatial extent of the 2000/01 drought (see Chapter 5), then the impacts would likely be far greater as options such as relocation of stock or buying supplementary feed may become more difficult and expensive (Lucas, 1989). Based on the analysis, the drought was severe on the Canterbury Plains (Winchmore) and closer to Banks Peninsula (Lincoln). Historic reports suggest the drought was widespread throughout the Canterbury Plains and North Canterbury sub-regions (and North Otago) (Figure 6-3). This spatial extent of the drought is similar to the 1988/89 drought.

- As shown in the 1988/89 drought, the economic and political situation of the country can influence the scale of drought impacts. These factors may increase or lessen drought impacts in the future.

- Reliability of irrigation. The dairy industry in Canterbury relies on irrigation water as the climate is not naturally suited to dairy farming (Grout et al., 2022; Smith & Montgomery, 2004; Joy et al., 2022). Irrigation in Canterbury is from both groundwater and surface water sources. Many of these are reliable, even in drought conditions (especially the deep aquifers and larger, alpine feed rivers). However, irrigation restrictions and bans can still occur, even in the larger rivers. Environmental regulations in the Canterbury region are also becoming stricter, which may impact irrigation (and dairy farming in general) in the future (ECAN, 2024a; ECAN, 2025; Williams, 2024). If substantial bans or limitations on irrigation occurred during an extreme drought event then the impacts would likely be substantial and wide ranging (e.g. costs to farmers to supply food to stock, culling or relocating stock, loss of jobs, reduction in milk production and supply, impacts on processing plants, and multiple knock-on effects such as mental health issues).

- Low rainfall is not the only variable contributing to drought, especially agricultural droughts. Many of the more impactful Canterbury droughts (Chapter 5 and 7) have been associated with high temperatures, the northwesterly wind (which contributes to high temperatures and evapotranspiration) and high soil moisture deficit. If the

rainfall from 1897/98 was to recur, the effects of climate change are likely to mean the temperature now will be between one to two degrees warmer. This will increase the drying out of soils and prolong the drought (see Chapter 9) (Lewis et al., 2023).

- The continued intensification of dairy farming in Canterbury. Since the late 1990s, dairy farming has rapidly expanded in the region. However, tightening environmental regulations has appeared to slow this expansion and may limit dairy conversions in the future (Williams, 2024). Both farming intensification and tightening of environmental regulations will affect the impacts that droughts have in the region.

8.5 Summary

The 1897/98 drought event is a plausible worst case scenario drought event for the Canterbury region as it has happened before. Given that this event was over 125 years ago, it is outside our living memory and may not be considered in adaptation planning, which often only considers events within living memory (Wilhite, 2019). If the 1897/98 event occurred today, the impacts could be far-reaching and catastrophic for the Canterbury region. The impacts would possibly be more extreme than those highlighted in 1988/89, 1997/98, and 2000/01. Understanding the potential drought risk of 1897/98 can help inform proactive adaptation and mitigation measures to minimise the impacts of a catastrophic drought on the Canterbury region.

9 Implications

Throughout this thesis, there has been a systematic investigation on how meteorological droughts in Canterbury vary spatially and temporally. There are distinct sub-regions in Canterbury, where there are similar rainfall experiences indicating that drought is not experienced the same over the entire region.. The analysis has also uncovered extreme low rainfall events in the past and ones that would, if seen today, impact the intensive dairy farming areas of the Canterbury Plains. Chapter 8 highlighted the drought of 1897/98 as being a plausible worst case meteorological drought scenario (and a likely extreme agricultural drought) for the Canterbury Plains and intensive dairy farming area. Based on both the analysis and historical reports this drought lasted for approximately fifteen months and had a large spatial footprint, impacting the Canterbury Plains, particularly the Central and Coastal areas, and the North Canterbury sub-regions. The impacts of this drought were significant in the region and it is possible a similar event in today's world would have far-reaching implications, potentially worse than those seen in 1988/89 and 1997/98, for example.

We know that 1897/98 was a bad drought and would be potentially catastrophic today. However, if climate change predictions of increasing temperatures, wind, and rainfall changes are taken into account, an equivalent drought could be significantly worse, both in scale, severity, and impact. Rainfall predictions for Canterbury in a warming future are currently inconsistent, however other drought drivers such as temperature, wind and PED are all predicted to increase (Bodeker et al., 2022; IPCC, 2021; Lewis et al., 2023). Even though the changes in mean rainfall are not clear, it is expected that the rainfall will not be evenly distributed, resulting in more severe storms, leading to hazards such as flooding, and more dry spells, leading to drought conditions (Bodeker et al., 2022; Harrington, 2024). Drought occurrence in the next century is projected to increase by 10–20% under RCP8.5 (IPCC, 2023; Bodeker et al., 2022).

Harrington et al. (2024) estimate that the cumulative rainfall from pronounced dry events could decrease by a further 10–15% (see their Figure 4e) when comparing scenarios of 3°C of global warming (above pre-industrial levels) versus scenarios consistent with 0.9°C of warming associated with the early twenty-first century. Thus, if we assume the drought of

1897/98 could be as much as 15% drier if the same weather systems were to recur in the future, this would correspond to rainfall deficits of 52% of normal for Lincoln and 42% of normal at Winchmore between the 1 March to 31 May (year 2) scenario. This is compared to 61% and 49% of normal experienced at Lincoln and Winchmore respectively in 1897/98. Under this rainfall scenario alone, the likely impacts would be significant.

However, the predictions for climate change in the Canterbury region, indicate that temperature, wind and PED will all increase (IPCC, 2023; Bodeker et al., 2022). This will mean that soils will dry out quicker and earlier than they currently do and they will be dry for longer. In the case of the 1897/98 drought which was estimated to last at least 15 months, possibly longer, this could extend into a much longer drought, further increasing the negative impacts on the socioeconomic and environmental systems of Canterbury and New Zealand. Taking climate change into account, a drought the magnitude of the 1897/98 event could be catastrophic for the Canterbury region.

The potential for a catastrophic drought based on the 1897/98 event and climate change predictions will require stress testing for adaptation and resilience planning. Understanding the hazard and how well the system can cope or withstand this type of event and what adaptation and mitigation strategies are required is essential for proactive management and resilience planning. The potential for this scale of event also highlights more fundamental questions on the dairy industry and the reliability and limitations of irrigation in the area in the future. To date, irrigation has been mostly reliable, but changes in the climate and/or environmental regulations could alter this.

10 Summary

Droughts are a complicated hazard that have widespread impacts in Canterbury. Through a systematic analysis using historic rainfall data from 1950–2022, the spatial and temporal characteristics of droughts were investigated. It was found that there were spatial and temporal variations in how droughts are experienced over the Canterbury region, with variations in the severity and how droughts are experienced differently throughout the region. No relationship between ENSO state was found, with significant droughts occurring in both the El Niño and La Niña phases. However, other drivers of drought, such as winds (northwesterly in particular) were important factors in Canterbury droughts. The importance of looking at winter droughts as well as summer droughts in Canterbury was also highlighted. Five subregions, North Canterbury, Banks Peninsula, Canterbury Plains, Canterbury Lakes and Canterbury High Country in Canterbury ,were identified by performing a Spearman's rank correlation.

An analysis of rainfall data pre-1950 was carried out on stations with at least 100 years of records. This identified that there were some significant historical meteorological droughts pre-1950, in particular 1897/98, which spanned approximately fifteen months between March 1897 to May 1898. The 1897/98 drought was further analysed at two areas, Lincoln and Winchmore, that are located in the intensive dairy farming area of the Canterbury Plains. 1897/98 was compared to more recent droughts of 1988/89, 1997/98 and 2000/01. Over the fifteen months it was found that 1897/98 rainfall was lower than any other equivalent year on record, including the more recent severe droughts. Historic accounts recall a devastating year for agriculture over much of the coastal Canterbury Plains and North Canterbury. This year was identified as a plausible worst case scenario drought that could happen in Canterbury today or in the near future. However, with the effects of climate change and the high potential for droughts and their drivers to get worse, it is possible that this event could be even more extreme. The potential for an extreme event, such as the 1897/98 event happening in the near future raises important questions about adaptation planning and mitigation strategies that will allow proactive management and increase resilience to droughts in the region. Extreme drought events and the effects of climate change also raise questions about the reliability of irrigation and the viability of the dairy industry on the Canterbury Plains.

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Appendices

Appendix A – Cumulative rainfall graphs

The figures below were used to estimate the dry periods for the years of interest. Also see Figure 5-1.

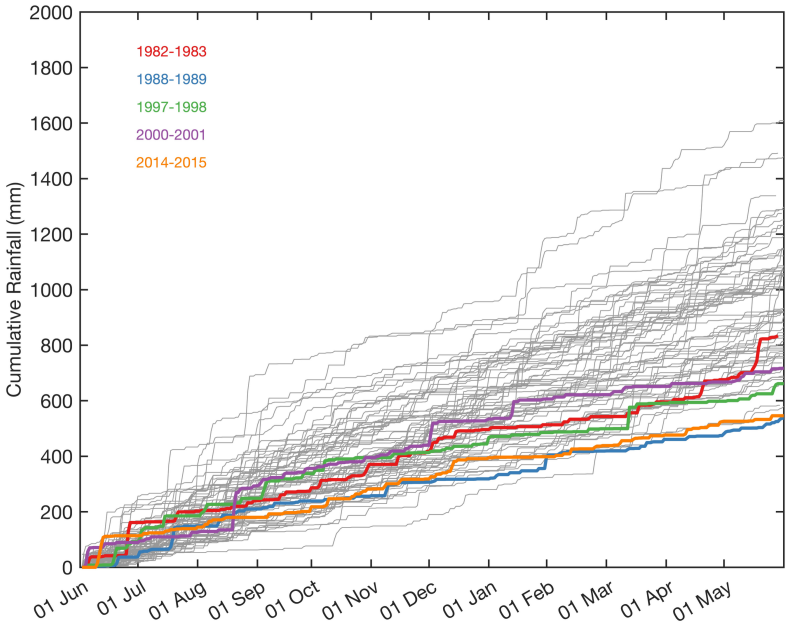

Figure A-1. Cumulative rainfall at Keinton Combe. Highlighted years are the years of interest. The grey lines are all other years between 1950–2022. This figure was one of six used to estimate the driest months for the years of interest.

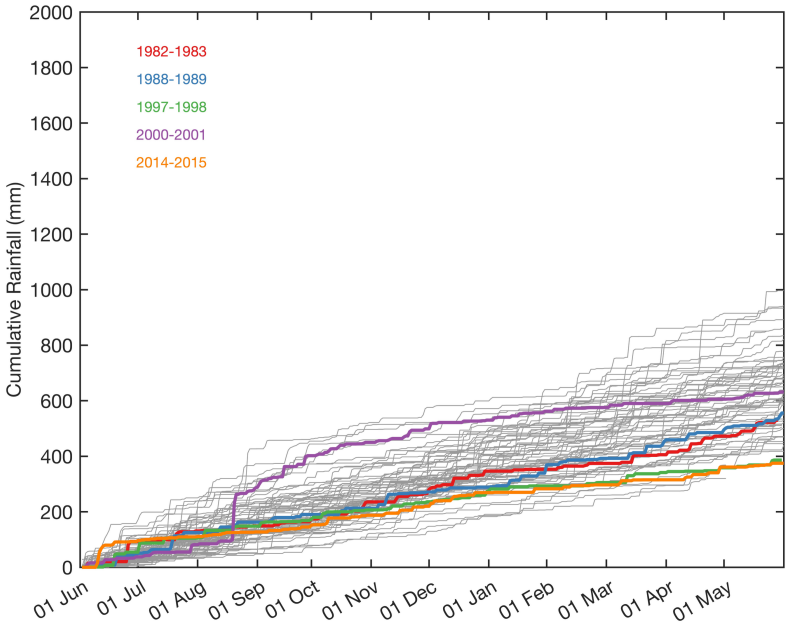

Figure A-2. Cumulative rainfall at Waipara. Highlighted years are the years of interest. The grey lines are all other years between 1950–2022. This figure was one of six used to estimate the driest months for the years of interest.

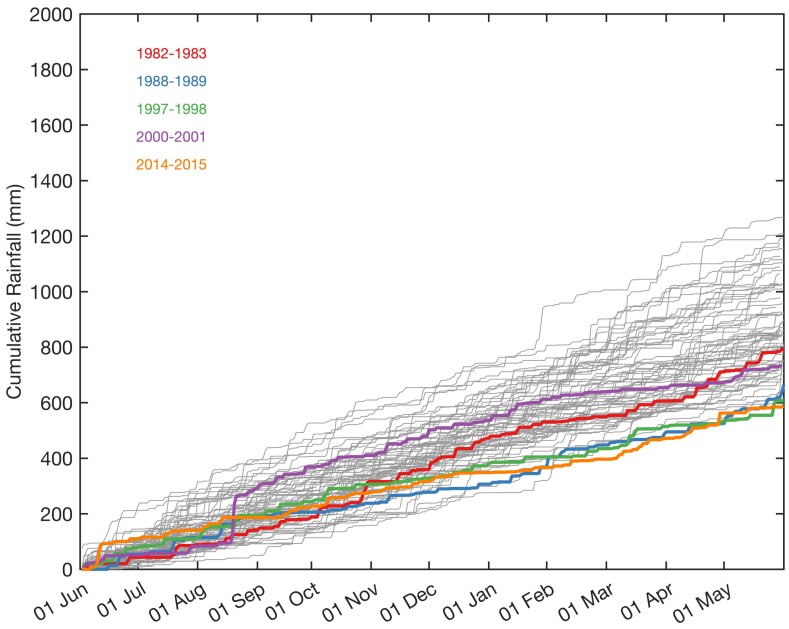

Figure A-3. Cumulative rainfall at Hororata. Highlighted years are the years of interest. The grey lines are all other years between 1950–2022. This figure was one of six used to estimate the driest months for the years of interest.

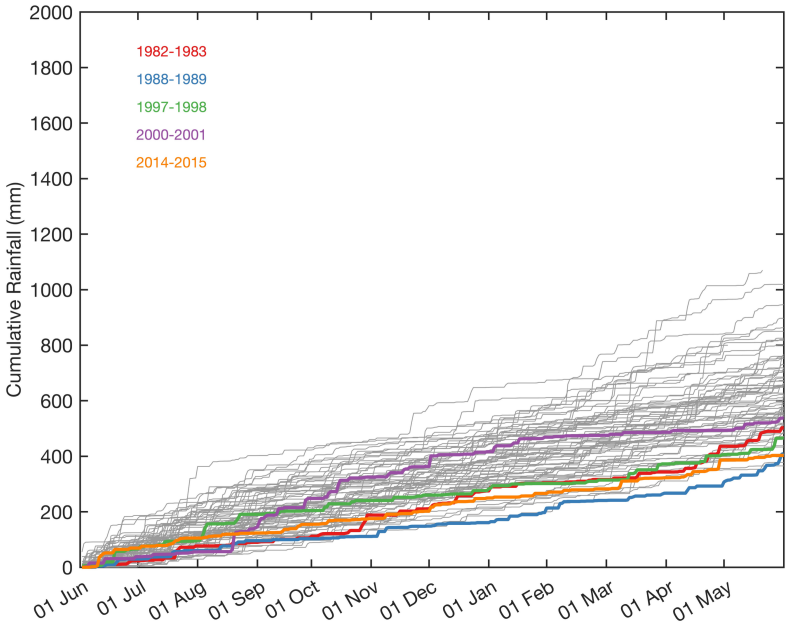

Figure A-4. Cumulative rainfall at Christchurch Aero. Highlighted years are the years of interest. The grey lines are all other years between 1950–2022. This figure was one of six used to estimate the driest months for the years of interest.

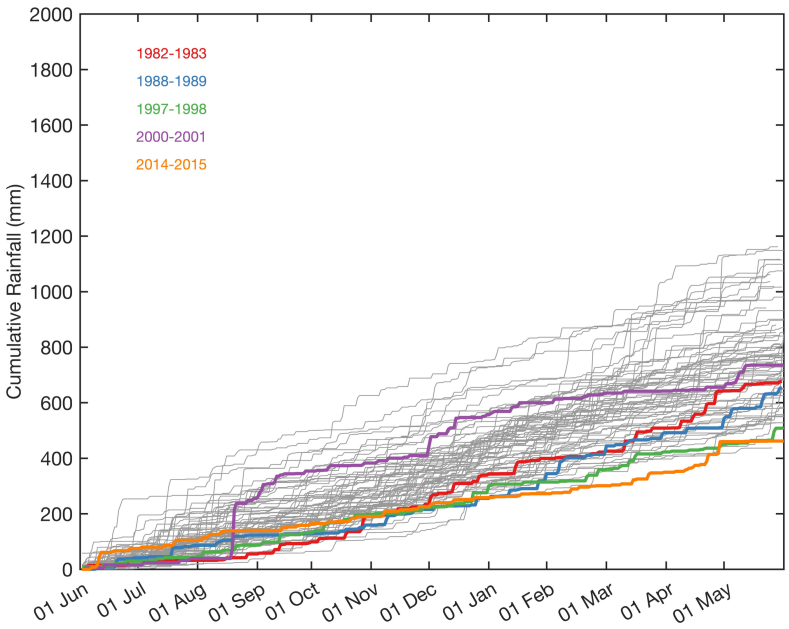

Figure A-5. Cumulative rainfall at Kakahu Bush. Highlighted years are the years of interest. The grey lines are all other years between 1950–2022. This figure was one of six used to estimate the driest months for the years of interest.

Appendix B – Rainfall statistics

Basic rainfall statistics for each weather station are shown in Table B-1 to Table B-25. Note that for some locations and periods, the period rainfall is lower than the minimum rainfall. This is due to the climatology being calculated between 1991–2020, so lower values that occurred prior to this are not picked up in the climatology calculations. For example, at Christchurch Aero between 1 January 1983– 31 March 1983, the period rainfall was 53.6 mm vs a minimum recorded of 69.1 mm for the climatology (Table B-1).

Table B-1. Christchurch Aero rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	53.6	124.2	267.2	69.1
1 September 1988–31 March 1989	141.1	308.5	467.3	181.6
1 October 1997–31 March 1998	168.0	265.4	384.7	167.6
1 December 2000–30 April 2001	92.2	227.1	420.2	92.2
1 October 2014–31 March 2015	167.6	265.4	384.7	167.6

Table B-2. Okuti rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	104.6	202.5	434.4	66.8
1 September 1988–31 March 1989	289.0	538.0	901.3	242.3
1 October 1997–31 March 1998	184.8	443.1	631.5	184.8
1 December 2000–30 April 2001	156.6	337.6	910.8	142.1
1 October 2014–31 March 2015	267.4	443.1	631.5	184.8

Table B-3. Glentui 1 rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	179.2	235.9	458.7	102.7
1 September 1988–31 March 1989	429.3	579.1	901.1	338.9
1 October 1997–31 March 1998	267.9	505.2	711.1	267.9
1 December 2000–30 April 2001	154.7	421.2	650.8	154.7
1 October 2014–31 March 2015	309.1	505.2	711.1	267.9

Table B-4. Hororata West rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	135.1	217.8	423.4	95.0
1 September 1988–31 March 1989	361.0	523.7	747.6	234.6
1 October 1997–31 March 1998	279.5	457.5	657.4	198.4
1 December 2000–30 April 2001	172.4	380.3	605.8	172.4
1 October 2014–31 March 2015	198.4	457.5	657.4	198.4

Table B-5. Hororata rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	126.5	202.0	361.7	101.3
1 September 1988–31 March 1989	302.2	485.0	680.2	285.5
1 October 1997–31 March 1998	263.5	424.5	579.9	244.8
1 December 2000–30 April 2001	169.5	351.5	538.6	169.5
1 October 2014–31 March 2015	244.8	424.5	579.9	244.8

Table B-6. Riverside rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	79.1	151.7	354.0	38.1
1 September 1988–31 March 1989	269.4	390.8	632.9	222.6
1 October 1997–31 March 1998	165.8	333.9	546.0	165.8
1 December 2000–30 April 2001	127.1	261.0	460.9	115.4
1 October 2014–31 March 2015	224.3	333.9	546.0	165.8

Table B-7. Ashburton Council rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	81.2	171.8	388.1	50.4
1 September 1988–31 March 1989	205.8	403.0	596.3	260.8
1 October 1997–31 March 1998	227.5	352.0	495.5	209.8
1 December 2000–30 April 2001	112.9	297.3	572.9	112.9
1 October 2014–31 March 2015	251.7	352.0	495.5	209.8

Table B-8. Hawkswood rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	126.5	214.6	472.0	74.9
1 September 1988–31 March 1989	330.0	518.2	901.0	269.0
1 October 1997–31 March 1998	244.0	437.6	692.1	229.3
1 December 2000–30 April 2001	153.5	361.9	710.2	153.5
1 October 2014–31 March 2015	233.6	437.6	692.1	229.3

Table B-9. Springburn rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	171.3	220.1	444.4	88.7
1 September 1988–31 March 1989	435.3	525.3	861.6	316.1
1 October 1997–31 March 1998	351.0	461.2	747.0	255.3
1 December 2000–30 April 2001	166.0	386.0	633.5	166.0
1 October 2014–31 March 2015	279.1	461.2	747.0	255.3

Table B-10. McQueens Valley rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	67.3	142.7	270.2	67.2
1 September 1988–31 March 1989	183.3	367.7	546.0	216.5
1 October 1997–31 March 1998	180.5	316.4	497.7	180.5
1 December 2000–30 April 2001	131.2	269.7	566.0	125.3
1 October 2014–31 March 2015	260.2	316.4	497.7	180.5

Table B-11. Rakaia, Greenfields rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	148.6	201.7	338.7	93.5
1 September 1988–31 March 1989	361.1	497.8	725.6	350.5
1 October 1997–31 March 1998	291.0	436.2	614.5	291.0
1 December 2000–30 April 2001	199.2	356.7	625.2	199.2
1 October 2014–31 March 2015	312.4	436.2	614.5	291.0

Table B-12. Lyndhurst, Limewood Farm rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	128.5	178.4	368.3	61.3
1 September 1988–31 March 1989	312.5	430.4	701.0	241.8
1 October 1997–31 March 1998	276.2	374.8	564.7	211.1
1 December 2000–30 April 2001	134.8	315.0	547.5	134.8
1 October 2014–31 March 2015	211.1	374.8	564.7	211.1

Table B-13. Whalesback Station rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	120.4	272.2	498.3	128.2
1 September 1988–31 March 1989	383.3	695.3	1108.7	430.2
1 October 1997–31 March 1998	330.9	595.2	929.1	330.9
1 December 2000–30 April 2001	205.6	468.0	784.5	205.6
1 October 2014–31 March 2015	387.2	595.2	929.1	330.9

Table B-14. Little Akaloa, Brockworth rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	74.2	135.6	344.9	45.2
1 September 1988–31 March 1989	180.2	344.7	538.9	167.1
1 October 1997–31 March 1998	150.1	294.2	497.5	150.1
1 December 2000–30 April 2001	111.1	253.9	625.6	111.1
1 October 2014–31 March 2015	193.9	294.2	497.5	150.1

Table B-15. Waipara, Wattle Grove rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	59.0	134.8	311.9	46.3
1 September 1988–31 March 1989	296.6	331.0	497.5	188.0
1 October 1997–31 March 1998	161.2	289.3	464.1	153.3
1 December 2000–30 April 2001	87.2	242.5	458.9	87.2
1 October 2014–31 March 2015	162.0	289.3	464.1	163.3

Table B-16. Keinton Combe rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	92.6	208.7	395.6	81.8
1 September 1988–31 March 1989	250.8	499.2	836.1	296.5
1 October 1997–31 March 1998	241.8	433.3	687.2	241.8
1 December 2000–30 April 2001	148.6	350.0	531.0	148.6
1 October 2014–31 March 2015	258.5	433.3	687.2	241.8

Table B-17. Lake Tekapo, Air Safaris rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	114.1	122.4	332.4	51.8
1 September 1988–31 March 1989	330.3	318.4	564.2	190.5
1 October 1997–31 March 1998	226.6	268.5	526.2	162.4
1 December 2000–30 April 2001	107.6	221.7	451.3	107.6
1 October 2014–31 March 2015	173.6	268.5	526.2	162.4

Table B-18. Orari Estate rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	146.2	171.3	376.3	77.7
1 September 1988–31 March 1989	290.5	395.3	666.8	227.7
1 October 1997–31 March 1998	272.8	350.4	548.7	194.7
1 December 2000–30 April 2001	116.4	295.7	623.0	116.4
1 October 2014–31 March 2015	194.7	350.4	548.7	194.7

Table B-19. Lake Pukaki, Braemar rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	164.6	176.6	434.1	71.5
1 September 1988–31 March 1989	443.4	497.1	814.0	297.9
1 October 1997–31 March 1998	398.7	412.8	660.4	237.7
1 December 2000–30 April 2001	172.7	330.9	574.3	156.4
1 October 2014–31 March 2015	-	412.8	660.4	237.7

Table B-20. Kakahu Bush rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	164.4	190.3	428.9	77.5
1 September 1988–31 March 1989	369.0	448.0	795.1	209.9
1 October 1997–31 March 1998	283.9	396.1	662.6	184.9
1 December 2000–30 April 2001	178.4	333.4	708.5	178.4
1 October 2014–31 March 2015	184.9	396.1	662.6	184.9

Table B-21. Lake Ohau Station rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	236.0	242.1	488.6	223.0
1 September 1988–31 March 1989	918.8	649.9	881.3	635.1
1 October 1997–31 March 1998	619.2	545.4	835.7	538.9
1 December 2000–30 April 2001	336.5	434.0	671.0	392.4
1 October 2014–31 March 2015	446.0	545.4	835.7	538.9

Table B-22. Ferniehurst rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	120.0	215.3	454.5	64.0
1 September 1988–31 March 1989	312.5	538.9	909.5	273.5
1 October 1997–31 March 1998	211.5	452.8	712.0	211.5
1 December 2000–30 April 2001	164.0	373.3	678.5	153.0
1 October 2014–31 March 2015	253.9	452.8	712.0	211.5

Table B-23. Hapuku, Grange Hill rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	251.1	330.1	527.3	150.4
1 September 1988–31 March 1989	557.6	753.8	1139.2	440.8
1 October 1997–31 March 1998	436.4	660.4	1007.1	383.3
1 December 2000–30 April 2001	249.6	551.5	1024.7	249.6
1 October 2014–31 March 2015	455.3	660.4	1007.1	383.3

Table B-24. Christchurch Gardens rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	75.2	128.9	299.6	52.2
1 September 1988–31 March 1989	157.0	317.6	470.8	169.2
1 October 1997–31 March 1998	158.5	273.5	421.2	158.5
1 December 2000–30 April 2001	92.1	239.2	546.5	92.1
1 October 2014–31 March 2015	191.1	273.5	421.2	158.5

Table B-25. Magnet Bay rainfall statistics

Period	Rainfall (mm)			
		Climatology		
	Period	Mean	Maximum	Minimum
1 January 1983–1 March 1983	98.7	142.5	301.3	65.9
1 September 1988–31 March 1989	204.4	345.0	490.7	213.1
1 October 1997–31 March 1998	173.3	296.2	451.4	186.6
1 December 2000–30 April 2001	120.6	263.3	483.7	120.6
1 October 2014–31 March 2015	186.6	296.2	451.4	186.6

Appendix C – Spearman's Rank Correlations

The Spearman's rank correlations for the other three periods analysed are shown in the figures below (see also Figure 6-2).

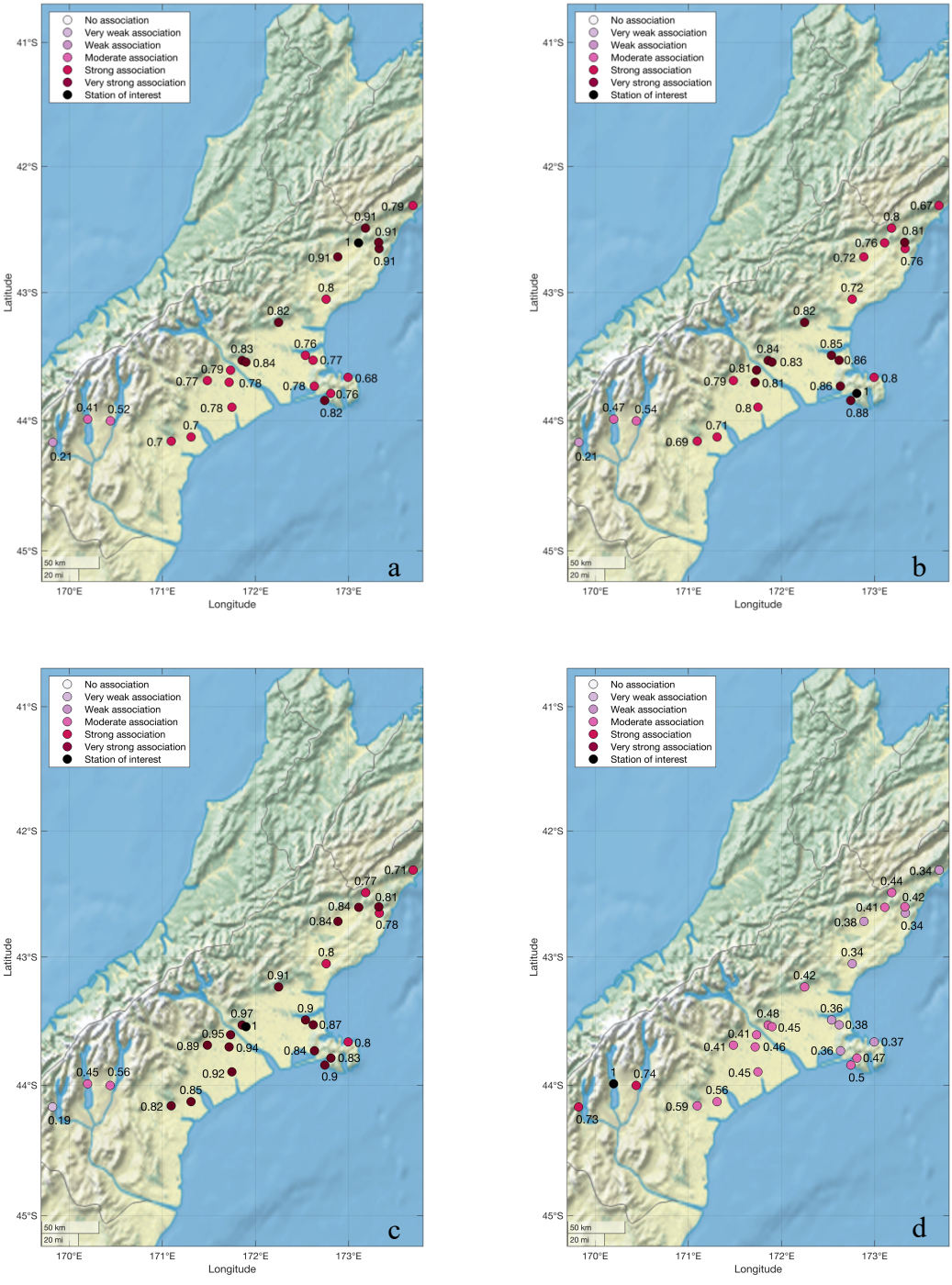

Figure C-6. Spearman's rank correlation of rainfall between 1 January–31 March for the years 1950–2022 relative to (a) Keinton Combe, (b) Okuti, (c) Hororata, (d) Lake Pukaki. The station of interest is marked 1. Generally the closer to the station of interest, the higher the correlation between rainfall experiences.

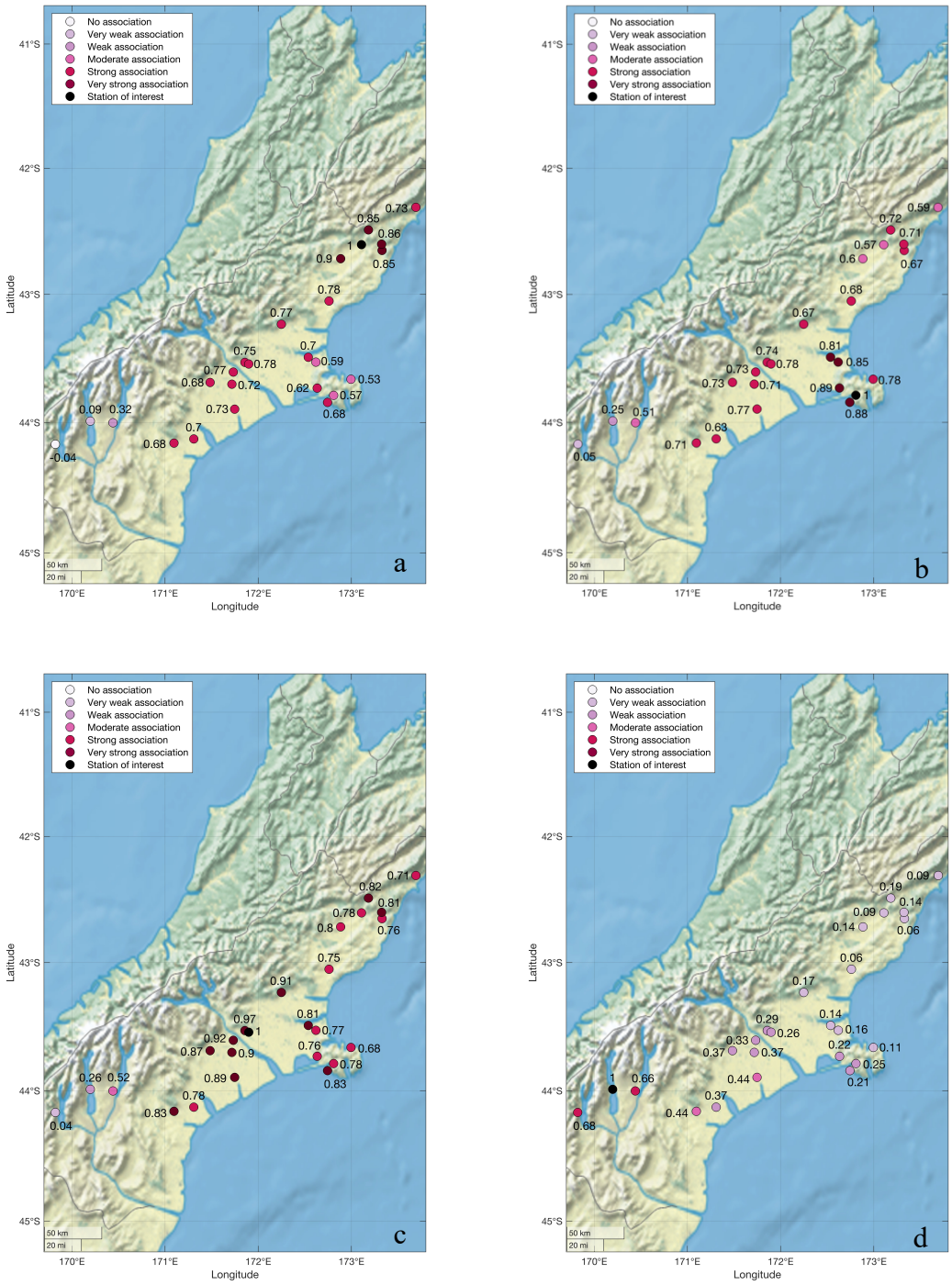

Figure C-7. Spearman's rank correlation of rainfall between 1 September–31 March for the years 1950–2022 relative to (a) Keinton Combe, (b) Okuti, (c) Hororata, (d) Lake Pukaki. The station of interest is marked 1. Generally the closer to the station of interest, the higher the correlation between rainfall experiences.

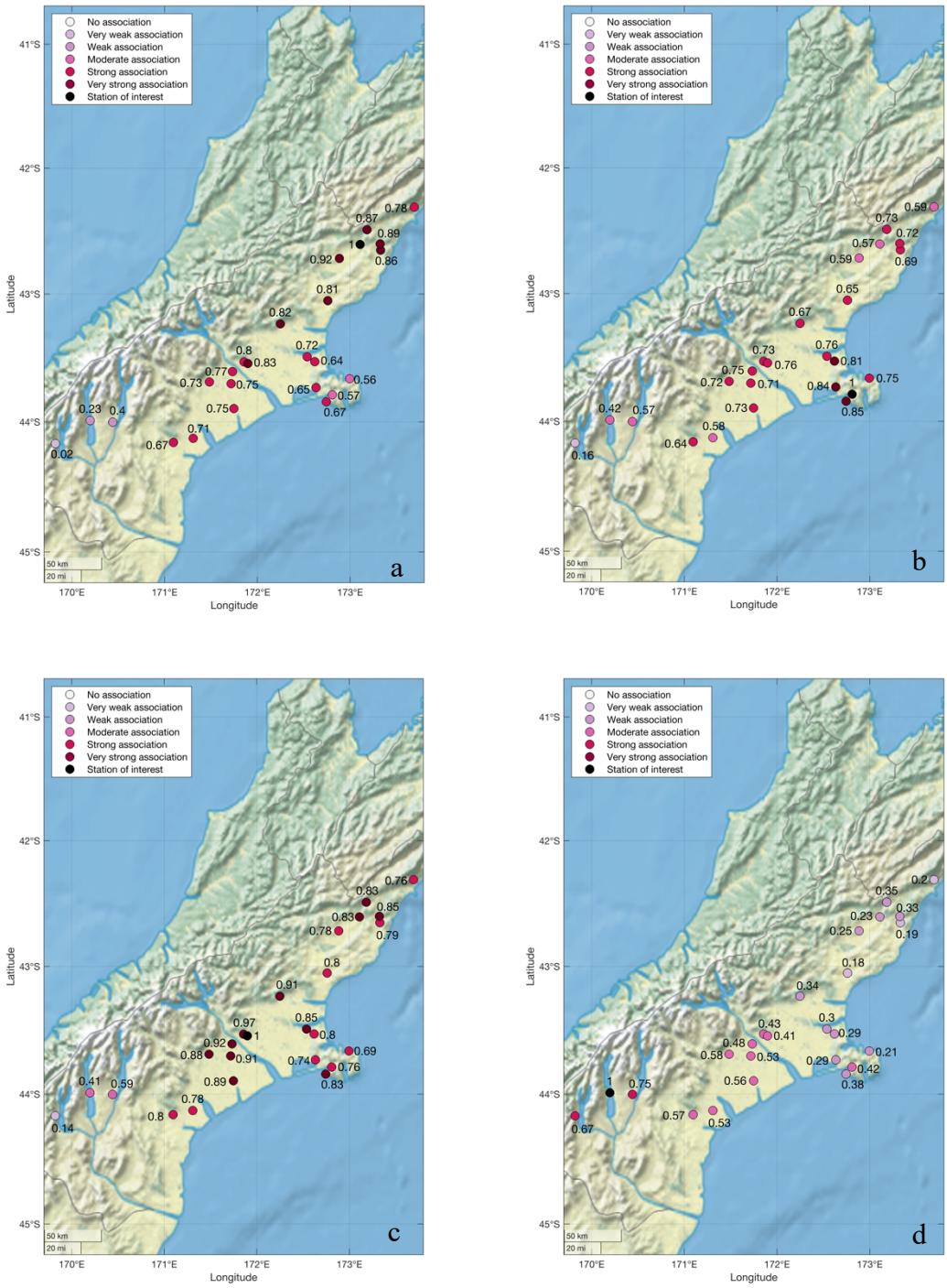

Figure C-8. Spearman's rank correlation of rainfall between 1 October–31 March for the years 1950–2022 relative to (a) Keinton Combe, (b) Okuti, (c) Hororata, (d) Lake Pukaki. The station of interest is marked 1. Generally the closer to the station of interest, the higher the correlation between rainfall experiences.

Appendix D – Rainfall statistics for Lincoln and Winchmore

The rainfall statistics for Lincoln and Winchmore are shown in the tables below.

Table D-1

Table D-26. Rainfall at Lincoln and Winchmore between 1 March–30 November for selected years. The mean climatology is between 1991–2020.

Location	Rainfall (mm)				
	Mean climatology	**1897/98**	**1988/89**	**1997/98**	**2000/01**
Lincoln	455.7	274.5	226.2	384.0	537.0
Winchmore	553.0	282.3	268.0	499.2	789.0

Table D-27. Rainfall at Lincoln and Winchmore between 1 December–31 May for selected years. The mean climatology is between 1991–2020.

Location	Rainfall (mm)				
	Mean climatology	**1897/98**	**1988/89**	**1997/98**	**2000/01**
Lincoln	279.1	171.3	227.5	167.1	141.4
Winchmore	366.3	169.3	361.7	266.6	162.0

Table D-28. Rainfall at Lincoln and Winchmore between 1 March (year 1)–31 May (year 2) for selected years. The mean climatology is between 1991–2020.

Location	Rainfall (mm)				
	Mean climatology	**1897/98**	**1988/89**	**1997/98**	**2000/01**
Lincoln	733.1	445.8	503.7	551.9	678.4
Winchmore	920.0	451.6	629.7	765.8	951.0