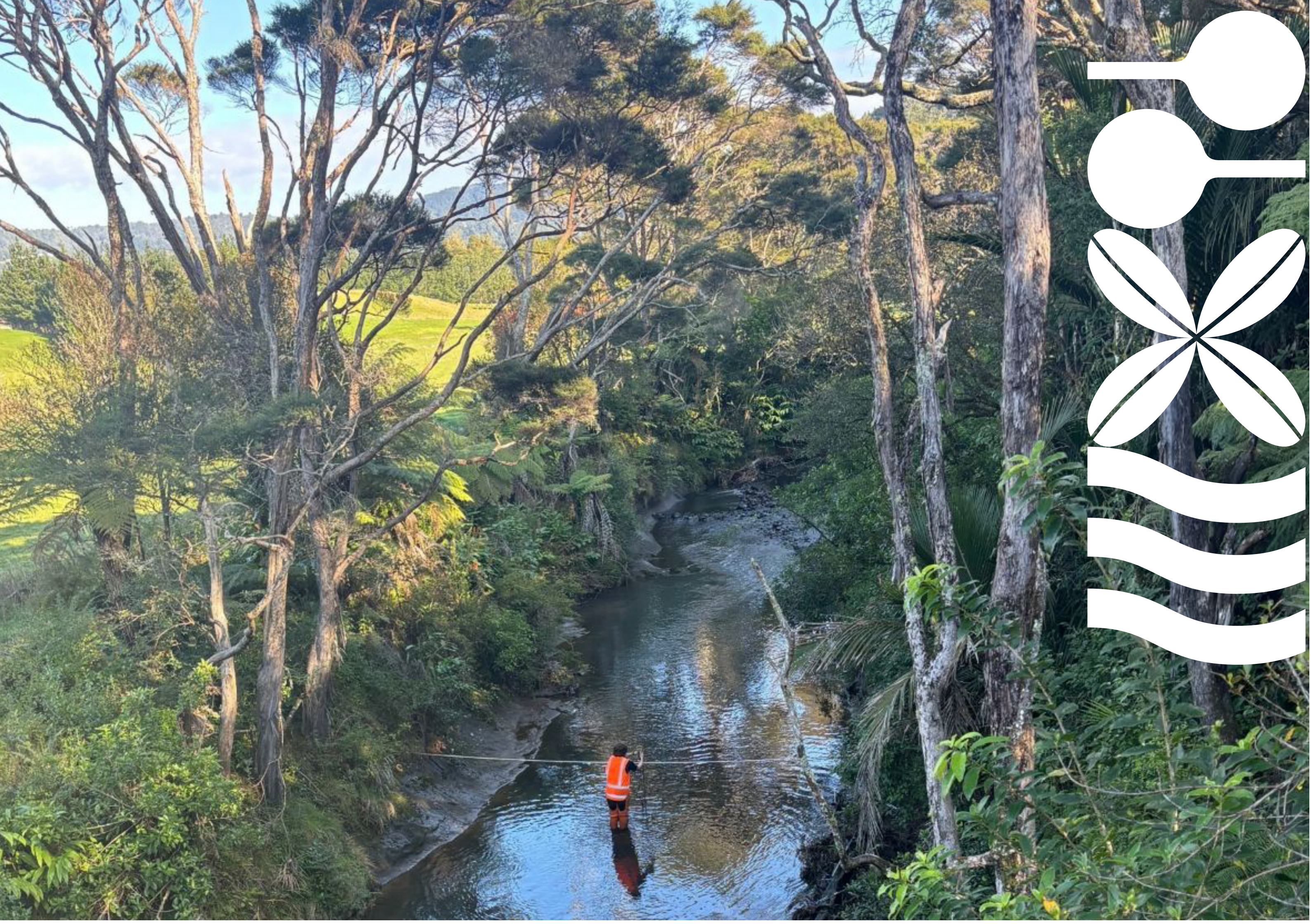

Hydrological State and Trends for Tāmaki Makaurau / Auckland 2025

State of the Environment Reporting

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September 2025

Technical Report 2025/27

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Cover and page 2 image: At Opanuku Stream in Henderson, Environmental Specialist Nick Oliver measures the total discharge across a section of river during routine fieldwork in winter. Photograph by Madison Ganicz-White.

List of abbreviations

Abbreviation	Definition
AEP	Annual Exceedance Probability
ALF	Annual low flow
BFI	Base Flow Index
CMIP5/6	Coupled Model Intercomparison Project (5/6 refer to iteration)
EEMU	Environmental Evaluation and Monitoring Unit
ENSO	El Nino-Southern Oscillation
FDC	Flow Duration Curve
FRE3	Frequency of eco-system disturbance (Frequency of flow events that exceed three times median flow)
IOD	Indian Ocean Dipole
MALF	Mean Annual Low Flow
$MALF_7$	Seven-day Mean Annual Low Flow
NIWA	National Institute of Water and Atmospheric Research LTD (now Earth Sciences New Zealand)
NPS-FM	National Policy Statement for Freshwater Management
NZDI	New Zealand Drought Index
$Q5_7$	The five-year seven-day low flow which has a 20% probability of occurring in any one year.
RBI	Richards-Baker Index
RIMU	Research Investigation and Monitoring Unit
RMA	Resource Management Act 1991
SMI	Soil Moisture Index
SOE	State of the Environment
SOE2025	State of the Environment 2025 report
WMO	World Meteorological Organization

Executive summary

For the State of the Environment 2025 (SOE2025) hydrology report, rainfall, soil moisture, river flow and groundwater level observations were analysed for the most recent five-year period ending in mid-2024 and further back in time to evaluate long-term trends.

Key findings for climate conditions:

- A significant and protracted La Niña episode unfolded during SOE2025 and it influenced Auckland's regional climate and weather conditions. Hydroclimatic observations over the SOE2025 period (mid- 2019 to mid-2024) shows the Auckland region experienced some of the most significant hydroclimatic variability and extreme events since instrumental observations began in the mid-1800s. Important short-term rainfall variability shown during SOE2025, with seasons that experienced 100s of millimetres more or less rainfall than normal, is strongly apparent for Auckland, and that variability exists on top of emerging long-term rainfall trends.
- There are subtle long-term rainfall trends, but many were not statistically significant using standard linear trend approaches employed for SOE2025 reporting. Rainfall observations at Whenuapai, where there is a long record, showed a reduction in autumn rainfall and lower overall hydrological year rainfall amounts since the mid-20th century. This drying trend is in line with regional atmospheric circulation changes, and climate change projections for Auckland that indicate an increasing frequency of dry days emerging during the 21st century.
- Short-term climate variability observed for SOE2025 resulted in lower overall rainfall in autumn for most years relative to the years in SOE2020 (2014-2019). Multiple dry summer seasons were observed in the north, west and central part of the region during SOE2025. The relatively dry autumns observed for SOE2025 are notable because if they become more frequent, then more significant overall drying will occur if climate change projections of drier spring conditions in the future also arise.

Key findings for rainfall observations:

- Exceptionally high rain amounts across multiple seasons led to an extraordinarily wet 2022-23 hydrological year that saw multiple sub-daily, daily, multiday, monthly, seasonal and annual rainfall records broken. The Auckland Anniversary 2023 storm event was a significant factor for setting new rainfall records. The influence of individual seasons (like autumn 2023) was important for determining overall short-term climate averages at some sites. Isolated significant long-term trends for increased winter and spring rainfall were identified along the southern margin of the Auckland region.
- Succession of rain events in some seasons and the absence of rainfall that led to drought in others also highlights the importance of observing rainfall continually over the long-term. Overall, the local and regional meteoric water balance for SOE2025 at many locations may have been much lower without several distinct, very strong and exceptional rainfall events that occurred in the past five years.
- The 2019-20 drought was the most severe that has occurred since instrumental observations began in the mid-1800s. There has been an increase in the number of dry spells for Auckland and evidence that dry conditions and drought are becoming more common in spring alongside rising temperatures for the region. These observations are consistent with new climate change projections that indicate an increase in the number of dry days during spring with reduced rainfall in that season, as well as an increased frequency, intensity and duration of drought for northern regions of New Zealand.

Key findings for soil moisture and river flow observations:

- During SOE2025 there was high variability of soil moisture and pronounced shifts in both high and low river flow metrics, with 80% of monitoring sites observing new peak instantaneous flows. The 1% flood Annual Exceedance Probability (AEP) was exceeded at all sites during SOE2025. The Auckland Anniversary 2023 storm caused over half of the observing sites to show more than a 10% increase in 1% Annual Exceedance Probability (AEP) for flood frequency values.
- 49% of observing sites experienced their lowest or equal lowest flow during SOE2025 and of those about 3 out of every 4 observing sites experienced their lowest flow or lowest equal flow during the 2019-20 hydrological year when the significant drought occurred.
- An increase in FRE3 (frequency of flow events greater than 3 times the median flow) was observed at six sites (mostly in urban catchments) while decreases in FRE3 were observed for six catchments in mostly rural or native forest settings. Significant linear trends were observed for the mean annual low flow at multiple sites, but some of the observed changes were very small. Otara showed a significant increase in the annual low flow level across all time periods both with and without 2022-23 data included.

Key findings for groundwater observations:

- Significant negative trends for groundwater levels at Maraeorahia and at Quintals suggest there could be connections to long-term climate changes as well as groundwater abstraction. A decreasing trend at Maraeorahia shows a trend toward fewer months of groundwater surplus through time during the main recharge season. Declining groundwater levels along with groundwater level variability that aligns with rainfall and soil moisture deficits highlights the vulnerability of groundwater resources to drought.

There will be repeated climate and hydrological impacts that continue to place pressures on our water-sensitive assets like stormwater systems, parks and public spaces and our water supplies. Maintaining and improving the current hydrology observation network to enhance understanding of both short- and long-term changes for the Auckland region will support the development of early warnings about extremes (like storms that can cause flooding) and climate events (like drought) that can help to minimise impacts and inform on water resource management strategies for agriculture and reticulated water supply schemes.

Recommendations for the development of future observations that can support and enhance SOE reporting:

- a more detailed view of soil type spatial variation, soil moisture changes at depth, and more coverage across the region including approaches that combine observations, modelling and remote sensing,
- additional groundwater aquifer monitoring bores that are distributed across recharge areas, central locations in the aquifers and near discharge areas or located down-gradient near aquifer boundaries,
- high-quality groundwater use and groundwater consents data, including water level and volume usage,
- additional statistical and trend detection approaches, and new composite and synthetic data series for robust analysis of hydrological and hydroclimatic change,
- ‘Sentinel hydrological monitoring sites’ where a full suite of observations (including lysimeters and additional soil moisture sensors) to inform on hydrological processes more completely.

Contents

1 Introduction

The landscape of Tāmaki Makaurau is characterised by thousands of kilometres of streams, many lakes, estuaries, and a multitude of beaches. Significant groundwater aquifers stretch laterally beneath the region and are highly connected to streams. The hydrological cycle is at work in every corner of the landscape and these waterscapes are intrinsic to our connection to the region. Auckland water bodies support a diverse array of plants and animals, provide for amenity and recreation, and are an important source for mahinga kai. Auckland water bodies are also sources of water for people, agriculture, and industry. Surface water and groundwater are vital sources for both municipal supply and agricultural water use, including livestock drinking, rural domestic supply, and irrigation of valuable crops. These competing values underscore the importance of long-term monitoring to detect changes in the hydrological water cycle across Auckland to inform evidence-based decision-making.

Long-term monitoring provides the data necessary to quantify the movement of water through the landscape and detect changes in hydrological metrics like river flow or groundwater level. Changes and trends in these metrics are often a direct result of weather and climate but can also be significantly altered by human activities like urbanisation and water abstraction. The purpose of this report is to analyse data from all stages of the hydrological cycle and investigate changes or trends, particularly for river flows and groundwater levels, which are the subject of water management policies. The interpretation of the results aims to increase our understanding of the long-term health and sustainability of Auckland's water resources.

1.1 National and regional directives

The National Policy Statement for Freshwater Management (NPS-FM, Ministry for the Environment 2024) sets requirements for regional councils to protect freshwater ecosystems. In addition, it provides direction for local decision-making under the Resource Management Act 1991 (RMA, Resource Management Act 1991). The NPS-FM requirements include sustainable management of freshwaters including discharges to water bodies, water allocation and land use. Section 35 of the RMA requires regional councils to report on the effectiveness of plans in achieving objectives set for resource management. A key component to evaluating the effectiveness of council management plans is to identify any relevant trends in hydrological observations that can help to determine whether the rules governing resource use are enabling these objectives to be achieved.

The Auckland Unitary Plan (Auckland Council 2016) specifies several objectives for the management of freshwater resources, including:

- Water in rivers and aquifers is available for use provided the natural values of water are maintained and established limits are not exceeded
- Water resources are managed within limits to meet current and future water needs for social, cultural, and economic purposes

- Freshwater resources available for use are managed and allocated in order of priority to provide for domestic and municipal water supplies, animals, and economic development
- Water resources are managed to maximise the efficient allocation and efficient use of available water.

Policies specific to streams:

- Minimum flows in rivers and streams are established to protect instream ecological values
- Flow variability is maintained in rivers, streams, and springs.

Policies specific to aquifers:

- Maintain baseflow to connected streams
- Avoid subsidence
- Avoid saltwater intrusion.

1.2 State of the environment report series

The hydrological observations that are collected, curated and analysed by Auckland Council and presented via the State of the Environment (SOE) reports (Auckland Council 2021) provide evidence and a retrospective view, respectively, that assists the evaluation of objectives, policies and rules that govern water resource management where water plays a major role in dictating the environmental values for Auckland. The authors of this report have worked collectively to analyse state and trend data for multiple hydrological variables over the same period for the most recent five years of observations (2019-2024), with additional historical observations brought to bear. Specifically, this report addresses the state and trends observed in rainfall, soil moisture, river flows, and groundwater levels to compare against past conditions and to aid the assessment of environmental outcomes against management objectives. As part of an ongoing State of the Environment programme, this report provides a comparison point for past and future reporting to track environmental change.

1.2.1 Supporting information

This report is one of a series of technical publications prepared in support of *Te oranga o te taiao o Tāmaki Makaurau – The health of Tāmaki Makaurau Auckland's Natural Environment in 2025: a synthesis of Auckland Council State of the Environment reporting*. It continues the approach established by the Environment Evaluation and Monitoring Unit (EEMU; formerly RIMU) for SOE2020 (Johnson 2021). The basis of long-term trend and snapshot analyses aims to better identify links between disciplines and inform the overall State of the Environment five-yearly reporting in a more consistent manner.

All related reports (past and present) are available on Auckland Council's Knowledge Auckland website: www.knowledgeauckland.org.nz. Time series and data used in this report are available through the Environment Auckland Data Portal for download at https://evironmentauckland.org.nz. Here you can also view live rainfall data and use several data explorer tools. Specific data requests, further enquiries, and requests for summary analysis outputs from this report (Excel format) can be directed to environmentaldata@aucklandcouncil.govt.nz.

1.3 Importance of hydrological monitoring

The objectives, policies, and rules that govern water management in the Auckland region address a wide range of stakeholders, environments and values. The overarching governance that is provided for decision-making requires an evidence base, and therefore an understanding of the water cycle for Auckland and the water systems for our region. By extension, the hydrological monitoring network that is maintained by Auckland Council provides critical observations about key parts of the water cycle that inform on managing water resources, water quality, infrastructure and asset planning, urban development, resilience to extreme events (like droughts and floods), and adaptation to climate change. Below, we describe the main hydrological variables that are observed within the Auckland Council region and briefly touch on some of the applications of the observational datasets that are generated from that monitoring. We provide overviews of rainfall, soil moisture, rivers and streams, and aquifers and groundwater which comprise the major classes of hydrological observations that have been analysed for SOE2025.

1.3.1 Rainfall

Rainfall is the main form of precipitation that occurs outside of polar and alpine regions on Earth, and it is a major constituent of the global water cycle. Rainfall is one of the most important delivery mechanisms of freshwater for the planet (Barua et al. 2013). Therefore, the relative amount of rainfall that is received at a location each year as well as the seasonality of rainfall occurrence helps dictate the suitability of a particular environment for life, civilisation and different activities. There are important rainfall gradients that exist for Aotearoa New Zealand due to topography and how land intercepts prevailing regional atmospheric flow (Kidson 2000; Rampal, Lorrey, and Fauchereau 2022; Renwick 2011). The narrow isthmus of Auckland and oceans surrounding it means the region has a subtropical maritime climate (Chappell 2013). Auckland is open to the delivery of rainfall from most directions, and it is subjected to rainfall impacts from weather systems of tropical, mid-latitude and polar origins (Griffiths 2007; Jiang, Griffiths, and Lorrey 2013; Lorrey et al. 2014; Prince et al. 2021; Reid et al. 2021). As the primary input to the water cycle, rainfall exerts a strong influence on all the other hydroclimate variables that are regularly monitored by Auckland Council. Notably, rainfall is crucial to for the municipal water resources of Auckland, which rely on reticulated storage dams located in the Waitakere Ranges and Hunua Ranges (Auckland Council 2022).

1.3.2 Soil moisture

Soil moisture refers to the amount of water that is present in the soil and it plays a fundamental role in the water cycle that links hydrological, biological, and biochemical processes (Mondal and Mishra 2024). The soil moisture observation network across Auckland has use for understanding weather and climate impacts on water-sensitive environments and assets (like wetlands and parks), infrastructure, agribusiness activities (livestock management, irrigation, effluent application, crop renewal and harvesting) and recreation. Soil moisture observations are also used to analyse long-term climatic trends, for civil water supply management (including predictions for water allocation and advice on efficient water use ahead of and during drought (Dobriyal et al. 2012)), and to evaluate soil conditions that lead to shrinking and swelling of soil that induce hazards like slope creep, instabilities and landslides (Cook et al. 2023). Soil moisture data has also become increasingly valuable for understanding the state of environmental saturation related to floods (Furtak and Wolińska 2023). There is strong spatial heterogeneity for soils and land use across soil types that are found in Auckland (Hewitt, Balks, and Lowe 2021), and thus variable soil moisture patterns across the region.

1.3.3 Auckland rivers and streams

Auckland has a diverse range of streams that vary in size from small spring-fed streams in urban catchments to large rivers in rural areas (Snelder and Biggs 2002). Many Auckland streams have small catchments with flowing waters that only travel a short distance to the sea. The connection of rivers and streams to groundwater systems varies considerably from high-baseflow spring-fed streams in volcanic geology, to low-baseflow streams in allochthonous marine-derived sediments (Edbrooke, 2001). Urban streams tend to exhibit 'flashy' characteristics due to a high proportion of impervious cover that contributes to high stormwater runoff. Spring-fed streams sourced from volcanic aquifers tend to be very stable throughout the year due to consistently high groundwater baseflow. Other streams show variations in flow patterns that range between these extremes, which are governed by topography, land use, geology, and other related factors (Carlier et al. 2018). Well-functioning rivers and streams with balanced flows can absorb and slowly release water, which reduces flood risks to homes, roads and infrastructure. As such, observations of flows over time underpins our ability to contend with hydroclimatic extremes, including floods and droughts, and the impacts of those events on the built environment.

Abstraction (water removal) from streams for a variety of uses can result in an instantaneous reduction in downstream flow. This type of consented activity is important to consider because aquatic plant and animal communities rely on a variety of flows occurring during different times of the year (Strayer and Findlay 2010). Changes in flow have impacts on depths and velocities in a stream, which in turn have effects on instream biota that require specific physical habitat characteristics for continued survival (Jowett, Richardson, and Bonnett 2005). Flow reductions can diminish habitats for flow-demanding species, so maintaining natural flows are important for the management of stream values that protect stream ecology and maintain biodiversity, and which also help to build resilience against environmental challenges. As such, monitoring a range of flows – especially extreme flows – and relating physical water quality characteristics to them (including temperature and dissolved oxygen) helps to establish how flow regimes impact on instream biota. Urbanisation increases runoff and changes the quantity and the timing of flows during the year. Thus, understanding the characteristics of flows helps to ensure that ecosystems can also thrive during periods of extreme flows.

1.3.4 Auckland aquifers and groundwater

Groundwater is water that is held within the pores between grains of sand and rock or cracks in rocks underground below the water table. Connections between the pore spaces and cracks allow water to flow through the material. Aquifers are sediment or rock formations that are saturated with groundwater, and those that have many well-connected pores or cracks have more flow and are useful for transmitting an economic quantity of water (Fetter 2001). Auckland does not have many large rivers and the surface water limitations for abstraction relative to other New Zealand regions means groundwater is a valuable and important water resource (Kalbus. et al. 2017). In Auckland, groundwater is used for domestic water supply, stock drinking water, and irrigation and provides approximately 1.0% of the freshwater resource for the region (Watercare, 2010).

Groundwater extraction pumps water from 10s to 100s of metres below ground to the surface. Aquifer porosity, fracturing and recharge collectively influence how groundwater levels will react to this type of groundwater use activity (Freeze and Cherry 1979). Effects of groundwater extraction can be highly variable in terms of the magnitude, extent, and timing of impacts on an aquifer. There are often delayed impacts from groundwater takes than can range from hours to years, and which can be spread over large distances. Groundwater extraction can impact streams with a reduction in baseflow by reducing normal groundwater discharges into the streambed (Freeze and Cherry, 1979).

The limits that are currently placed on groundwater availability for specific aquifers are intended to ensure that baseflow to streams is maintained, for the same reasons mentioned above that have been articulated for rivers and streams (Auckland Unitary Plan). Groundwater level trends have application as a proxy for one part of the contribution to the baseflow of rivers and streams (e.g. decreases in groundwater levels could indicate a reduction in baseflow).

2 Overview of the Auckland Council hydrological monitoring network

Auckland Council operates a hydrological monitoring network that measures rainfall, soil moisture, lake level, river flow and groundwater levels throughout the region across a terrain with a variety of land uses, topography and differing degrees of urbanisation (Figure 2.1). There are 79 rain gauges that are used to observe rainfall amounts and intensities across the 4,894km^2 spatial extent of the region (including offshore islands). The rainfall sites have an average site observation history spanning 23 years, and 54 sites have rainfall data for more than 20 years. Of significance, rainfall monitoring has taken place at Albert Park as far back as 1852 (formerly on the site of the Albert Barracks by the Royal Engineers), making the ongoing rainfall observations in Auckland one of the longest environmental observation datasets in New Zealand (Anthony M. Fowler 2021).

Thirty-eight groundwater bores are spaced across 123 aquifer management areas and eight major geology types that underpin Auckland. Most groundwater level records began between 1977 and 1997, providing a long-term record for the region with an average observation length of 34 years. Soil moisture monitoring is undertaken at 10 sites with an average observational record length of nine years. Many of the groundwater level observations show evidence of human activity, including abstraction of groundwater and discharge of stormwater to groundwater aquifers. Soil moisture observations are spaced across a range of sites that include urbanised, semi-rural and rural areas.

River flows and river levels are monitored at 42 sites, and the longest flow record extends back to 1966. These sites offer a representative view of the 51 catchments and more than 16,500km of river length that are contained in the Auckland region covering approximately 30% of the mainland area. Two lakes are monitored for water level, with the oldest record extending back to 1984. A detailed view of the anthropogenic impacts on flows and lake levels is outside the scope of this SOE report.

Below, details about the hydrological monitoring stations for rainfall, soil moisture, river flows and groundwater observations for sites that were selected for use in SOE2025 are outlined (Figure 2.1; Table 2.1-Table 2.4). The location of these sites can be seen in Figure 2.1. The reasons why a selected subset of stations have been chosen are provided in the Data preparation and methods section. Therein, we describe the physical setting for standardised hydrological observations at Auckland Council hydrological monitoring sites including basic details about site setting, positioning of instrumentation (and guidelines related to how that is done), operation of instruments (including telemetry and data loggers) and redundancies. We then discuss the selection of observations, data treatments and show the background climatological information from which many other analyses are based (for rainfall and groundwater).

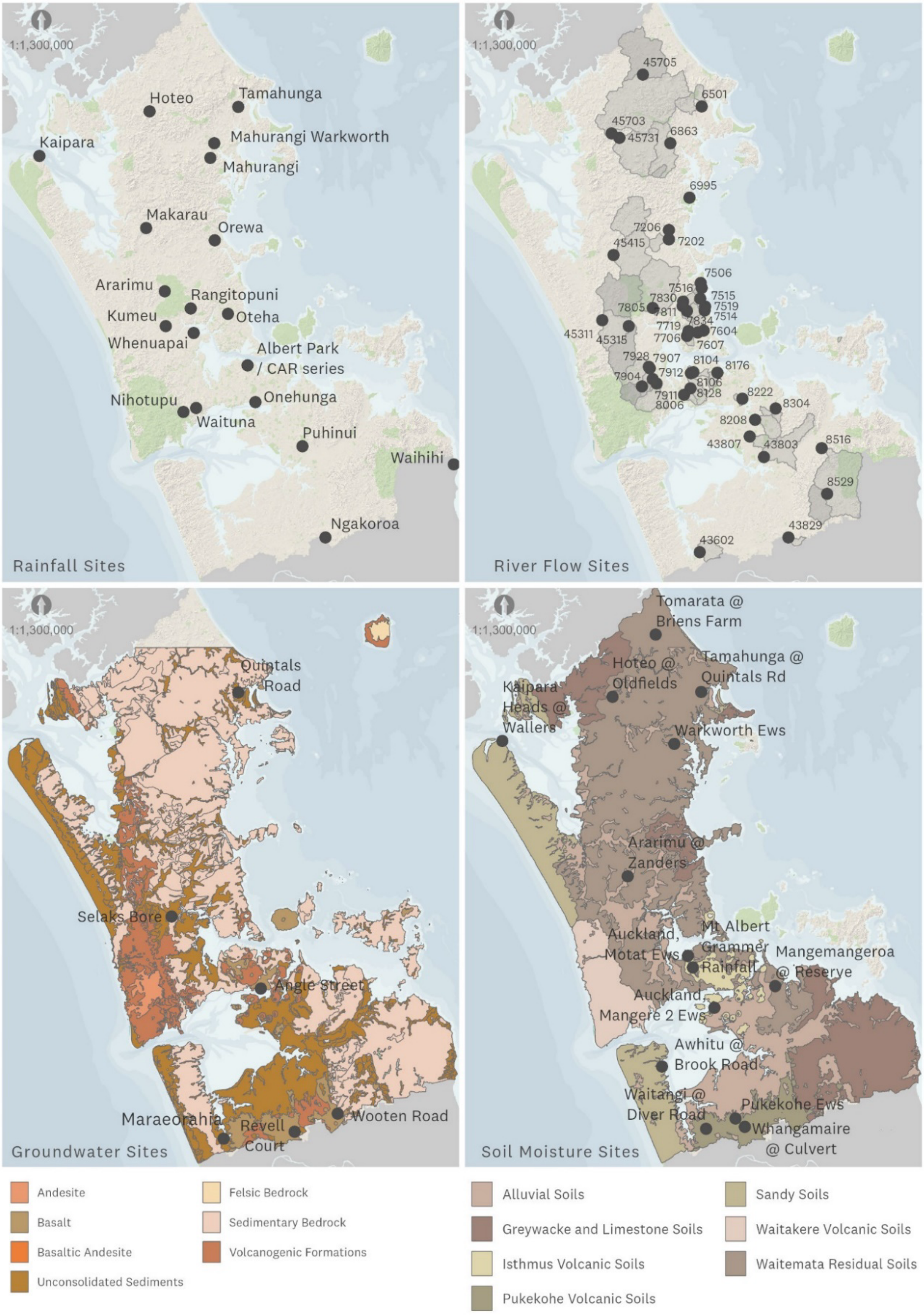


Figure 2.1 Locations of hydrometric observations from Auckland Council and other service providers for rainfall (upper left), river flow (upper right), groundwater borehole (lower left) and soil moisture (lower right). Catchment extent for river flow sites is shaded in grey. Groundwater monitoring sites show primary geological formation composition that has been simplified from GNS 1:250K mapping (Edbrooke, 2001), and Table 2.4 indicates how each site intercepts different parts of the composite aquifer delineation across the Auckland region. Soil moisture is simplified from SMAP courtesy of Manaaki Whenua (Landcare Research New Zealand Ltd 2011).

Table 2.1 Rainfall sites selected for State of the Environment 2025 report. The start of each series represents the first month of complete data used to make monthly climate statistics. A standard climatological normal period of 1991-2020 was adopted for SOE2025 rainfall analysis and the percentage complete climatology column indicates the completeness of monthly statistics for each series across that interval. Site elevations are rounded to the nearest metre and are relative to New Zealand Vertical Datum 2016 (NZVD2016). All series are current to the time of reporting except Onehunga (from Watercare Services Ltd.) which ends in March 2023. Mahurangi Warkworth is a Watercare site that is provided to Auckland Council via a data feed. There is variable quality of rainfall at these sites due to a range of factors, however only data completeness was considered for the climatological assessment that was undertaken in SOE2025.

Site	Location	Site number	Latitude	Longitude	Elevation (m asl)	Start of series	% complete	% complete climatology
Hoteo	Oldfields	643510	-36.3405	174.5106	60	1/06/1978	97	99
Tamahunga	Quintals Road	643713	-36.3278	174.7329	12	1/06/1977	93	94
Kaipara	Wallers	644211	-36.4332	174.2363	46	1/12/1971	76	73
Mahurangi	Satellite Dish	644616	-36.4321	174.6649	54	1/08/1982	98	98
Mahurangi Warkworth	Sewage Treatment Plt	644626	-36.4023	174.6742	3	1/08/1921	97	96
Orewa	Treatment Ponds	646619	-36.5984	174.6793	5	1/12/1979	96	98
Makarau	Folded Hills Farm	645519	-36.5760	174.5067	100	1/01/1968	90	68
Ararimu	Zanders	647510	-36.7036	174.5560	44	1/12/1978	98	98
Kumeu	Maddrens	647513	-36.7740	174.5606	22	1/08/1977	93	98
Whenuapai	Airbase	647601	-36.7870	174.6305	25	1/10/1945	94	99
Rangitopuni	Walkers	647614	-36.7371	174.6217	16	1/10/1978	99	99
Oteha	Rosedale Ponds	647727	-36.7476	174.7156	41	1/06/1984	93	94
Albert Park / CAR series	ACC rainfall enclosure	648719	-36.8503	174.7676	48	1/01/1853	100	100
Nihotupu	Arataki Visitors Centre	649514	-36.9466	174.6076	212	1/02/1975	85	79
Waituna	Huia Filter Station	649641	-36.9389	174.6405	105	1/01/1991	100	100
Puhinui	Botanical Gardens	740945	-37.0122	174.9099	64	1/04/1983	99	99
Ngakoroa	Donovans	742914	-37.1950	174.9732	145	1/11/1980	95	96
Waihihi	Waharau Regional Park	750213	-37.0415	175.2930	20	1/05/1983	93	93
Onehunga	Rowe St	649723	-36.9246	174.7894	5	1/11/1988	99	99

Table 2.2. Soil moisture sites selected for the SOE2025 State of the Environment report. Daily observations are used for the analysis of these time series, and their short length means they only qualify for a "snapshot" analysis to compare SOE2020 to SOE2025 conditions. Site elevations are rounded to the nearest 0.1 metre and are relative to New Zealand Vertical Datum 2016 (NZVD2016). At Mangemangeroa, two records from locations closely spaced have been spliced to create a composite site record, however this is only used in SOE2025 for examining the soil moisture response for rainfall during 2022-23. All other sites are complete to present.

Site	Location	Site number	Latitude	Longitude	Elevation (m asl)	Start of series	% complete
Ararimu	Zanders	647510	-36.7036	174.556	44.2	30/04/14	100
Awhitu	Brook Road	741611	-37.0882	174.6512	20.6	31/07/13	98
Hoteo	Oldfields	643510	-36.3405	174.5106	60.2	30/09/15	100
Kaipara Heads	Wallers	644211	-36.4332	174.2363	45.8	30/06/14	100
Mangemangeroa	Reserve	649941	-36.9208	174.9331	59.4	30/09/18	100
Mt Albert	Grammar School	648717	-36.8859	174.7248	39.9	30/09/15	99
Tamahunga	Quintals Road	643713	-36.3277	174.7329	11.9	30/04/14	100
Tomarata	Briens Farm	64068001	-36.2136	174.6164	66.4	30/06/14	100
Waitangi	Diver Road	742736	-37.2124	174.7656	51.4	31/07/13	100
Whangamaire	Culvert	741813	-37.1908	174.8396	65.6	28/02/14	100

Table 2.3. River flow sites used in the SOE2025 report. Catchment area refers to the region upstream of the gauging site and not the complete catchment boundary for each river. All sites are currently active. Waitangi is courtesy of NIWA.

Site	Location	Site number	Latitude	Longitude	Catchment area (km²)	Start	% complete
Alexandra	Rosedale Rd	7834	-36.7416	174.7067	2.48	14/12/1979	100%
Awaruku stream	Glenvar Rd	7516	-36.6945	174.7428	1.59	14/05/2004	100%
Eskdale Stream	Lauderdale Res	7706	-36.7917	174.7077	3.84	7/08/2005	95%
Hoteo River	Gubbs	45703	-36.3844	174.5099	270.1	4/08/1977	99%
Kaipara River	Waimauku	45311	-36.7632	174.4941	156.09	6/10/1978	99%
Kaipatiki Stream	Kaipatiki Rd	7719	-36.782	174.7109	1.37	7/12/2006	97%
Kaukapakapa	Taylors	45415	-36.6306	174.519	61.6	4/07/1994	85%
Kourawhero	Hudsons Ln	45731	-36.3935	174.53	73.43	19/11/2019	99%
Kumeu	Maddrens Weir	45315	-36.774	174.5603	45.8	1/12/1983	79%
Lucas	Gills Rd	7830	-36.723	174.6961	6.14	10/10/2006	100%
Mahurangi Argonaut	College	6863	-36.4028	174.6567	47.04	20/04/2009	99%
Mairangi Bay Stream	Tennis Club	7514	-36.74	174.7513	0.94	8/08/2003	96%
Mangawheau Stream	Weir	8529	-37.1056	175.0683	30.76	15/06/1988	96%
Mangemangeroa		8304	-36.9357	174.9341	4.76	13/07/2000	97%
Meola Creek	Motions Rd	8106	-36.8668	174.7187	7.83	2/04/1998	99%
Motions Stream	Western Springs	8104	-36.8648	174.7246	5.44	26/08/1994	99%
Newmarket Stream	Ayr St	8176	-36.8647	174.7856	6.47	9/05/2006	100%
Ngakoroa Stream	Mill Rd	43829	-37.1955	174.9735	4.67	28/03/1980	99%
Oakley Creek	Richardson Rd	8128	-36.8981	174.7189	8.13	29/05/2002	79%
Opanuku	Vintage Reserve	7912	-36.8801	174.6224	24.3	23/06/1999	100%
Opanuku Stream	Candia Rd Bridge	7904	-36.8952	174.5955	15.57	8/08/2006	93%
Oratia	Millbrook Rd	7911	-36.8892	174.6331	27.48	10/06/1999	100%
Orewa	Kowhai Av	7202	-36.5974	174.6579	9.58	20/06/1980	99%
Otara	Hills Rd Bridge	8208	-36.9585	174.8828	18.71	28/04/1992	99%
Oteha River	Days Bridge	7811	-36.732	174.6948	11.53	12/12/1979	98%
Papakura	Great South Rd	43803	-37.0334	174.9067	51.62	16/06/1969	93%
Paremuka Stream	Universal Dr	7928	-36.8589	174.6151	4.34	23/06/2008	98%
Puhinui	Drop Structure	43807	-36.9926	174.8701	11.31	5/12/1978	98%
Rangitopuni River	Walkers	7805	-36.737	174.6194	83.64	16/05/1975	98%
Swanson Stream	Woodside Reserve	7907	-36.856	174.6129	23.41	3/02/1994	100%
Taiaotea stream	Freyberg Pk	7515	-36.7165	174.7396	2.3	8/08/2003	96%
Taiorahi Stream	Westbourne Av	7519	-36.7315	174.7513	1.07	27/03/2006	93%
Tamahunga River	Quintals	6501	-36.327	174.7339	8	23/02/1978	98%
Tamaki Trib	Bowden Rd	8222	-36.9166	174.8504	2.93	14/04/2006	100%
Te Muri	Project Site	6995	-36.5123	174.7076	0.27	17/12/2013	99%
Vaughn Stream	Lower Weir	7506	-36.6844	174.7394	2.39	21/12/2000	90%
Wairau Creek	Chartwell Rd	7607	-36.7843	174.734	1.4	17/04/1980	64%
Wairau Creek	Motorway	7604	-36.7802	174.7489	11.14	16/03/1978	97%
Wairoa River	Tourist Rd	8516	-37.0133	175.0532	148.72	13/02/1979	99%
Waitangi	SH Bridge	43602	-37.2288	174.7494	17.93	30/03/1966	100%
Waiteitei River	Sandersons	45705	-36.265	174.5861	81.63	21/02/1996	99%
West Hoe	Halls	7206	-36.5787	174.6576	0.53	24/02/2003	100%
Whau Stream	Blockhouse Bay	8006	-36.9114	174.7023	4.82	8/09/2005	99%

Table 2.4. Groundwater sites that are used in the SOE2025 report. Standard climatological normal period of 1991-2020 was adopted for SOE2025 and therefore only six boreholes match these criteria with long term measurements with no obvious step changes due to aquifer management practices or significant data gaps out of the total number of bores across the region. Site elevations are rounded to the nearest metre and are relative to New Zealand Vertical Datum 2016 (NZVD2016). Casing diameter is 100mm for these sites, except Quintals Road (200mm) and Revell Court (150mm). See appendix A2 for additional information about bores not used. All sites are presently recording at 15-minute intervals. C = confined; UC = unconfined. M= Manual; A = Automatic.

Site	Location	Site Number	Latitude	Longitude	Aquifer	Total Depth / Casing depth (m)	Start of series	Confinement / Recording
Quintals Road	Omaha	6437005	-36.3284	174.7354	Omaha Waitematā	129.6 / 94	3/02/77	C / M
Selaks Bore	Kumeu	6475003	-36.7843	174.5774	Kumeu East Waitematā	299 / 101	12/02/86	C / M
Angle Street	Onehunga	6498003	-36.9273	174.8057	Mt Wellington volcanic	25 / 9.78	6/06/89	UC / A
Maraeorahia	Awhitu	7427005	-37.2323	174.7178	Awhitu Kaawa	62 / 51.5	5/01/87	C / A
Revell Court	Pukekohe Central	7429011	-37.2151	174.8976	Pukekohe central volcanic	54.6 / 10.4	14/08/79	UC / A
Wooten Road	Bombay	7510005	-37.1765	175.0057	Bombay volcanic	76.5 / 58.3	15/12/91	UC / M

3 Data preparation and methods

3.1 Rainfall

Rainfall observations are made within fenced enclosures of approximately 5m x 5m that are situated on open-aired relatively flat land that has experienced a long-term consistent use and that is largely clear of obstructions (trees, buildings, etc.). The ground surface inside a rainfall observation enclosure is typically weed matted and barked to reduce vegetation growth, and this (along with other positioning factors) helps to limit rain splashback that could compromise the measurement of event-based and total rainfall amounts over longer timescales (i.e. aggregated monthly rainfall). Two rain gauges (bucket-like receptacles) are used to measure rainfall simultaneously. One gauge is a tipping bucket that registers the time when 0.5mm of rainfall occurs. The other is an Octapent volumetric reference gauge that is used to verify total rainfall amounts established using the tipping bucket.

The verification of total rainfall received occurs when there are regularly scheduled site visits (typically every two to three months). The tipping bucket allows an evaluation of rain intensity and establishes the precise timing of precipitation, which can be linked to the occurrence of specific storms. Each tip of 0.5mm is recorded and uploaded via a battery/solar powered data logger and transferred via telemetry to a data telemetry system – HydroTel. This system ingests the rainfall observation in near real-time performing any operations that are required of the data, including sending alerts for threshold exceedances and distributing the data to public and internal data portals, data users, and to the data management system – Hydstra. The Hydstra data management system allows for storage of metadata, documentation, data processing, quality control, data analysis and is the long-term data archive of hydrometric data. At Auckland Council, Hydstra is maintained by the Hydrology and Environmental Data team. The arrangement of the rain gauges within the enclosure and their vertical position follows best-practice approaches set out in World Meteorological Organization (WMO), NIWA and National Environmental Monitoring Standards guidelines(Judd and Hyde 2025).

For the current State of the Environment reporting period (referred to in this report as SOE2025) we have focused on hydroclimatic observations that capture climate variability, climate extremes and trends. This report uses a selected subset of Auckland Council rainfall monitoring sites (Figure 2.1) that had sufficient data to calculate a *standard climatological normal*, which is the best-practice approach recommended by WMO for calculating climate statistics (Table 2.1). A standard climatological normal uses a fixed 30-year period to indicate average climate conditions at a site. All selected rainfall observing sites were pre-screened to ensure at least 80% temporal coverage over the period1991-2020 following WMO recommended guidelines (Devasthale et al. 2023), with three additional stations (Kaipara, Makarau and Nihotupu) also that had at least 2/3rd coverage for the current standard climatological normal period to define contemporary climate conditions (Table 2.1). The inclusion of those three stations improved spatial coverage for SOE2025 analysis. This approach also allows for historical trends, percentages relative to a common normal period, deviations from normal conditions and relative changes across shorter time spans (e.g. 5-year windows) can be evaluated for a collection of sites that have different mean annual and mean seasonal rainfall totals.

The annual year (January – December), hydrological year (July – June), seasonal (June-August, winter; September-November, spring; December-February, summer; March-May, Autumn), and monthly rainfall statistics were generated relative to the 1991-2020 standard climatological normal base period. Rainfall total amount statistics are an essential climate variable that rely on having complete data, so any annual year, hydrological year or season that had missing monthly total rainfall amounts were not included in statistics calculated for the SOE2025 report. At a finer time scale, and preceding the calculation of annual, hydrological year and seasonal rainfall totals, any month that had fewer than 21 days of daily rainfall observations were also excluded per standard practice by the WMO that has been adopted by NIWA. Pre-screening based on data availability meant out of the 42 rainfall observation sites currently operated by Auckland Council, 19 were selected and used for this SOE analysis. The Albert Park station that is included in the SOE2025 dataset has been independently evaluated and it forms the modern end of an extended concatenated rainfall reconstruction time series termed the "Central Auckland Rainfall series" (A.M. Fowler 2021). Here, we use the Central Auckland Rainfall series for SOE2025 analyses.

Rainfall for all sites monitored in the Auckland Council region show seasonality, with more rain observed during the winter months and less during late spring and summer (See Figure 3.1 for details described below). The month with the highest average rainfall for the region is typically July (between 125-215mm for all sites) and the lowest rainfall usually occurs during January (55-100mm for all sites). Rainfall observations for monitoring sites located in northwest Auckland within the Waitakere ranges (like Nihotupu and Waituna) show higher average rainfall totals, while lower annual and seasonal totals occur for central, northern and southeastern sites (e.g. Albert Park, Kaipara Heads, Puhinui). See Table 3.1 for climatological details about rainfall at individual sites.

The rainfall amounts for SOE2020 (the previous State of the Environment reporting period inclusive of observations for hydrological years 2014-15 to 2018-19) and SOE2025 (inclusive of observations for hydrological years 2019-20 to 2023-24) reporting intervals were indexed and separated into quintiles (5 categories; with q1 representing the lowest rainfall and q5 representing the highest rainfall). This was done to determine how each season, hydrological year or annual rainfall total at a site for the past 10 years encompassing the current and last SOE reporting cycle compared to the long-term climatological normal. Rainfall index values were achieved by creating z-scores for seasonal and annual rainfall totals via subtracting the 30-year climatological mean from a seasonal, annual or hydrological year value and then dividing that result by the standard deviation based on the 30-year climatological period. This method allowed the relative rainfall anomalies for sites with different means and variances for rainfall to be compared within and outside the climatological period and allowed an objective categorical determination of how each season or year rainfall rated across the Auckland region with respect to a common, fixed period (See Section 4.2.1 results and thereafter). In addition, rainfall index values allow the proportion of long-term rainfall monitoring sites to be grouped into objective quantitative categories relative to the 1991-2020 standard climatological normal period and this offers a way to calculate a mean rainfall index value using all available site data.

For the purposes of characterising five-year rainfall snapshots comparing conditions relevant to SOE2025 and SOE2020, statistics were calculated using annual (calendar year 1 January-31 December), hydrological year (1 July-30 June) and seasonal (autumn, 1 March – 31 May; winter, 1 June-31 August; spring, 1 September – 30 November; summer, 1 December-28 February of the following year) rainfall totals. The data cut off for the rainfall analyses for SOE2025 was mid-2024, meaning the last complete hydrological year included in SOE2025 is the 2023-24 hydrological year (1 July 2023 to30 June 2024), and the last complete annual year is 2023. The 5-year comparison time slices focused on seasonal data were aligned with the end of the last full calendar year that was included in SOE2025. Thus, the last season included for the canonical season analysis is summer 2023-24, which includes December 2023-February 2024 observations.

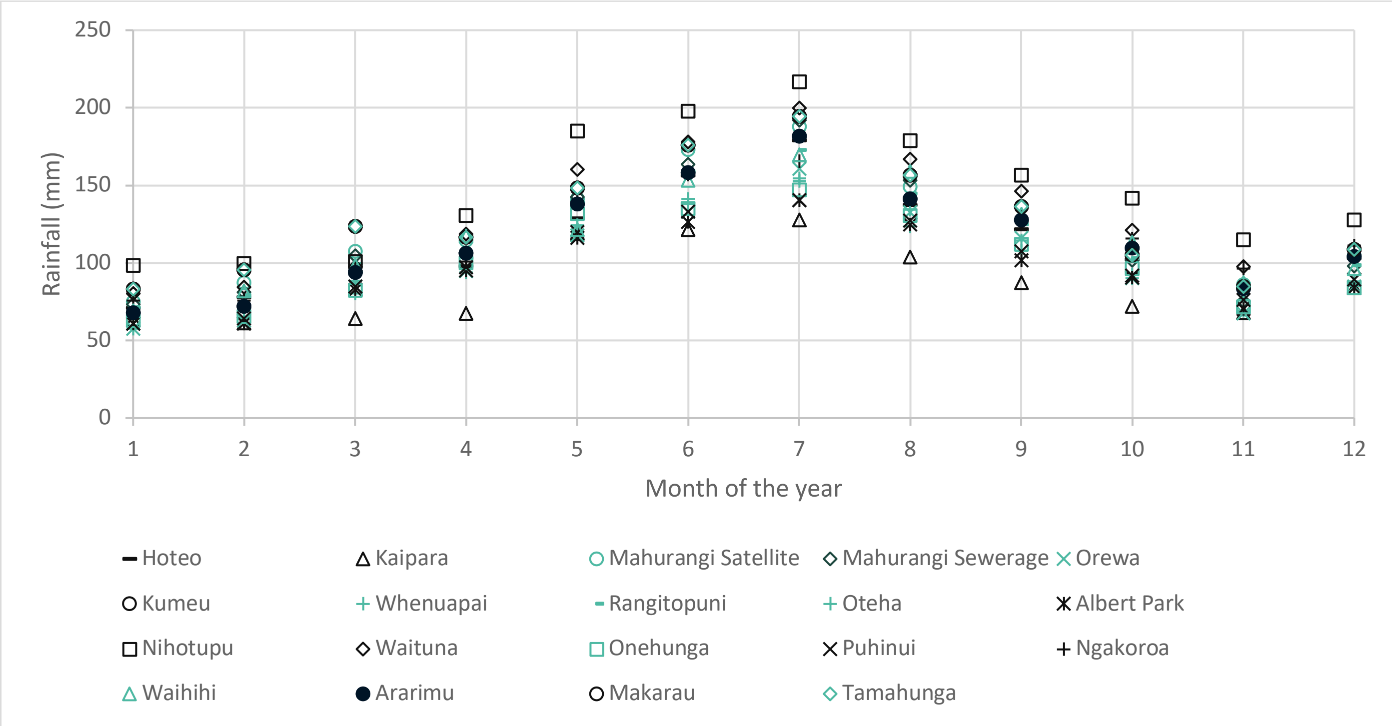


Figure 3.1 Climatological distribution of rainfall through the year for selected rainfall sites based on the 1991-2020 standard climatological normal period. Mean values are shown for all months (January = 1; December = 12). Additional details about the spread for each month are shown in Appendix 1.

Table 3.1. Annual, hydrological year and seasonal rainfall averages for selected Auckland Council stations based on the standard climatological normal interval 1991-2020. All rainfall values are in millimetres.

Site name	Annual	Hydro year	Autumn	Winter	Spring	Summer
Hoteo	1349.5	1349.0	320.8	470.3	307.2	250.5
Tamahanga	1550.1	1531.0	390.6	508.0	328.4	292.1
Kaipara Heads	1046.3	1038.7	253.0	353.3	227.6	206.5
Mahurangi @ Satellite	1474.3	1469.3	363.3	510.4	327.9	269.6
Mahurangi @ Warkworth Sewage	1417.3	1414.4	353.7	511.6	311.0	257.7
Makarau	1289.0	1282.4	319.6	444.4	280.2	240.5
Orewa	1192.6	1179.1	294.6	430.1	273.1	208.4
Ararimu	1388.5	1385.0	339.8	481.4	321.3	248.2
Kumeu	1314.6	1310.7	322.6	473.3	296.2	226.9
Whenuapai	1213.4	1210.1	300.6	428.8	277.8	204.9
Rangitopuni	1389.5	1383.7	343.0	479.0	314.1	248.8
Oteha	1210.6	1206.7	312.0	409.6	269.8	217.4
Albert Park	1158.0	1196.6	293.9	392.2	261.2	206.8
Nihotupu	1757.7	1741.2	415.4	593.6	413.5	323.2
Waituna	1560.5	1554.2	376.6	545.0	365.1	272.3
Onehunga	1214.3	1207.5	314.9	412.0	280.5	212.8
Puhinui	1175.7	1180.2	300.7	401.2	275.5	215.5
Ngakoroa	1403.4	1403.5	337.5	464.3	339.9	266.5
Waihihi	1440.8	1419.6	334.4	482.2	332.3	253.0

All the selected rainfall observation sites (Table 2.1) that were used for the standard climatological normal analysis also permitted an assessment of the significance of long-term rainfall trends. All these sites were evaluated for significant rainfall amount trends for the annual year, hydrological year and canonical seasons. Mann-Kendall significance tests were conducted on all the selected time series, which is sensitive to the number of observations (overall length of time series), and significance was evaluated at the 90^{th}, 95^{th} and 99^{th} confidence intervals. Only the results where a significant trend was found for a site is reported.

Event-based statistics for the 2022-23 summer deluge case study has a focus on sub-daily rainfall amounts that occurred during the Auckland Anniversary 2023 flood event across 27-28 January 2023. These observations were extracted from Hydstra using the subset of rainfall observing stations employed in the climatological analysis of rainfall. Statistics on 1-, 2-, 6-, and 12-hourly rainfall totals are based on 0.5mm intensity observations encapsulating the maximum amount of rainfall in those two days. For comparison, other significant multi-day rainfall episodes within the SOE2025 reporting period are brought to bear. Additional observations were also used from NIWA within spatially interpolated maps for the 2022-23 summer and for selected multi-day periods of high rainfall within SOE2025.

3.2 Soil moisture

Soil moisture monitoring commenced the Auckland region around 1999 with four sites in Warkworth, Kumeu, central Auckland and Pukekohe (Chibnall and Curran-Cournane 2018) . Although the monitoring equipment at these sites were operated in accordance with manufacturing guidelines, they were considered uncalibrated by NEMS. The Auckland Council soil moisture network was subsequently re-established and expanded in the mid-2010s. Detailed information on the sites is provided in *Soil Moisture Monitoring in the Auckland Region – Programme Establishment* (Chibnall & Curran-Cournane, 2018). Soil moisture observations at these sites are obtained via AQUAFLEX sensors that express soil moisture as a percentage of soil volume. The sensor is a long flexible ribbon, approximately 3m in length that is buried between 10 to 35cm beneath the surface and within the root zone. In addition to soil moisture, soil temperature observations are also collected. The soil moisture monitoring network now has 10 sites across the Auckland region, with calibration of equipment ongoing. Figure 2.1 provides an overview of the spatial extent of the soil moisture monitoring and Table 2.2 provides a summary of the metadata for the soil moisture sites.

The SOE2025 presents an analysis of soil moisture that is much shorter in length than the other hydrological observations maintained by Auckland Council. The short-term average soil moisture conditions are presented in this section as a baseline reference, and soil moisture averages are made from all available monthly mean soil moisture percentage data for each site with at least 10 years of observations (see metadata in Table 2.2). For SOE2025, soil moisture observations from multiple sites that had been used to make a composite were also excluded. The remaining sites rely on soil moisture observations from 2014 to 2024 that were gathered at 15-minute intervals and then aggregated into averages for monthly and longer time periods. Due to operational reasons, not all the soil moisture monitoring sites have a complete record starting from 2014, and some sites that had significant temporal breaks and/or comprised composite observations were not used.

For the SOE2025 report, all the analysed sites had a soil moisture anomaly relative to average calculated for the months, seasons, canonical year and hydrological years contained in the five years within the SOE2025 reporting window. In addition, similar anomalies were calculated for the months, seasons and years with the five years in the SOE2020 period to show the relative short-term change in soil moisture (See Results section 4.3). Monthly and subseasonal soil moisture anomalies were also brought to bear as a context in case studies of extreme seasonal climate conditions that were analysed in this report. As such, soil moisture observations are expressed in different analyses and discussion sections as a percentage of normal relative to the short-term average value or as a soil moisture index value (SMI). The SMI calculation essentially produces a z-score (standard deviation unit) that is derived by subtracting the arithmetic mean that characterises a discrete observation period (i.e. daily, monthly, seasonal, etc) from the discrete observation that has the same temporal focus and then dividing that number by the standard deviation of the discrete observation period. An extended analysis of soil moisture trends is not undertaken due to the shortness of the observation period.

Based on the relatively short instrumental observation period for soil moisture observations across Auckland, the sites used in SOE2025 show little seasonality (Waitangi, Kaipara) to moderate seasonality (all other locations). Higher soil moisture percentages are observed during mid-to-late winter and early spring and low soil moisture percentages occur during summer and early autumn (Figure 3.2). Tomarata shows the strongest seasonality for soil moisture and Waitangi shows the least seasonality (Table 3.3). The month with the highest soil moisture percentage is typically July or August and the lowest is usually January or February (Table 3.2).

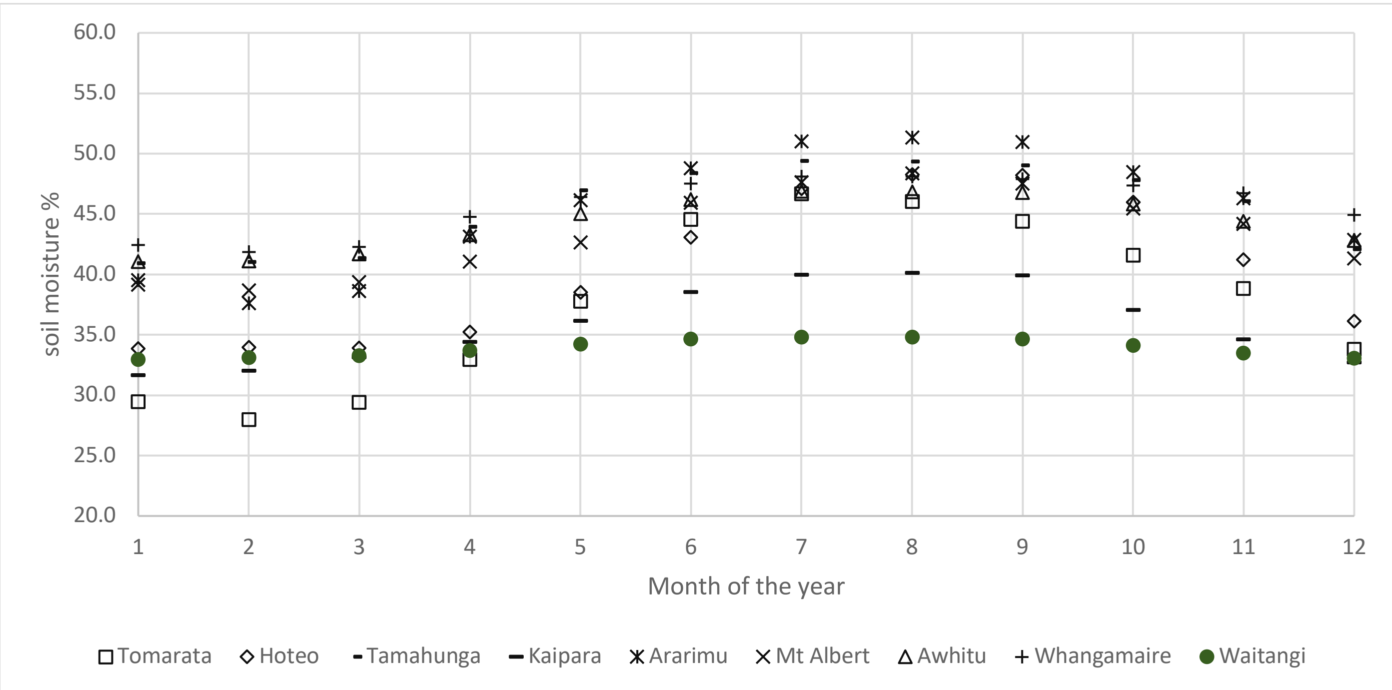


Figure 3.2 Climatic variation of average soil moisture conditions for Auckland Council observation sites used in SOE2025. This plot is based on a limited number of years since 2013 and includes all months from the time observations began at each site (see Table 2.2 for site details).

Table 3.2. Short-term average monthly soil moisture percentages for the sites analyses in SOE2025 (See Table 2.2 for details) using the full length of each record. The monthly observations were used to generate seasonal and annual averages and are brought to bear in describing extreme events later in this SOE report.

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tomarata	29.5	28.0	29.4	33.0	37.8	44.6	46.7	46.1	44.4	41.6	38.9	33.8
Hoteo	33.9	34.0	33.9	35.3	38.5	43.1	47.1	48.3	48.2	46.0	41.2	36.1
Tamahunga	40.9	41.0	41.3	43.9	47.0	48.4	49.4	49.3	49.0	47.8	46.1	42.1
Kaipara	31.7	32.0	33.1	34.4	36.2	38.6	40.0	40.1	39.9	37.0	34.6	32.7
Ararimu	39.6	37.7	38.6	43.2	46.2	48.8	51.0	51.3	51.0	48.5	46.3	42.9
Awhitu	41.1	41.2	41.7	43.3	45.0	46.2	46.9	46.9	46.8	45.9	44.4	42.8
Whangamaire	42.4	41.9	42.3	44.8	46.4	47.6	48.1	48.1	47.9	47.4	46.8	44.9
Waitangi	33.0	33.1	33.3	33.7	34.2	34.7	34.8	34.8	34.7	34.1	33.5	33.1

Table 3.3. Short-term average annual, hydrological year, and seasonal soil moisture percentages for the sites analyses in SOE2025. These values provide a baseline for comparing years within SOE2025, and SOE2025 to SOE2020 and are used in extreme events analysis described later in the report.

Site	Annual	Hydro year	Autumn	Winter	Spring	Summer
Tomarata	36	37	33	46	42	30
Hoteo	40	40	36	46	45	35
Tamahunga	45	45	44	49	48	41
Kaipara	36	36	35	40	37	32
Ararimu	45	45	42	50	49	40
Mt Albert	43	44	41	47	46	40
Awhitu	44	45	44	47	46	42
Whangamaire	45	46	44	48	47	43
Waitangi	34	34	34	35	34	33

3.3 Rivers

Auckland Council maintains continuous flow series for all river monitoring sites using continuous water level monitoring and periodic physical measurements of river discharge, called flow gaugings (Johnson, 2021a). Gaugings are a fundamental field-based component of calculating river flows that are established at fixed locations for long periods. They are important for understanding how the flow regime of a river varies through time and in response to rainfall. Primary observations that are used to quantify flow regimes are water velocity and water level. Current meters, acoustic doppler current profilers, weirs, and flumes are used to measure river velocity at each gauging station (Figure 2.1). Continuous water level observations are collected using various hydrological instruments including stilling wells, pressure sensors, radar, ultrasonic sensors and staff gauges (fixed graduated measuring scales surveyed relative to a known datum).

When velocity is simultaneously combined with a detailed cross-sectional area of a river based on stage (water level), an accurate estimate of flow (discharge) can be established. By measuring flows repeatedly across a range of conditions at a gauging station, a robust statistical relationship can be developed between the instantaneous water level of the river and the instantaneous flow. A long-term relationship between water level and discharge is established by plotting gauging against water level and fitting a curve to all the observations. This procedure is referred to as a rating, and the “rating curve” is used to convert continuous water level observations to a quantitative river flow. Continued monitoring of the river water level through time allows flow (and discharge) to also be calculated in real time with use of a rating curve as long as it has been kept up to date and that significant physical changes to the channel geometry have also not occurred. Higher river levels are associated with larger flows and discharge volumes while lower river levels are associated with low flows and discharge volumes. More detail on water level measurements, river flow ratings, and flow time series can be found in the National Environmental Standards for Water Level and Rating Curves (Watson, Doyle, and Horell 2025).

Raw river level observations are processed, quality coded, and archived in Auckland Council’s Hydstra database and managed by the Hydrology and Environmental Data team. Archived flows have a partially adopted NEMS quality code for many observations. Flow data for SOE2025 analyses rely on observations that have been screened to remove poor quality observations prior to time series analysis.

3.3.1. Site selection and data treatment

The river flow observations from 43 flow monitoring sites (Figure 2.1) were considered for the analysis to allow for a wide spatial view across the Auckland region (Table 3.4). Sites with less than seven years of data were excluded from frequency analysis, and closed sites were also excluded from this SOE2025 analysis. All observations were obtained from the Hydstra database maintained by the Hydrology and Environmental Data team in EEMU at Auckland Council. Daily mean flow, instantaneous maximum and instantaneous minimum values were used for the analyses, except the basic statistical data summaries which used the 10- minute flow data. Aggregation to monthly and annual averages was completed using the daily mean flows functions available in the R package xts (Ryan and Ulrich 2024). Daily mean flows were first screened to remove NAs and negative values, and zero values were checked against the presence of a QC code. All zero values with a NEMS QC code of 200 or 400 were removed from the datasets. All zero values were checked against a “cease to flow” level. Where the gauge level was below the cease to flow level, the zero-flow value was retained and for other occurrences the zero-flow value was converted to a NA and then removed from the series prior to analysis. For the Auckland region, the Orewa River is the only known stream that is monitored which occasionally ceases flow during the summer, but others like Vaughn Stream also have had multiple occurrences of cease flow conditions. Eight of the flow records used in SOE2025 analysis are in catchments that have permitted water abstraction activities. Several others are in urban areas that have experienced significant land use changes through time and the addition of impervious surfaces. None of the analyses below make any adjustments for these known activities through time but are discussed later in the context of observed changes.

To understand the patterns and correlations of river flows with rainfall and for the comparison of flows between catchment the analysis focused on the following time periods:

- From the start of each record to 30 June 2024,
- From 1 July 2014 to 30 June 2019 (SOE2020)
- From 1 July 2019 to 30 June 2024 (SOE2025)

Additional criteria were applied to the frequency analysis methods and return periods for sites with less than 10 years of observations were not undertaken (Griffiths et al., 2020).

River flow analyses produce descriptive statistics of flow regimes, flow frequency, flow duration and calculations of flow indices that support an understanding of river dynamics (transport) and river water quality. Hydrological flow analyses are categorised as:

- High flow frequency analysis,
- Low flow frequency analysis, and
- Environmental flow analysis

High flow frequency analysis, also known as flood frequency analysis, estimates the probability that a flow might exceeded a given value on the high end of the observation range. It is used to understand the likelihood of a flood of a given magnitude being exceeded, which supports flood risk management and hydraulic design (Poff and Zimmerman 2010). For Auckland, high flows are generally precipitation-related and are associated with increased magnitude rain events (Johnson 2021). Low flow frequency analysis establishes the probability that flows might be below a threshold on the low end of the observation range, which can be defined on hydrological design or with biological/ecological values in mind. This type of flow is given in terms of a discrete averaging period (typically 7-days) and frequency of recurrence (usually one-in-ten years for hydrology and one-in-three years for biology/ecology; (Poff and Zimmerman 2010; Suren and Jowett 2006)). This analysis also has utility for water resource planning and water allocation limits. For Auckland, these types of flows are associated with seasonally variable climate and the development of dry periods and droughts.

While the general understanding and meaning of a high and a low flow is widely understood and accepted, the thresholds for each class are idiosyncratically defined in the context of the flow regime and the purpose of the study being conducted at a catchment or rivel level. Generally, high (low) flows are defined by the top (bottom) 5%- 10% of the flow duration curve (FDC), or by some multiple or fraction of the mean flow or median flow, or by use of extreme value sampling (Henderson and Diettrich 2007) . Environmental flow analysis established how different flow regimes can impact instream physical environment and stream ecosystems (Henderson and Diettrich 2007; Jowett et al. 2005). They inform water resource sustainability and water management decisions by setting environmental flow limits that support ecological servicing requirements (Poff et al. 2010). Frequency of flows equal to or greater than 3 times the median flow (FRE3) with a five-day separation are used as a proxy indicator of ecosystem disturbance that would have been experienced by in stream organisms (Clausen and Biggs 1997).

In considering the requirements for SOE2025, high flows have been considered as occurring above the FRE3 and, in conjunction with the trend of the annual instantaneous maximum flows, are used to explain high flow occurrences. Low flows are considered in context of the annual instantaneous low flow (ALF), and the seven-day mean annual low flow ($MALF_7$) (Suren and Jowett 2006). The mean and median flows have been used to describe the “middle” or the normal flow regime.

Base flow is the portion of the water that is derived from groundwater used to distinguish the stream discharge that originates from groundwater or delayed subsurface flow rather than from direct runoff. The Base Flow Index (BFI) is the ratio of the base flow to the total stream flow. High base flows indicate stronger groundwater influences and usually associated with permeable soils and well-connected aquifers. The base flow and the base flow index were developed in accordance with standard statistical definitions and calculated based on the WMO methodology (World Meteorological Organisation 2008) using code available in the lfstat package for R (Gauster 2022).

Flashiness is defined as a rapid variation in flow over time. The Richards-Baker Index (RBI) is a hydrological index for flashiness that quantifies the variability of streamflow for a given period. It is an index of how quickly streamflow levels rise or fall in response to precipitation events. The Richards-Baker index is derived using the formula below (Equation 3.1) and was calculated using the RBI function in the ContDataQC package for R (Gauster 2022).

Table 3.4. Groups of flow analyses that were developed for SOE2025.

Group	Analysis / Metric
Summary statistics	Maximum, Median, Seven-day mean, $MALF_7$, Baseflow, RBI, BFI
Frequency	Annual maximum and annual minimum series; Flood frequency and low flow analysis.
Threshold	Days above 3 x Median flow (FRE3), Days below $MALF_7$
Relationship	Trends: number of events above 3x Median Flow (FRE3), Annual Low Flow (ALF), days below $MALF_7$; clustering and spatial analysis of poorly correlated series

3.3.2 Flow summary statistics

Environmental data summaries serve as a preliminary decomposition and overview that shows superficial similarities across and within sites that monitor river flows. Typical summary statistics calculated for rivers include the mean flow, median flow, and extremes (high and low). Although there is no analysis or interpretation intended when producing summary statistics, they form a basis for trend, threshold analyses and interpretations. Summary statistics can be used to understand the relationships for flows within and between sites. This report includes summary metrics of historical mean, median, maximum and minimum flows that describe the contribution of groundwater to rivers (baseflow and baseflow index) and the magnitude of response to rain events or “flashiness” which is defined as a rapid variation in flow over time. To understand changes between the long term, intermediate (10-year) and the recent, (5-year), the summary statistics for flows cover the following intervals aligned to the hydrological year:

- the start of the record to 30 June 2024
- 1 July 2014 to 30 June 2024 (10 years)1 July 2019 to 30 June 2024 (SOE2025).

$$RBI = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i}$$

Equation 3.1

A higher RBI indicates a flashy stream with rapid changes while a low RBI suggests a more stable flow. Analysing the trend within the RBI can be useful in understanding the change in the catchment land use. Increasing trends generally indicate urbanisation or changes that have reduced infiltration.

3.3.3 Cluster and spatial relationships

Statistical measures for each catchment can be used to group catchments that have flows that behave in a similar fashion. Catchment similarity within the Auckland region can be empirically determined by using clustering approaches such as K-means (Isik and Singh 2008), which is a machine learning technique that can identify groups of sites with hydrological regimes that arise from rainfall events and climate conditions in a similar manner. Grouping catchments based on the standardised features such as specific flow, area and catchment indices can help identify why some catchments of a similar nature (size, aspect, topography, vegetation/land cover) respond the way they do in certain conditions.

Hydrological variables that are highly correlated can distort cluster identification techniques like k-means. As such, a pairwise correlation was undertaken as an initial step to determine highly correlated hydrological variables based on the series included in the Data Summaries (see previous section). Then, highly correlated variables were removed, and the remaining poorly correlated variables were used in a principal components analysis followed by k-means clustering to help determine why flows at different sites occur.

For k-means, the elbow method was used to determine an optimum number of clusters, and the silhouette method was also utilised for a comparison in objectively partitioning the dataset (Humaira and Rasyidah 2020). The purpose of these two methods as a pre-processing step provides a way to assign k (the number of clusters parameterised in the k-means algorithm), which decomposes the observational data down to the lowest number of distinct members. The objectively determined clusters based on k-means may have meaning in terms of how some of the partitioned sites identify with co-occurring local physical environmental conditions like land cover or land use (e.g. they may constitute an “archetypal catchment”). A trial-and-error approach was adopted to determine the impact of each variable that was used in the clustering algorithm. Area, RBI and BFI were used to classify the catchments using k-means clustering, and then those results were grouped in a plot that ascribed each catchment relative to principal component outcomes.

3.3.4 Flow frequency

Frequency analyses establish the probabilities of reoccurrence (return periods) for flow events. The processes for determining high-flow (flood) and low-flow events are similar; however, differences exist in how the data are processed and how return periods are determined for both types of hydrological extremes. Flood frequency analysis uses annual peak discharge values to construct frequency distributions, which are then used to determine the likelihood of a given discharge based on its recurrence interval or exceedance probability (England et al. 2018). Low-flow frequency analysis follows a similar approach but uses the n-day mean flow (typically a 7-day average) instead of the annual peak discharge.

The generic process for flow frequency analysis presented in SOE2025 is summarised as follows:

- The annual peak discharge or the 7-day mean annual low flow is established,
- The annual flows are ranked,
- The exceedance, non-exceedance probability of the annual flows and their return period are determined,
- The non-exceedance probability is plotted against the flows,
- An estimate of the moments for the appropriate distribution is calculated and probability plots are generated,
- The recurrence interval is determined.

General practice suggests that a minimum of ten years of observations is required for reliable flow statistics (Henderson and Diettrich, 2007). Stream discharge depends on both short- and long-term weather patterns as well as groundwater conditions. In many areas, decadal-scale climate fluctuations produce significant influences on flow extremes (McKerchar and Henderson 2003) and this can introduce uncertainty into flow extreme estimates based on short-term observations. The use of a limited period can also lead to errors in the interpretation of return periods (Hu et al. 2020). Thus, flood frequency analysis requires long observational data sets to obtain reliable statistic of extreme flows.

Flood frequency estimates based on the annual maximum series tend to converge toward median reference values (derived from a 70-year record) when using records of 35 years or longer, but with substantial uncertainty. A 35-year record carries approximately 50% greater uncertainty, and a 20-year record carries about 100% greater uncertainty for estimating the magnitude of the 100-year Annual Recurrence Interval (ARI) flood. The choice of the statistical model and the parameter estimation procedure can result in greater uncertainty in flood frequency estimates (Hu et al. 2020) . Several types of statistical distributions can be fit to flow observations depending on the nature of the extreme events under consideration. High-flow events are typically estimated using distributions such as Log-Pearson III, Log-Normal, Normal, Gumbel, Generalized Extreme Value (GEV), Weibull, Gamma, Pearson III, Exponential, Kappa, Generalized Logistic, PE3, and gevR. Low-flow events are better represented by distributions such as Gumbel (gum), Weibull (wei), Log-Normal Type III (ln3), and Gamma (gam) (Ul Hassan, Hayat, and Noreen 2019). The selection of an appropriate probability distribution depends on several factors, including the length and frequency of the available observations, flow hydraulics that are influenced by geology and hydrology. The length of available records from Auckland Council varies across sites. Since no prescribed method exists for evaluating flow statistics, a best-fit approach was used for the flow frequency analysis.

The R statistical software packages lmoco, lmom (Hosking 2024), extRemes (Gilleland 2025) and fitdistrplus (Lüdecke et al. 2021) were used for flood frequency analysis (Asquith 2024) to iteratively fit all the distributions mentioned above , while the lfstat package (Gauster 2022) was used to determine the low flow statistics for all 43 gauging sites. Each distribution was evaluated based on how well it fit the ranked data. The assessment criteria included the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), coefficient of determination (R^2), adjusted R^2, root mean squared error (RMSE), and residual standard deviation (σ). The distribution that provided the best fit according to these criteria was selected, and the probabilities and return periods derived using that distribution.

Flood flows usually result from rainfall events that exceed a minimum intensity. As the climate changes, more intense rainfall patterns are expected to alter flood flows. These changes can cause sudden increases in streamflow, which may skew flood frequency distributions. A single high-flow event can significantly impact flood frequency analysis. In contrast, low flows are influenced by gradual changes in base flow and variations in groundwater. As a result, low flow statistics are less sensitive to short-term fluctuations and unlikely to be impacted by a single event. To assess the impact of the Auckland Anniversary 2023 event on flood frequency analysis, we compared frequency statistics for the entire period of record, both with and without that event included.

3.3.5 Flow thresholds

Statistical estimates of flood and low flow recurrence intervals, while useful for engineering and planning purposes, do not provide any significant insight into the impact of stream flow variations on in-stream use or ecological values. Time above and below thresholds are useful to understand the impact of stream flow on ecological species within the stream. The FRE3 and $MALF_7$ are two important metrics that can be used to assess the ecological impact of species in a river or stream.

FRE3 is the frequency of events that exceed three times the median flow. High flows impact instream ecology primarily through disturbance-related changes to physical habitat, but also through changes to water quality via increased sedimentation, entrainment of contaminants washed from the land surface, and dilution of contaminants from point-source discharges. Physical disturbance of stream channels is necessary to maintain physical habitat variability and to flush systems of nuisance algae and macrophytes. The frequency of high flows has been shown to be an ecologically significant metric with which to classify high flow regimes of New Zealand streams. Three-times the median flow was found to approximate bed-disturbance flows, thus constituting a change to physical habitats in a river (Clausen and Biggs, 1997).

The seven-day mean annual low flow ($MALF_7$) can be used for low flow limits as they provide limiting low-flow thresholds that reflect conditions under which aquatic systems are vulnerable (Henderson and Diettrich 2007; Johnson 2021). The $MALF_7$ has been used in various contexts in New Zealand and elsewhere to indicate low flows, stresses to the ecological environment (Henderson and Diettrich 2007) and is commonly used in New Zealand to allocate flows from rivers. To understand changes to the high flow and low flow regimes, the number of events above 3x median flow, and total number of days below the $MALF_7$ for each year of the full record were analysed. This was completed for the last ten years and the last five years, like previous SOE reporting (Johnson, 2021). A comparison of the three periods of analysis with the previous SOE analysis of the full record is also provided.

3.3.6 Flow trends

Trend analysis for stream flows helps to identify long-term changes in water availability, detect the impacts of climate change, assess flood and drought risks, and support sustainable water resource management. Understanding streamflow trends also aids in planning infrastructure, protecting ecosystems, and guiding policy decisions for future resilience. Trend analysis was run using linear regression and a Mann-Kendall test for significance on $MALF_7$ and FRE3 time series for each site over multiple periods, starting at the beginning of different decades at the start of each record through the last full decade of observations. Flow events exceeding three times the median flow (FRE3), the lowest absolute annual flow (ALF) and duration in minutes below $MALF_7$ were tabulated from Hydstra and aggregated on a hydrological year basis using the HYFRE3 and HYMALF tools, respectively. Each series was evaluated for missing data, and hydrological years with more than 10% missing observations were removed and not considered in calculation of statistics using hydrological year totals or averages. In addition, flow observations that were used to calculate FRE3 and $MALF_7$ needed to meet a pre-screening as being predominantly complete through the SOE2025 analysis period, with at least four of five years covered (Oakley Creek was rejected on this criterion), and with at least 90% of time covered in each year.

To reiterate, a FRE3 time series was constructed from occurrences of FRE3 events with a five-day separation period between peaks to determine the number of events in a year (counts per year), and $MALF_7$ was aggregated into total time below $MALF_7$ in days (duration). Successive time intervals for FRE3 and $MALF_7$ trends assessment focused on the full period of observation for all records, and then four snapshot periods: 1980-present, 1990-present, 2000-present, 2010-present for all records that temporally overlapped. To qualify for snapshot period trend analysis, each record needed to have at least 60% coverage for the first decade in each period (i.e. six out of 10 years covered). Correlation coefficients were calculated and sites with a significant trend were shown. If any contiguous steps were missing in the snapshot period analysis, results above the temporal break were disregarded including the long-term trend for the entire record. Relationships between the flow trends and catchment characteristics are brought to bear in the discussion.

3.4 Groundwater

Boreholes across Auckland region are used for groundwater level monitoring and the borehole network intersects different geological formations, requiring subtle construction variations from site to site. Nevertheless, basic requirements for Auckland Council monitoring borehole usually consists of a galvanised steel casing standpipe at least 0.5m above ground level, sealed off from surface water interaction, with a bentonite seal in ground on the sides of the casing and capped with a concrete plinth on surface. Borehole casings are generally constructed of either PVC or stainless steel and often fitted with a slotted screen across the target formation to prevent ingress of sediment while allowing water to enter the borehole. The screen is installed where groundwater was intersected during drilling, and this is the area where the groundwater flows into the borehole. The boreholes are drilled from shallow to depth ranging from 8m down to a depth of 350m to 400m on the deepest aquifers in the region. Auckland Council are in the process of increasing the number of telemetered groundwater bores in the network, consisting of vented pressure transducers and dataloggers that record the groundwater level in 15-minute intervals. Groundwater observations are directly transmitted directly into the Hydrotel data management system at the 15-minute intervals.

Continuing the SOE2025 approach adopted for rainfall, groundwater levels were selected for sites that had enough data to calculate a standard climatological normal period of 30 years. Out of the 48 boreholes that are monitored across the region, six were selected based on an initial screening that indicated an absence of temporal heterogeneities, followed by an assessment of whether they had enough observations to cover 30 years (1991 – 2020) and no obvious step changes due to aquifer management influences. Focusing on the selected six boreholes (Table 2.4), a more in-depth analysis of the state and trend methodology was adapted. Groundwater is at the bottom end of the water cycle and last in line to receive rainfall in the form of recharge. Due to the lag in the recharge process from meteoric source to receptor basins, groundwater observations tend to not always temporally correlate with what is observed above ground in terms of the timing of rainfall-driven events, such as meteorological drought, and episodic flooding due to storms.

3.4.1 Aquifer units represented in SOE2025

The selected boreholes intersect shallow, intermediate, deep and very deep depths for the aquifers that underlie Auckland. From north to south, the Quintals Road borehole and the Selaks Road borehole represent the deep aquifer system within the Waitematā Group. The Waitematā Group lies unconformably over the basement greywacke rock composed of interbedded sandstone and mudstone that constitutes a major groundwater source for Auckland. Most of the groundwater production comes from fractures within the sandstone layers which is spatially variable (Edbrooke, 2001). The Angle Street, Revell Court and Wooten Road boreholes all intersect volcanic formations, and they are located within the Mt Wellington volcanics, the Pukekohe Central volcanics, and the Bombay volcanics, respectively. These groundwater monitoring sites observe aquifers that occur due to layered rock formations composed of basaltic lavas, scoria beds, and roughly bedded tuffs (volcanic ash) with interspersed volcanic bombs being superimposed above an erosional unconformity of the underlying Waitematā and Tauranga Group sedimentary rocks (Edbrooke, 2001).

The monitoring borehole at Marae O Rahia Road (referred to in this report as Maraeorahia (because of how it is labelled in the database) intersects the Kaawa Formation, which is a shell-rich sedimentary sequence dating from the Pliocene Epoch that is extensively present throughout the South Auckland region. It lies unconformably atop the older Waitematā Group. The thickness of the Kaawa Formation is influenced by the paleo-topographic surface of the underlying Waitematā Group, past regional tectonic history, and local depositional settings.

Based on the known details of the Kaawa Formation, it is considered that it was deposited in a combination of shallow marine and estuarine environments (Edbrooke, 2001). It consists of a surficial unit of loose, uncemented sands that are typically 20-30 metres thick. These sands are interbedded with sandstone units containing variable amounts of shell material, along with siltstone and conglomerate. The unit interbedding shows considerable variability in degree of induration, strength, and weathering, but it is generally weak, and layer thicknesses are inconsistent across the lateral extent of the formation.

3.4.2 Approach for analysis groundwater levels

The approach to understanding groundwater level variability and changes over the long-term used the complete record for each selected borehole and plotted monthly mean groundwater levels with reference to a standard climatological normal period. Groundwater level observations were normalised to remove noise, seasonality and pumping effects from the data. The normalised timeseries were then evaluated with reference to long-term conditions (the climatological period mean) to determine if there were above normal (surplus), normal, or below normal (deficit) groundwater levels. The annual year (January – December), hydrological year (July – June), seasonal (June-August, winter; September-November, spring; December-February, summer; March-May, Autumn), and monthly rainfall statistics were generated relative to the 1991-2020 standard climatological normal base period. Rainfall total amount statistics are an essential climate variable that rely on complete data, so any annual year, hydrological year or season with missing monthly total rainfall amounts were not included in groundwater statistics calculated for the SOE2025 report.

3.4.3 Groundwater level data considerations

The regularity (i.e. timestep) in groundwater level time series is inconsistent for most bores in the Auckland region. Most early records consist of monthly manual groundwater level measurements or “dips”. Continuous groundwater level measurements and data telemetry have been progressively introduced across much of the groundwater monitoring network. In some cases, continuous monitoring was ceased due to resourcing constraints or other operational factors. These aperiodic observations have been interpolated using the Hydstra software package to derive a monthly mean groundwater level for SOE2025. Those values are undifferentiated from high-resolution 15-minute monitoring observations that are aggregated into monthly mean values. We recognise this sampling bias as a potential source of unquantified error for some of the individual monthly mean groundwater level time series values (including the potential of temporal aliasing), with the knock-on effect that there is added uncertainty for monthly mean groundwater levels for periods with only manual dips. For this report, we recognise this as a source of potential error for some of the included observations but have not quantified any uncertainties or impacts from them on calculating the long-term groundwater level trends. This issue does not significantly impact the characterisation of groundwater levels in recent years and the comparison of SOE2025 to SOE2020 groundwater levels on climatic timescales.

Groundwater level climatological plots exhibit a sinusoidal seasonal variation throughout the year, which is like rainfall, but peak and low levels are temporally displaced from the variations observed for meteoric water. The highest groundwater level values are observed for mid-winter through mid- to late-spring (Figure 3.3). For the most part, the lowest groundwater levels are observed during late summer and early autumn, however some locations show the lowest groundwater levels on average occurring later in autumn (Figure 3.3 and Table 3.5; Revell Court and Wooten Road).

Interannual variation in groundwater levels are more prominent at a seasonal level for summer than winter, but there are some shallow bore sites (e.g. Angle Street) where winter variability is more prominent. The inter-seasonal variability range of groundwater levels across representative bores spans several metres at some sites to less than 2m at other locations. Intraseasonal variability of groundwater levels is typically within the sub-metre scale and can be observed across most seasons relative to the background groundwater level state.

Table 3.5. Average groundwater level for selected observing sites in the Auckland Council region that were analysed for SOE2025. Level is in metres above sea level with respect to NZVD2016.

Site name	Annual	Hydro year	Autumn	Winter	Spring	Summer
Quintals Road	7.08	7.05	6.70	7.49	7.42	6.60
Selaks Bore	23.25	23.11	21.80	23.68	24.54	22.79
Angle Street	2.34	2.34	2.30	2.43	2.35	2.27
Maraeorahia	3.06	3.05	2.87	3.30	3.28	2.77
Revell Court	63.01	62.96	62.52	62.75	63.69	63.15
Wooten Road	156.32	156.36	155.56	155.95	157.31	156.38

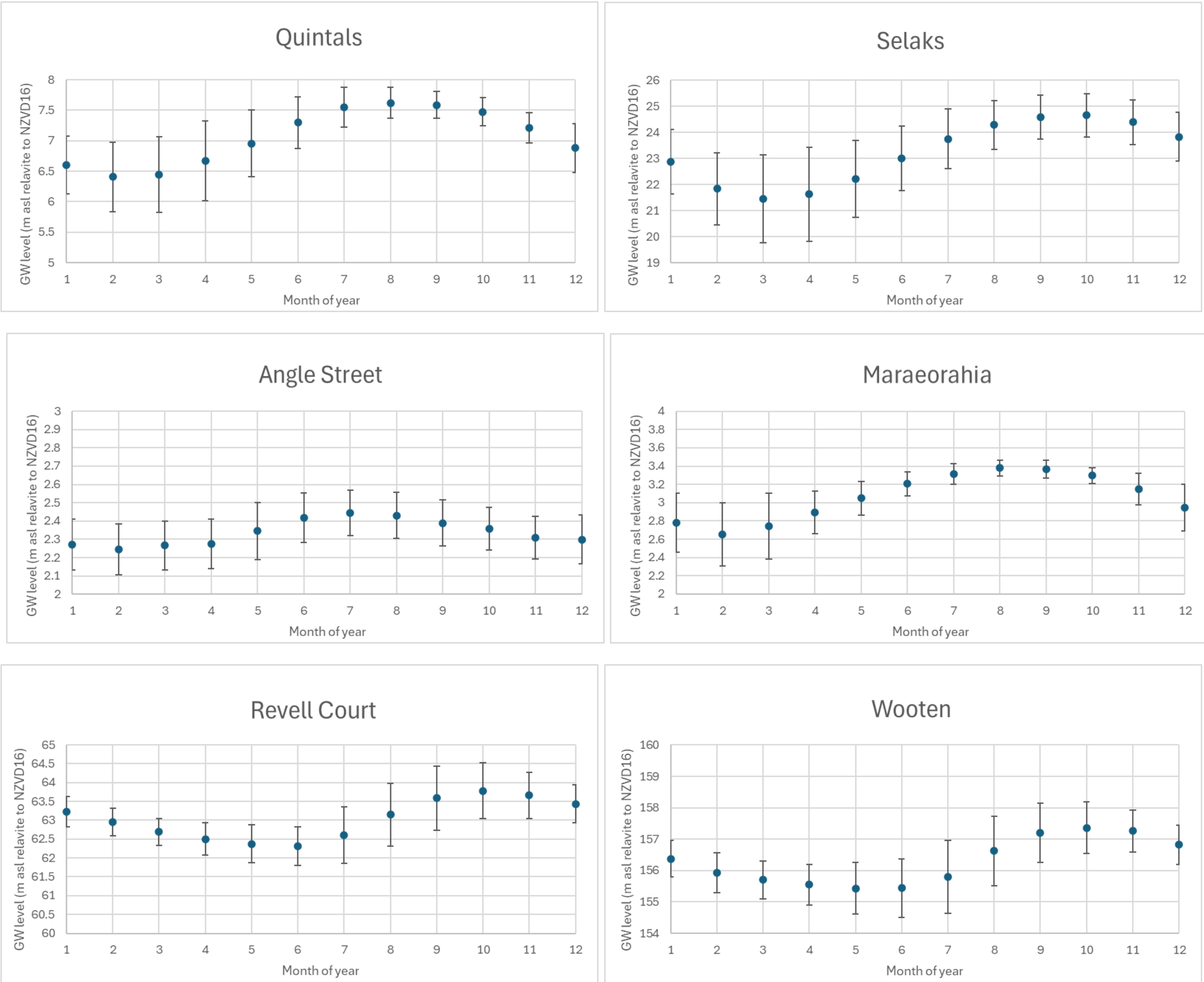


Figure 3.3 Climatological distribution of groundwater levels at six locations across the Auckland Council region based on the 1991-2020 standard climatological normal period. Mean values (blue dots) and the spread (whiskers; 1 standard deviation) are shown for all months (January = 1; December = 12).

4 Results

4.1 Climate conditions during SOE2025

The state of the tropical Pacific Ocean and atmosphere contributed to the regional climate patterns that Auckland experienced between mid-2019 – mid-2024 that are covered in SOE2025. El Niño-Southern Oscillation (ENSO) activity is a linked ocean-atmosphere climate phenomenon that can be described as a jointly operating seesaw of atmospheric pressure spanning the Indo-Australian sector and the western Pacific, along with near-equatorial oceanic temperature anomalies that span the Pacific Basin (Wang et al. 2017). ENSO directly influences the strength of the equatorial trade winds (Anderson, Perez, and Karspeck 2013), the atmospheric and oceanic climates of the Indo-Pacific (including the occurrence of tropical cyclones) (Diamond, Lorrey, and Renwick 2013), and it has far-reaching teleconnections with known global climate impacts (Alizadeh 2024). ENSO operates on a quasi 3-to-7 year timescale, with events typically building from austral winter into spring and summer and decaying in mid-autumn (Allan 1988). Links between the New Zealand sector of the SW Pacific and the subtropical atmosphere to the north of the country means ENSO contributes significantly to the variability of weather systems Auckland experiences on an inter-seasonal and interannual basis. It is considered an important 'mode of variability' that impacts our climate.

NIWA seasonal climate summaries describe the broadscale conditions for wind, temperature, rainfall and soil moisture that were associated with variable climate linked to modes like ENSO. Those summaries are drawn on here as a backdrop for describing regional climate conditions for SOE2025 (https://niwa.co.nz/climate-and-weather/climate-summaries-0). El Niño conditions were present in the Tropical Pacific in mid-2019, with more frequent westerly-quarter airflow occurring across the region at the time. From 2020-2023, a "triple-dip" La Niña unfolded, which is rare (but not unprecedented) within the context of the historical climate record. During this sequence of three consecutive years of La Niña presence, the Auckland region experienced more frequent northerly, northeasterly and easterly flows. A transition to El Niño at the end of winter 2023 saw the return of more frequent westerly and southwesterly flow, except for spring 2023 which was typified by more frequent northeasterly winds.

During 2019 to 2024, New Zealand experienced some of the warmest national average temperatures (relative to 1991-2020 standard climatological normal period), except for autumn 2024 which saw below average temperatures recorded across most regions. The sequence of record-breaking high average temperatures is part of a robust ongoing climate change trend (Pearce et al. 2018). Winter 2021 through winter 2022 was characterised by a sequence of persistently warm average seasonal temperatures, with a record warm winter 2021 season being quickly surpassed the following year. The intervening spring 2021, summer 2021/22 and autumn 2022 seasonal average temperatures during this time were also ranked within the top five on record. Multiple occurrences of marine heatwaves that were intense and protracted (extended for multiple seasons) featured significantly during the past five years. The anomalously warm conditions for the oceans around the northern part of New Zealand have strongly influenced Auckland's air and coastal marine temperatures, as well as other climate variables.

Regional hydroclimatic conditions for New Zealand and Auckland were highly variable between seasons and from year to year for 2019 through 2024. Prolonged periods with little rainfall across the North Island resulted in dry conditions for much of Auckland from late 2019 through early 2020. During summer 2019-20, there were near-record and record dry spells (defined as consecutive days with <1mm rainfall) for the region, including a 47-day span from 6 January 2020 to 21 February 2020 that was the longest on record at the time. Meteorological drought receded slightly during autumn 2020, but this season was one of the driest on record and created significant water shortage issues for locations in the Auckland region that had also experienced a preceding dry summer. After a return to mostly normal conditions for the remainder of 2020 and early 2021, the rest of 2021 as well as summer 2021/22 and autumn 2022 was characterised by drier seasonal climate conditions, except for strong episodic rainfall during late winter and spring 2021 when above normal rainfall totals occurred for parts of northern and western Auckland.

Winter 2022 saw a significant hydrological shift for the Auckland region that started a remarkable sequence of consecutive seasons with above normal, well above normal and record-breaking rainfall totals that persisted through autumn 2023. During winter 2022, atmospheric rivers and subtropical lows brought significant rainfall to the region that caused heavy rainfall, strong winds and impacts due to surface flooding. During spring 2022, many stations recorded rainfall totals that were ranked amongst some of the highest on record. During summer 2022/23, a series of four significant meteorological events – the most notable related to rain that fell during the Auckland Anniversary weekend in 2023 and the passage of ex-tropical cyclone (TC) Gabrielle to the east of the North Island – contributed to record-shattering rainfall for the Auckland region. TC Gabrielle and rainfall events within the summer 2023 rainfall will be covered in detail elsewhere in the State of the Environment report using details from Auckland Council rainfall stations. More broadly, NIWA reported that the Auckland region experienced >5.5 times the normal summer rainfall during summer 2022/23, with 63% percent of the typical annual rainfall being recorded based on an analysis of the New Zealand Virtual Climate Station Network (VCSN; Tait et al. 2006). January 2023 was the wettest month on record for Auckland because of ex TC Hale in early-to-mid January and a two-day deluge late in the month (which caused the Auckland Anniversary 2023 floods). An update of the Central Auckland Rainfall series (A.M. Fowler 2021) illustrates that it was our wettest month overall since February 1869. Winter 2023 saw a return to drier-than-normal rainfall and then normal rainfall through the end of the year and into summer 2023/24. Autumn 2024 was typified by reduced regional rainfall, keeping with the theme of nationally drier-than-normal conditions where no stations reported record or near-record high rainfall.

4.2 Rainfall

4.2.1 Annual, hydrological year and seasonal mean rainfall

For the SOE2025 analysis period, which considered years and seasons between 2019 to 2024, the selected Auckland Council rainfall monitoring sites showed five-year annual average rainfall amounts between 1050mm – 1770mm, and slightly higher average amounts between 1100mm-1840mm for the hydrological year (July-June). Across all sites, autumn average rainfall amounts varied between 200mm-350mm, winter rainfall average rainfall amounts varied between 350mm-625mm, spring average rainfall amounts varied between 270mm-440mm, and summer average rainfall amounts varied between 230mm to just over 400mm. Kaipara experienced the lowest average rainfall amount across all seasons for 2019-2024, while Nihotupu recorded the highest average rainfall amount, except during summer where Tamahunga had the highest average rainfall amount. See Table 4.1 for details of each site.

Table 4.1. Annual, hydrological and seasonal rainfall averages for SOE2025, based on the years and seasons between 2019-2024. Italicised and underscored values indicate lowest averages across the selected sites, while bold values indicate the highest averages. All rainfall values are in millimetres.

Site	Annual	Hydro Year	Autumn	Winter	Spring	Summer
Hoteo	1443.8	1482.1	290.3	453.8	371.8	336.5
Tamahunga	1684.3	1722.9	349.0	502.3	438.3	**401.4**
Kaipara	*<u>1057.9</u>*	*<u>1104.9</u>*	*<u>213.3</u>*	*<u>356.3</u>*	*<u>273.2</u>*	*<u>230.9</u>*
Mahurangi	1568.1	1611.8	322.7	497.7	385.4	371.6
Mahurangi Sewage	1396.6	1340.1	300.4	514.4	416.8	367.8
Orewa	1334.1	1350.7	277.7	442.4	332.5	285.2
Makarau	1371.9	1390.1	280.9	444.6	341.4	310.2
Ararimu	1517.5	1552.4	305.3	521.4	354.7	344.1
Onehunga	1089.2	1018.8	204.1	457.5	298.7	310.3
Kumeu	1445.9	1467.5	290.3	516.8	329.5	314.8
Whenuapai	1345.1	1362.3	272.8	468.1	302.3	308.2
Rangitopuni	1542.0	1569.2	301.3	539.8	367.5	339.7
Oteha	1349.9	1379.8	260.7	443.9	352.4	298.1
Albert Park	1292.1	1380.9	250.7	426.1	316.7	301.4
Nihotupu	**1769.0**	**1837.1**	**337.6**	**622.6**	**438.7**	383.2
Waituna	1561.4	1604.5	303.4	549.3	379.4	338.9
Puhinui	1252.3	1299.9	263.4	420.5	310.5	268.1
Ngakoroa	1374.8	1418.8	278.6	444.9	377.8	292.8
Waihihi	1334.7	1393.6	249.0	456.2	381.4	273.3

4.2.2 SOE2025 rainfall comparison to climatological baseline conditions

Overall, most of the selected Auckland Council rainfall sites received annual and hydrological year average rainfall amounts that were near normal during the SOE2025 period. With respect to the 1991-2020 climatology period, only Kumeu and Nihotupu (western sites) had rainfall averages that were wetter-than-normal for annual and hydrological year conditions (with a five-year average value >120% of normal); however, Oteha and Onehunga (central sites) experienced overall drier-than-normal annual and hydrological year conditions (with a five-year average value <80% of normal rainfall). For Autumn 2019-2024, most sites had near average percentage of normal rainfall values (within the normal range), except Rangitopuni, Ngakoroa and Waihihi which were above normal (120-149% normal) while Nihotupu and Kumeu where were well above normal (>150% normal). Winter also saw most sites with an average rainfall percentage of normal value within the normal range (80% to 119% normal), except for Nihotupu which was above normal (on average 139% normal for this time of year), and Oteha and Onehunga (a Watercare site) which were below normal (on average about 75% of normal for the winter season). There was a similar spatial pattern for spring as for winter during 2019-2024 for the five-year average relative to climatology, but with the addition of central and northern sites of Albert Park, Mahurangi (Warkworth) and Tamahunga also showing below normal average rainfall amounts. Most of the Auckland Council sites with long-term rainfall observations that were used in the SOE2025 analysis showed below normal average rainfall amounts on average during the summers between 2019-2024, and only one site (Nihotupu) showed an average rainfall percentage of normal that was above 100% of normal during that time (See Table 4.2 for more details).

Table 4.2. SOE2025 average rainfall expressed as a percentage of normal relative to the 1991-2020 standard climatological normal period. Light blue and dark blue shades indicate average rainfall between 120% to 149% of normal and >150% of normal, respectively. Light orange shading indicates average rainfall between 51% to 79% of normal.

Site	Annual	Hydro year	Autumn	Winter	Spring	Summer
Hoteo	93.5	91.0	110.5	103.6	82.6	74.5
Tamahanga	92.0	88.9	111.9	101.1	74.9	72.8
Kaipara Heads	98.9	94.0	118.6	99.2	83.3	89.5
Mahurangi @ Satellite	94.0	91.2	112.6	102.6	85.1	72.6
Mahurangi @ Warkworth Sewage	101.5	105.5	117.7	99.5	74.6	70.0
Makarau	96.6	94.9	115.1	100.4	84.3	84.3
Orewa	86.9	84.8	104.9	96.7	80.0	67.2
Ararimu	91.5	89.2	111.3	92.3	90.6	72.1
Kumeu	120.7	128.6	158.1	103.4	99.2	73.1
Whenuapai	83.9	82.5	103.5	83.0	84.3	65.1
Rangitopuni	103.3	101.6	125.8	102.3	103.9	80.7
Oteha	78.5	76.9	103.5	75.9	73.4	64.0
Albert Park	85.8	86.7	112.8	88.3	74.1	69.4
Nihotupu	136.0	126.1	165.7	139.3	130.5	107.2
Waituna	88.2	84.6	111.5	87.5	83.2	71.0
Onehunga	77.8	75.3	103.8	75.0	73.9	62.8
Puhinui	93.9	90.8	114.2	95.4	88.7	80.4
Ngakoroa	102.1	98.9	121.2	104.4	90.0	91.0
Waihihi	107.9	101.9	134.3	105.7	87.1	92.6

4.2.3 Comparison of rainfall between SOE2025 and SOE2020

Examining time slices aligned with the SOE2020 and SOE2025 reporting intervals (2014-2018 and 2019-2023, respectively) allows an examination of short-term climate variability, which is a different approach from examining how rainfall conditions compare to the long-term 30-year average. Pervasive changes in the average rainfall amounts during SOE2025 relative to SOE2020 were observed most widely for Autumn, with most sites showing lower average rain accumulation on the order of 60mm to 100mm less at northern and central sites and more than 130mm less at western and southeastern sites during March- May (see Table 4.3). For the sites that had the strongest Autumn net average rainfall changes over the past 5 years relative to the previous 5-year interval, with more than +/-100mm of change (Table 4.3), this seasonal difference accounted for most of the short-term negative rainfall shift that was observed for average annual rainfall totals. A change to above average seasonal rainfall amounts relative to SOE2020 (2014-2018 years and seasons) also occurred for summer for many sites, but this was counterbalanced in many respects by drier overall Autumn conditions for 2019-2023. This meant that only five sites showed some appreciable positive short-term rainfall change (more than +50mm shift) in the annual average rainfall amount, and notably this change was exemplified by slightly more hydrological year rainfall received on average for Tamahunga, Orewa, Ararimu and Rangitopuni. The exceptionally high rainfall received during summer 2022-23 strongly contributed to this specific short-term annual and hydrological year variation. It also helped to counteract (and in some cases overpower) relatively drier Autumn conditions that were experienced on average during the 2019-2023 interval (See Table 4.4). Few appreciable changes for the average rainfall amount between SOE2020 and SOE2025 were observed for Winter (see Table 4.4 for more details).

Table 4.3. Difference between five-year averages for rainfall from the SOE2020 report (2014-2019) and the SOE2025 report (2019-2024). Differences are in millimetres. Sites highlighted in grey are missing monthly total rainfall data for one or more seasons/years and are not included. Light blue and dark blue shading highlight a difference in the average rainfall amount between the last SOE and current SOE report that was between +50mm to +100mm and greater than +100mm, respectively. Light orange and dark orange shading indicates a difference in the average rainfall amount between the last SOE and current SOE between -50mm to -100mm and less than -100mm, respectively.

Site	Annual	Hydro Year	Autumn	Winter	Spring	Summer
Hoteo 643510	-14.3	49.6	-75.1	-39.5	54.1	55.0
Tamahunga 643713	89.4	146.8	-64.4	-23.3	119.2	67.8
Kaipara 644211	-93.3	-37.0	-72.1	-23.6	11.3	6.7
Mahurangi 644616	11.5	82.2	-61.3	-19.3	63.8	43.9
Mahurangi Sewage 644626						
Orewa 646619	135.9	157.2	-48.6	46.3	65.6	73.2
Ararimu 647510	71.5	130.7	-84.4	60.5	25.7	79.9
Onehunga 649723						
Kumeu 647513	-4.5	41.5	-84.4	23.9	10.7	54.7
Whenuapai 647601	32.8	62.7	-97.9	30.8	24.4	85.8
Rangitopuni 647614	89.0	141.5	-77.9	68.1	49.5	59.4
Oteha 647727	25.1	75.2	-98.7	36.9	65.7	35.3
Albert Park 648719	57.3	86.1	-85.5	31.7	40.5	74.5
Nihotupu 649514	-114.7	9.2	-150.6	5.3	7.9	40.8
Waituna 649641	-55.7	19.9	-131.1	17.3	21.7	49.9
Puhinui 740945						
Ngakoroa 742914	-185.1	-92.4	-137.9	-41.0	11.4	13.2
Waihihi 750213	-338.6	-252.5	-182.1	-88.2	3.4	-43.2

Comparison of five-year aggregated rainfall amounts for SOE2025 relative to SOE2020 provides a proxy for local water balance input changes due to meteoric precipitation (Table 4.5). SOE2025 shows the most significant meteoric water balance change occurred during autumn, where all sites had a rainfall deficit relative to the total rainfall amount received during the previous SOE period. All sites were relatively reduced by at least a full autumn season of rainfall with reference to SOE2020, with some sites reduced by two-to-three times that amount. The annual and hydrological year rainfall totals, however, show the relative seasonal rainfall variability during autumn was countered by wetter conditions on average for spring and summer during 2019-2023. This assertion is confirmed by examining the SOE2025 seasonal water balance relative to the SOE reporting period, which shows some northwestern and southern sites with net rainfall deficits, and positive short-term rainfall balances for all other sites except for Hoteo and Kumeu. Of interest, increased rainfall during summer of 2022-23 helped to counteract the successions of relatively dry autumns in the three years prior.

Table 4.4. Difference in average % normal rainfall from SOE2020 to SOE2025. Light blue shading indicates a relative swing towards wetter conditions (20-50% of normal), while light orange and dark indicate a relative swing towards drier conditions (-20 to -50% and below -50% of normal).

Site	Annual	Hydro year	Autumn	Winter	Spring	Summer
Hoteo	-0.9	3.2	-22.7	-8.3	14.1	14.5
Tamahanga	5.2	8.3	-17.4	-4.5	28.0	14.8
Kaipara Heads	-8.0	-3.0	-30.0	-6.2	3.6	2.7
Mahurangi @ Satellite	0.7	4.9	-18.0	-3.8	16.9	9.7
Mahurangi @ Warkworth Sewage	-6.2	-9.5	-19.1	-2.1	17.6	31.0
Makarau	11.0	12.5	-17.1	11.8	20.7	29.1
Orewa	-2.4	1.2	-26.1	-3.7	14.9	7.0
Ararimu	4.5	8.2	-24.1	12.1	7.1	21.8
Kumeu	-21.1	-20.3	-69.5	9.8	3.4	28.6
Whenuapai	-0.3	2.4	-23.3	4.0	2.8	13.7
Rangitopuni	2.6	4.9	-33.2	7.2	9.1	31.1
Oteha	4.8	7.6	-21.3	11.0	11.4	13.5
Albert Park	1.6	5.0	-31.0	8.0	17.0	9.3
Nihotupu	6.3	8.4	-42.2	11.2	19.1	35.2
Waituna	-5.4	0.4	-34.4	0.8	1.5	8.5
Onehunga	-2.7	0.9	-31.3	2.4	4.5	10.8
Puhinui	2.7	4.8	-35.2	3.3	4.0	9.5
Ngakoroa	-12.1	-6.0	-40.1	-8.8	2.8	4.3
Waihihi	-21.8	-15.6	-56.7	-17.1	0.8	-12.6

Table 4.5. Difference of five-year total rainfall amounts observed from SOE2020 to SOE2025 in millimetres as a proxy for short-term meteoric water balance. Sites highlighted in grey are missing monthly total rainfall data for one or more seasons/years and are not included. Small differences in WB totals from the arithmetic sum of tabulated seasonal values is due to rounding.

Site	Annual	Hydro year	Autumn	Winter	Spring	Summer	WB
Hoteo	-71.5	248.0	-375.6	-197.4	270.3	274.8	-28.0
Tamahanga	447.0	734.1	-321.9	-116.5	596.0	339.0	496.6
Kaipara Heads	-466.4	-184.8	-360.7	-118.2	56.6	33.7	-388.7
Mahurangi @ Satellite	57.7	411.0	-306.6	-96.4	319.0	219.3	135.3
Mahurangi @ Warkworth							
Makarau	-190.9	93.1	-464.9	-87.7	268.8	146.9	-136.9
Orewa	679.7	786.0	-242.9	231.7	328.0	366.2	683.1
Ararimu	357.6	653.5	-421.8	302.7	128.6	399.4	408.9
Kumeu	-22.3	207.7	-422.2	119.5	53.4	273.7	24.5
Whenuapai	164.1	313.5	-489.5	153.8	122.1	428.8	215.2
Rangitopuni	445.2	707.6	-389.3	340.5	247.7	296.8	495.6
Oteha	125.7	376.1	-493.5	184.5	328.3	176.6	195.9
Albert Park	286.3	430.4	-427.7	158.7	202.6	372.5	306.0
Nihotupu	-573.7	46.1	-753.2	26.4	39.4	203.8	-483.5
Waituna	-278.5	99.6	-655.6	86.6	108.6	249.6	-210.8
Onehunga							
Puhinui				70.7	66.7	141.4	
Ngakoroa	-925.3	-462.1	-689.3	-204.9	56.8	65.7	-771.6
Waihihi	-1693.1	-1262.7	-910.6	-441.1	17.0	-216.2	-1551.0

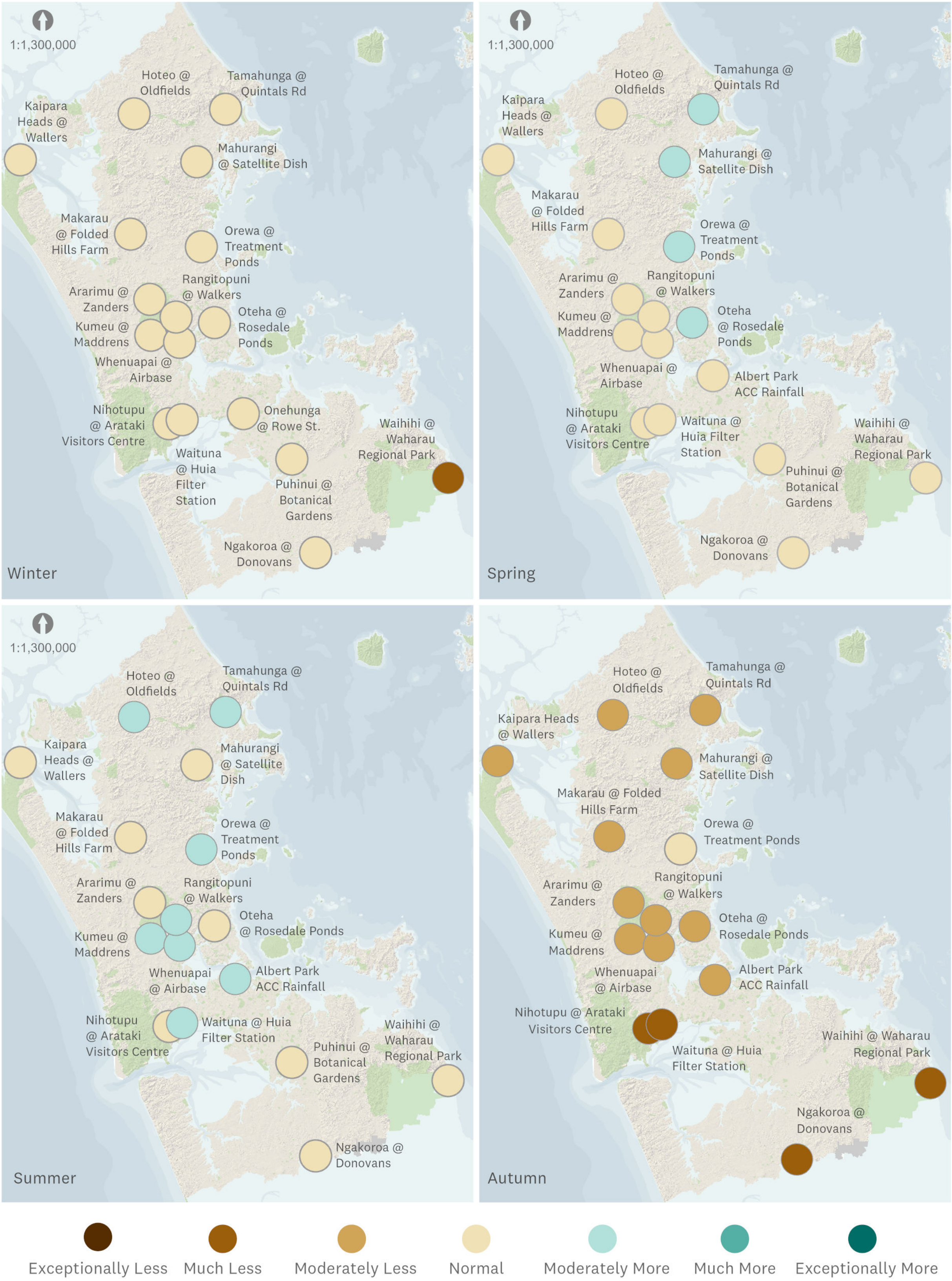


Figure 4.1 Accumulated rainfall differences from SOE2020 to SOE2025 for winter, spring, summer and autumn used to show qualitatively wetter and drier conditions from one time period of analysis to the next. Categorical rainfall shifts are based on rainfall differences between the two time slices that are listed in Table 4.5.

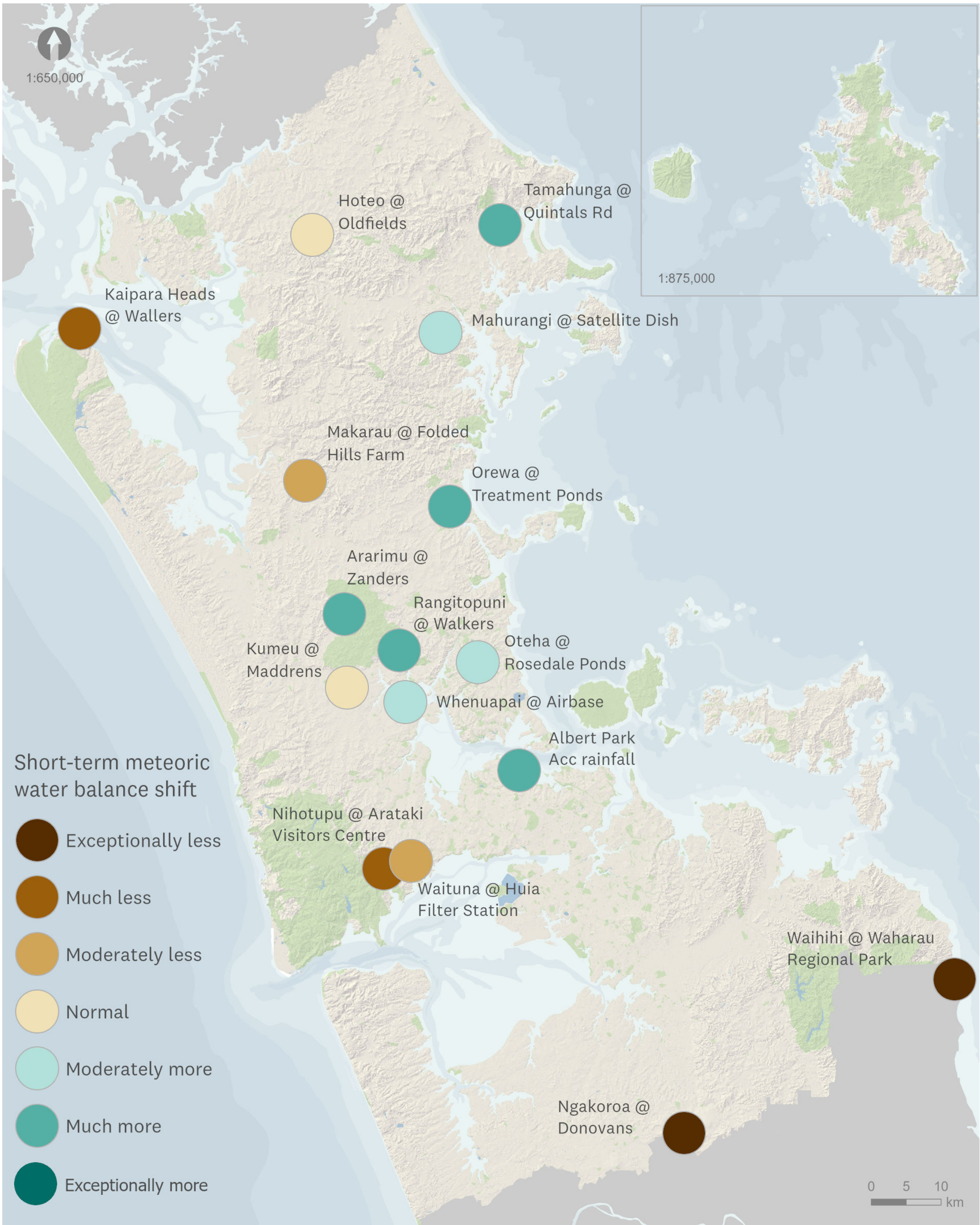


Figure 4.2 Short-term meteoric water balance based on differences between SOE2020 and SOE2025 based on seasonal amounts.

4.2.4 Regional variability of rainfall for SOE2025

Autumn rainfall conditions were predominantly in quintile 1 for 2019, 2020 and 2021 (63% or more of all sites in all three seasons) with q2 registered at most of the other sites during those years. These three autumn seasons show the main contributions toward overall drier than normal autumn rainfall average for 2019-2024, including significantly lower rainfall that occurred during the drought of 2019-2020 (described in more detail later). There was a spatial mix of rainfall anomalies for autumn 2022, followed by very wet (q5) to moderately wet (q4) conditions across 76% and 24% of sites, respectively, during autumn 2023. With respect to the SOE2020 reporting period, which had a mix of seasonal rainfall conditions (relatively dry 2014 and 2018, moderately wet 2015 and 2018, and a very wet 2017 autumn), the succession of drier-than-normal autumns in the last five years reinforces the relative meteoric water balance shift observed for autumn on average. Overall, the spatial pattern of change saw stronger rainfall reductions in the far south of the region during this season (Figure 4.1).

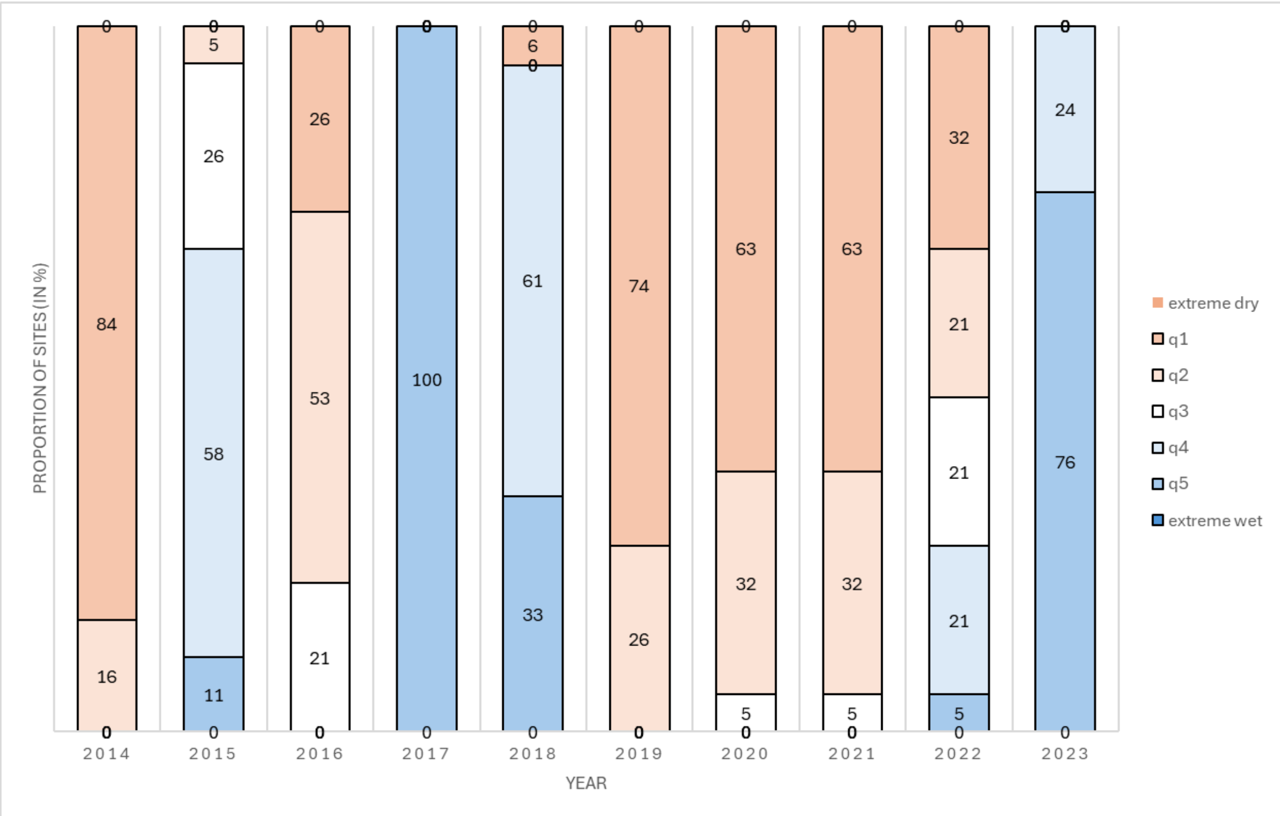


Figure 4.3 Proportion of long-term rainfall monitoring sites that had rainfall amounts for autumn (March, April and May) in different quintiles in relation to 1991-2020. All seasons within the years covering the last SOE report and the current report are shown. Percentage of the total number of sites is indicated within each color-coded quintile segment. Zero values at the top and the bottom of each year indicate specific quintiles relative to the climatological distribution or extreme observations outside the five quintile ranges were absent. See colour coding for details.

The relative changes between SOE2020 and SOE2025 for winter was not prominent, and no strong spatial contrasts for changes are noted (Figure 4.4). This is likely because both SOE intervals captured seasonal rainfall variations that were both relatively dry and relatively wet – and these within-SOE anomalies largely offset one another when differences between the last and the current SOE reporting interval was calculated. Of note, winter 2022 saw most sites (89%) with q5 rainfall index values and the remainder of sites (11%) with extreme rainfall amounts at levels not captured in the 1991-2020 climatological normal period. In addition, almost half of the sites in total were classified as either having received q1 (21%) or q2 (26%) rainfall in winter 2019, which was a contributing factor toward the 2019-20 drought. Both seasons will be revisited later in in-depth review of the deluge and drought that occurred in this SOE period.

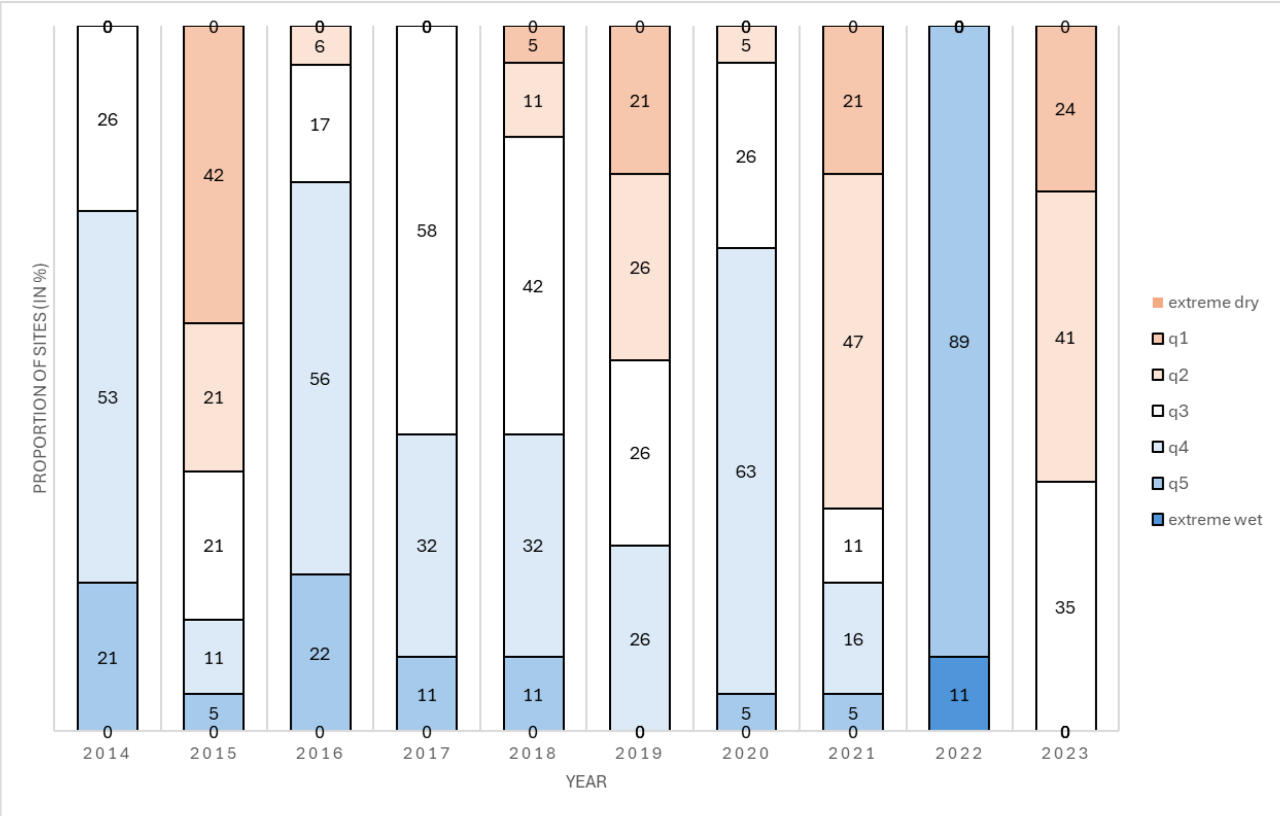


Figure 4.4 Proportion of long-term rainfall monitoring sites that had rainfall amounts for winter (June, July, August) in different quintiles in relation to 1991-2020. All seasons within the years covering the last SOE report and the current report are shown. Percentage of the total number of sites is indicated within each color-coded quintile segment. Zero values at the top and the bottom of each year indicate specific quintiles relative to the climatological distribution or extreme observations outside the five quintile ranges were absent. See colour coding for details.

A string of major hydrological episodes that occurred during SOE2025 were the very wet and exceptionally wet seasonal conditions in 2022 that followed closely on the back of a comprehensively wet spring in 2021. For spring 2022, 68% of the long-term rainfall sites used in this report had seasonal rainfall totals that were above q5 rainfall as calculated from the 1991-2020 period, while the remaining sites (32%) received q5 rainfall (Figure 4.5). This season also followed directly on the heels of a winter in 2022 with very high rainfall totals. One reason why the relative shift between the last SOE reporting window and this SOE report only shows a modest relative rainfall increase is that the 2014 and 2016 winters were also predominantly wet across most sites, with most locations receiving q5 rainfall in 2014 (63%) and in 2016 (79%). So, in other words both the last SOE and this SOE had relatively wet average spring conditions, making the primary differentiating factor between the two time slices attributable to the 2022 extremely high rainfall conditions. The spatial pattern for the relative shift was strongest for eastern sites north of the central city (Figure 4.2).

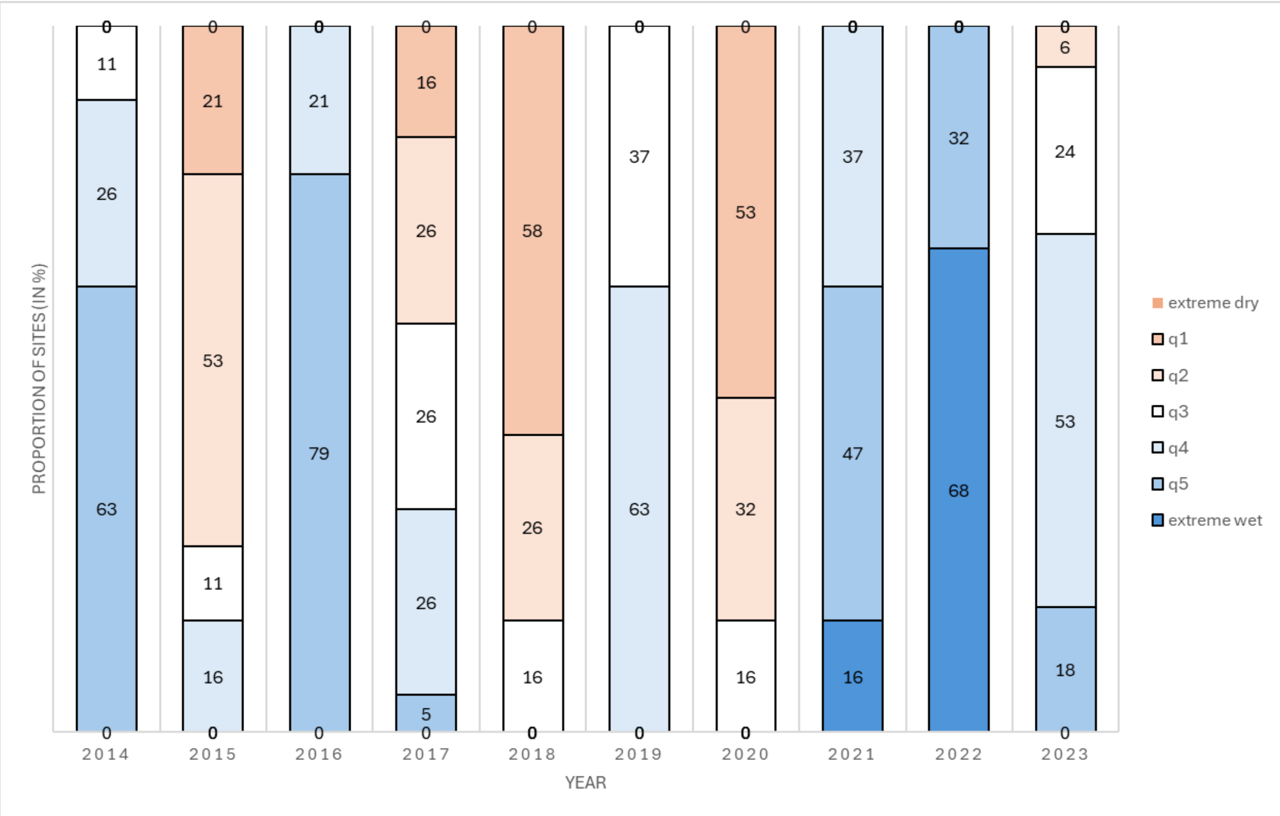


Figure 4.5 Proportion of long-term rainfall monitoring sites that had rainfall amounts for spring (September, October, November) in different quintiles in relation to 1991-2020. All seasons within the years covering the last SOE report and the current report are shown. Percentage of the total number of sites is indicated within each color-coded quintile segment. Zero values at the top and the bottom of each year indicate specific quintiles or extreme observations outside the five quintile ranges based on climatology were absent. See colour coding for details.

Exceptional rainfall anomalies characterised two of the summers within the SOE2025 reporting interval. The first was very dry conditions for the 2019-20 summer that caused a drought, and the second was record-shattering rainfall over summer 2022-23. In both cases, 95% of the sites with long-term rainfall observations experienced q1 and above q5 rainfall, respectively (Figure 4.6). Each of these events will be covered in detail below. In the absence of the exceptionally wet 2022-23 summer, it is highly likely that regional rainfall deficits for Auckland with respect to the previous SOE reporting interval would have been much more dramatic. The largest swing in rainfall amounts from SOE2020 to SOE2025 are seen in central and northeastern locations (Figure 4.1).

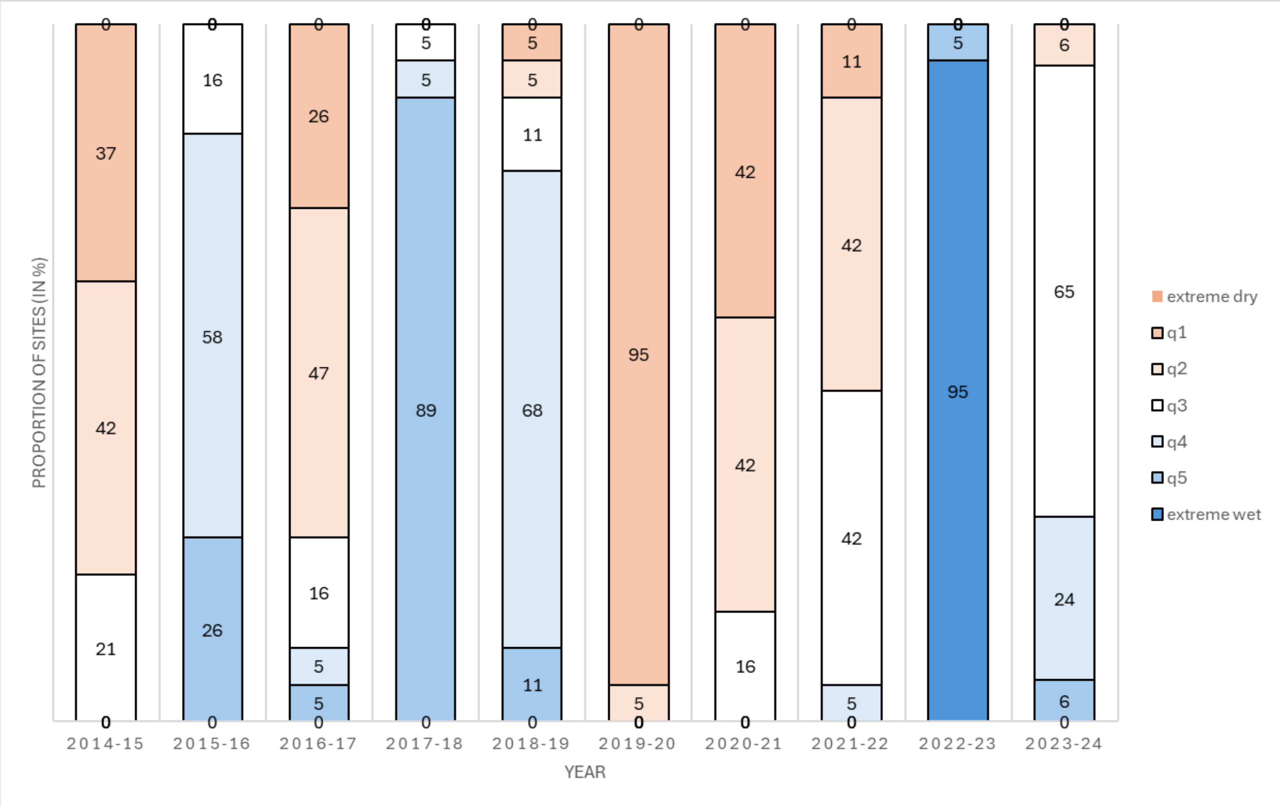


Figure 4.6 Proportion of long-term rainfall monitoring sites that had rainfall amounts for summer (December, January, February) in different quintiles in relation to 1991-2020. All seasons within the years covering the last SOE report and the current report are shown. Percentage of the total number of sites is indicated within each color-coded quintile segment. Zero values at the top and the bottom of each year indicate specific quintiles relative to the climatological distribution or extreme observations outside the five quintile ranges were absent. See colour coding for details.

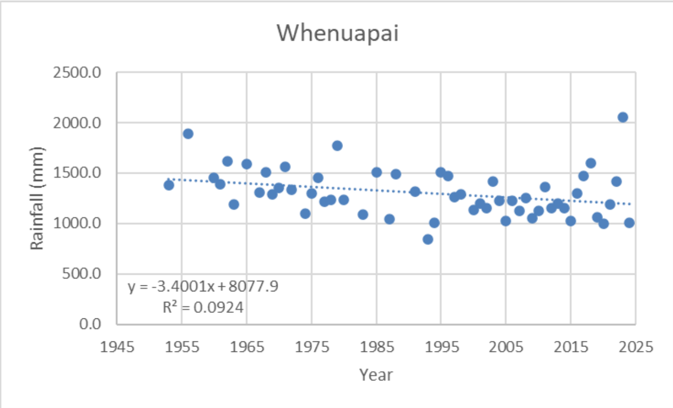
4.2.5 Long-term rainfall trends

Sites with long records in the northwest and northeastern part of Auckland show significant trends for lower rainfall for the hydrological year for the entire length of the record that was analysed (Table 4.6). Only Whenuapai shows a significant trend for the canonical (annual) year and autumn (Figure 4.9). Seasonally significant rainfall reduction is seen for Whenuapai at the 0.05 significance level. The significant trend observed for Mahurangi Warkworth Sewerage (hydrological year; Figure 4.8) and Ngakoroa (annual; Figure 4.7) could be due to an artefact arising from compositing, so these trends need to be interpreted with caution. The most southern and southeastern sites with significant trends show increasing rainfall amounts during winter and spring (at the 0.1 significance level), with a more significant trend being observed in winter at Waihihi and during spring at Ngakoroa (Figure 4.10 and Figure 4.11). No significant linear rainfall trends were observed for any of the Auckland Council rainfall sites for summer across their entire record.

Table 4.6. Long-term Auckland Council rainfall observing sites that exhibited significant linear trends for rainfall amount. March-April-May (MAM), June-July-August (JJA), September-October-November (SON).

	Annual			Hydrological year			MAM			JJA			SON		
Site	***a***	***b***	***c***	***a***	***b***	***c***	***a***	***b***	***c***	***a***	***b***	***c***	***a***	***b***	***c***
Kaipara					-	-		-	-			-			
Whenuapai	-	-	-	-	-	-		+	+						
Mahurangi WS						-									
Ngakoroa			+									+		+	+
Waihihi											+	+			+

a=sig 0.01; b=sig 0.05; c=sig 0.10



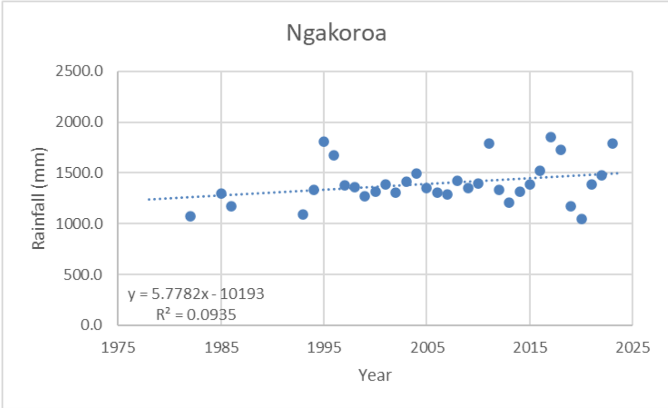
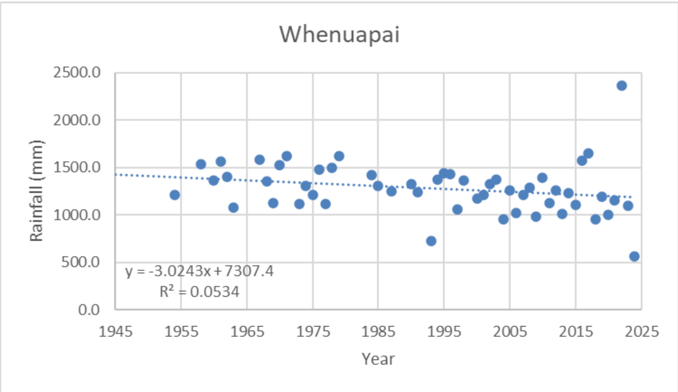


Figure 4.7 Annual rainfall trends that are significant for the selected sites used in SOE2025. See Table 4.6 for significance level achieved for Mann-Kendall tests, and Table 2.1 for details about temporal coverage of observations.



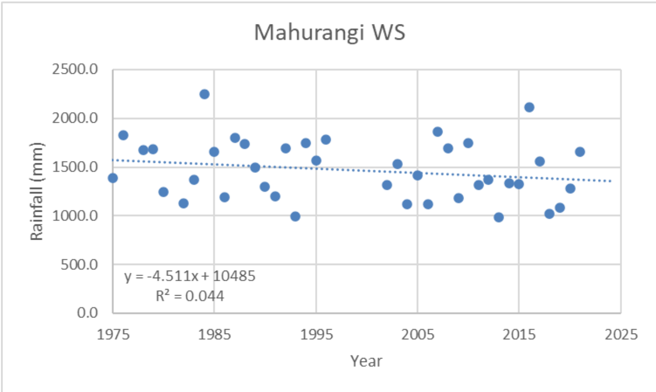


Figure 4.8 Hydrological year rainfall trends that are significant for the selected sites used in SOE2025. See Table 4.6 for significance level achieved for Mann-Kendall tests, and Table 2.1 for details about temporal coverage of observations. Mahurangi is a composite site that should be interpreted with caution.

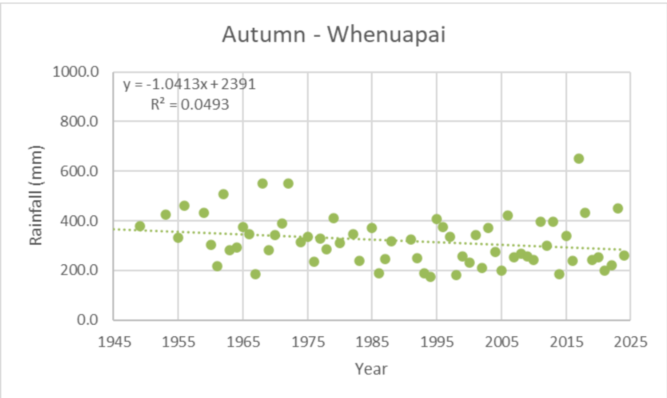


Figure 4.9 Autumn rainfall trends that are significant for the selected sites used in SOE2025. See Table 4.6 for significance level achieved for Mann-Kendall tests, and Table 2.1 for details about temporal coverage of observations.

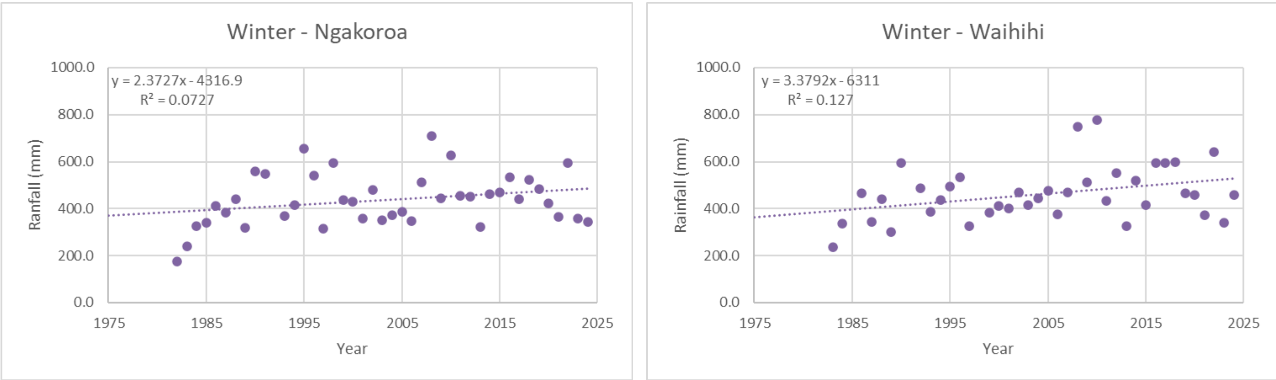


Figure 4.10 Winter rainfall trends that are significant for the selected sites used in SOE2025. See Table 4.6 for significance level achieved for Mann-Kendall tests, and Table 2.1 for details about temporal coverage of observations.

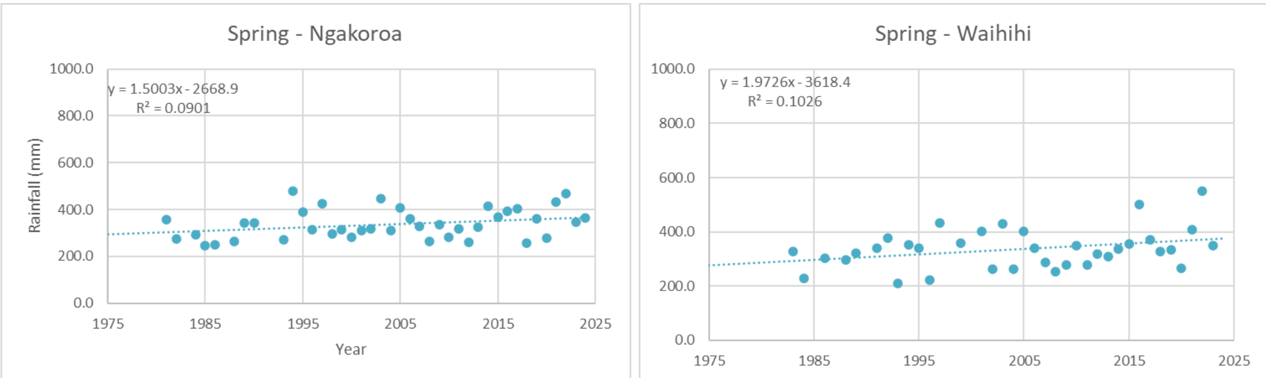


Figure 4.11 Spring rainfall trends that are significant for the selected sites used in SOE2025. See Table 4.6 for significance level achieved for Mann-Kendall tests, and Table 2.1 for details about temporal coverage of observations.

4.3 Soil moisture

4.3.1 Average annual, hydrological year and seasonal soil moisture percentages during SOE2025

For the SOE2025 analysis period, including years and seasons between 2019-2024, the selected Auckland Council soil moisture monitoring sites showed five-year average values that were mostly close to normal (Table 4.7). The average soil moisture percentages also adhered to seasonal cycles typical of higher soil moisture content during winter and spring and lower soil moisture occurring during summer and autumn. The highest average soil moisture was observed at Ararimu for winter, while the lowest average soil moisture observed at Tomarata during summer. The modest differences for the soil moisture anomalies (with reference to the short-term average) relates to the abbreviated length of the soil moisture observations. On average, Tomarata also showed lower overall soil moisture percentages relative to other sites across all seasons (Table 4.8).

Table 4.7. The average soil moisture percentage for Auckland Council monitoring sites during all years and seasons within SOE2025.

Site	Annual	Hydro	Autumn	Winter	Spring	Summer
Tomarata	35	36	30	44	40	29
Hoteo	40	40	34	45	46	35
Tamahunga	46	46	44	50	48	42
Kaipara	35	36	33	39	37	33
Ararimu	46	47	42	52	50	42
Mt Albert	43	43	39	46	46	39
Awhitu	45	45	43	47	46	43
Whangamaire	45	45	43	47	46	43
Waitangi	34	34	34	35	34	33

Table 4.8. Short-term climate average for soil moisture anomalies for Auckland Council monitoring sites during SOE2025. These percentages are based on values shown in Table 4.7 with reference to short-term climate averages that are shown in Table 3.3. For example, a 100% soil moisture anomaly for Hoteo is equivalent to a 40% soil moisture percentage level at that site from Table 4.7. Note, all SOE2025 values are also included in the short-term climate average due to brevity of soil moisture observations in Auckland.

Site	Annual	Hydro	Autumn	Winter	Spring	Summer
Tomarata	95	95	89	97	96	95
Hoteo	100	100	94	98	101	102
Tamahunga	101	101	99	101	101	103
Kaipara	101	101	96	99	101	101
Ararimu	103	103	100	103	103	105
Mt Albert	98	98	95	98	100	99
Awhitu	101	101	99	100	101	101
Whangamaire	98	98	97	98	98	99
Waitangi	99	99	99	100	99	99

4.3.2 Comparison of soil moisture between SOE2025 and SOE2020

Only modest soil moisture changes between SOE2020 and SOE2025 occurred, with the most noticeable change being lower average annual and hydrological year soil moisture at Tomarata (Table 4.9). Hoteo, Whangamaire and Mt Albert also showed subtle signs of annual soil moisture averages being lower in SOE2025 than during SOE2020, with the largest seasonal shift for those sites observed during autumn. Ararimu showed a subtle positive shift for average soil moisture conditions since SOE2025 with indications that winter, spring and summer contributed to that overall average soil moisture change (Table 4.9). When viewed through a lens of what the overall percentage swing for soil moisture was relative to SOE2020 conditions, most years and seasons for most sites were close to normal or showed a reduction of soil moisture except for Ararimu and to a lesser extent Awhitu (Table 4.10).

Table 4.9. Shift in soil moisture percentage (absolute values) based on 5-year average soil moisture percentages for SOE2025 relative to SOE2020. Negative values show a reduction in overall average soil moisture percentage while positive values show an increase in the average soil moisture percentage.

Site	Annual	Hydro year	Autumn	Winter	Spring	Summer
Tomarata	-6	-5	-10	-4	-4	-4
Hoteo	-2	0	-6	-2	2	1
Tamahunga	1	1	-1	1	2	2
Kaipara	0	0	-2	0	1	1
Ararimu	2	3	-1	3	3	4
Mt Albert	-2	-2	-5	-2	0	0
Awhitu	1	1	0	1	1	1
Whangamaire	-2	-2	-3	-2	-2	-1
Waitangi	0	0	-1	0	0	-1

Table 4.10. Shift in soil moisture percentage based on 5-year average soil moisture percentages for SOE2025 period relative to SOE2020. Negative values indicate there was a shift toward lower soil moisture percentages and positive values indicate a shift to higher soil moisture values.

Site	Annual	Hydro year	Autumn	Winter	Spring	Summer
Tomarata	-19	-14	-30	-10	-10	-14
Hoteo	-4	-1	-17	-4	4	4
Tamahunga	1	3	-3	3	4	4
Kaipara	0	1	-6	-1	2	2
Ararimu	5	7	-2	7	7	9
Mt Albert	-5	-4	-12	-5	0	-1
Awhitu	2	2	0	1	2	3
Whangamaire	-5	-3	-7	-4	-4	-3
Waitangi	-1	-1	-2	0	-1	-2

4.3.3 Regional variability of soil moisture during SOE2025 and comparison to SOE2020

To evaluate the SOE2025 vs SOE2020 snapshot changes in more detail, and to view the spatial differences across the sites, each year and season with available soil moisture observations were compiled. For the annual average soil moisture percentage change, the signature at Tomarata is largely guided by the years in SOE2020 that had higher soil moisture percentages relative to lower year averages in SOE2025. Hoteo, Mt Albert and Whangamaire follow a similar temporal pattern, but with average soil moisture percentage anomalies within each of the SOE reporting intervals that were not as large (Table 4.11). The relatively high annual percent anomalies seen in 2022 at some sites and in 2023 at most sites were countered by three years of relatively lower soil moisture percentage in the other three years used in generating SOE2025 annual soil moisture percent averages. The hydrological year site and temporal pattern is like what is observed for the annual pattern, but to a slightly lesser intensity (Table 4.12).

Table 4.11. Annual % anomaly of soil moisture from short-term average. Shading in the cells is used to emphasise the categorisation of soil moisture anomalies (% of short-term average based on the entire record) using breakpoints corresponding to well below (<80%), below (80-89%), above (110-119%) and well above (>120%) average. Grey cells = missing observations.

Year	Tomarata	Hoteo	Tamahunga	Kaipara	Ararimu	Mt Albert	Awhitu	Whangamaire	Waitangi
2014									
2015	112		95	100	89		97	100	98
2016	122	104	103	99	97	96	99	105	101
2017	109	105	101	102	99	107	100	103	101
2018	114	103	103	103	108	106	102	105	102
2019	100	95	98	95	96	98	98	97	102
2020	85	93	96	93	96	89	97	95	98
2021	96	97	101	98	103	96	100	98	100
2022	98	99	104	103	107	99	101	98	100
2023	109	115	109	110	115	111	107	104	100

Table 4.12. Hydrological year % anomaly of soil moisture from short-term average. Shading in the cells is used to emphasise the categorisation of soil moisture anomalies (% of short-term average based on the entire record) using breakpoints corresponding to well below (<80%), below (80-89%), above (110-119%) and well above (>120%) average. Grey cells = missing observations.

Year	Tomarata	Hoteo	Tamahunga	Kaipara	Ararimu	Mt Albert	Awhitu	Whangamaire	Waitangi
2014			96	102	94		98	100	99
2015	121		100	97	91		97	102	100
2016	108	105	100	101	99	104	100	103	102
2017	110	102	101	102	102	104	100	104	101
2018	98	95	97	94	98	99	98	99	101
2019	87	94	95	93	94	92	97	95	99
2020	90	92	98	95	100	91	98	96	98
2021	96	95	102	100	102	94	100	97	99
2022	107	112	108	111	116	109	106	103	101
2023	95	104	104	105	105	104	104	102	99

On a seasonal level, the soil moisture percentage anomalies observed during individual years within SOE2025 were most prominent during autumn and summer (Table 4.13 and Table 4.16), and much less so for winter and spring (Table 4.14-Table 4.16). The relatively short period of soil moisture observations means the calculated anomalies for soil moisture percentages are likely to change in years ahead. However, the temporal and spatial patterning shows regionally pervasive impacts of the 2019-20 drought at most sites, and how that impact was reflected most strongly during autumn 2020. Tomarata showed the biggest soil moisture percentage reduction in summer 2022-23 and in autumn 2023. In addition, the very wet summer 2022-23 and autumn 2023 periods show up for most sites and likely reflect the occurrence of repeated very high rainfall through summer 2022-23. In addition, these two different soil moisture signatures show how a relative counterbalance of extreme years and seasons operates when annual and hydrological year averages are considered (Table 4.11 and Table 4.12).

Table 4.13. Autumn % anomaly of soil moisture from short-term average. Shading in the cells is used to emphasise the categorisation of soil moisture anomalies (% of short-term average based on the entire record) using breakpoints corresponding to well below (<80%), below (80-89%), above (110-119%) and well above (>120%) average. Grey cells = missing observations.

Year	Tomarata	Hoteo	Tamahunga	Kaipara	Ararimu	Mt Albert	Awhitu	Whangamaire	Waitangi
2014									
2015	94		92	102	92		97	99	99
2016	135	106	104	94	95	91	96	106	101
2017	127	120	107	109	108	122	103	106	103
2018	117	107	106	103	113	108	102	105	102
2019	91	88	95	85	90	94	95	95	101
2020	58	89	88	87	87	84	94	93	98
2021	87	90	99	93	99	92	99	97	99
2022	92	88	104	98	102	89	98	95	98
2023	115	116	111	117	121	116	110	106	101

Table 4.14. Winter % anomaly of soil moisture from short-term average. Shading in the cells is used to emphasise the categorisation of soil moisture anomalies (% of short-term average based on the entire record) using breakpoints corresponding to well below (<80%), below (80-89%), above (110-119%) and well above (>120%) average. Grey cells = missing observations.

Year	Tomarata	Hoteo	Tamahunga	Kaipara	Ararimu	Mt Albert	Awhitu	Whangamaire	Waitangi
2014			97	100	92		98	101	100
2015	109		97	99	88		98	99	99
2016	105	99	100	99	96	94	98	103	100
2017	108	106	100	101	99	109	100	103	100
2018	105	102	98	101	104	106	101	103	101
2019	100	94	100	97	96	98	99	97	101
2020	103	93	100	99	102	91	98	95	100
2021	93	95	101	95	102	94	100	98	99
2022	91	96	101	100	107	101	101	98	100
2023	96	110	103	105	106	105	104	101	100

Table 4.15. Spring % anomaly of soil moisture from short-term average. Shading in the cells is used to emphasise the categorisation of soil moisture anomalies (% of short-term average based on the entire record) using breakpoints corresponding to well below (<80%), below (80-89%), above (110-119%) and well above (>120%) average. Grey cells = missing observations.

Year	Tomarata	Hoteo	Tamahunga	Kaipara	Ararimu	Mt Albert	Awhitu	Whangamaire	Waitangi
2014	108		98	103	99		100	102	102
2015	112	87	94	97	88		95	99	99
2016	109	104	101	101	98	98	100	103	101
2017	103	101	98	99	97	101	100	103	101
2018	100	97	98	94	99	100	99	101	100
2019	103	99	100	97	99	99	100	98	101
2020	87	92	97	95	98	89	96	95	97
2021	101	103	102	104	105	101	102	99	100
2022	96	104	103	106	109	102	102	99	100
2023	93	110	105	101	105	106	104	100	99

Table 4.16. Summer % anomaly of soil moisture from short-term average. Shading in the cells is used to emphasise the categorisation of soil moisture anomalies (% of short-term average based on the entire record) using breakpoints corresponding to well below (<80%), below (80-89%), above (110-119%) and well above (>120%) average. Grey cells = missing observations.

Year	Tomarata	Hoteo	Tamahunga	Kaipara	Ararimu	Mt Albert	Awhitu	Whangamaire	Waitangi
2014	123		95	101	92		98	100	97
2015	134	102	103	98	92	95	98	105	99
2016	86	94	93	94	92	99	97	101	102
2017	106	95	102	106	102	102	98	103	102
2018	97	102	98	99	101	104	101	101	104
2019	70	94	94	89	89	90	96	92	99
2020	76	93	94	92	100	92	97	95	98
2021	92	91	99	100	99	94	100	97	98
2022	131	132	118	119	129	120	109	107	103
2023	106	100	108	106	108	100	106	104	99

4.4 Rivers

4.4.1 Summary flow statistics

Summary flow statistics for the full record, the most recent ten-year period and the current SOE2025 reporting period are provided in Table 4.19. As discussed in the methods these statistics provide a general overview of flows for each catchment, and they can be used to evaluate general changes in flows between SOE2020 and SOE2025 reporting intervals (Table 4.20). The largest maximum flows occurred at 33 of the 41 (80 %) sites within the SOE2025 reporting window. Sites that did not record the highest instantaneous maximum during SOE2025 reporting window were Mangawheau, Ngakoroa, Papakura, Paremuka, Tamahunga, Tāmaki, Wairau at Chartwell and the Waititi rivers (See Figure 2.1 for locations and Table 2.3 for site details).

The lowest minimum flow on record was equalled at 19 sites during SOE2025. The mean and median flows were elevated during SOE2025 relative to the SOE2020 records at 68% and 61% of sites respectively (Table 4.20). Close to 44% of flow monitoring sites experienced lower $MALF_7$ during SOE2025 relative to the SOE2020 data. Of the sites analysed, 51% experienced an increase in baseflow, with Kaukapakapa, Mahurangi and Mairangi showing a moderate baseflow increase while Oakley and West Hoe showed the most significant change in baseflow relative to SOE2020. However, only five of these sites had a relative change that was noticeable beyond a longer-term average (Te Muri, Rangitopuni, Oratia, Kaipatiki, Kaipara) or with a reduction that was much more significant (Opanuku). Most sites showed a shift towards lower BFI values for SOE2025, but most of the change for this index was within a range close to what occurred during SOE2020. RBI changes were relatively modest from SOE2020 to SOE2025, with only Orewa and Kaipara showing appreciable increases for that index (Table 4.20). We consider these changes with respect to other metrics and climate variability below in the Discussion.

The pairwise correlations for base statistics of Auckland's rivers were undertaken over the full length of each record. This shows significant relationships exist between all flow categories that describe different tendencies, specific partitions, or extremes of flow (inclusive of maximum, minimum, mean, median, Q5 and $MALF_7$; Figure 4.12). These base statistics are poorly correlated to BFI, RBI and catchment area, and only BFI/RBI and RBI/area are significantly correlated.

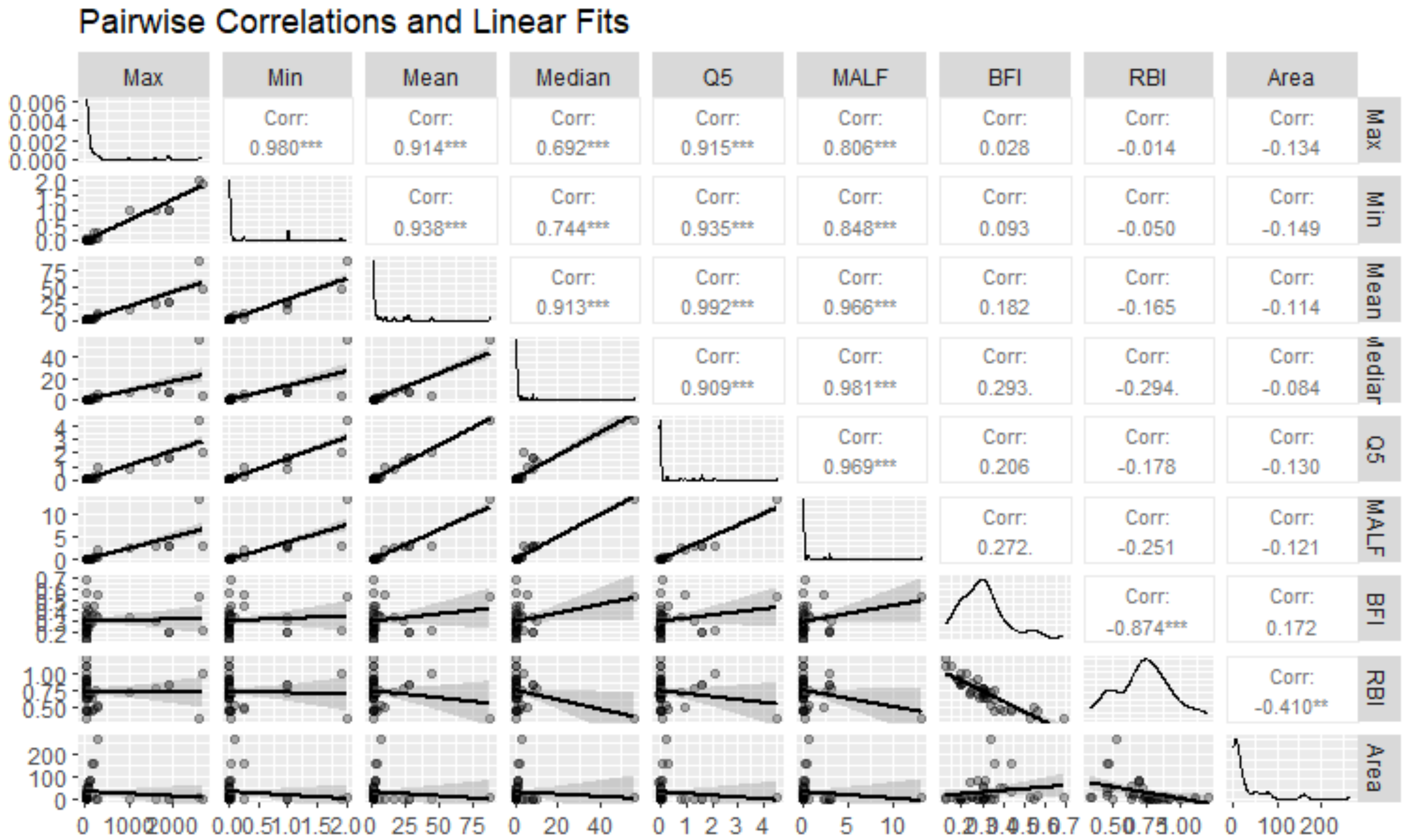


Figure 4.12 Correlation matrix of flow variables for Auckland Council observing sites used in SOE2025. Q5 – 5-year 7 day low; MALF – Mean annual low flow; BFI – Baseflow index; RBI – Richards-Baker Index.

Table 4.17. Base statistics for the full extent of each record ending July 2024. Flow statistics (Maximum, minimum, mean, median, baseflow and $MALF_7$) are in litres/second. See methods section for calculations of Baseflow Index (BFI) and Richards-Baker Index (RBI).

Site	Maximum	Minimum	Mean	Median	MALF7	Baseflow	BFI	RBI
Alexandra	32732.8	0.1	63.72	16.7	3.7	11.62	0.18	0.91
Awaruku stream	23422.4	0.3	27.38	7.1	1.63	5.51	0.2	0.87
Eskdale Stream	23845.6	1.9	65.96	22.7	7.93	19.54	0.3	0.77
Hoteo River	306567.9	58.7	6044.4	2600.05	513.7	2080.6	0.34	0.53
Kaipara River	438674.3	32.4	3035.78	1228.8	181.25	1070.91	0.35	0.47
Kaipatiki Stream	8308.4	0.1	24.23	8.9	2.98	7.36	0.3	0.78
Kaukapakapa	216426.4	4.6	1267.4	467.4	33.58	384.49	0.3	0.65
Kourawhero	204550.3	2	1585.15	514.9	76.72	362.31	0.22	0.74
Kumeu	56189.1	1.1	933.48	405	41.35	363.79	0.39	0.49
Lucas	76704.1	0.1	151.58	41.7	8.51	27.95	0.18	0.89
Mahurangi	247257.7	13.8	1210.54	442	93.64	361.56	0.3	0.73
Mairangi Bay Stream	8471.6	0.8	16.07	6.6	2.22	5.41	0.34	0.73
Mangawheau Stream	167726.5	14.4	703.67	369.5	91.99	308.12	0.44	0.46
Mangemangeroa	22961.7	0.1	61.34	20.3	1.77	18.44	0.3	0.63
Meola Creek	41629.3	2.8	187.97	111.6	48.54	104.99	0.56	0.47
Motions Stream	68239.5	0.1	261.34	199	122.45	178.72	0.68	0.36
Newmarket Stream	53033.9	0.1	46.68	8.6	3.19	6.17	0.13	1.19
Ngakoroa Stream	9044.2	1.7	89.06	55.2	11.75	47.55	0.53	0.34
Oakley Creek	26141	2.5	168.64	59	27.4	51.83	0.31	0.76
Opanuku	86070.1	24.9	680.51	278.9	58.93	204.32	0.3	0.69
Opanuku Stream	154288.7	0.1	479.77	165.9	41.13	137.87	0.28	0.62
Oratia	143333.3	9.4	608.04	293.1	63.28	216.03	0.36	0.64
Orewa	113465.7	0.1	194.45	63.9	1.09	47.99	0.25	0.75
Otara	69482.4	3.4	361.04	120.7	20.41	88.25	0.24	0.74
Oteha River	161699.7	0.7	247.28	68.1	17.33	48.16	0.19	0.92
Papakura	86503.8	0.2	845.95	401.4	59.68	331.53	0.39	0.46
Paremuka Stream	9625	0.4	45.94	3.6	2.97	9.52	0.21	0.99
Puhinui	66466	0.2	207.07	85.7	20.5	62.68	0.3	0.74
Rangitopuni River	311137.9	0.1	1472.27	508.6	35.92	410.54	0.28	0.69
Swanson Stream	154705.3	9.2	535.17	242.9	27.32	170.2	0.31	0.67
Taiaotea stream	15491	0.3	60.93	10.1	3.18	7.64	0.13	1.07
Taiorahi Stream	10757.1	0.1	27.46	6.4	2.6	5.49	0.2	0.86
Tamahunga River	94387.1	0.1	199.22	53.8	7.91	41.63	0.21	0.86
Tamaki Trib	18863.6	5.1	67.6	15.9	8.36	13.27	0.2	1
TE MURI	5227.5	0.1	4.3	1.9	0.67	1.58	0.37	0.75
Vaughn Stream	18189.6	0.1	35.71	11.6	0.75	9.8	0.28	0.8
Wairau Creek (Chartwell)	28775.3	0.3	33.27	11.6	4.93	9.19	0.28	0.92
Wairau Creek (Motorway)	142093	1	249.27	53.3	15.95	38.31	0.15	1.07
Wairoa River	475098.5	117.3	2684.51	1409.3	441.56	1179.01	0.44	0.48
Waitangi	37330.5	16.7	246.12	143.7	42.11	141.51	0.57	0.35
Waiteitei River	228556.2	20	1696.85	556.5	144.22	532.85	0.31	0.69
West Hoe	3636.6	0.4	9.82	4.7	2.15	5.34	0.54	0.51
Whau Stream	27996.7	0.1	105.64	34	12.13	26.25	0.24	0.84

*Table 4.18. Base statistics from July 2014 to July 2024. All sites start at the beginning of July unless noted (with *), which will be the beginning of that record (sometime after 1 July 2014 – see Table 2.3 for details). Units are in litres/second.*

Site	Maximum	Minimum	Mean	Median	MALF7	Baseflow	BFI	RBI
Alexandra	32732.8	0.30	86.48	20.60	4.91	13.68	0.16	0.88
Awaruku stream	23422.4	0.40	30.25	7.90	1.85	5.81	0.19	0.90
Eskdale Stream	23845.6	1.90	69.94	24.60	9.02	20.31	0.29	0.78
Hoteo River	296860.2	97.30	6586.85	2767.30	557.07	2184.93	0.33	0.52
Kaipara River	438674.3	35.80	3294.51	1214.60	209.50	1100.51	0.34	0.49
Kaipatiki Stream	8308.4	0.10	25.85	10.00	3.70	7.91	0.31	0.78
Kaukapakapa	216426.4	4.60	1356.83	516.50	45.95	402.42	0.30	0.64
Kourawhero *	204550.3	2.00	1579.29	520.50	76.72	363.02	0.22	0.73
Kumeu	56189.1	1.10	934.79	407.20	41.35	364.11	0.39	0.49
Lucas	76704.1	0.10	162.34	46.00	10.34	29.75	0.19	0.89
Mahurangi	247257.7	13.80	1311.02	476.80	107.30	377.33	0.29	0.74
Mairangi Bay Stream	8471.6	0.80	17.58	7.50	2.57	5.75	0.33	0.74
Mangawheau Stream	107666.7	14.40	744.10	387.60	101.29	305.38	0.41	0.47
Mangemangeroa	22961.7	0.10	67.27	20.80	2.92	18.02	0.27	0.67
Meola Creek	41629.3	23.20	212.85	120.40	55.47	113.00	0.53	0.47
Motions Stream	68239.5	0.10	289.27	212.80	132.60	184.91	0.64	0.41
Newmarket Stream	53033.9	0.10	47.39	8.90	3.57	6.47	0.14	1.20
Ngakoroa Stream	6476.7	3.70	92.22	53.00	14.22	46.27	0.50	0.37
Oakley Creek	26141	2.50	241.45	93.60	49.47	80.59	0.34	0.76
Opanuku	86070.1	24.90	718.88	292.60	76.32	215.87	0.30	0.68
Opanuku Stream	154288.7	0.10	517.83	139.20	38.14	118.07	0.22	0.62
Oratia	143333.3	9.40	564.46	263.60	57.80	195.69	0.35	0.64
Orewa	113465.7	0.10	211.84	58.60	1.43	47.59	0.23	0.77
Otara	69482.4	13.10	459.37	153.60	36.18	95.26	0.21	0.77
Oteha River	161699.7	0.70	351.83	72.30	23.23	47.88	0.14	1.02
Papakura	61725.6	15.80	955.61	433.50	76.91	338.68	0.36	0.50
Paremuka Stream	9625	0.40	20.40	3.30	2.61	3.10	0.15	1.40
Puhinui	66466	7.90	241.88	97.50	26.68	66.33	0.28	0.77
Rangitopuni River	311137.9	3.40	1496.26	496.70	49.16	415.37	0.28	0.69
Swanson Stream	154705.3	14.20	566.71	255.50	41.91	177.13	0.31	0.71
Taiaotea stream	15491	0.30	74.54	10.90	3.25	7.52	0.10	1.08
Taiorahi Stream	10757.1	0.10	31.04	7.00	2.76	5.83	0.19	0.83
Tamahunga River	50896.9	0.10	221.38	60.50	10.62	48.09	0.22	0.88
Tamaki Trib	18824.2	5.10	68.94	16.40	8.42	13.48	0.20	1.01
TE MURI*	5227.5	0.10	4.41	2.00	0.52	1.60	0.36	0.76
Vaughn Stream	18189.6	0.10	33.05	8.80	1.22	7.01	0.22	0.81
Wairau Creek (Chartwell)	27777.6	0.70	35.30	5.40	2.49	5.00	0.14	1.07
Wairau Creek (Motorway)	142093	12.00	295.09	63.70	22.84	45.92	0.16	1.05
Wairoa River	475098.5	255.60	2805.48	1462.60	431.41	1201.63	0.43	0.49
Waitangi	37330.5	16.70	259.74	150.90	45.48	144.79	0.56	0.39
Waiteitei River	184830.1	20.00	1615.03	405.70	127.32	398.07	0.25	0.81
West Hoe	3636.6	0.70	11.30	5.10	2.70	6.75	0.60	0.42
Whau Stream	27996.7	0.10	110.13	33.40	11.46	24.26	0.21	0.85

*Table 4.19. Base statistics for SOE2025. All sites start at the beginning of July unless noted (with *), which will be the beginning of that record (sometime after 1 July 2014– see Table 2.3 for details). Units are in litres/second. Kumeu had too many missing years to qualify for SOE2025 timeslice analysis.*

Site	Maximum	Minimum	Mean	Median	MALF7	Baseflow	BFI	RBI
Alexandra	32732.80	1.70	106.86	20.80	4.45	12.61	0.12	0.88
Awaruku stream	23422.40	0.40	31.88	8.20	1.85	5.78	0.18	0.93
Eskdale Stream	23845.60	1.90	72.39	24.80	8.39	19.26	0.27	0.81
Hoteo River	296860.20	97.30	7279.16	3074.70	546.52	2230.18	0.31	0.53
Kaipara River	438674.30	35.80	3134.48	1075.20	231.62	927.57	0.30	0.55
Kaipatiki Stream	8308.40	0.10	25.59	9.30	3.19	6.92	0.27	0.82
Kaukapakapa	216426.40	4.60	1602.39	604.00	48.22	450.32	0.28	0.64
Kourawhero *	204550.3	2.00	1579.29	520.50	76.72	363.02	0.22	0.73
Kumeu								
Lucas	76704.10	2.70	169.71	47.70	11.02	29.79	0.18	0.91
Mahurangi	247257.70	13.80	1551.95	548.70	102.31	413.66	0.27	0.77
Mairangi Bay Stream	8471.60	1.00	19.00	8.70	3.08	6.44	0.34	0.73
Mangawheau Stream	107666.70	19.90	706.45	379.60	105.02	293.31	0.42	0.45
Mangemangeroa	22961.70	0.10	65.98	23.20	2.49	19.09	0.29	0.65
Meola Creek	41629.30	31.50	236.76	122.10	57.12	120.05	0.51	0.48
Motions Stream	68239.50	0.10	295.33	207.10	126.84	180.12	0.61	0.44
Newmarket Stream	53033.90	0.10	50.36	8.80	3.49	6.35	0.13	1.23
Ngakoroa Stream	6476.70	4.20	84.34	50.50	13.23	41.91	0.50	0.35
Oakley Creek	26141.00	10.70	330.40	179.90	73.62	115.44	0.35	0.73
Opanuku	86070.10	24.90	717.29	284.00	78.37	214.38	0.30	0.68
Opanuku Stream	154288.70	0.10	639.76	83.20	21.24	81.82	0.12	0.58
Oratia	143333.30	9.40	525.49	218.00	39.23	164.64	0.31	0.67
Orewa	113465.70	0.10	244.95	62.60	1.68	47.27	0.19	0.85
Otara	69482.40	13.10	493.12	163.90	38.02	103.43	0.21	0.78
Oteha River	161699.70	10.90	435.12	74.20	23.87	49.08	0.11	1.10
Papakura	59160.70	15.80	943.53	433.20	80.79	330.30	0.35	0.49
Paremuka Stream	9625.00	2.30	21.03	3.30	2.64	3.07	0.14	1.44
Puhinui	66466.00	13.00	244.44	96.50	26.50	66.45	0.27	0.78
Rangitopuni River	311137.90	3.40	1468.28	487.35	43.56	364.36	0.25	0.72
Swanson Stream	154705.30	14.20	568.38	247.30	38.20	166.21	0.28	0.75
Taiaotea stream	15491.00	0.30	93.25	11.00	3.12	7.19	0.08	1.07
Taiorahi Stream	10757.10	0.10	35.63	7.70	2.91	5.70	0.16	0.79
Tamahunga River	50896.90	0.10	244.67	65.30	9.06	49.88	0.21	0.88
Tamaki Trib	18824.20	6.00	71.55	16.70	9.35	14.17	0.20	1.01
TE MURI	5227.50	0.10	4.09	1.80	0.23	1.33	0.33	0.78
Vaughn Stream	18189.60	0.10	39.51	11.20	1.22	6.97	0.18	0.79
Wairau Creek (Chartwell)	27777.60	0.70	35.08	5.40	2.71	5.47	0.16	1.10
Wairau Creek (Motorway)	142093.00	12.70	311.05	62.80	21.68	45.21	0.15	1.09
Wairoa River	475098.50	255.60	2795.28	1487.60	435.82	1160.85	0.42	0.49
Waitangi	37330.50	16.70	235.59	141.00	40.51	133.42	0.57	0.37
Waiteitei River	184830.10	20.00	1796.25	416.55	108.68	379.53	0.22	0.85
West Hoe	3636.60	0.70	15.50	6.20	3.51	9.64	0.62	0.39
Whau Stream	27996.70	0.10	120.40	33.40	11.11	25.62	0.19	0.83

Table 4.20. Differences between 2014-2024 and 2019-2024 for base statistics of river flows. Papakura had maximum flows that occurred outside the Auckland Anniversary 2023 event. Kourawhero and Kumeu are excluded due to QC and observations absence issues.

Site	Maximum	Minimum	Mean	Median	MALF7	Base Flow	BFI	RBI
Alexandra	0	-1.4	-19.99	-0.30	0.45	1.04	0.04	0.01
Awaruku stream	0	0	-1.69	-0.40	0.00	-0.01	0.01	-0.03
Eskdale Stream	0	0	-2.56	-0.50	0.63	1.00	0.02	-0.03
Hoteo River	0	0	-712.59	-307.60	10.55	-55.98	0.03	-0.01
Kaipara River	0	0	158.75	130.60	-22.12	172.41	0.04	-0.06
Kaipatiki Stream	0	0	0.19	0.70	0.51	0.94	0.03	-0.04
Kaukapakapa	0	0	-252.01	-97.00	-2.27	-49.69	0.01	0.00
Kourawhero								
Kumeu								
Lucas	0	-2.6	-7.88	-1.75	-0.68	-0.18	0.01	-0.02
Mahurangi	0	0	-244.12	-73.90	4.99	-37.14	0.02	-0.03
Mairangi Bay Stream	0	-0.2	-1.49	-1.20	-0.50	-0.72	-0.01	0.02
Mangawheau Stream	0	-5.5	38.13	5.65	-3.74	11.98	-0.01	0.02
Mangemangeroa	0	0	1.21	-2.50	0.43	-1.57	-0.03	0.02
Meola Creek	0	-8.3	-23.47	-1.90	-1.64	-7.31	0.02	0.00
Motions Stream	0	0	-6.16	5.30	5.76	4.61	0.03	-0.03
Newmarket Stream	0	0	-2.87	0.10	0.08	0.12	0.01	-0.03
Ngakoroa Stream	0	-0.5	7.85	1.80	1.00	4.21	0.00	0.02
Oakley Creek	0	-8.2	-88.38	-85.20	-24.15	-35.80	-0.02	0.03
Opanuku	0	0	0.63	5.50	-2.06	-0.01	0.00	0.01
Opanuku Stream	0	0	-114.29	57.20	16.91	37.65	0.10	0.04
Oratia	0	0	39.42	45.30	18.57	32.22	0.04	-0.03
Orewa	0	0	-34.20	-5.30	-0.25	-0.82	0.03	-0.07
Otara	0	0	-32.82	-9.90	-1.84	-8.23	0.00	0.00
Oteha River	0	-10.2	-82.87	-2.10	-0.64	-1.19	0.02	-0.07
Papakura	2564.9	0	11.80	-5.40	-3.88	6.27	0.00	0.01
Paremuka Stream	0	-1.9	-0.52	0.00	-0.03	0.02	0.01	-0.04
Puhinui	0	-5.1	-2.38	0.90	0.18	-0.55	0.00	-0.01
Rangitopuni River	0	0	20.07	-1.30	5.60	48.53	0.03	-0.03
Swanson Stream	0	0	-2.36	6.30	3.71	9.43	0.02	-0.04
Taiaotea stream	0	0	-18.54	-0.30	0.13	0.25	0.02	0.01
Taiorahi Stream	0	0	-4.53	-0.80	-0.15	0.11	0.03	0.04
Tamahunga River	0	0	-23.55	-5.50	1.56	-1.62	0.01	0.00
Tamaki Trib	0	-0.9	-2.63	-0.30	-0.94	-0.75	0.00	0.00
TE MURI	0	0	0.31	0.20	0.29	0.28	0.04	-0.04
Vaughn Stream	0	0	-6.81	-2.80	0.00	-0.38	0.03	0.02
Wairau Creek (Chartwell)	0	0	0.19	0.00	-0.21	-0.46	-0.01	-0.02
Wairau Creek (Motorway)	0	-0.7	-15.93	0.50	1.16	0.57	0.01	-0.04
Wairoa River	0	0	14.61	-31.40	-4.42	40.97	0.01	0.01
Waitangi	0	0	23.91	9.20	4.97	11.21	-0.01	0.02
Waiteitei River	0	0	-188.75	-12.40	18.64	16.11	0.04	-0.03
West Hoe	0	0	-4.15	-1.10	-0.81	-2.85	-0.02	0.04
Whau Stream	0	0	-10.16	-0.50	0.36	-1.44	0.02	0.02

4.4.2 Cluster and spatial analysis

The initial correlation matrix with all flow observations shows a high degree of correlation ($r > 0.9$) with between the maximum, minimum, mean, median and $MALF_7$ (Figure 4.12). The RBI, BFI and catchment area show a poor correlation for all parameters. A principal components analysis was conducted using catchment area, the RBI and the BFI to produce 3 Principal Components (PCs), with PC1 and PC2 representing 67% of the variance of those summary data categories. The variables that were initially poorly correlated (RBI, BFI, Catchment area) and $MALF_7$ as a representation of the maximum, minimum, mean and median were then used in k-means clustering, with optimal number of four assigned for the k-means algorithm. K-means analysis produced 4 clusters, and when they were tagged and plotted against PC1 and PC2, it was decided to group cluster 3 and 4 together for simplicity. As such, there are three catchment 'groups' for the Auckland region containing 13 catchments (Group 1; cluster 1), 11 catchments (Group 2; cluster 2) and 19 catchments (Group 3; clusters 3 and 4) respectively (Figure 4.13 shows the clusters and Figure 4.14 shows the spatial distribution).

The first catchment group is composed of almost entirely urban sites, except for Tamahunga at Quintals. Group 1 contains sites with a median area of 3.05 km^2, a median base flow value of 0.2 l/s and a median RBI value of 0.92 (Figure 4.13; Table 4.21). These catchments can be characterised as small with little base flow and high flashiness with a large proportion of impervious surface area, a quick time of concentration and a low groundwater contribution. Group 1 catchments are likely to be prone to impacts from extremes like flash floods and droughts, and are predominantly surface water fed. They will commonly have a flow response of similar magnitude and timing (time of concentration) that mirrors the occurrence of rainfall patterns experienced within the catchment.

The second catchment group is composed of mostly rural environments or includes high proportion of native forest, except for Motions at Western Spring, Meola Creek at Motions Weir and Papakura at Great South Road Bridge. Group 2 contains sites with a median area of 30.40 km^2, a median base flow value of 0.44 l/second and a median RBI value of 0.47 (Figure 4.13; Table 4.21). They are generally characterised by larger rivers and catchment areas with stronger base flow contributions and a lower flashiness index. Group 2 catchments have approximately equal amounts of groundwater and surface flow contributions to the flow. They are also likely to have pervious areas and are unlikely to be as susceptible to flash flooding and drought impacts as Group 1. These types of catchments are also expected to have a mixed response to rainfall, depending on the intensity of the rainfall within the catchment and antecedent conditions. Group 2 catchments are also expected to have a subdued response to small and less intense rainfall events, while larger and more intense rainfall events would appear delayed relative to a faster response for Group 1 catchments.

The third group is a mix of rural and urban catchments with a median area of 15.4 km^2, a median base flow value of 0.3 l/s and a median RBI value of 0.73 (Figure 4.13; Table 4.21). They are mid-size catchments that are more prone to flash flooding than Group 2 but not as susceptible to flash flooding as Group 1. These catchments are likely to have a higher groundwater contribution, making them more resilient to droughts than Group 1 but less resilient to droughts that Group 2. They are expected to have a flow response similar to but with a slightly delayed response to rainfall as Group 1 catchments, and with a quicker response to rainfall events than group 2 catchments.

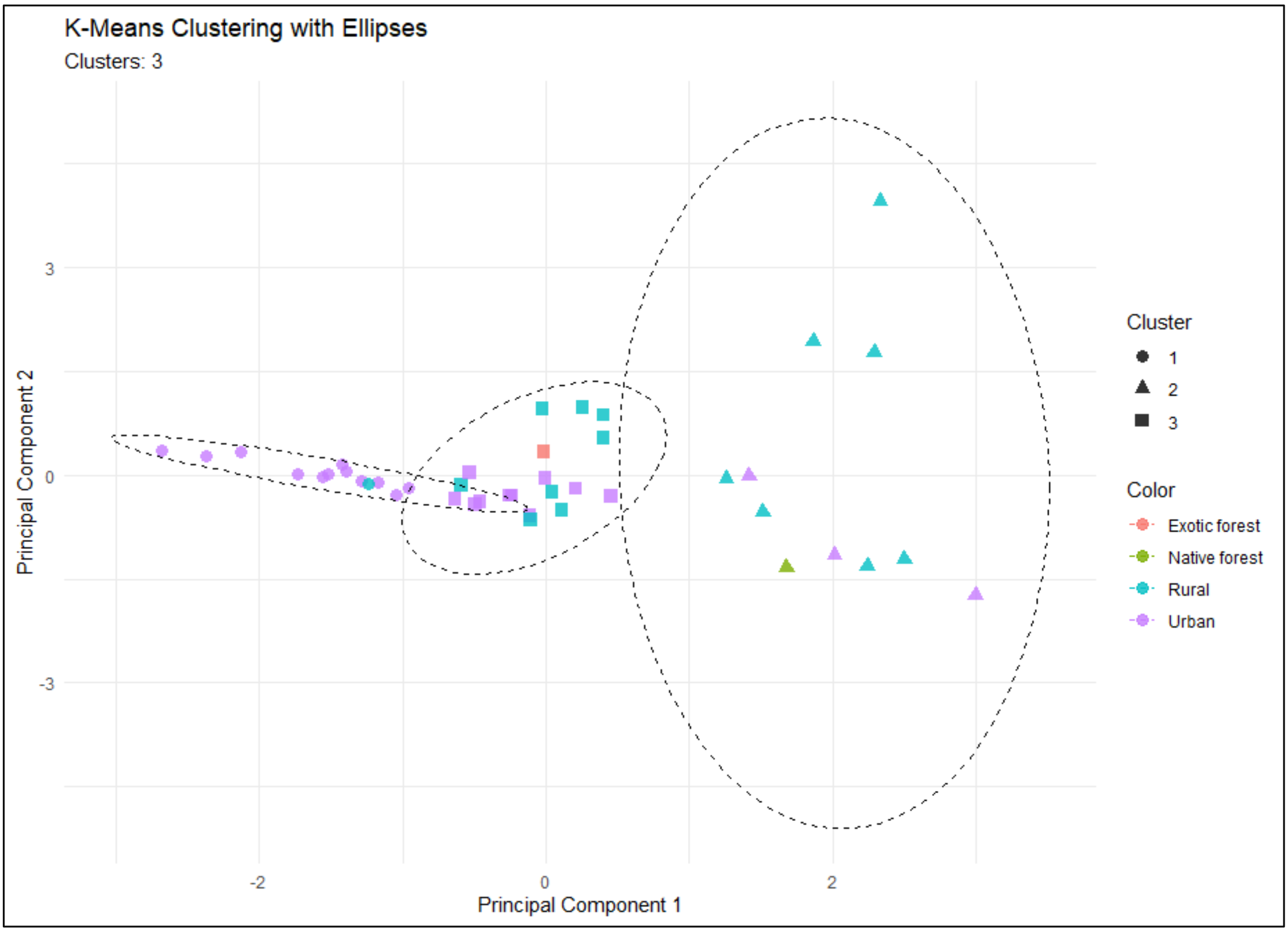


Figure 4.13 Cluster analysis identified using k-means based on the base statistics summary measures.

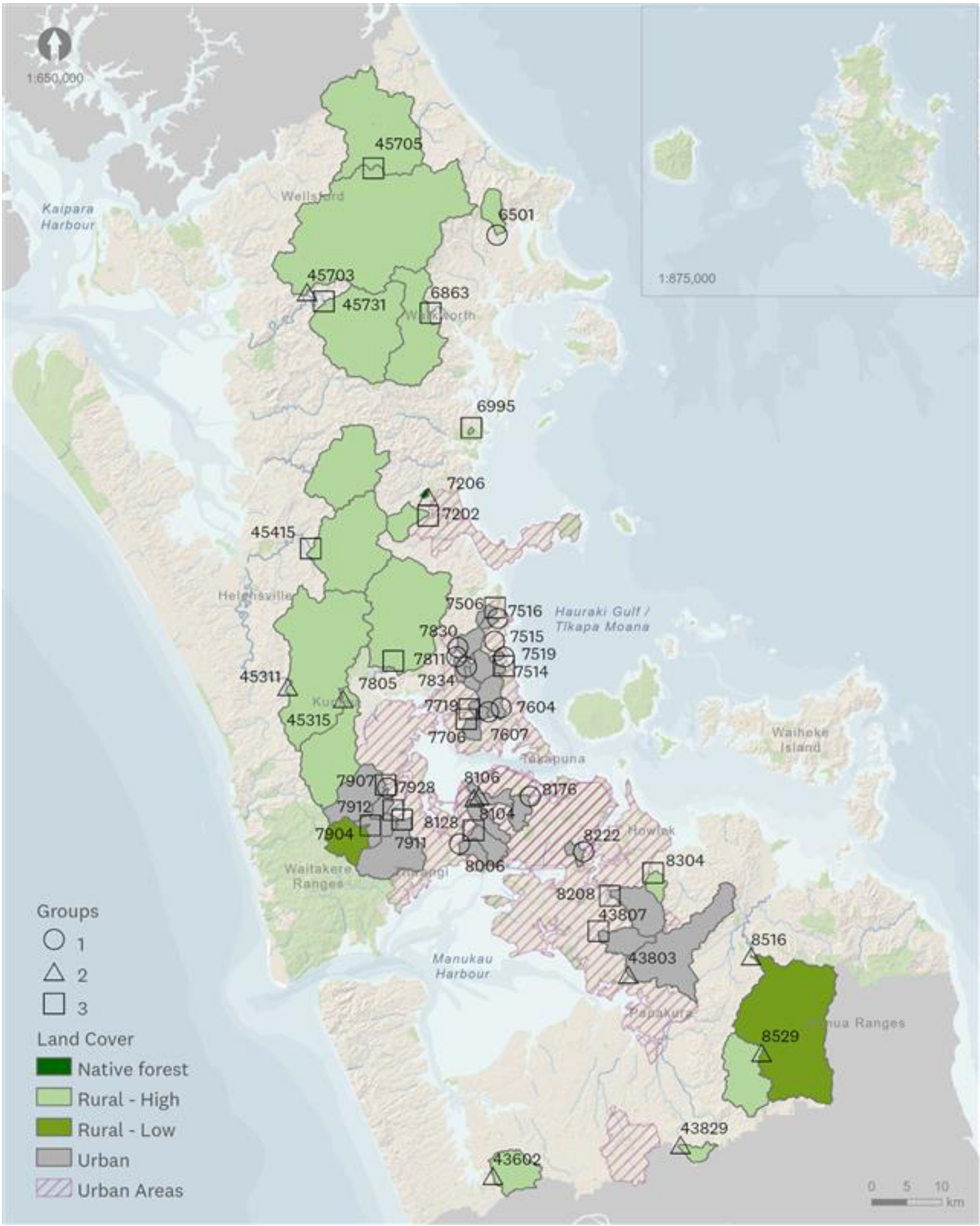


Figure 4.14 Cluster analysis based on k-means showing the spatial distribution of three main groups of catchments across the Auckland region. Rural – high (low) is more (less) than 50% cover exotic or native forestry cover remaining in the upstream/surrounding catchment.

Table 4.21. Catchment Area, Base Flow Index (BFI), Richards-Baker Index (RBI), catchment type and catchment grouping after principal component analysis and k-means clustering.

Site	Catchment Area (km^2)	BFI	RBI	Catchment type	Catchment group
Tamahunga River	7.97	0.21	0.86	Rural	1
Whau Stream	4.66	0.25	0.85	Urban	1
Wairau Creek (Motorway)	11.10	0.15	1.07	Urban	1
Wairau Creek (Chartwell)	1.40	0.28	0.91	Urban	1
Tamaki Trib	3.05	0.20	1.00	Urban	1
Taiorahi Stream	1.00	0.20	0.83	Urban	1
Taiaotea stream	2.20	0.13	1.08	Urban	1
Paremuka Stream	4.40	0.22	0.99	Urban	1
Oteha River	12.20	0.19	0.92	Urban	1
Newmarket Stream	5.50	0.13	1.19	Urban	1
Lucas	6.26	0.19	0.89	Urban	1
Awaruku stream	1.70	0.20	0.87	Urban	1
Alexandra	2.64	0.18	0.92	Urban	1
West Hoe	0.34	0.54	0.51	Native forest	2
Waitangi	17.60	0.57	0.35	Rural	2
Wairoa River	161.00	0.44	0.48	Rural	2
Ngakoroa Stream	4.73	0.53	0.34	Rural	2
Mangawheau Stream	30.40	0.44	0.46	Rural	2
Kumeu	47.60	0.38	0.49	Rural	2
Kaipara River	155.40	0.36	0.47	Rural	2
Hoteo River	268.00	0.34	0.53	Rural	2
Papakura	51.60	0.40	0.46	Urban	2
Motions Stream	7.50	0.69	0.36	Urban	2
Meola Creek	14.70	0.56	0.47	Urban	2
Mahurangi	46.90	0.30	0.73	Exotic forest	3
Waiteitei River	80.60	0.31	0.70	Rural	3
TE MURI	0.30	0.36	0.76	Rural	3
Rangitopuni River	81.50	0.28	0.69	Rural	3
Orewa	9.73	0.25	0.75	Rural	3
Opanuku Stream	15.45	0.29	0.65	Rural	3
Mangemangeroa	4.57	0.31	0.64	Rural	3
Kourawhero	73.59	0.24	0.70	Rural	3
Kaukapakapa	61.92	0.30	0.64	Rural	3
Vaughn Stream	2.30	0.28	0.80	Urban	3
Swanson Stream	22.60	0.32	0.65	Urban	3
Puhinui	11.60	0.31	0.74	Urban	3
Otara	18.90	0.24	0.74	Urban	3
Oratia	22.88	0.36	0.63	Urban	3
Opanuku	26.50	0.30	0.69	Urban	3
Oakley Creek	12.73	0.31	0.76	Urban	3
Mairangi Bay Stream	0.60	0.34	0.73	Urban	3
Kaipatiki Stream	1.50	0.30	0.79	Urban	3
Eskdale Stream	3.85	0.30	0.78	Urban	3

4.4.3 Frequency Analysis

4.4.3.1 High flow frequency analysis

High flow frequency statistics for the 20% (~one-in-five year ARI), the 10% (~one-in-ten year ARI), the 2% (~one-in-fifty year ARI) and the 1% (~one–in-100 year ARI) annual exceedance probabilities (AEPs) for the full hydrological observation record including and excluding the Auckland Anniversary flooding events are presented below (and Table 4.23). Stationarity was assumed for this analysis. Flow records at the Kourawhero Farm Bridge Site are only available since November 2019, so that site has been excluded for the analysis in this section. During the Auckland Anniversary 2023 floods, several flow sites were completely submerged or damaged by flood debris or tree falls, causing failure of the data logger. Observations are available for these sites up to the point of failure and are presented but marked to indicate the peak flow was not recorded.

Comparison between the AEP using the flood flow statistics with and without the Auckland Anniversary 2023 floods (Table 4.24) indicates that the AEPs increased across almost all sites due to the rainfall impacts from that event. The largest increase in the 1% AEP was at for the Swanson Stream at Woodside Reserve. This site also shows an increase across all the reported AEPs. There is no indication of a failure or any malfunction at this site during that flood event.

4.4.3.2 Low Flow frequency analysis

Low flow frequency statistics for the 20% (one-in-five year ARI), the 10% (~one-in-ten year ARI), the 5% (~one-in-twenty year ARI), the 2% (~one-in-fifty year ARI) and the 1% (~one–in-100 year ARI) annual exceedance probabilities (AEPs) for the full hydrological observation record are presented in Table 4.25. As flow records at the Kourawhero Farm bridge site have only been available since November 2019 it has been excluded from the reporting in this section.

The best fit for the Te Muri Project site data was the gevR distribution, however it yielded negative results for the 5%, 2% and 1% AEPs. As data at this site was available for only 11 years from 2013 to 2024 the distribution for the site was updated using the gamma distribution. Frequency analysis results for this site requires careful consideration prior to interpretation. The Orewa River is known to cease to flow during the summer, therefore the minimum annual flow for most years is zero. The resulting best fit (pe3) therefore returns a zero value for all return periods. The distribution was therefore visually assessed and the pe3 distribution is replaced by a gamma distribution, which accounts for the flows dropping below zero. This reflects the observed hydraulic at the site where there is a 10% chance that in any given year the flows will drop to zero. The Opanuku at Candia Road bridge has data available from 2006 to 2024. The Gumbel distribution, although the best fitting distribution, results in negative minimum annual low flow magnitude values for the 5%, 2% and 1% AEPs. The distribution was updated using a visual assessment choosing the gamma distribution.

The lowest annual flow was also assessed and shows 49% of observing sites (18 out of 37 sites) experienced their lowest flow during SOE2025. Of those 18 sites, 13 (72%) experienced their lowest flow or lowest equal flow during the 2019-20 hydrological year.

Table 4.22. High flow frequency analysis for the full dataset (see Table 2.3) at all selected river flow sites used in SOE2025. Amounts are in litres per second. Sites that were affected by the Auckland Anniversary floods where peak flows may have been missed are noted with an asterisk.

Site	Distribution	20%	10%	5%	2%	1%
Alexandra *	Gamma	14733	19941	25011	31583	36488
Awaruku stream	GEV	4295	6388	9241	14744	20816
Eskdale Stream	Generalised	9157	11909	15191	20711	26091
Hoteo River	Kappa	196541	241467	280543	324809	353560
Kaipara River	Pearson III	118703	184573	256771	358204	437973
Kaipatiki Stream	Pearson III	2287	3474	4806	6702	8206
Kaukapakapa *	Generalised	110866	133148	155214	185478	209726
Kourawhero *						
Kumeu	Kappa	42899	50777	54998	57659	58582
Lucas	Gumbel	23242	28684	33904	40660	45723
Mahurangi *	Log-Pearson III	114864	154290	199694	271198	335724
Mairangi Bay Stream	GEV	1919	2612	3487	5034	6604
Mangawheau Stream	Kappa	51730	71935	95541	133212	167652
Mangemangeroa	Generalised	7932	9799	11849	14998	17812
Meola Creek	Generalised	15082	18963	23607	31444	39106
Motions Stream *	Generalised	20500	25556	31593	41765	51689
Newmarket Stream	Log-Pearson III	16283	22830	31080	45446	59710
Ngakoroa Stream	GEV	3965	4984	6029	7489	8669
Oakley Creek	Kappa	13458	17043	20877	26450	31116
Opanuku*	Kappa	61252	71066	77141	81725	83665
Opanuku Stream	GEV	46529	64306	86872	126979	167896
Oratia *	Pearson III	67426	88509	109525	137241	158175
Orewa	Kappa	43467	57123	69882	85578	96659
Otara	Generalised	34765	42389	50630	63072	74007
Oteha River	Generalised	38764	51358	66278	91194	115304
Papakura	Pearson III	40826	52342	63329	77354	87704
Paremuka Stream	Log-Pearson III	7376	7677	7785	7831	7842
Puhinui	GEV	22230	30157	39654	55455	70584
Rangitopuni River	Kappa	145506	177829	201146	222185	232944
Swanson Stream	Generalised	62938	77503	93141	116572	137015
Taiaotea stream	Gamma	10315	12080	13674	15623	17013
Taiorahi Stream	GEV	3355	4330	5501	7454	9329
Tamahunga River	GEV	37268	47124	56907	70068	80312
Tamaki Trib	Generalised	10577	12068	13524	15491	17045
TE MURI	Pearson III	1021	1446	1876	2449	2884
Vaughn Stream	GEV	7587	9808	11981	14858	17061
Wairau Creek –	Pearson III	9872	14519	19428	26165	31388
Wairau Creek –	Generalised	42860	53699	66241	86646	105907
Wairoa River	Kappa	159057	218545	285000	385601	472911
Waitangi	Kappa	17946	22009	25215	28474	30374
Waiteitei River	Pearson III	135046	161499	185247	214088	234583
West Hoe	Weibull	1488	1722	1917	2137	2284
Whau Stream *	Log-Pearson III	12754	16427	20673	27413	33553

Table 4.23. High flow frequency analysis for the full dataset (see Table 2.3) with the Auckland Anniversary 2023 event removed at all selected river flow sites used in SOE2025. Amounts are in litres per second.

Site	Distribution	20%	10%	5%	2%	1%
Alexandra	Kappa	14442.5	19298.81	23761.58	29135.28	32843.74
Awaruku stream	Log-Normal	4210.92	5617.37	7126.71	9315.71	11137
Eskdale Stream	Kappa	9173.16	11233.09	13141.47	15498.17	17177.92
Hoteo River	Kappa	196540.5	241467.3	280543.2	324809.1	353559.5
Kaipara River	Pearson III	116416.6	176737.8	241892.5	332597.7	403537.3
Kaipatiki Stream	Gamma	1998.8	2368.79	2705.37	3118.76	3415.13
Kaukapakapa	Pearson III	111008.2	128886.9	143841	160877.9	172357.5
Kourawhero						
Kumeu	Kappa	42905.76	50776.56	54991.47	57647.58	58568.57
Lucas	Gumbel	23241.7	28683.56	33903.52	40660.24	45723.44
Mahurangi	Log-Pearson III	114240.2	152331.9	195628.6	262841.1	322679.8
Mairangi Bay Stream	Pearson III	1834.19	2187.85	2510.07	2906.32	3190.69
Mangawheau Stream	Kappa	51730.25	71934.62	95541.28	133211.9	167651.5
Mangemangeroa	Generalised	7931.65	9798.79	11849.2	14998.47	17812.18
Meola Creek	Generalised	14799.23	17943.57	21436.93	26871.41	31786.59
Motions Stream	Generalised	19468.19	22388.9	25304.86	29339.73	32600.25
Newmarket Stream	Pearson III	15607.7	20241.89	24851.76	30922.68	35503.33
Ngakoroa Stream	GEV	3965.09	4983.5	6028.87	7489.21	8668.77
Oakley Creek	Kappa	13634.89	16214.3	18178.37	20072.63	21112.69
Opanuku	Kappa	61377.84	69501.77	73654.1	76144.78	76964.95
Opanuku Stream	GEV	42134.02	58089.14	78856.96	116843.4	156677.6
Oratia	Kappa	64766.39	81691.52	97935.78	118652.3	133845.7
Orewa	Kappa	43467.1	57122.9	69881.66	85578.23	96658.64
Otara	Log-Pearson III	35646.42	42022.59	47531.03	53885.58	58154.46
Oteha River	Gumbel	38642.01	48017.17	57010.04	68650.39	77373.2
Papakura	Pearson III	40562.16	51861.6	62619.72	76328.84	86434.82
Paremuka Stream	Log-Pearson III	7375.52	7676.67	7785.2	7831.11	7841.62
Puhinui	Pearson III	23348.32	31402.71	39514.24	50291.14	58471.28
Rangitopuni River	Kappa	143519.9	175626.3	199429.9	221664	233467.3
Swanson Stream	Pearson III	61574.33	71739.99	80551.79	90927.82	98118.52
Taiaotea stream	Kappa	10511.93	12114.33	13373.61	14663.16	15424.05
Taiorahi Stream	Generalised	3117.98	3589.89	4056.56	4695.59	5206.8
Tamahunga River	Generalised	36098.76	45443.41	55484.2	70541.62	83689.71
Tamaki Trib	Generalised	10312.67	11775.79	13222.69	15204.05	16789.13
TE MURI	Log-Pearson III	916.61	1323.87	1803.72	2570.62	3267.45
Vaughn Stream	Kappa	7667.09	9105.19	10027.58	10763.66	11096.52
Wairau Creek	Kappa	9454.58	13143.6	16773.75	21419.11	24800.93
Wairau Creek	Kappa	42701.16	50077.38	56341.76	63350.45	67875.02
Wairoa River	Kappa	159056.7	218545.1	285000.1	385600.6	472911.1
Waitangi	Log-Pearson III	17523.42	21265.83	24180.65	27113.98	28811.22
Waiteitei River	Pearson III	135046.3	161499	185247.1	214087.8	234582.7
West Hoe	Kappa	1528.41	1632.52	1674.25	1693.9	1698.94
Whau Stream	Log-Pearson III	12638.2	16067.01	19938.02	25923.55	31246.84

Table 4.24. Difference between the high flow frequency analysis for the full length of the record that includes and does not include the Auckland Anniversary 2023 flood event. Amounts are in litres per second. Significance testing was not conducted on these changes.

Site	20%	10%	5%	2%	1%
Alexandra	290.54	642.49	1250.12	2448.63	3644.63
Awaruku stream	84.3	770.21	2113.96	5428.46	9678.86
Eskdale Stream	-15.85	675.72	2049.19	5213.14	8913.08
Hoteo River	0	0	0	0	0
Kaipara River	2286.12	7835.42	14878.23	25606.08	34435.91
Kaipatiki Stream	288.09	1105.68	2100.51	3583.58	4790.83
Kaukapakapa	-142.01	4260.8	11372.68	24600.18	37368.54
Kourawhero					
Kumeu	-6.4	0.75	6.65	11.3	13.18
Lucas	0	0	0	0	0
Mahurangi	623.9	1957.89	4065.79	8357.04	13044.14
Mairangi Bay Stream	85.04	424.03	976.84	2127.4	3412.89
Mangawheau Stream	0	0	0	0	0
Mangemangeroa	0	0	0	0	0
Meola Creek	282.73	1019.63	2169.73	4572.7	7319.3
Motions Stream	1031.82	3166.75	6288.6	12424.77	19088.88
Newmarket Stream	675.48	2588.58	6228.73	14522.92	24206.71
Ngakoroa Stream	0	0	0	0	0
Oakley Creek	-176.88	828.82	2698.63	6377.07	10003.12
Opanuku	-126.14	1563.92	3486.94	5580.24	6700.18
Opanuku Stream	4394.93	6217.35	8014.94	10135.32	11218.12
Oratia	2659.29	6817.48	11588.72	18589.02	24329.66
Orewa	0	0	0	0	0
Otara	-880.97	366.15	3099.15	9186.88	15852.75
Oteha River	122.22	3340.48	9268.44	22543.42	37930.31
Papakura	263.72	480.33	709.61	1024.67	1269.25
Paremuka Stream	0	0	0	0	0
Puhinui	-1118.36	-1245.43	139.34	5163.76	12113.19
Rangitopuni River	1986.38	2203.03	1716.25	520.65	-523.04
Swanson Stream	1363.17	5762.83	12589.14	25644.24	38896.65
Taiaotea stream	-196.7	-34.78	300.75	959.34	1589.25
Taiorahi Stream	236.92	740.13	1444.25	2758.43	4122.11
Tamahunga River	1168.75	1680.18	1422.98	-473.43	-3377.84
Tamaki Trib	264.2	291.86	301.17	287.33	255.93
TE MURI	104.24	122.46	72.46	-122.1	-383.86
Vaughn Stream	-80.49	702.47	1953.34	4093.86	5964.6
Wairau Creek – Chartwell	417.02	1375.54	2654.58	4746.33	6587.03
Wairau Creek – Motorway	159.3	3621.79	9899.33	23295.05	38031.43
Wairoa River	0	0	0	0	0
Waitangi	422.27	743.56	1034.55	1360.39	1562.28
Waiteitei River	0	0	0	0	0
West Hoe	-40.24	89.56	242.82	443.47	585.38
Whau Stream	115.87	359.61	735.46	1488.95	2306.31

Table 4.25. Low flow frequency analysis (Full dataset), at all selected river flow sites used in SOE2025. Amounts are in litres per second.

Site	Distribution	20%	10%	5%	2%	1%
Alexandra	gum	1.65	1.14	0.77	0.40	0.17
Awaruku stream	gevR	0.83	0.71	0.65	0.62	0.61
Eskdale Stream	gevR	5.44	4.71	4.27	3.93	3.78
Hoteo River	gevR	292.51	213.93	162.31	118.44	96.92
Kaipara River	gam	74.93	48.67	32.75	19.96	13.91
Kaipatiki Stream	gam	1.61	1.21	0.94	0.69	0.55
Kaukapakapa	gevR	10.22	9.07	8.71	8.58	8.56
Kourawhero	-	-	-	-	-	-
Kumeu	ln3	10.25	6.44	4.39	2.85	2.14
Lucas	gevR	5.36	5.01	4.87	4.79	4.77
Mahurangi	gum	51.17	36.98	26.55	15.97	9.51
Mairangi Bay Stream	gevR	1.31	1.26	1.25	1.25	1.24
Mangawheau Stream	pe3	59.16	50.40	44.91	40.33	38.07
Mangemangeroa	gevR	0.33	0.19	0.14	0.11	0.11
Meola Creek	pe3	34.66	28.84	24.39	19.78	16.91
Motions Stream	gevR	97.12	90.27	86.32	83.41	82.18
Newmarket Stream	gam	2.24	1.87	1.60	1.34	1.18
Ngakoroa Stream	gam	6.31	4.64	3.53	2.52	1.98
Oakley Creek	pe3	9.79	9.77	9.77	9.77	9.77
Opanuku	pe3	36.09	32.20	30.24	28.99	28.52
Opanuku Stream	gam	13.34	7.66	4.56	3.39	2.35
Oratia	wei	36.36	26.07	18.94	12.53	9.19
Orewa	pe3	0.009	0.001	0	0	0
Otara	gevR	8.13	5.93	4.85	4.18	3.95
Oteha River	gevR	10.01	7.12	4.95	2.79	1.56
Papakura	ln3	22.12	15.48	11.53	8.27	6.63
Paremuka Stream	pe3	2.43	2.43	2.43	2.43	2.43
Puhinui	gevR	12.93	10.28	8.55	7.09	6.37
Rangitopuni River	gam	8.01	3.87	1.92	0.78	0.40
Swanson Stream	pe3	13.59	13.21	13.15	13.13	13.13
Taiaotea stream	gevR	1.91	1.52	1.27	1.07	0.98
Taiorahi Stream	gevR	1.79	1.67	1.61	1.58	1.57
Tamahunga River	gam	3.39	2.26	1.56	0.98	0.70
Tamaki Trib	pe3	7.17	6.63	6.20	5.73	5.43
TE MURI	gam	0.126	0.071	0.041	0.03	0.021
Vaughn Stream	pe3	0.12	0.12	0.12	0.12	0.12
Wairau Creek – Chartwell	wei	1.53	0.82	0.45	0.21	0.12
Wairau Creek – Motorway	pe3	11.41	10.18	9.39	8.70	8.34
Wairoa River	gevR	321.67	291.36	273.89	261.03	255.59
Waitangi	gevR	29.13	24.90	22.20	19.97	18.91
Waiteitei River	wei	87.63	64.45	48.00	32.77	24.62
West Hoe	gevR	1.10	1.01	0.97	0.96	0.95
Whau Stream	ln3	9.65	8.69	7.97	7.23	6.78

4.4.4 Threshold analysis

4.4.4.1 Events above threshold (FRE3)

Comparing the average number of high flow events between the full record and the SOE2025 (Table 4.26), 20 sites showed an increase in the average number of high flow events over the site specific FRE3 threshold, while 16 sites showed a decrease in the average number of high flow events and three sites showed no change. Comparison of SOE2025 to SOE2020 showed nine sites had an increase in the average number of high flow events over the FRE3 threshold, while 27 sites showed a decrease in the average number of high flow events and three sites showed no change. Eight sites (three increasing, five decreasing) had a change greater than 10% between the SOE2025 and the long-term record. 15 sites (five increasing and 10 decreasing) had a change greater than 10% between SOE2020 and SOE2025.

4.4.4.2 Comparison with $MALF_7$

Comparing the $MALF_7$ between the full record and the SOE2025 (Table 4.27) 30 sites showed an increase in the $MALF_7$, while seven sites showed a decrease in the $MALF_7$ and one site showed no change. Comparison of SOE2025 to SOE2020 34 sites showed an increase in the $MALF_7$, while four sites showed a decrease in the $MALF_7$. 27 sites (24 increasing, three decreasing) had a change greater than 10% between the SOE2025 and the long-term record. 16 sites (13 increasing and three decreasing) had a change greater than 10% between SOE2020 and SOE2025. This indicates that the level of the mean annual low flow was changed because of hydrological states experienced during SOE2025.

4.4.4.3 Duration below threshold ($MALF_7$)

Comparing the average number of days below $MALF_7$ between the full record and SOE2025 (Table 4.28), 19 sites showed an increase in the average number of days below $MALF_7$, while 19 sites showed a decrease in the average number of days below $MALF_7$. In a comparison of SOE2025 to SOE2020 $MALF_7$ durations, 28 sites showed an increase in the average number of days below $MALF_7$, while 10 sites showed a decrease in the average number of days below $MALF_7$. 31 sites (17 increasing, 14 decreasing) had a change greater than 10% between the SOE2025 and the long-term record. 35 sites (28 increasing and seven decreasing) had a change greater than 10% between SOE2020 and SOE2025.

Table 4.26. Summary of the mean exceedance value for high flow events (FRE3) for the full record, 10-year and last two SOE reporting periods.

Site	Full record	STD (Full)	2014-2023	SOE2020	SOE2025
Alexandra	19.8	3.6	21.6	21.6	21.6
Awaruku stream	21.4	2.9	21.1	20.8	21.4
Eskdale Stream	20.7	4.0	21.7	22.8	20.6
Hoteo River	11.8	3.1	11.8	11.8	11.8
Kaipara River	11.2	3.0	10.9	10.0	11.8
Kaipatiki Stream	22.5	3.7	23.3	23.8	22.8
Kaukapakapa	11.0	3.4	10.7	11.8	9.6
Lucas	20.4	2.9	20.7	21.2	20.2
Mahurangi Argonaut	15.2	2.7	15.7	15.8	15.6
Mairangi Bay Stream	21.2	3.2	21.9	23.0	20.8
Mangawheau Stream	13.7	2.7	14.3	14.8	13.8
Mangemangeroa	14.7	3.8	14.6	14.6	14.6
Meola Creek	23.2	3.3	22.9	24.8	21.0
Motions Stream	24.7	4.0	24.4	26.2	22.6
Newmarket Stream	19.9	3.4	19.4	18.2	20.6
Ngakoroa Stream	13.3	3.5	14.0	14.2	13.8
Oakley Creek	16.8	5.0	17.2	19.7	14.7
Opanuku Stream	16.2	2.8	18.9	20.2	17.6
Opanuku Vintage	18.9	3.4	15.5	18.0	13.0
Oratia	19.6	2.5	20.2	20.8	19.6
Orewa	12.3	3.4	11.5	12.0	11.0
Otara	19.0	3.3	20.7	22.0	19.4
Oteha River	20.3	3.7	21.6	22.0	21.2
Papakura	14.5	4.3	17.6	19.2	16.0
Puhinui	22.0	3.7	23.4	24.2	22.6
Rangitopuni River	12.1	3.4	10.9	10.2	11.6
Swanson Stream	17.7	2.9	18.4	17.8	19.0
Taiaotea stream	20.5	4.1	20.0	20.2	19.8
Taiorahi Stream	19.6	4.5	20.2	21.6	18.8
Tamahunga River	15.2	3.6	15.1	15.8	14.4
Tamaki Trib	21.3	3.2	21.6	21.8	21.4
Vaughn Stream	15.1	5.4	17.4	15.8	19.0
Wairau Creek Chartwell	20.0	5.3	21.5	22.4	20.6
Wairau Creek Motorway	20.5	3.4	21.1	21.2	21.0
Wairoa River	13.3	3.2	13.4	13.0	13.8
Waitangi	10.2	2.6	10.6	9.6	11.6
Waiteitei River	11.5	2.5	11.9	11.8	12.0
West Hoe	13.8	4.5	13.1	14.8	11.4
Whau Stream	22.1	3.9	22.6	23.6	21.6

Table 4.27. Summary of the $MALF_7$ (l/s) for the full record calculated ending in mid-2019 (SOE2020) and mid-2024 (SOE2025), the most recent 10-year interval, and the most recent 5-year period (SOE2025). Missing values relate to too many missing observations.

Site Name	Long-term $MALF_7$ (SOE2020)	Long-term $MALF_7$ (SOE2025)	10-year $MALF_7$	5-year $MALF_7$ (SOE2025)
Alexandra Stream	3.0	3.7	4.9	4.5
Awaruku Stream	1.5	1.6	1.9	1.8
Eskdale Stream	7.6	7.9	9.0	8.4
Hoteo River	503.2	513.7	557.1	546.5
Kaipara River	165.3	181.3	209.5	231.6
Kaipatiki Stream	2.8	3.0	3.7	3.2
Kaukapakapa Stream	23.6	33.6	45.9	48.2
Kourawhero		76.7	76.7	76.7
Kumeu		41.4	48.1	8.7
Lucas Creek	7.5	8.5	10.3	11.0
Mahurangi River at Argonaut	83.2	93.6	107.3	102.3
Mairangi Bay Stream	1.8	2.2	2.6	3.1
Mangawheau Stream	87.6	92.0	101.3	105.0
Mangemangeroa Stream	1.4	1.8	2.9	2.5
Meola Stream	46.7	48.5	55.5	57.1
Motions Stream	123.0	122.4	132.6	126.8
Newmarket Stream	3.1	3.2	3.6	3.5
Ngakoroa Stream	11.1	11.8	14.2	13.2
Oakley		27.4	49.5	73.6
Opanuku Stream at Candia Road	44.3	58.9	76.3	78.4
Opanuku Stream at Vintage Reserve	54.1	41.1	38.1	21.2
Oratia Stream	72.8	63.3	57.8	39.2
Orewa Stream*	0.8	1.1	1.4	1.7
Otara Stream	16.8	20.4	36.2	38.0
Oteha Stream	15.1	17.3	23.2	23.9
Papakura Stream	49.9	59.7	76.9	80.8
Paremuka		3.0	2.6	2.6
Puhinui Stream	19.9	20.5	26.7	26.5
Rangitopuni Stream	31.7	35.9	49.2	43.6
Swanson Stream	25.6	27.3	41.9	38.2
Taiaotea Stream	3.0	3.2	3.2	3.1
Taiorahi Stream	2.5	2.6	2.8	2.9
Tamahunga Stream	7.5	7.9	10.6	9.1
Tamaki Stream Tributary	8.2	8.4	8.4	9.4
Te Muri		0.7	0.5	0.2
Vaughan Stream	0.5	0.8	1.2	1.2
Wairau Creek at Chartwell Rd	5.4	4.9	2.5	2.7
Wairau Creek at Motorway	15.5	15.9	22.8	21.7
Wairoa River	439.9	441.6	431.4	435.8
Waitangi Stream	42.2	42.1	45.5	40.5
Waiteitei River	149.4	144.2	127.3	108.7
West Hoe Stream	1.6	2.2	2.7	3.5
Whau Stream	10.4	12.1	11.5	11.1

Table 4.28. Average number of days each year spent below the $MALF_7$ for the full record, SOE2020 and SOE2025. Data gaps for some of the records has meant that some of the averages for the two most recent SOE periods (noted with an asterisk) rely on less than five years of observations.

Year	Full record	STD (full)	10 year	SOE2020	SOE2025
Alexandra	3.34	4.62	1.37	0.21	2.52
Awaruku stream	8.46	5.62	7.41	6.18	8.64
Eskdale Stream	4.78	5.62	4.30	1.92	6.68
Hoteo River	3.79	4.20	1.37	0.21	2.52
Kaipara River	5.42	5.75	6.57	6.25	6.88
Kaipatiki Stream	4.92	6.15	4.01	1.10	6.92
Kaukapakapa	6.33	5.84	7.54	5.86	9.21
Lucas	5.27	4.20	3.84	4.04	3.64
Mahurangi Argonaut	7.28	7.51	5.91	4.91	6.92
Mairangi Bay Stream	6.70	6.04	7.12	7.82	6.42
Mangawheau Stream	4.55	5.26	6.17	3.71	8.14
Mangemangeroa	7.04	6.58	6.98	6.14	7.82
Meola Creek	4.11	4.88	2.92	2.43	3.41
Motions Stream	5.17	4.67	2.07	1.16	2.98
Newmarket Stream	6.22	6.16	4.55	3.04	6.06
Ngakoroa Stream	3.62	4.67	4.26	1.68	6.32
Oakley Creek*	10.98	7.85	8.08	16.15	0.00
Opanuku Vintage	3.85	4.65	4.63	2.17	7.08
Opanuku Stream*	7.55	13.61	12.22	2.33	25.41
Oratia	4.96	6.25	7.16	2.04	12.28
Orewa*	8.02	6.33	8.10	6.25	10.41
Otara	6.06	6.16	0.54	0.77	0.31
Oteha River	3.58	4.65	0.30	0.12	0.49
Papakura	4.77	5.04	3.83	2.49	5.18
Puhinui	3.95	4.84	2.68	1.53	3.82
Rangitopuni River*	4.99	4.67	7.24	5.49	9.44
Swanson Stream	4.94	3.81	3.89	2.63	4.64
Taiaotea stream	5.77	6.70	6.96	6.10	7.82
Taiorahi Stream	8.11	5.70	7.73	8.54	6.91
Tamahunga River*	4.33	4.36	2.61	2.67	2.53
Tamaki Trib	2.72	3.07	2.40	3.08	1.73
Vaughn Stream	14.15	8.67	16.85	15.38	17.73
Wairau Creek Chartwell	12.94	13.92	16.59	27.99	5.18
Wairau Creek Motorway	3.80	3.80	0.63	0.65	0.61
Wairoa River	5.98	6.25	9.03	6.85	11.21
Waitangi	5.24	5.98	5.91	2.60	9.22
Waiteitei River	5.72	6.70	7.27	4.10	10.44
Whau Stream*	4.86	6.53	1.34	2.68	0.00

4.4.5 Trend Analysis

4.4.5.1 Events above threshold (FRE3)

The length of the time series and choice of the window of trend analysis (i.e. starting point for trend analysis) had an influence on identifying statistically significant trends for FRE3, as demonstrated for four different trend analysis windows (Figure 4.15). There are a variable proportion of sites with significant FRE3 trends when examining different time periods, which underscores the importance of individual year, seasons and meteorological events and impacts on a subregional-to-local scale that can disturb a catchment and create an elevated flow regime. Over the long-term record for each site, only three flow observation sites had a significant FRE3 trend, with two of the sites (Oteha and Papakura) showing an increase and one (Rangitopuni) showing a decrease. Two of these sites (Papakura and Rangitopuni) also had significant trends register in multiple analysis windows; Papakura was increasing in the 1980-present and 1990-present time slice, and Rangitopuni shows a decrease in the 1980-present and 2000-present window.

From 2000-present and 2010-present, Vaughn Stream showed an increase in average number of FRE3 events (Figure 4.15). For Oteha, FRE3 event occurrence was much lower in the earliest part of that site history (prior to 2000) but after a rising trend this site has remained relatively stable since the 1990s onward. A similar change is also observed at Papakura and Otara since the 2000s. Since the turn of the century, FRE3 event occurrence has been reducing significantly at four of five sites (Kaukapakapa, Motions Stream, Rangitopuni, and Orewa). An increase during the most recent period occurred at Kaipara and Swanson, while a decreasing trend is simultaneously observed for Wairau Creek (at Chartwell), Opanuku and West Hoe. Average number of FRE3 event increases for the four time periods analysed occurred in mostly urban catchments and included sites from all three clusters. Average number of FRE3 event decreases occurred in mainly native and forest site catchments in clusters 2 and 3, with Motions and Wairau occurring in urban catchments of clusters 1 and two.

4.4.5.2 Mean Annual Low Flow ($MALF_7$)

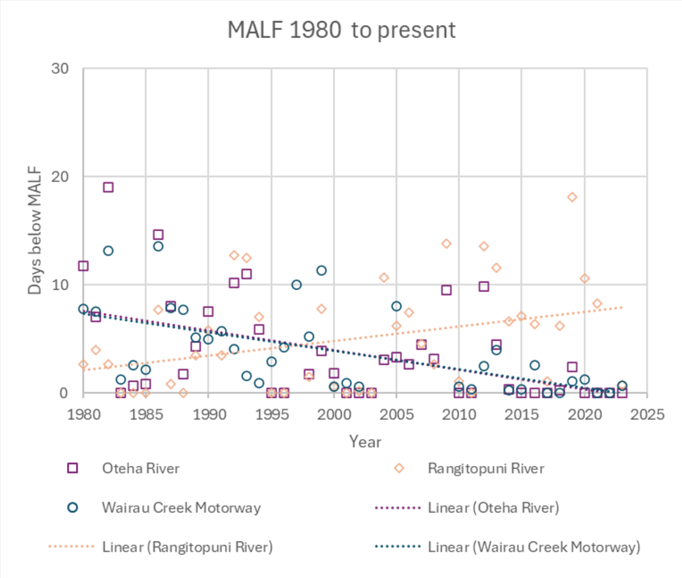
The trends for $MALF_7$ were evaluated two ways. The first included an analysis of a time series that summarised the annual low flow for each hydrological year (which is the basis for calculating $MALF_7$), and the second examined the duration of time for each river below $MALF_7$ during each hydrological year.

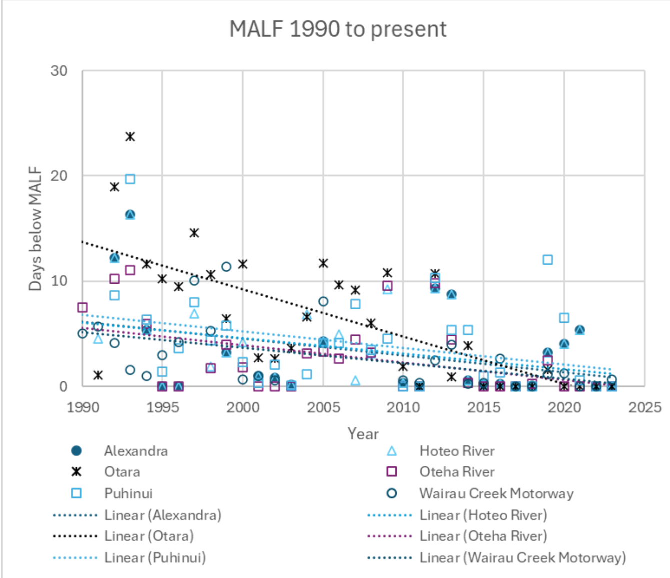
The annual low flow trend analysis showed several sites with significant positive and negative trends (Table 4.27). However, linear trends in water quantity are difficult to ascertain because of variable record length, changing decade of the starting point for each site, and because of extreme event occurrences. In addition, sites that experience ephemerally dry conditions, such as Orewa, must be interpreted with caution. Otara was the only site that showed a consistent, positive trend both with and without the 2022-23 hydrological year, indicating the annual low flow has been steadily rising at that site.

Only two sites showed a significant negative annual low flow trend inclusive of 2022-23, showing how strong an influence that particular year has on this type of analysis. When the 2022-23 values are removed, Oratia shows consistent negative trend in the annual low flow, indicating progressively lower flow levels being reached. Several other rivers, including Rangitopuni and Wairau (Motorway), show negative trends for multiple time spans of analysis, which suggests a sensitivity of the analysis to decadal variability that those sites may have experienced.

Significant negative linear trends for MALF$_7$, indicating a lower MALF$_7$ through time, are observed almost exclusively in urban catchments. Many of these significant decreases also showed up in most recent period of analysis (2010-present). The exception is for West Hoe, which shows a decrease in MALF$_7$. Significant MALF$_7$ increases occurred in urban catchments during the last two time slices for type 1 and 3 catchments only (see Section 4.4.2). The only rural catchment that had this signature is Rangitopuni in the 1980-present and 2000-present period. Caution is required in the interpretation of the significant trends with some of the records because of the small scale of change relative to the accuracy of the measurement method (Table 4.29).

Figure 4.15 Hydrological monitoring sites that showed significant trends for events above three times the median flow (FRE3). The trends analysis is broken down by different starting points where observation series share a nearly equivalent period of overlap. All sites except one (Oakley Creek) had observations covering SOE2025. Symbology for each site that reoccurs across the different periods of analysis has been carried through from one panel to another. Upper left: 1980-present; Upper right 1990-present; Lower left: 2000-present; Lower right: 2010-present.





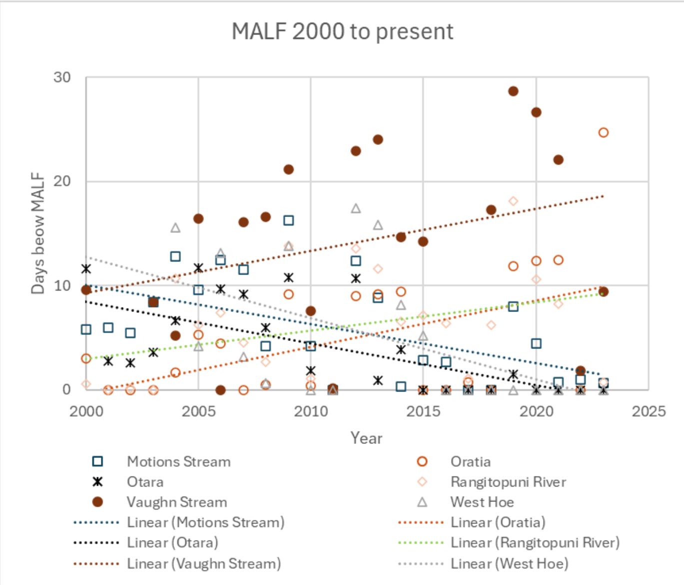
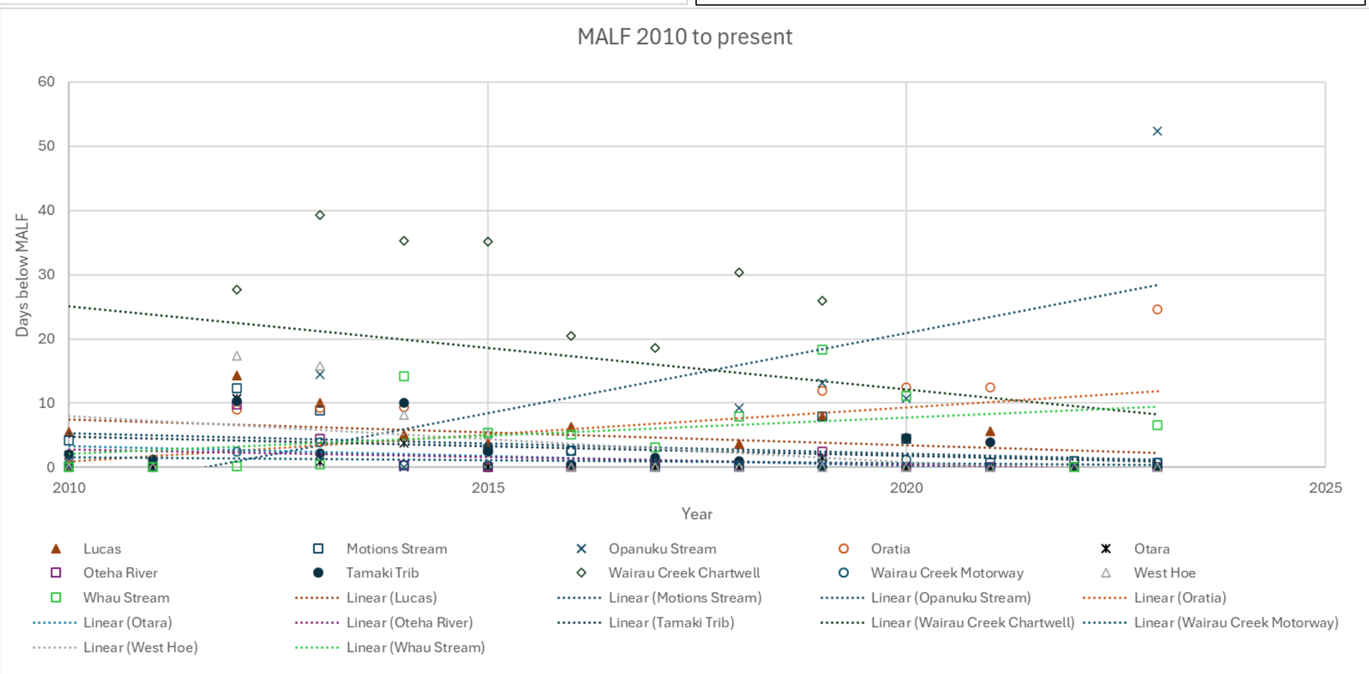


Figure 4.16 Hydrological monitoring sites that showed significant trends for the total duration (amount of time in days-equivalent) below the mean annual low flow ($MALF_7$). $MALF_7$ was calculated across the entire length of each record. The trends analysis is broken down by different starting points where observation series share a nearly equivalent period of overlap. All sites except one (Oakley Creek) had observations covering SOE2025. Symbology for each site that reoccurs across the different periods of analysis has been carried through from one panel to another. Upper left: 1980-present; Upper right 1990-present; Middle left: 2000-present; Lower panel: 2010-present.



The duration of time for each river below $MALF_7$ level showed some sites with significant trends (Figure 4.16). Of note, the length of the time series and choice of the window of trend analysis (i.e. starting point for trend analysis) had an influence on identifying statistically significant trends. More of the sites that had significant $MALF_7$ trends showed a decreasing number of days below $MALF_7$ than an increase. A small number of sites also showed consistency regarding the direction of an identified significant negative $MALF_7$ trend and included Oteha and Wairau Creek (1980-present; 1990-present, 2010-present), Otara (1990-present, 2000-present, 2010-present) Motions Stream and West Hoe (2000-present, 2010-present).

For the sites with a significant decrease in the number of days below $MALF_7$, the range of reduction through time is variable, but suggest much of the change has occurred since 2000 (ranging on average from 2-8 days fewer over the duration of each site-specific record). For sites that had an increasing duration of time below $MALF_7$, repeat locations were Rangitopuni (1980-present, 2000-present) and Oratia (2000-present, 2010-present). Other sites with recent increases in the time spent below $MALF_7$ include Waiau Creek (2000-present) and Whau and Opanuku (2010-present). The strong rise in the Opanuku trend is significantly guided by a very high jump toward the most recent end of the time series (Figure 4.16).

Table 4.29. Significant linear trends in the annual low flow for Auckland rivers at the 90% confidence interval. The starting point of analysis represents the decade when the trend analysis begins (at least 6 of 10 years in the decade needed to be present). Results without the 2022-23 hydrological year are shown the last two columns and indicates the sites that had a significant linear trend after that year was removed. Otara (in bold) showed the most robust linear trend as it was retained both with and without the 2022-23 annual low flow value. Sites with an asterisk have significant linear trends that also satisfy a criterion of the slope being acceptably interpreted with respect to the precision and accuracy of the observations of 1 litre/second (or 0.001 cumec).

Starting point of analysis	Positive trend	Negative trend	Positive trend without 2022	Negative trend without 2022
1980-present	Oteha, Puhinui	(Nil)	Oteha, Wairau	Orewa, Rangitopuni, Wairoa*
1990-present	Alexandra, **Otara***, Oteha, Puhinui, Swanson, Tamahunga, Wairau	(Nil)	Alexandra, **Otara**, Oteha, Puhinui, Wairau	(NIL)
2000-present	Mairangi, **Otara***, Oteha, Puhinui, Wairau (Chartwell)	Oratia*	Mairangi, Motions*, **Otara***, Wairau (Chartwell)	Hoteo*, Oratia*, Rangitopuni*, Wairau (Motorway), Waiteitei*
2010-present	Kaipara*, Lucas, **Otara***, Tamaki	Opanuku*	**Otara***	Oratia*, Whau

4.5 Groundwater

Monthly groundwater level anomalies were analysed across multiple bore sites to highlight seasonal and annual variability and long-term trends spanning several decades (Table 4.17-Table 4.22). Standardised anomaly values (in metres) were used as a diagnostic tool for each borehole. The plots used to support this analysis (Figure 4.17-Figure 4.22) show deviations from normal in the form of a heat map with time-evolving patterns of change to highlight positive groundwater anomalies (groundwater surplus; blue shades), negative groundwater anomalies (groundwater deficit; orange and red shades) and near normal conditions (white/cream tones). In addition to the monthly heat map, there is an annual summary bar chart that shows the net surplus or deficit of each year that has been derived from summing the monthly groundwater anomalies. Green bars indicate a net annual groundwater surplus while red bars indicate a net annual deficit and the labels for each bar indicate the total anomaly value in metres.

The groundwater visualisation for each of the representative sites enables a rapid identification of the impacts from dry or drought periods linked to aquifer stress (e.g. deep red bands, consecutive annual deficits), recharge events or recovery periods (e.g. persistent blue stretches in each heat map, and strong green bars in the annual groundwater balance plots), and hydroclimatic shifts over time, including the potential impact of climate variability, land use change or water management interventions. These plots are collectively used in SOE2025 to provide a basis for understanding the temporal dynamics of regional groundwater systems across Auckland. They offer a baseline for evaluating aquifer resilience, identifying vulnerable years, and assessing how specific bore sites have responded to external pressures or favourable hydrological periods. The following site-specific analyses offer a narrative of groundwater behaviour and change through both drought and recharge cycles that occurred during SOE2025 and earlier episodes as a long-term context for groundwater changes. The results from the groundwater analysis for surplus and deficit are also used to compare with rainfall analyses to illustrate response time differences for groundwater levels reacting to natural influences.

4.5.1 Surplus and deficit of groundwater

Surplus and deficit plots show spatial heterogeneity across the selected groundwater monitoring sites on an interannual basis. In general, the monthly groundwater anomaly heat maps also reflect this type of pattern and show the details about strong temporal heterogeneity for each site. The selected groundwater observations for the Auckland region indicate periods of relative recharge and stress on groundwater that are neither similar in their timing of occurrence from year-to-year, nor uniform temporal extent across all sites and aquifers. The months and years within SOE2025 were characterised by strongly negative groundwater anomalies at Quintals, Selaks, Maraeorahia and Revell Court during summer and autumn – and those negative anomalies occasionally extended into winter during some years (Figure 4.17, Figure 4.18, Figure 4.20 and Figure 4.21). Wooten and Angle Street (Figure 4.19 and Figure 4.22) showed strongly positive groundwater anomalies during SOE2025 relative to the long-term record for most of the year, except for a patch of strongly negative anomalies during the mid-to-late winter and early spring at Wooten during 2019-2022. All sites showed a multi-month temporal occurrence of positive groundwater anomalies within the 2022-23 hydrological year, and notable common groundwater surpluses that include 2012-13 and 2022-23.

During SOE2025 there were notable occurrences of major groundwater deficits for most sites. Quintals saw a major succession of deficits during SOE2025, starting in 2019 with a -5.8m deficit overall for that year (Figure 4.17). This year also demarcates the onset of the contemporary groundwater stress phase at that site. This sharp drop was followed by a single-year deficit of -12.87m, the single-worst year on record for the site. 2021 also saw a negative year with a deficit of -5.59m. For comparison with the earlier part of the observational record, one needs to go back more than 30 years at Quintals to 1987 (-6.47m) to find a comparable drop in a single year on the order of what transpired between 2019-2021. Moving into SOE2025, Selaks was experiencing a short-term groundwater rebound phase that was sharply interrupted by a three-year deficit period spanning 2020-2022 (with annual deficit values of -16.99m, -16.07m, and -10.99m). However, these years were set within a long-term rising groundwater trend with many more significantly negative years in the 2000s and 2010s (Figure 4.18). Maraeorahia also experienced major deficits in 2020-2022 (−5.58 m, 2021: -3.52m, 2022 -4.88m) marking the worst consecutive string of groundwater deficits at that site (Figure 4.20). There was an earlier registration for groundwater deficit at Revell Court (Figure 4.21), beginning in 2019 (-3.96m) and this was followed by two additional very strongly negative years in 2020 (-10.16m) and 2021 (-11.95m; second worst on record) making this the strongest negative multi-annual stretch in the surplus/deficit record. In terms of comparison to individual years, 1983 was worse, and both 2020 and 2021 were worse than 1994 when the Auckland water crisis emerged. Across a predominantly rising groundwater trend at Wooten Road (Figure 4.22), none of the deficit years were registered strongly; however, it is clear that site experienced a hydrological response between 2019-2021, as there is a conspicuous dip in surplus/deficit values set within a sequence of overall high groundwater surplus years.

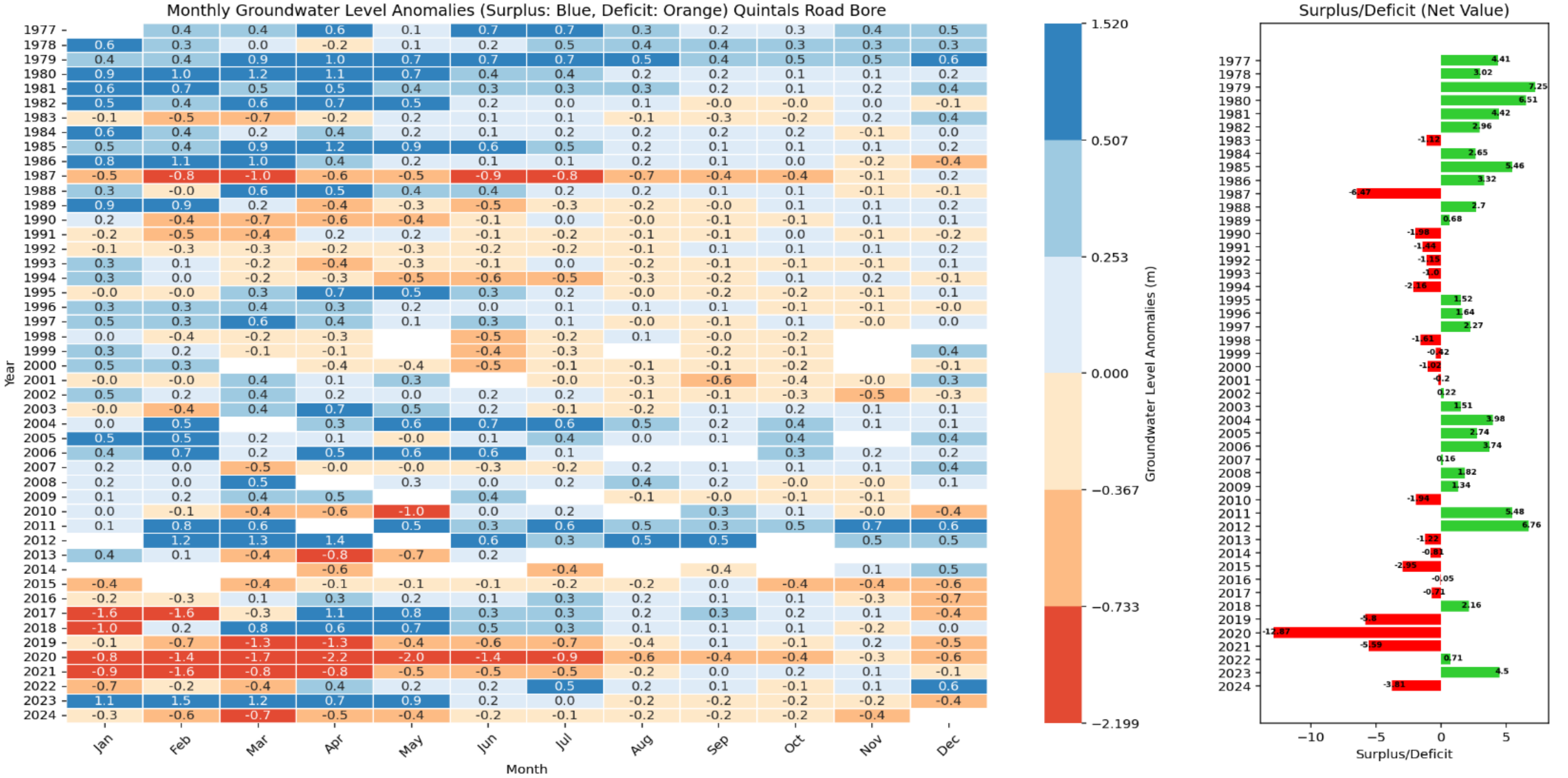


Figure 4.17 Deviations from normal highlighting positive and negative groundwater anomalies for Quintals Road (left) and an annual net surplus or deficit based on monthly groundwater anomalies (right). Green bars in the surplus and deficit plot indicate a net annual groundwater surplus, while red bars indicate a net annual deficit. The labels for each bar indicate the total anomaly value in metres

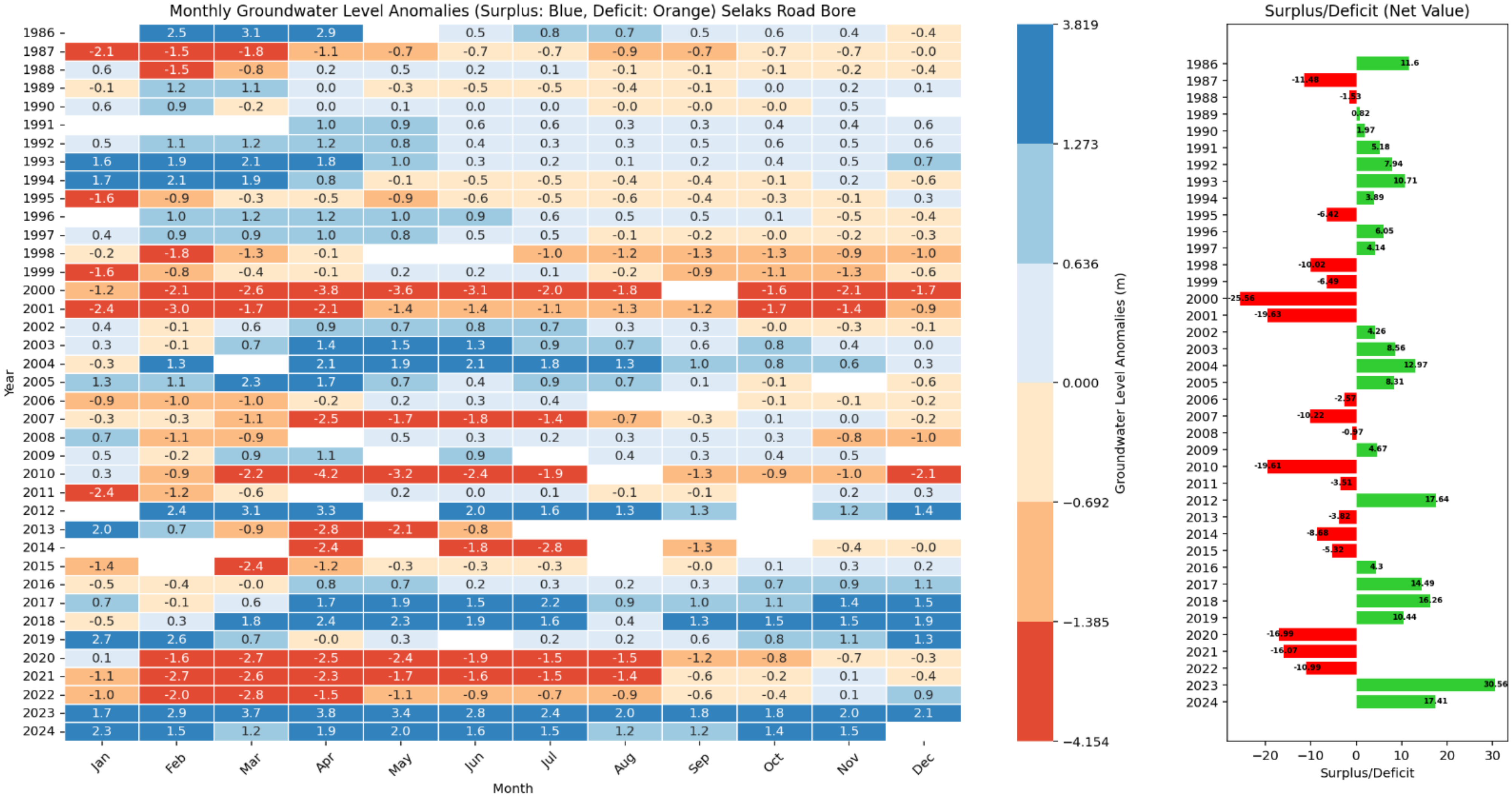


Figure 4.18 Deviations from normal highlighting positive and negative groundwater anomalies for Selaks Bore (left) and an annual net surplus or deficit based on monthly groundwater anomalies (right). Green bars in the surplus and deficit plot indicate a net annual groundwater surplus, while red bars indicate a net annual deficit. The labels for each bar indicate the total anomaly value in metres.

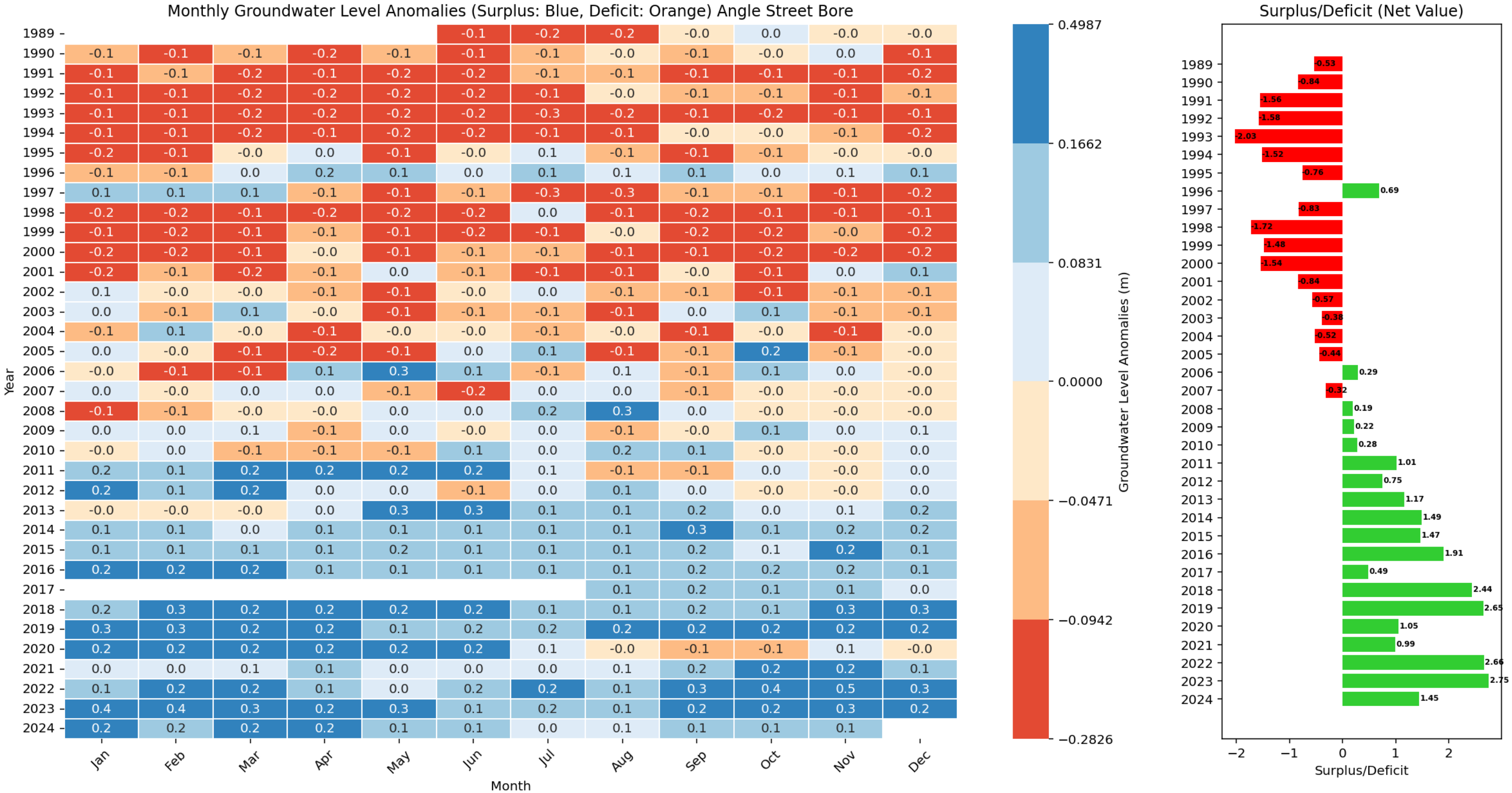


Figure 4.19 Deviations from normal highlighting positive and negative groundwater anomalies for Angle Street (left) and an annual net surplus or deficit based on monthly groundwater anomalies (right). Green bars in the surplus and deficit plot indicate a net annual groundwater surplus, while red bars indicate a net annual deficit. The labels for each bar indicate the total anomaly value in metres.

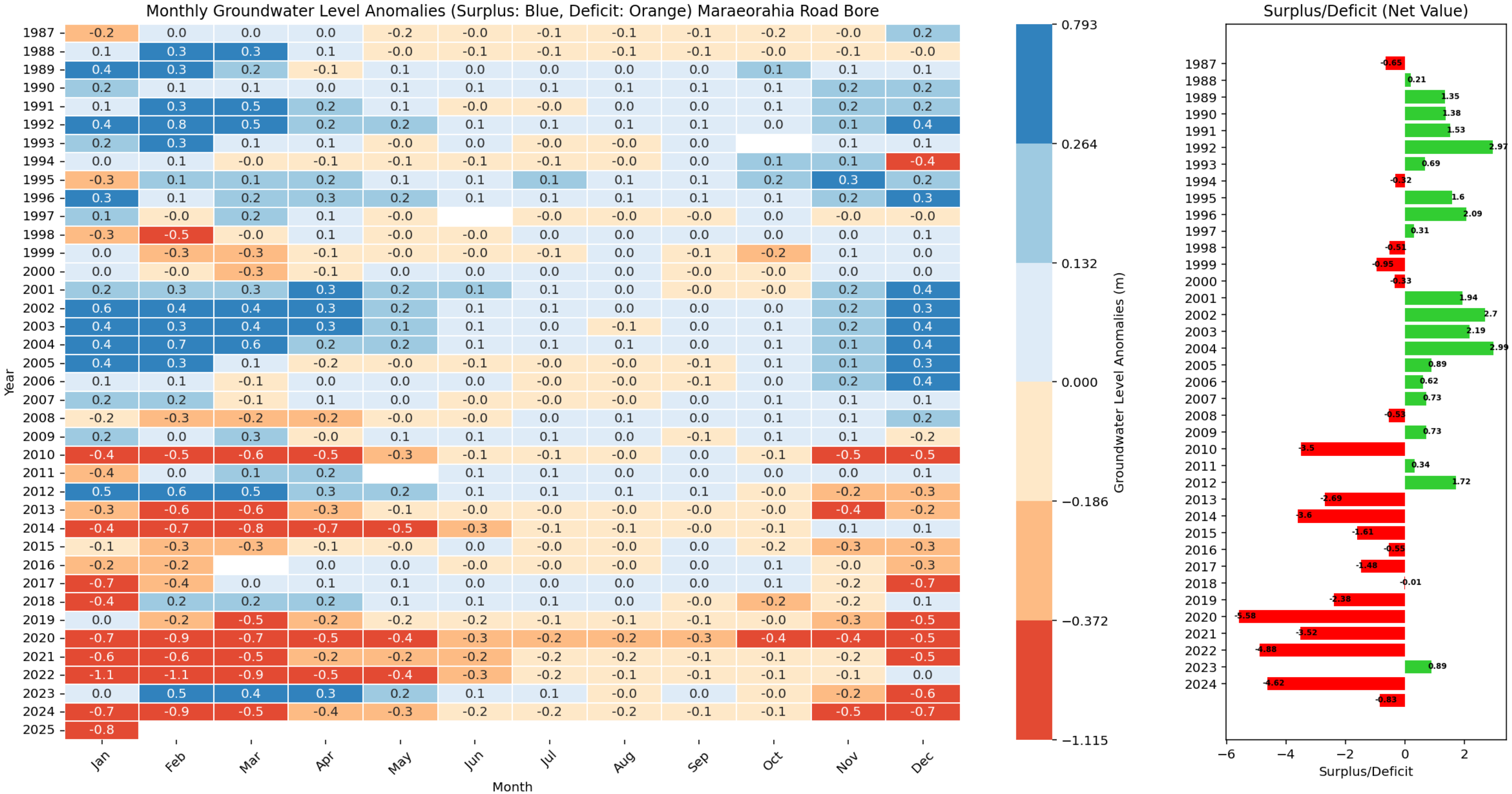


Figure 4.20 Deviations from normal highlighting positive and negative groundwater anomalies for Maraeorahia (left) and an annual net surplus or deficit based on monthly groundwater anomalies (right). Green bars in the surplus and deficit plot indicate a net annual groundwater surplus, while red bars indicate a net annual deficit. The labels for each bar indicate the total anomaly value in metres

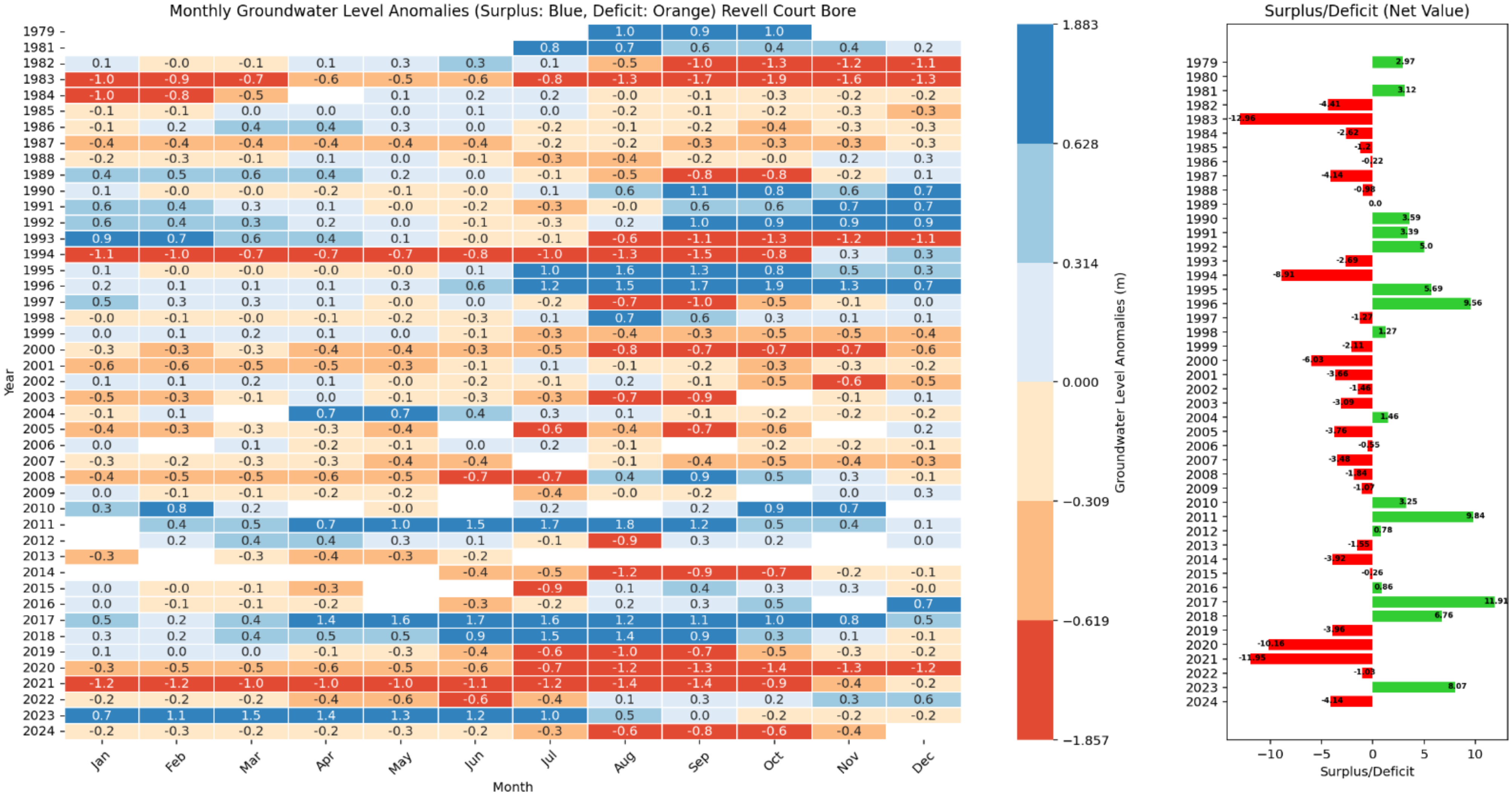


Figure 4.21 Deviations from normal highlighting positive and negative groundwater anomalies for Revell Court (left) and an annual net surplus or deficit based on monthly groundwater anomalies (right). Green bars in the surplus and deficit plot indicate a net annual groundwater surplus, while red bars indicate a net annual deficit. The labels for each bar indicate the total anomaly value in metres.

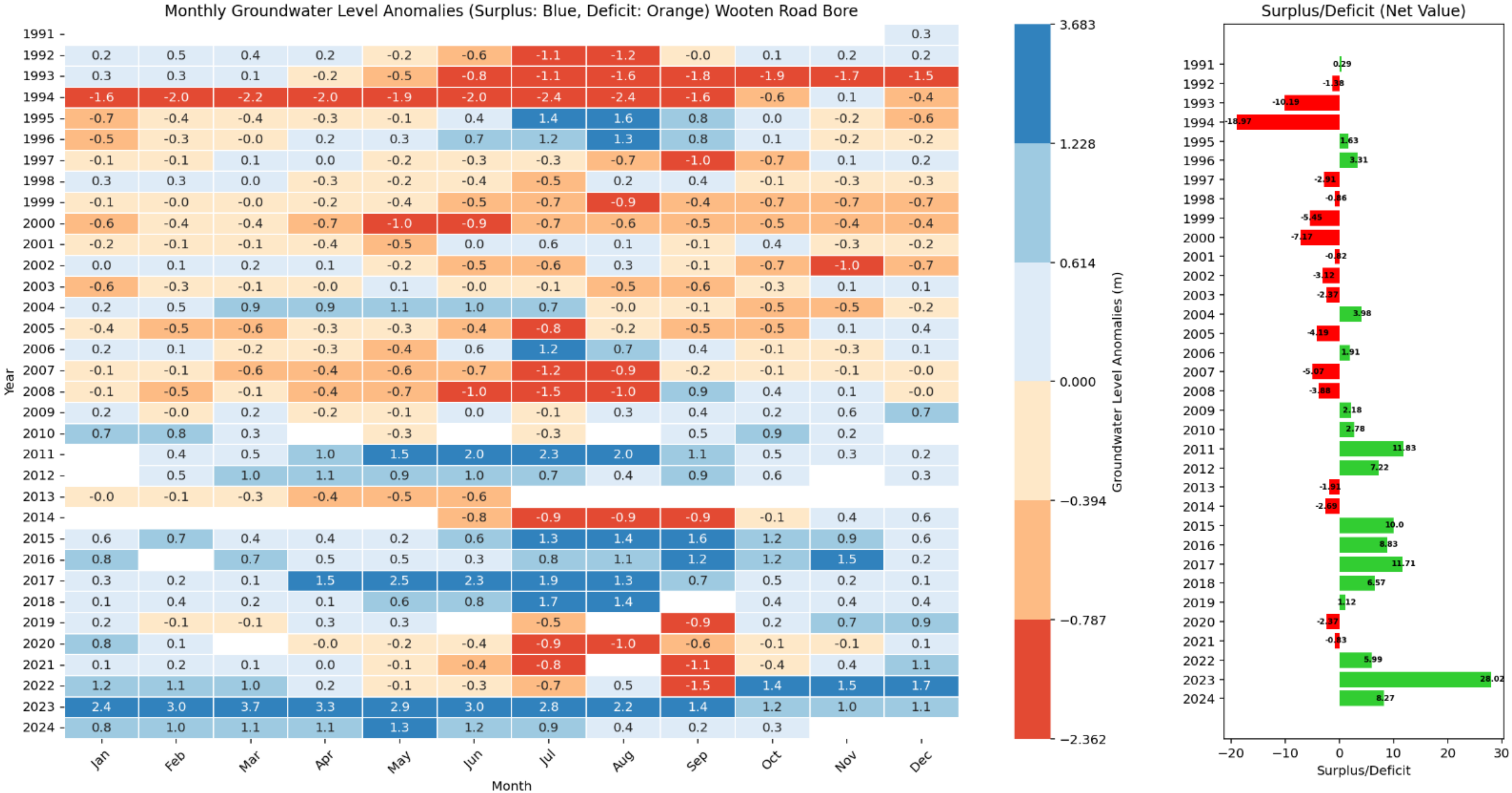


Figure 4.22 Deviations from normal highlighting positive and negative groundwater anomalies for Wooten Road (left) and an annual net surplus or deficit based on monthly groundwater anomalies (right). Green bars in the surplus and deficit plot indicate a net annual groundwater surplus, while red bars indicate a net annual deficit. The labels for each bar indicate the total anomaly value in metres.

4.5.2 Mean seasonal and annual groundwater levels during SOE2025

Mean groundwater levels during the years and seasons within SOE2025 (Table 4.30 and Table 4.31) were largely below normal for Quintals, Selaks, Maraeorahia and Revell Court. Autumn levels were the most strongly negative at Revell Court and Quintals with respect to groundwater level, while spring and summer groundwater levels were the most negative at Revell Court and Maraeorahia, respectively. Angle Street showed groundwater levels that were above the long-term average across all years and seasons, while Wooten was close to average.

With respect to the long-term average, Maraeorahia had hydrological year average of 88% of normal, with the indication that summer and to a lesser extent autumn drove that relative departure. The anomaly index values (z scores) show positive high groundwater levels at Angle Street across all seasons and years on average for SOE2025, with peak in spring and summer (Table 4.32). Wooten also showed positive groundwater index values for SOE2025, with the largest anomalies for summer and autumn, respectively (Table 4.32 and Table 4.33).

Table 4.30. Mean groundwater level (in metres) of groundwater relative to NZVD16 for selected climatological observing sites based on the five years (2019-2024) included in SOE2025. Based on data availability, some averages may be based on fewer than five years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	6.77	6.79	6.20	7.28	7.33	6.26
Selaks	22.50	22.76	21.25	23.52	24.41	23.04
Angle Street	2.51	2.47	2.46	2.54	2.56	2.45
Maraeorahia	2.95	2.74	2.74	3.16	3.22	2.28
Revell Court	62.71	62.69	62.38	62.27	63.16	62.97
Wooten	156.88	156.97	156.38	156.12	157.60	157.52

Table 4.31. Groundwater level anomalies (in metres) for the mean annual, hydrological year and seasonal groundwater level for SOE2025 relative to 1991-2020 climatological normal elevation. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	-0.29	-0.27	-0.48	-0.21	-0.09	-0.37
Selaks	-0.72	-0.46	-0.52	-0.17	-0.14	0.18
Angle Street	0.17	0.13	0.16	0.11	0.20	0.18
Maraeorahia	-0.11	-0.32	-0.16	-0.14	-0.05	-0.52
Revell Court	-0.32	-0.33	-0.15	-0.42	-0.52	-0.23
Wooten	0.59	0.68	0.82	0.16	0.33	1.14

Table 4.32. Groundwater level anomalies (% of normal) of the mean annual, hydrological year and seasonal groundwater level for SOE2025 relative to 1991-2020 climatological normal elevation. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	96	96	93	97	99	94
Selaks	97	98	98	99	99	101
Angle Street	107	106	107	104	109	108
Maraeorahia	96	88	94	96	98	81
Revell Court	100	99	100	99	99	100
Wooten	100	100	101	100	100	101

Table 4.33. Groundwater level index value (z score) for the mean annual, hydrological year and seasonal groundwater level for SOE2025 relative to 1991-2020 climatological normal elevation. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	-0.64	-0.61	-0.78	-0.63	-0.39	-0.75
Selaks	-0.52	-0.35	-0.31	-0.15	-0.17	0.21
Angle Street	1.31	1.00	1.17	0.82	1.72	1.30
Maraeorahia	-0.57	-1.27	-0.57	-1.22	-0.38	-1.65
Revell Court	-0.52	-0.55	-0.33	-0.59	-0.70	-0.55
Wooten	0.89	1.03	1.23	0.17	0.48	1.87

4.5.3 Seasonal and annual maximum groundwater level

Seasonal and annual maximum groundwater levels for the years within SOE2025 ranged from 0m to >3.5m above their normal levels when all the representative monitoring sites are considered together (Table 4.34 and Table 4.35). The maximum level positive anomalies were very small at Maraeorahia (ranging from 0m to 0.36m above normal) to multiple metres at Selaks (1.92m to 3.58m) and Wooten (1.25m to 3.25m). At Revell Court and Wooten, all the groundwater seasonal and annual maximum levels were in the normal range, and this was similar at Maraeorahia except during summer which had a maximum seasonal level 112% above normal that occurred in 2023. Higher than normal maximum levels were observed for annual, hydrological year and all seasons at Quintals, Selaks and Angle Street, where maximum groundwater levels ranged from 108%-118% of normal (except during winter and spring at Quintals, which was close to normal). Despite some sites showing close to normal percentages for maximum groundwater levels relative to climatology (Table 4.36), groundwater index values (z scores) were exceptionally high at some locations during SOE2025 (Table 4.37). Record values were registered for annual, hydrological year and all seasons at Selaks, Angle Street and Wooten (except for spring); for the hydrological year and autumn at Revell Court, for summer and autumn at Quintals, and for autumn at Maraeorahia.

Table 4.34. Groundwater maximum levels (in metres) relative to NZVD16 for selected climatological observing sites based on the years (2019-2024) included in SOE2025. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	7.59	7.78	7.86	7.86	7.55	7.68
Selaks	25.75	25.01	25.35	26.16	26.44	24.98
Angle Street	2.57	2.64	2.55	2.62	2.77	2.64
Maraeorahia	3.15	3.12	3.25	3.30	3.29	2.89
Revell Court	63.69	63.71	63.88	63.60	63.96	63.99
Wooten	158.65	158.14	158.81	158.63	158.52	158.89

Table 4.35. Groundwater level anomalies (in metres) for the maximum annual, hydrological year and seasonal groundwater level for SOE2025 relative to 1991-2020 climatological normal elevation. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	0.53	0.72	1.17	0.37	0.13	1.05
Selaks	2.65	1.92	3.58	2.47	1.92	2.12
Angle Street	0.23	0.32	0.25	0.19	0.42	0.37
Maraeorahia	0.09	0.08	0.36	0.00	0.02	0.10
Revell Court	0.67	0.69	1.36	0.91	0.29	0.79
Wooten	2.36	1.85	3.25	2.67	1.25	2.52

Table 4.36. Groundwater level anomalies (% of normal) of the maximum annual, hydrological year and seasonal groundwater level for SOE2025 relative to 1991-2020 climatological normal elevation. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	108	111	117	105	102	116
Selaks	112	108	116	110	108	109
Angle Street	110	114	111	108	118	116
Maraeorahia	103	103	112	100	99	104
Revell Court	101	101	102	101	100	101
Wooten	102	101	102	102	101	102

Table 4.37. Groundwater level index value (z score) the maximum annual, hydrological year and seasonal groundwater level for SOE2025 relative to 1991-2020 climatological normal elevation. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	0.53	0.72	1.17	0.37	0.13	1.05
Selaks	2.17	1.70	2.17	2.23	2.28	1.87
Angle Street	1.84	2.43	1.80	1.50	3.52	2.64
Maraeorahia	0.43	0.10	1.50	0.02	0.44	0.25
Revell Court	1.49	1.57	3.25	1.46	0.40	1.95
Wooten	3.15	2.74	4.83	2.54	1.54	4.12

4.5.4 Seasonal and annual minimum groundwater level

The average seasonal and annual minimum groundwater levels was close to normal for Angle Street and Wooten during SOE2025, but in the middle to lower part of the normal range for Quintals, Selaks and Maraeorahia for annual, hydrological year and autumn (Table 4.38 and 4.39). Average minimum levels that reached below normal values were observed during autumn for Quintals (71%) and during summer at Maraeorahia (73%). For those two sites, the summer and autumn minimum groundwater level anomalies are seen as the main contributor to the overall mean annual and mean hydrological year minimum levels being on the below normal side of average for the period being considered (Table 4.40). Index value scores for the minimum groundwater level levels were largely negative for SOE2025 for all years and seasons for Quintals, Selaks, Mareorahia and Revell Court, with the strongest negative values seen during autumn at Quintals and Selaks, during summer at Maraeorahia and during spring at Revell Court (Table 4.41).

Table 4.38. Level (in metres) of groundwater minimum levels relative to NZVD16 for selected climatological observing sites based on the years (2019-2024) included in SOE2025. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	5.98	6.11	4.75	6.62	7.01	5.53
Selaks	21.79	21.74	19.37	22.28	23.76	21.16
Angle Street	2.42	2.35	2.36	2.46	2.33	2.27
Maraeorahia	2.63	2.68	2.34	3.10	3.11	2.05
Revell Court	62.02	61.89	61.52	61.47	62.33	62.02
Wooten	156.14	156.19	155.51	155.17	156.85	156.59

Table 4.39. Groundwater level anomalies (in metres) for the minimum annual, hydrological year and seasonal groundwater level for SOE2025 relative to 1991-2020 climatological normal elevation. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	-1.08	-0.95	-1.94	-0.87	-0.41	-1.10
Selaks	-1.43	-1.48	-2.40	-1.41	-0.79	-1.43
Angle Street	0.08	0.02	0.06	0.03	-0.03	0.00
Maraeorahia	-0.43	-0.38	-0.55	-0.20	-0.22	-0.74
Revell Court	-1.00	-1.13	-1.01	-1.22	-1.34	-1.18
Wooten	-0.15	-0.10	-0.05	-0.79	-0.43	0.21

Table 4.40. Groundwater level anomalies (% of normal) of the minimum annual, hydrological year and seasonal groundwater level for SOE2025 relative to 1991-2020 climatological normal elevation. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	84	86	71	88	94	83
Selaks	94	93	89	94	97	92
Angle Street	104	101	103	101	99	100
Maraeorahia	85	87	81	94	93	73
Revell Court	98	98	98	98	98	98
Wooten	100	100	100	99	100	100

Table 4.41. Groundwater level index value (z score) the minimum annual, hydrological year and seasonal groundwater level for SOE2025 relative to 1991-2020 climatological normal elevation. Based on data availability, some averages may be based on fewer than 5 years or seasons for these calculations.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	-2.42	-1.91	-3.20	-2.50	-1.77	-2.23
Selaks	-1.14	-1.19	-1.45	-1.27	-0.94	-1.36
Angle Street	0.63	0.12	0.48	0.21	-0.21	0.01
Maraeorahia	-2.08	-1.65	-2.27	-1.86	-2.44	-2.32
Revell Court	-1.88	-2.14	-2.39	-1.77	-1.87	-2.82
Wooten	-0.04	-0.05	-0.04	-0.72	-0.43	0.35

4.5.5 Short-term groundwater level variation (SOE2025 vs SOE2020 snapshots)

Most changes in the annual, hydrological year and seasonal average groundwater level across the climatological-length groundwater monitoring sites were negative, with the strongest signatures of change for raw groundwater level shifts observed at Selaks and Revell Court (Table 4.42), showing a swing from relatively higher mean groundwater levels for the years in SOE2020 to relatively lower levels for the years and seasons in SOE2025. In addition, subtle negative level changes were observed at Maraeorahia for the hydrological year that were likely guided by lower average groundwater levels during the summers within the SOE2025 interval. Wooten was the only site that showed a relative increase in the average groundwater level with reference to SOE2020, which is observed for summer and autumn (Table 4.42).

For SOE2025, the annual, hydrological year and seasonal maximum average groundwater levels were equivocal to those observed during SOE2020 at Angle Street, Maraeorahia and Revell Court (except for slightly lower maximum levels seen during winter and spring). Quintals, Selaks and Wooten largely experienced a relative increase in maximum groundwater levels, with the largest positive changes seen during autumn and summer (likely leading to higher annual and hydrological year maximums) for those sites (Table 4.43) . In contrast, Quintals, Selaks and Revell Court experienced swings toward lower minimum groundwater levels for summer autumn and winter (except Selaks), which likely contributed to lower observed annual and hydrological year average minimum groundwater levels. Summer, autumn and annual minimum levels were slightly higher at Wooten (Table 4.44).

Table 4.42. Change in the mean level (in metres) of groundwater for selected climatological observing sites based on the years (2019-2024) included in SOE2025 relative to the years (2014-2018) in SOE2020. Based on data availability, some differences founded on the average values may be based on fewer than 5 years or seasons for these calculations. Elevational changes are relative to NZVD16. Colours are used to emphasise changes of +/- 0.25-0.5, +/-0.51-1.0, and +/-1.0 metre groundwater level anomalies.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	-0.24	-0.14	-0.70	-0.20	0.00	0.08
Selaks	-1.33	-0.91	-1.08	-0.24	-0.62	-0.39
Angle Street	0.02	-0.03	0.02	-0.02	0.05	0.02
Maraeorahia	0.01	-0.25	0.05	-0.15	-0.02	-0.30
Revell Court	-0.55	-0.51	-0.60	-0.82	-0.83	-0.36
Wooten	0.11	0.08	0.45	-0.69	-0.37	0.93

Table 4.43. Change in the maximum level (in metres) of groundwater for selected climatological observing sites based on the years (2019-2024) included in SOE2025 relative to the years (2014-2018) in SOE2020. Based on data availability, some differences founded on the average values may be based on fewer than five years or seasons for these calculations. Elevational changes are relative to NZVD16. Colours are used to emphasise changes of +/- 0.25-0.5, +/-0.51-1.0, and +/-1.0 metre groundwater level anomalies.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	0.35	0.55	0.52	0.08	0.09	1.01
Selaks	1.09	0.44	1.44	0.90	0.44	0.07
Angle Street	0.03	0.10	0.05	0.05	0.22	0.06
Maraeorahia	0.07	0.06	0.24	-0.10	-0.06	0.15
Revell Court	0.11	-0.05	0.23	-0.31	-0.66	0.35
Wooten	1.34	0.76	1.88	0.78	-0.04	1.85

Table 4.44. Change in the minimum level (in metres) of groundwater for selected climatological observing sites based on the years (2019-2024) included in SOE2025 relative to the years (2014-2018) in SOE2020. Based on data availability, some differences founded on the average values may be based on fewer than five years or seasons for these calculations. Elevational changes are relative to NZVD16. Colours are used to emphasise changes of +/- 0.25-0.5, +/-0.51-1.0, and +/-1.0 metre groundwater level anomalies.

Site	Annual	Hydrological	autumn	winter	spring	summer
Quintals	-0.82	-0.60	-1.58	-0.33	-0.21	0.14
Selaks	-0.85	-0.23	-0.81	0.98	0.23	-1.23
Angle Street	-0.04	-0.12	-0.02	-0.07	-0.15	-0.12
Maraeorahia	-0.17	-0.27	0.05	-0.08	-0.04	-0.36
Revell Court	-0.90	-0.76	-0.78	-0.59	-0.83	-1.11
Wooten	0.50	-0.23	0.80	0.11	-0.28	0.67

4.5.6 Groundwater variability and trends

When examining broad trends using the heat map and surplus deficit plots (Figure 4.17-Figure 4.22), multiple groundwater monitoring sites show a long-term changes characterised by a mix of moderate surplus/deficit years in the earliest part of the observations, with worsening groundwater deficits emerging in late 1980s and 1990s. Similar patterns of groundwater depletion are observed during those decades at Selaks and Revell Court, which were characterised by strong seasonal and multi-year deficits. Following this multidecadal interval, there were repeated groundwater fluctuations at Quintals typified by inconsistent recharge and localised groundwater stress up to about 2011, when there was a dramatic rebound in groundwater levels. This rebound was only interrupted by drought conditions that emerged between 2019-2021. Selaks and Revell Court followed a similar change as Quintals through the early 2000s and up to 2010-2011, typified by alternating surplus and deficit years. However, Selaks then experienced a shift toward sustained and growing groundwater surplus levels, while Revell Court also experienced an emergence of a strong groundwater surplus but with a sharp and constrained local decline constrained to 2020-21 (akin to Quintals).

Angle Street shows a consistent long-term trend toward higher groundwater levels across most months and seasons. The opposite long-term trend is observed for Maraeorahia, but this trend is largely restricted to spring, summer and part of autumn. Notably, the period of the year when annual groundwater recharge typically occurs at Maraeorahia, during late-autumn through winter and into early-to-mid spring, appears to be getting shorter. There are fewer months of near-normal groundwater levels between the times of the year when groundwater deficits arise. Wooten road shows a largely increasing groundwater trend through time, with a steady transition toward surplus years in the most recent half of the record. The long-term trend for most months at Wooten is also different or mid-to-late winter and early spring, when a flurry of strong, multi-year stretches of negative and positive groundwater level anomalies have occurred.

Groundwater data were analysed for trends in a similar manner to rainfall. Sites with long records in the northeastern and western part of Auckland show statistically significant trends indicating a change to lower groundwater levels for some seasons as well as the annual and hydrological year (Quintals and Selaks; Table 4.45). A seasonally significant groundwater level decrease is seen for Quintals Road and Maraeorahia for spring, and at both of those sites for summer at all levels of significance that were tested (see Table 4.45). The central area of Auckland shows an increase in groundwater level at Angle Street and at the southeastern side of the city at Wooten Road Bore across all levels of significance for annual average, the hydrological year and for all seasons (except in winter and spring at Wooten at the 0.01 significance level; see Table 4.45).

Table 4.45. Long-term Auckland Council groundwater observing sites that exhibited significant linear trends for groundwater level.

Site	annual			hydro			autumn			winter			spring			summer		
	a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
Quintals					-	-									-	-	-	-
Selaks																		
Maraeorahia	-	-	-	-	-	-								-	-	-	-	-
Angle Street	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Revell																		
Wooten	+	+	+	+	+	+	+	+	+	+	+			+	+	+	+	+

a=sig 0.01; b=sig 0.05; c=sig 0.10

4.6 Extreme seasonal climate conditions during SOE2025

4.6.1 2019-20 summer drought

The 2019-20 drought was one of the most extreme drought events for the Auckland region recorded since instrumental climate observations began, and it was recently summarised in a technical report that included an analysis of rainfall, river flow, soil moisture, groundwater and water take information along with additional indices from NIWA (Johnson 2021). At the start of the 2019-20 hydrological year in July 2019, El Niño Modoki was fading in the tropical Pacific, and ENSO neutral conditions were reached by August. The overall winter climate pattern for New Zealand was influenced by a polar jet stream that remained south of the country that was weaker than normal in July, with unsettled windflow and weather occurring at the end of the season. During Spring 2019, more westerly quarter winds than normal occurred, with cool and dry southwesterlies prevailing in October that shifted to warm, moist northwesterlies in November. This atmospheric circulation pattern was partly influenced by a positive Indian Ocean Dipole (Saji et al. 1999), located far afield from New Zealand, which created a pattern over Indonesia and Australia that influenced our regional climate via a known teleconnection (Mullan 1992). At the onset of summer 2019-20, the tropical Pacific Ocean remained in an ENSO-neutral state. Summer 2019-20 was characterised by lower-than-normal mean sea level pressure over the South Island and much lower than normal pressure to the south and east of New Zealand, along with more frequent highs to the northwest of the country. This atmospheric circulation pattern produced more frequent westerly-quarter winds than normal during the first half of the season, and it was also associated with above normal temperatures for the Auckland region. Sharp drops in soil moisture periodically occurred throughout the region in late October to early November.

Antecedent climate conditions that led up to the summer 2019-20 drought were important factors in the severity of that event. Autumn 2019 was characterised by lower-than-normal rainfall and soil moisture levels across many parts of the North Island, followed by normal rainfall during winter and spring 2019. NIWA reported soil moisture levels had returned to below normal levels for much of the northern North Island including parts of the Auckland region by spring 2019. Summer 2019-20 was characterised by overall record-low regional rainfall relative to the historical record (Table 4.47; Figure 4.23). During this season, routine hydrological monitoring that was conducted by Auckland Council showed some of the lowest values on record for soil moisture, groundwater and river flows. The New Zealand Drought Index (NZDI)(Mol, Tait, and Macara 2017) for Auckland indicated that summer 2020 also had the highest drought index value since 2007.

Johnson (2021) described strong regional similarities for rainfall anomalies across the Auckland region that occurred during the most recent part of the instrumental record when there is robust spatial and temporal coverage. This finding also indicates fewer rainfall observation stations back in time can be used as a proxy to evaluate the severity and significance of events like the 2019-20 drought. The homogenised Central Auckland Rainfall series that covers the period 1853 to 2020 indicates the 2019-20 drought was probably the most severe on record (Fowler 2021). The Central Auckland Rainfall series shows 73.6mm of rain fell for 2019-20 summer (35.6% of normal, relative to 1991-2020), and that this season was characterised as the strongest of all notable droughts since mid-19th century (see Table 4.46 for comparisons to other historical events).

Table 4.46. List of significant meteorological drought for Auckland during summer in the historical record 1853-2023. Rainfall index values for central Auckland are based on Albert Park concatenated series developed by Fowler (2021) while the Auckland rainfall index incorporates that series and all other available sites. Both index series, z-scores, follow the procedure described above. Percentage of normal rainfall anomaly at Albert Park uses the central Auckland rainfall series (Fowler, 2021) evaluated against the 1991-2020 standard climatological normal period. Bold values indicate most extreme value on record. Number of sites refers to site coverage for the Auckland rainfall index series.

Drought event	Central Auckland rainfall index	Auckland rainfall index	Albert Park rainfall (mm)	Albert Park rainfall anomaly % of normal	number of sites
1862-63	-1.26	n/a	97.4	47.1	1
1873-74	-1.44	n/a	80.9	39.1	1
1899-00	-1.43	n/a	82.6	39.9	1
1915-16	-1.44	n/a	81.3	39.3	1
1927-28	-1.42	-1.31	83.5	40.3	2
1945-46	-1.45	**-1.62**	80.7	39.0	3
1972-73	-1.22	-1.30	100.8	48.7	5
1973-74	-1.31	-1.34	92.3	44.6	5
1993-94	-0.78	-0.85	138.8	67.1	14
2012-13	-1.51	-1.05	74.8	36.1	19
2019-20	**-1.53**	-1.44	**73.6**	**35.6**	19

At Albert Park, the wettest day during summer 2019-20 occurred on 17 December 2019, which constituted about 33% (25.1mm) of the total seasonal rainfall (which reached just over 75mm). There was little relief from small intervening rainfall events that happened every 3-9 days from mid-December 2019 to the end of January 2020. During this part of summer, there were stretches of six, eight and nine consecutive days without rainfall that further exacerbated dry conditions. Following that, a significant consecutive dry day stretch unfolded and reached 24 days duration between 29 January to 21 February 2020. Ten of 19 observing sites with long-rainfall observations that were used for SOE2025 showed the lowest seasonal rainfall totals on record occurred during summer 2019-20, with seven other stations registering the second or third lowest (Figure 4.23). The spatial interpolation of the rainfall anomalies for the summer indicates the severity of the event had a strong west-to-east gradient, and significant impacts on offshore islands in the Hauraki Gulf (Figure 4.24).

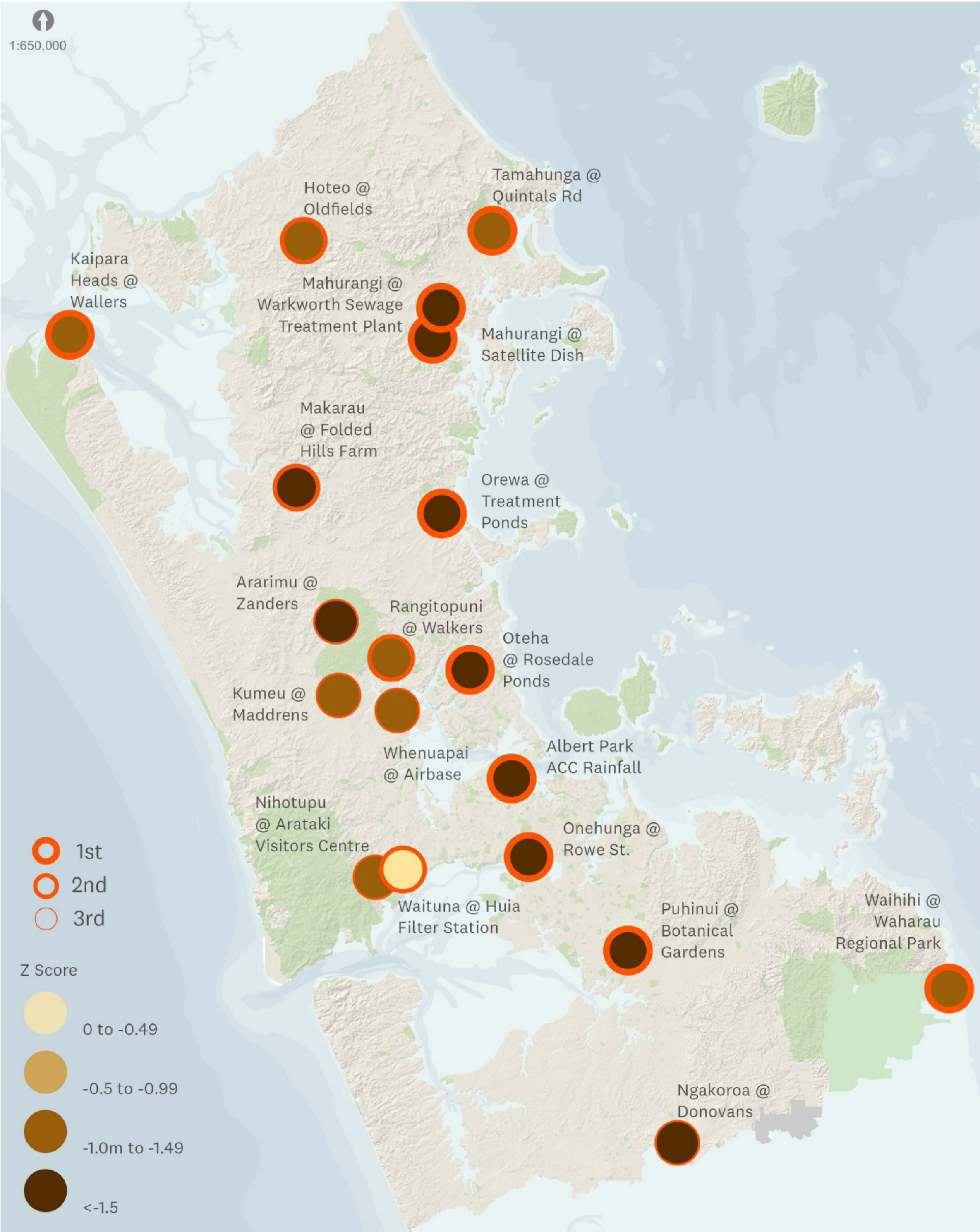
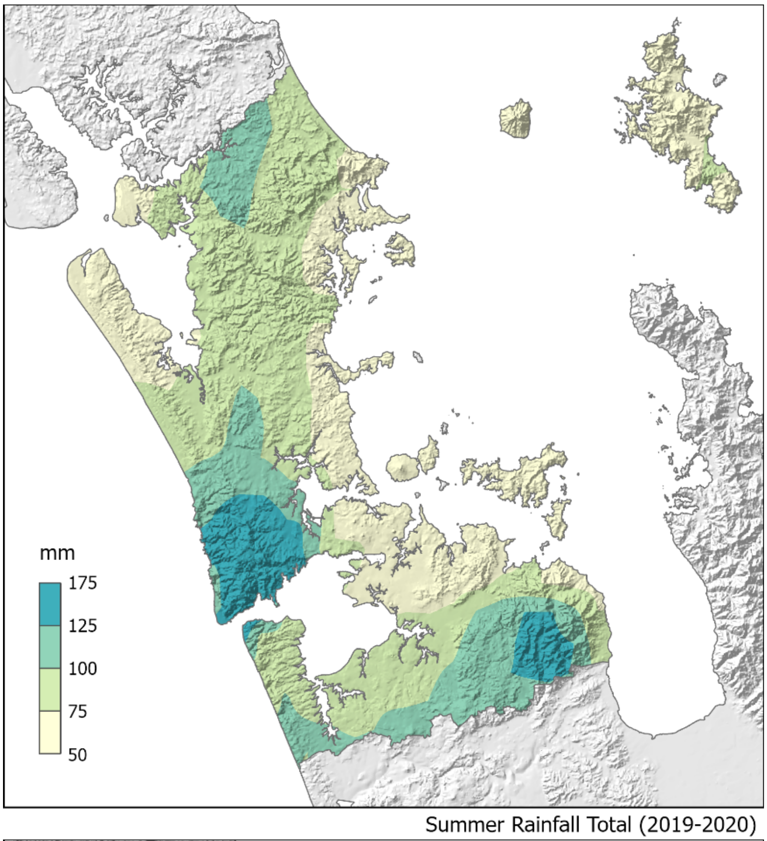


Figure 4.23 Seasonal rainfall anomalies for the 2019-20 summer classified by index values (z scores) that are partitioned by quintiles with reference to 1991-2020 climatology. Shading relates to rainfall index value thresholds. The weight of the orange outline indicates the all-time rank of the seasonal low rainfall anomaly.



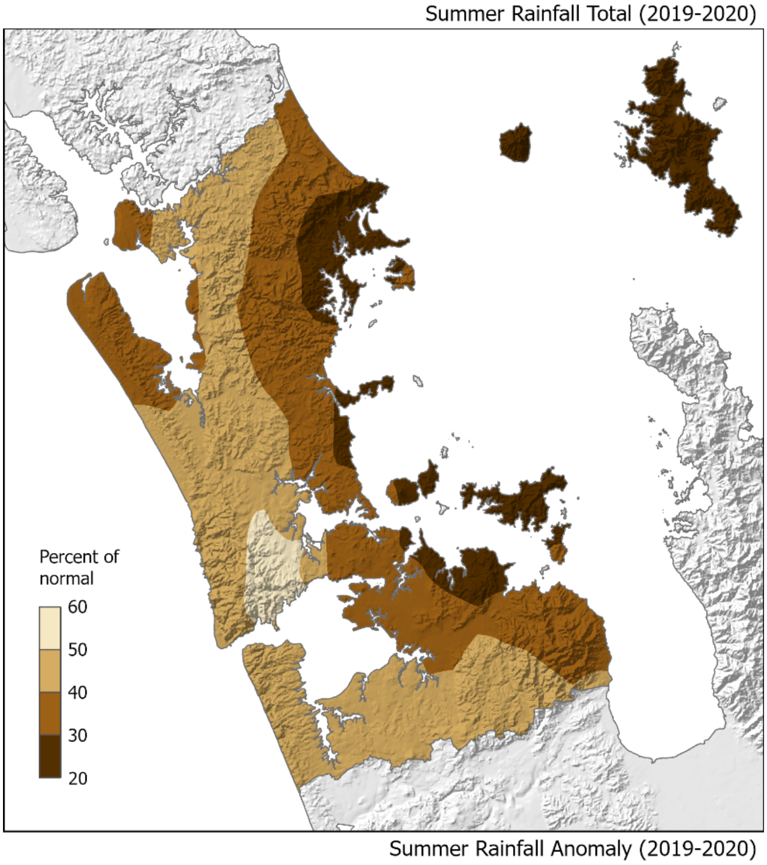


Figure 4.24 Interpolated regional rainfall totals in mm for summer 2019-20 (top) and rainfall anomalies expressed as a percentage of normal (bottom) relative to the 1991-2020 climatology period. Maps provided by NIWA as part of a regional update of the Virtual Climate Station Network dataset (Zammit et al. 2025) using the interpolation scheme described in Tait et al. 2006.

Table 4.47. Seasonal rainfall totals, percentage of normal (relative to 1991-2020 climatology) and Index values for Auckland Council stations for summer 2019-20. See section 3.1 for details about how index values are calculated. Rank is relative to the length of the entire available record (see Table 2.1 for details).

Site	2019-20 summer rainfall amount (mm)	% normal	Index value (z-score)	rank
Hoteo	146.5	58.5	-1.14	Eighth lowest
Tamahanga Quintalls	87.6	30.0	-1.49	Lowest
Kaipara	69.0	33.4	-1.48	Lowest
Mahurangi@Satellite	77.5	28.7	-1.88	Lowest
Mahurangi @Warkworth	53.5	20.8	-1.91	Lowest
Makarau	105.5	43.9	-1.60	2nd Lowest
Orewa	53.6	25.7	-1.68	Lowest
Ararimu	120.5	48.5	-1.53	Third lowest
Kumeu	111.9	49.3	-1.38	Third lowest
Whenuapai	97.0	47.3	-1.37	Third lowest
Rangitopuni	110.0	44.2	-1.36	2nd Lowest
Oteha	57.0	26.2	-1.50	Lowest
Albert Park	74.0	35.8	-1.53	Lowest
Nihotupu	165.3	51.1	-1.17	Third lowest
Waituna	121.4	44.6	-0.27	13th lowest
Onehunga	61.4	28.9	-1.65	Lowest
Puhinui	73.5	34.1	-1.53	Lowest
Ngakoroa	123.6	46.4	-1.51	2nd Lowest
Waihihi	86.8	34.3	-1.43	Lowest

NIWA's VCSN modelled soil moisture over Auckland Airport and the isthmus that encapsulates this time showed the development of an extended period with negative soil moisture anomalies (Lorrey, 2024). Relative to long-term daily soil moisture conditions, there were at least 50 consecutive days between the end of December 2019 and late February 2020 characterised by increasing daily soil moisture deficit (continued drying). This extended drying episode was typified by a worsening soil moisture deficit that was further influenced by the effects of relatively low rainfall concurrent with high temperatures.

The 2019-20 drought was one of the most significant hydrological low flow periods in the Auckland region. Previous analysis by Johnson (2021) analysed rivers for both the magnitude and duration of low flows for the 2019-20 drought, with nine sites (just under half selected for analyses in that report) had the lowest seven-day mean low flow on record (or were tied with the lowest on record). In addition, the greatest number of days below the mean annual low flow ($MALF_7$) occurred in 2020 for 13 of 23 sites that were analysed, and fourteen sites had greater than 90 days below $MALF_7$ in 2020 (Johnson 2021). Regional average total low flow days was also the highest since 1980. Three sites with more than 130 days below $MALF_7$ were the most northern.

During the 2019-20 drought, 28% of flow sites (12/43) used in SOE2025 analyses recorded their lowest minimum flows. The lowest flows were 0.1 l/s, recorded at Mangemangeroa, Orewa, Tamahunga, Te Muri, and the Vaughn stream sites. 18 flow sites had flows below 5 l/s, and 11 of these low flows were registered in urban catchments with areas ranging between 0.6 km^2 and 5.5 km^2. The other seven flow sites were non- urban with catchment areas ranging between 0.3 km^2 to 81.5 km^2.

The low flow summer period started in mid-November with most streams dropping below the threshold (Figure 4.25). A brief region wide respite occurred in early January, resulting in flows rising in all streams except for the Tamahunga at Quintals Falls. This was followed by longer periods of lower flows starting in mid-January and ending in late-February, where, after another brief respite from some rain, flows dropped below the threshold. Not all streams showed improving flows during late February 2020 despite some rainfall (Figure 4.25).

For some streams, the low flow spell started to end between mid-April 2020 and by early May (except for nine streams most streams entered a wetter spell). By late May/ early June all streams had recovered from the low flow period associated with the 2019-20 summer drought. The longest dry spell and spanned 199 days for the Te Muri Project site starting the 15th of November 2019 and ending the 31st of May 2020.

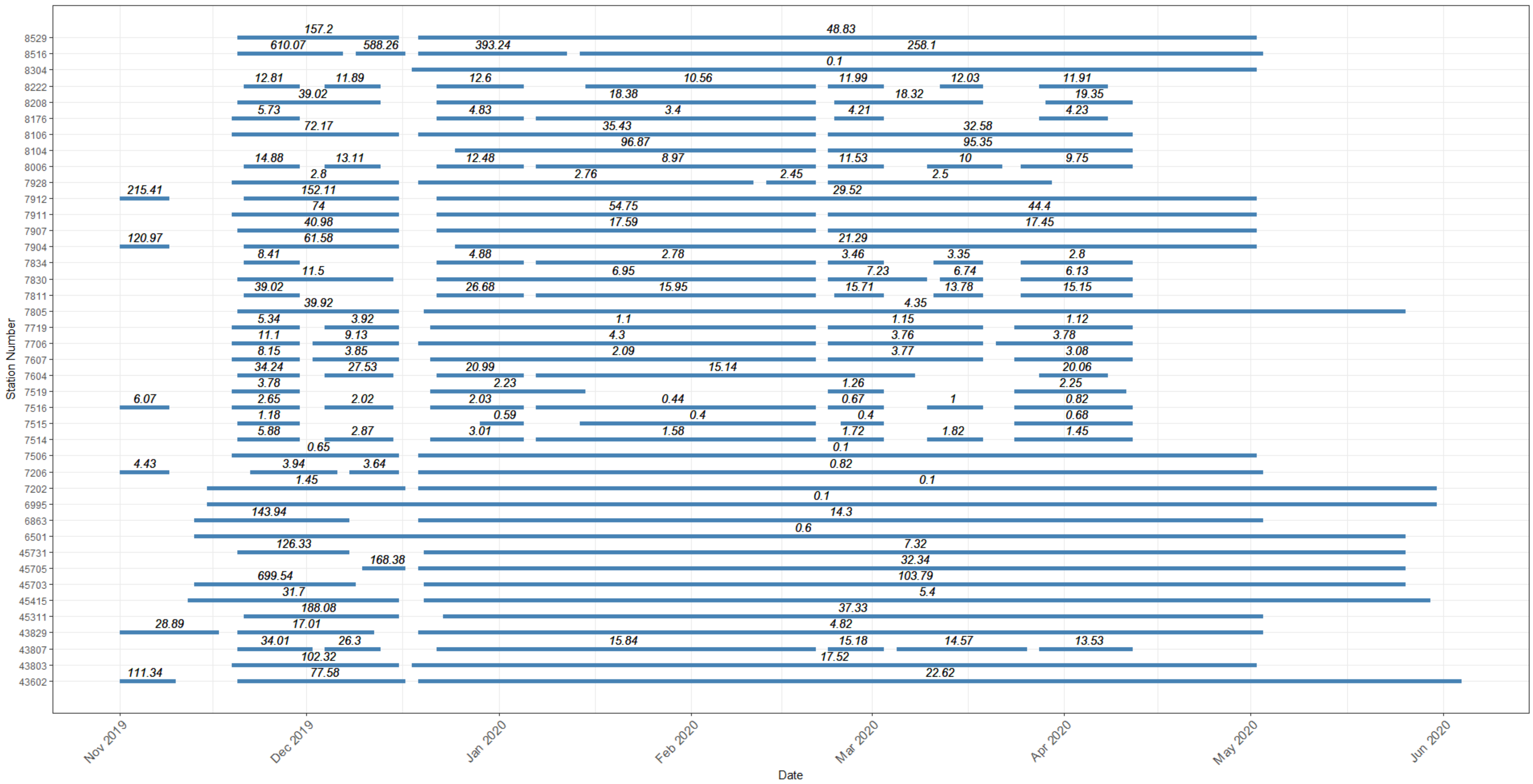


Figure 4.25 Time series plot for all rivers monitored that were evaluated in SOE2025, which shows the length of the time below the MALF threshold (blue line) and the lowest value during the 2019-20 drought event (black numbers). Site numbers on the left margin correspond to details in Table 2.3.

Summer 2019-20 groundwater observations showed very low levels for many aquifers across the Auckland region, and noticeable effects of the 2019-20 drought appear in most of the selected groundwater time series. Johnson (2021) previously analysed thirty-five groundwater monitoring sites showed monthly groundwater levels that were lower than the long-term inter-quartile range established for January-May across the historical period. Thirty-one of those sites had at least one month that was lower than the 25th percentile groundwater level for that month. Twelve of those sites had at least one month in 2020 that was the lowest on record for that month. In this report, we selected a fewer number of sites (six in total) which had long enough records for establishing a standard climatic normal between 1991-2020 and that did not exhibit any visual heterogeneities. Of those sites, three showed positive long-term groundwater trends, and no significant registration of anomalous seasonal groundwater levels associated with the 2019-20 drought. Three of the six sites showed significant and anomalously negative groundwater levels between 2019-2021 that were likely exacerbated by the 2019-20 drought. In addition to groundwater, record-low lake level at Rototoa in northwest Auckland was also recorded during this event, the lowest since records there began in 1984 (Johnson, 2021).

4.6.2 2022-23 summer deluge

The 2022-23 hydrological year saw the highest monthly and seasonal rainfall totals that have been recorded for Auckland since the instrumental era began in the early 1850s. The onset of the hydrological year saw La Niña conditions established in the Pacific for the third year in a row (also referred to as a "triple-dip La Niña"), which has rarely occurred in the recent historical past. Northerly and easterly quarter flow dominated the first two years of this protracted La Niña event, with warmer-than-normal temperatures typical of this type of atmospheric circulation pattern impacting the region. While 2020-21 and 2021-22 hydrological years coinciding with this event saw largely drier-than-normal or normal rainfall across the region for the summer and autumn seasons, the progression of seasonal rainfall totals from mid-2022 into early 2023 was markedly different. Autumn 2022 showed a mixture of rainfall anomalies and strong spatial heterogeneity (Figure 4.3). Winter 2022 showed 89% of Auckland Council sites received q5 rainfall, and the remainder received rainfall amounts exceeding those captured during any winter season during the 1991-2020 period (Figure 4.4). Spring 2022 was remarkably wet with 32% of sites receiving q5 rainfall and 68% receiving extreme rainfall totals that were outside the climatological boundaries (Figure 4.5). During summer, multiple rainfall records for Auckland were shattered, with 95% of sites registering extreme rainfall totals for December – February 2023 and the remaining 5% of sites recording q5 rainfall (Figure 4.6; See Figure 4.27 for spatial interpolation of amounts and percentage of normal and Figure 4.28 for index values).

According to NIWA, Auckland received over 5.5 times its normal summer rainfall during December 2022-February 2023, and 63% of the entire annual normal rainfall amount based on their analysis of the New Zealand Virtual Climate Station Network (VCSN) covering the region (Figure 4.27). During summer 2022-23, two ex-tropical cyclones impacted the Auckland region that contributed significantly to this record-breaking season. The first one, named Hale, occurred on 10-11 January and made landfall in the North Island. The second, named Gabrielle, occurred over 12-15 February and resulted in historic flooding for several parts of the North Island. In addition to these two ex-tropical cyclones, the warmth, humidity, and moisture availability for transient low-pressure weather systems was amplified by a protracted marine heatwave (MHW) that peaked during January 2023. The exceptionally warm waters around the Auckland region rivalled the exceptional MHWs of 2017-2018 and 2021-2022.

In addition to the ex-tropical cyclones Hale and Gabrielle, torrential rainfall between 27-28 January affected a large portion of the northern North Island, including Auckland. Rainfall in the Auckland region during these two days broke many previous records, with unprecedented maximum totals for recorded rainfall in durations of 1-hour, 2-hours, 6-hours, 12-hours, 24-hours, and 48-hours (Figure 4.26; Figure 4.29; Table 4.48 and 4.49).

The severe weather during late January 2023 caused four fatalities, led to a state of emergency being declared in Auckland, and impacted more than 5,000 Auckland properties. More than 2550 homes (2555 of more than 7300 properties) were “red or yellow stickered” because of damage from this severe rainfall event and associated impacts. Auckland Airport was severely flooded and as a result was temporarily closed, while large-scale flooding caused evacuations of homes, stranded motorists, and left many people requiring assistance and rescue.

Table 4.48. Maximum rainfall accumulation totals for the 27-28 January 2023 event in Auckland. Statistics for 1h, 2h, 6h, 12h and 24h are calculated using rain accumulation recorded within individual hours for contiguous time stretches within the two-day period beginning 12:00am on 27 January and ending at 11:59pm on 28 January.

Site	1h	2h	6h	12h	24h	48h
643510 – Hoteo	32.99	48.77	130.53	161.61	178.35	188.87
643713 – Tamahunga	22	39	95	141	173	190
644211 – Kaipara Heads	4.99	5.99	8.99	20.48	25.47	46.95
644616 – Mahurangi @ Satellite Dish	25.45	46.91	95.81	134.73	164.16	176.14
644626 – Mahurangi @ Warkworth	26.29	42.72	81.22	117.84	146	153.98
645519 – Makarau	37.52	54.35	109.19	155.86	170.77	171.73
646619 – Orewa	41.14	79.7	154.79	191.3	221.64	229.35
647510 – Ararimu	45.08	66.38	134.74	190.22	214.99	227.37
647513 – Kumeu	61	93.5	158	188	227.44	280.7
647601 – Whenuapai	48.35	81.4	148.5	184.02	224.97	240.76
647614 – Rangitopuni	63	87.5	158.5	197	241.5	247
647727 – Oteha	62.56	109.49	206.47	254.44	294.59	300.32
648719 – Albert Park	81.8	146.33	212.88	251.49	285.02	305.85
649514 – Nihotupu	60.65	71.99	130.17	175.53	215.47	219.9
649641 – Waituna	38.07	47.84	129.13	169.78	207.33	223.28
649723 – Onehunga	83.66	129.25	194.14	235.44	277.81	294.43
740945 – Puhinui	29.57	40.84	83.08	127.67	168.98	184
742914 – Ngakoroa	15.15	29.79	61.1	76.75	102	112.6
750213 – Waihihi	11.87	17.8	40.55	61.32	95.44	114.73

Table 4.49. Maximum rainfall accumulation totals for the 27-28 January 2023 event in Auckland. Statistics for 1h, 2h, 6h, 12h, 24h and 48h are calculated using rain intensity recorded across individual hours and across contiguous time stretches within the two-day period beginning 12:00am on 27 January and ending at 11:59pm on 28 January. The difference in the way these totals are calculated is why values shown here are larger than values in the prior table. Bold values = highest on record; italicised and underlined = 2nd highest on record; Underlined = 3rd highest on record; italicised = 4th highest on record.

Site	1h	2h	6h	12h	24h	48h
643510 – Hoteo	37.77	54.98	*130.54*	*161.61*	**178.35**	189.82
643713 – Tamahunga	29	50.5	102	143	*173*	192.5
644211 – Kaipara Heads	6.5	6.99	12.49	21.98	25.47	46.95
644616 – Mahurangi @ Satellite	28.94	47.41	*99.3*	*135.23*	164.17	*178.14*
644626 – Mahurangi @ Warkworth	29.58	44.6	*86.39*	*120.19*	*147.88*	157.74
645519 – Makarau	41.37	*58.2*	**131.32**	**155.86**	**173.17**	*176.54*
646619 – Orewa	44.22	*80.74*	**157.88**	**191.3**	**221.64**	**229.87**
647510 – Ararimu	**51.52**	**77.78**	**152.57**	**191.21**	**215.98**	**228.86**
647513 – Kumeu	**74.5**	**107**	**158**	**188**	**203.5**	**281.59**
647601 – Whenuapai	54.27	*83.87*	*149.49*	**185.01**	**224.97**	**241.25**
647614 – Rangitopuni	63.5	93.5	*160.5*	*201.5*	**242**	*247.5*
647727 – Oteha	*70.39*	**125.14**	**208.55**	**257.56**	**294.59**	**300.84**
648719 – Albert Park	**91.96**	**149.88**	**214.41**	**252**	**285.02**	**306.36**
649514 – Nihotupu	**61.64**	**74.46**	**130.67**	**175.53**	**215.47**	**220.4**
649641 – Waituna	*41.67*	48.88	**129.65**	**170.29**	**207.33**	**224.31**
649723 – Onehunga	**88.5**	**145.34**	**195.22**	**235.44**	**277.81**	**294.97**
740945 – Puhinui	*30.51*	*42.72*	**84.97**	**136.6**	**169.45**	**184.47**
742914 – Ngakoroa	21.72	31.81	61.6	79.28	103.52	115.13
750213 – Waihihi	13.36	18.3	40.55	61.82	95.93	135

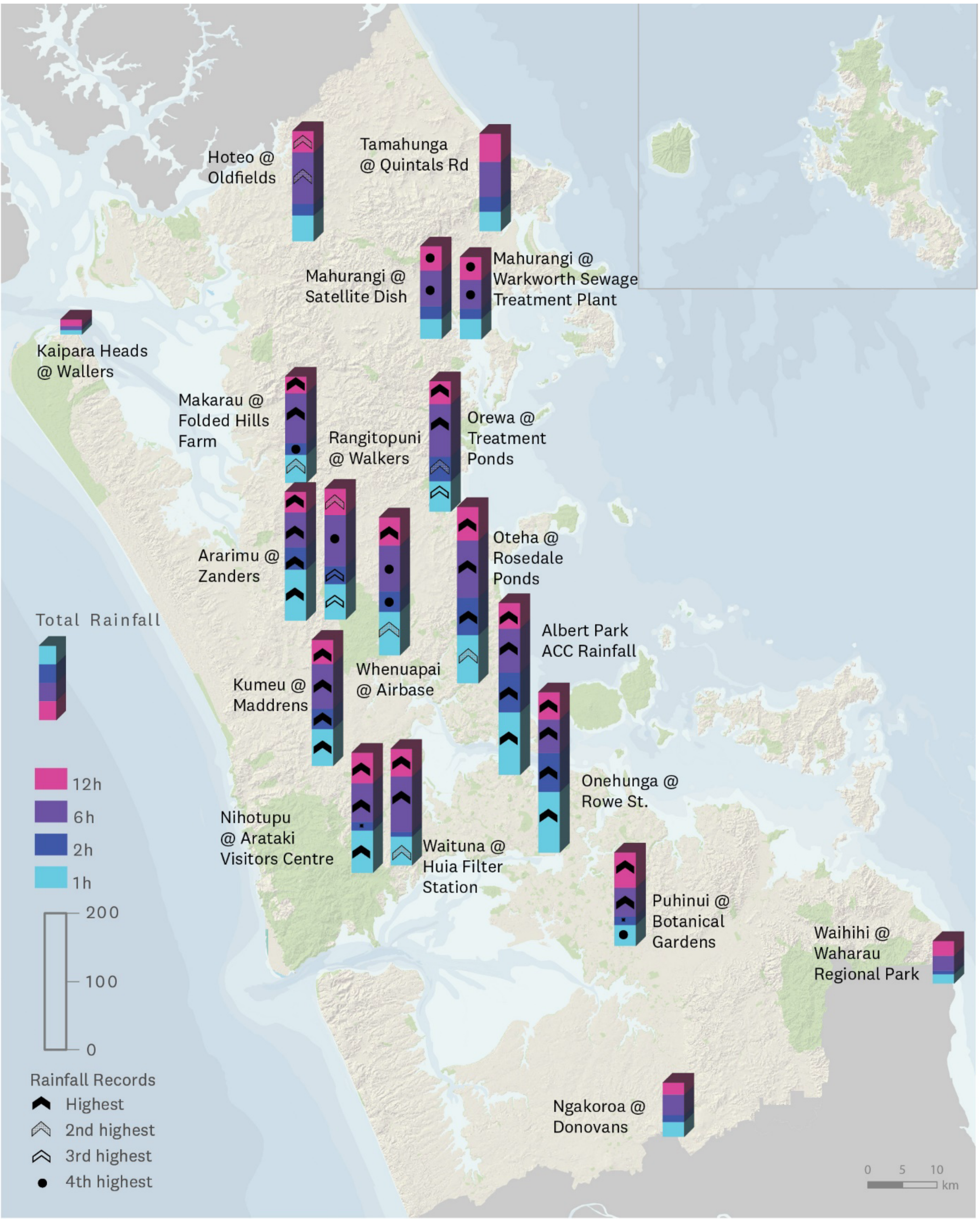


Figure 4.26 1, 2, 6, and 12h rain amounts during 27-28 January 2023 event in Auckland. Statistics for 1h, 2h, 6h, 12h are found in Table 4.49, and were calculated using rain intensity observations recorded across individual hours and across contiguous time stretches within the two-day period beginning 12:00am on 27 January and ending at 11:59pm on 28 January.

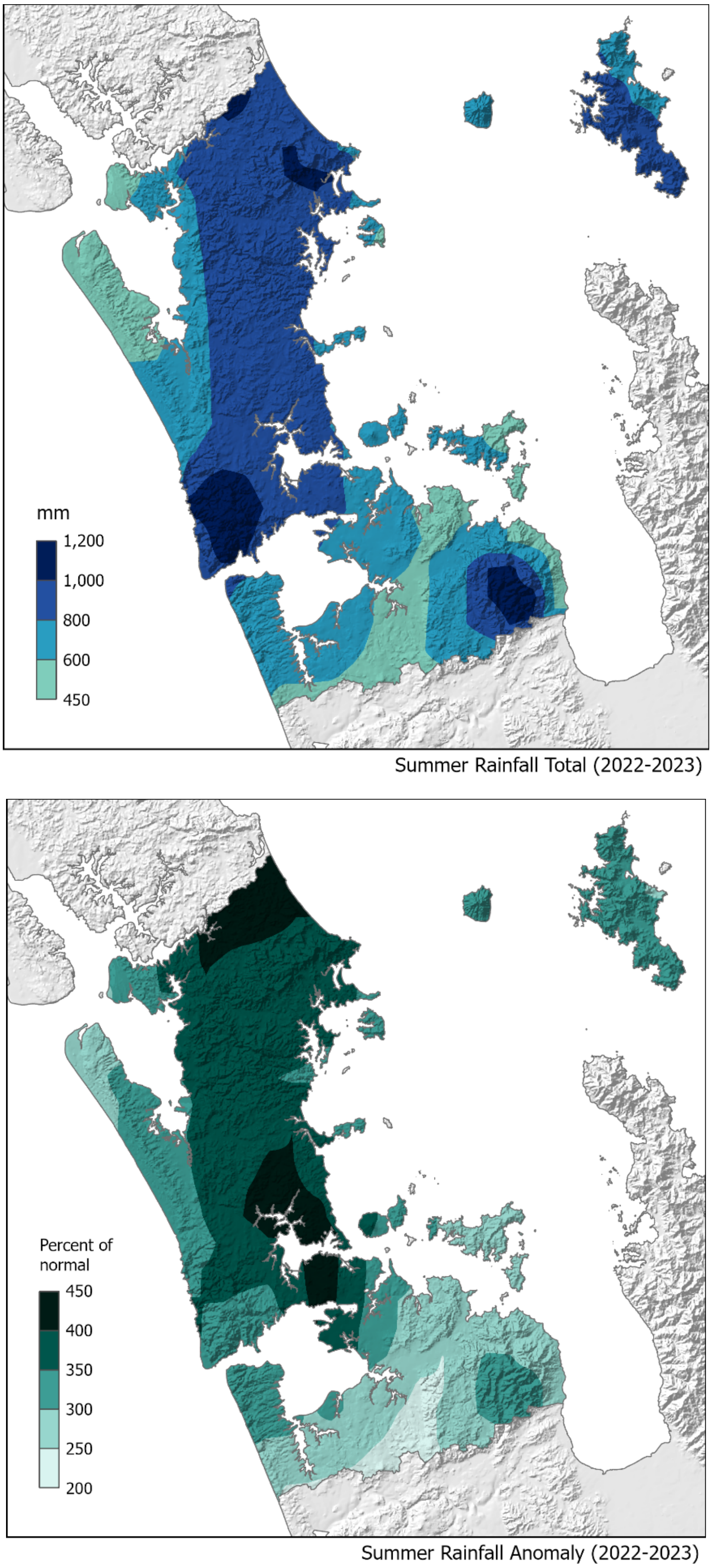


Figure 4.27 Interpolated regional rainfall totals in mm for summer 2022-23 (top) and rainfall anomalies expressed as a percentage of normal (bottom) relative to the 1991-2020 climatology period. See Table 4.50 for more details. Maps provided by NIWA as part of a regional update of the Virtual Climate Station Network dataset (Zammit et al. 2025) using the interpolation scheme described in Tait et al. 2006.

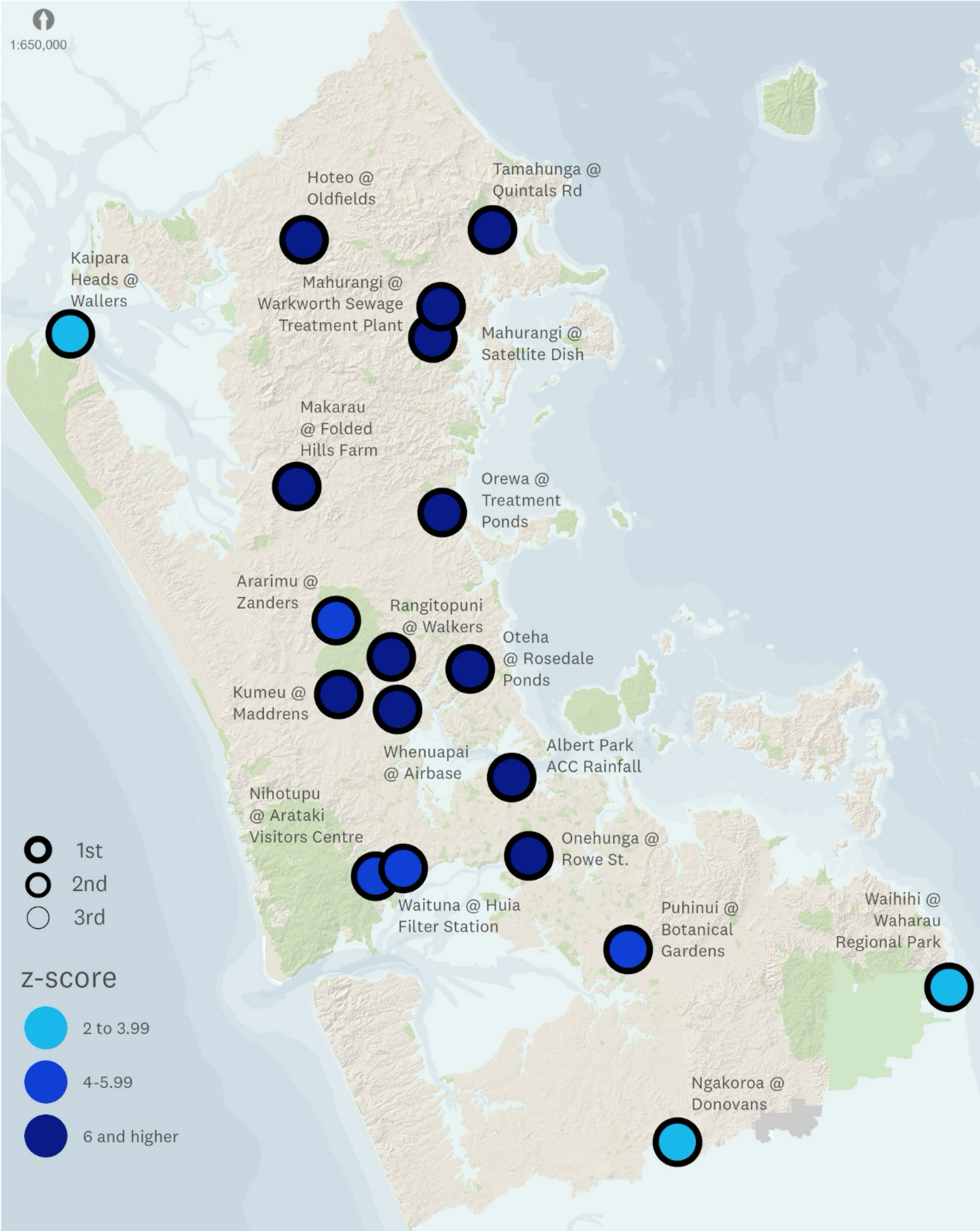
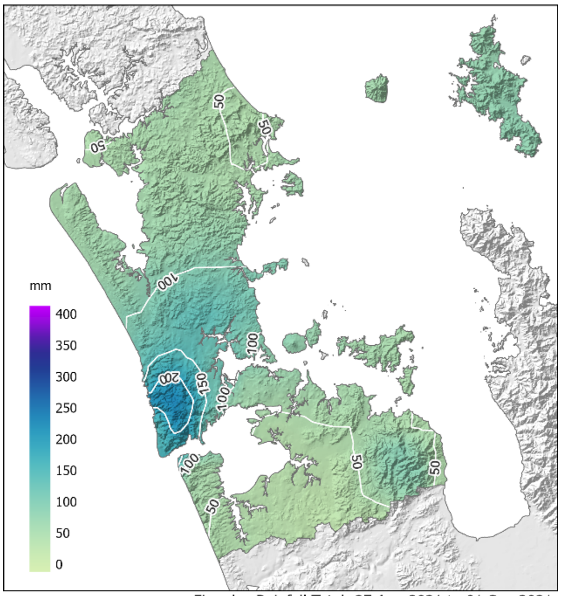


Figure 4.28 Seasonal rainfall anomalies for the 2022-23 summer classified by normalised index values that are partitioned by relative severity. Shading shows broad index value classes (2-4 Standard Deviations (STD), 4-6 STD, and >6 STD from normal seasonal rainfall). All the rainfall values for this season are beyond the distributions established for the climatic normal period except at Ngakoroa. The weight of the black outline indicates the all-time rank of the seasonal rainfall anomaly.

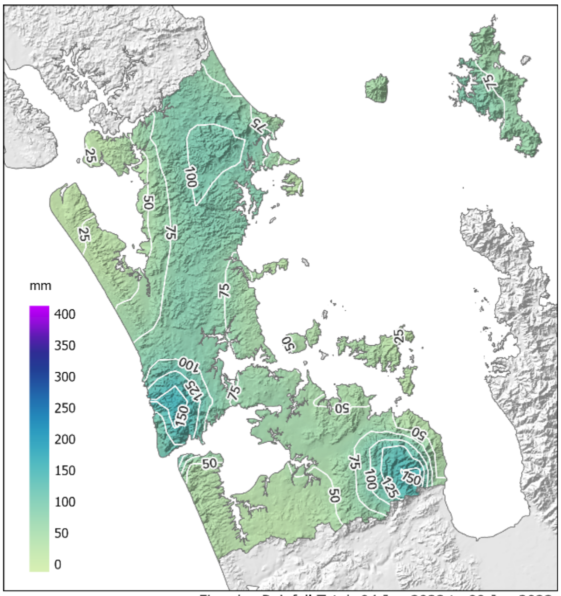
Table 4.50. Rainfall seasonal totals, percentage of normal (relative to 1991-2020 climatology) and Index values for Auckland Council stations for summer 2022-23. See section 3.1 for details about index value calculations. Rank is relative to the length of the entire available record (see Table 2.1 for details).

Site	Summer 2022-23 rainfall amount	% normal	Index value (z-score)	rank
Hoteo	987.1	394.1	8.05	Highest
Tamahanga Quintalls	1172.8	401.5	6.42	Highest
Kaipara	575.0	278.5	3.96	Highest
Mahurangi@Satellite	1069.1	396.6	7.83	Highest
Mahurangi	964.3	374.2	6.63	Highest
Makarau	922.3	383.5	8.06	Highest
Orewa	817.6	392.3	6.63	Highest
Ararimu	954.2	384.4	4.86	Highest
Kumeu	933.1	411.2	8.45	Highest
Whenuapai	909.4	443.8	8.92	Highest
Rangitopuni	1020.6	410.2	7.56	Highest
Oteha	892.0	410.3	6.29	Highest
Albert Park	893.9	432.3	7.97	Highest
Nihotupu	939.6	290.7	4.58	Highest
Waituna	909.4	334.0	4.60	Highest
Onehunga	862.0	405.1	7.05	Highest
Puhinui	649.4	301.3	4.66	Highest
Ngakoroa	571.1	214.3	3.22	2nd Highest
Waihihi	576.4	227.8	2.79	Highest

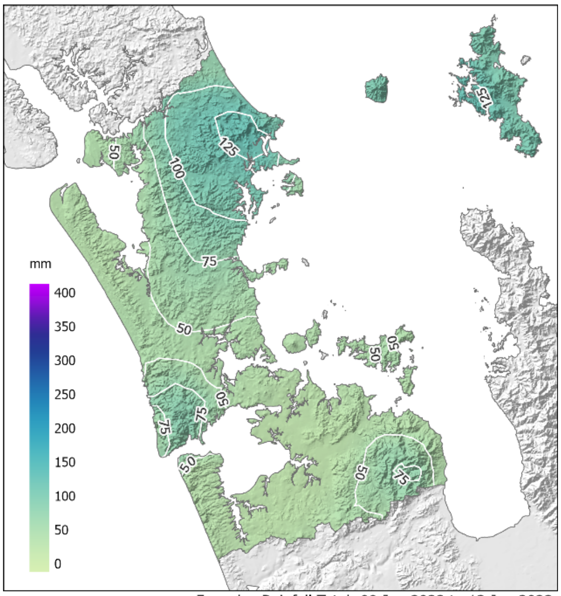
Rainfall index values for the selected Auckland Council stations used in the SOE2025 analysis shows summer 2022-23 was regionally the wettest on record at all sites except Ngakoroa (which had a wetter summer in 2003-04). The mean rainfall index value for the region for this season was 6.24 (see Figure 4.28 and Table 4.50) and this is the highest rainfall index value observed since 1853. There was spatial heterogeneity for the impacts of the rainfall events across the region that contributed to the seasonal rainfall totals for summer 2022-23, and this is reflected in the spread of rainfall index values across the sites (Figure 4.28), which ranged from a low of 2.79 to a high of 8.92. The reduction of spatial coverage for rainfall observing sites across the Auckland region and the relative bias associated with a lower number of observing sites that increases into the past means some historical summer seasons from the mid-to-early 20th Century and in the 19th Century may have received comparable rainfall amounts as summer 2022-23. Unequivocally, the Auckland regional rainfall index shows summer 2022-23 had the highest rainfall totals for any summer season in the last 50 years. In a long-term context, the Central Auckland Rainfall series (Fowler, 2024) which incorporates Albert Park rainfall shows summer 2022-23 was probably the most extreme in 170 years of observations at that site (Figure 4.30). 539mm of rain fell at Albert Park in January 2023, shattering the previous highest monthly total of all time which was 420mm in February 1869.



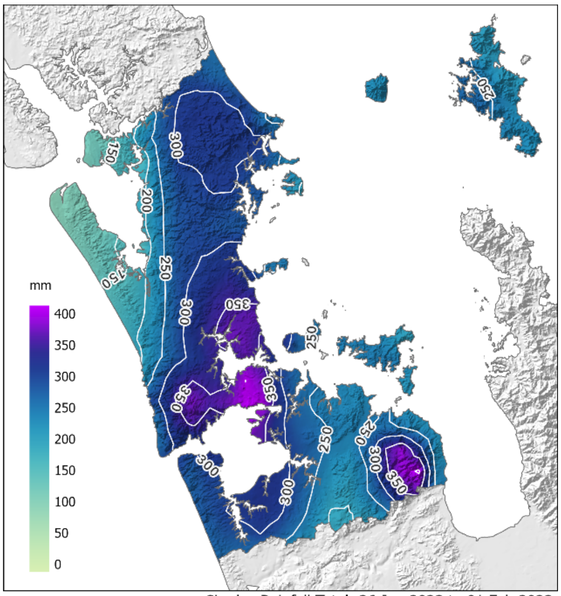
Five-day Rainfall Total: 27 Aug 2021 to 01 Sep 2021



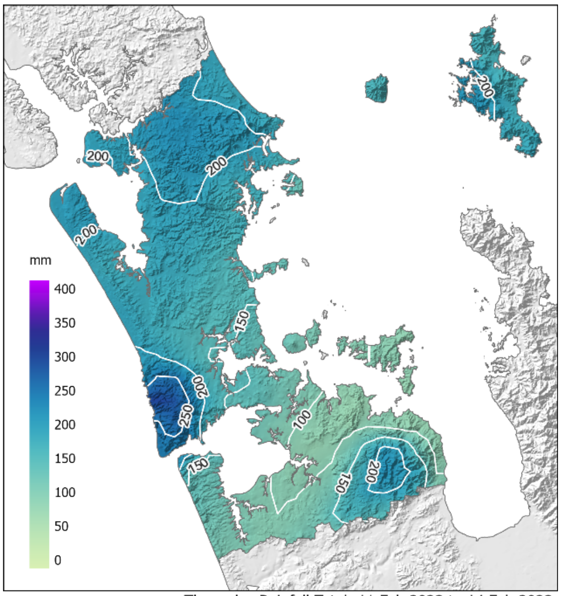
Five-day Rainfall Total: 04 Jan 2023 to 09 Jan 2023



Four-day Rainfall Total: 09 Jan 2023 to 13 Jan 2023



Six-day Rainfall Total: 26 Jan 2023 to 01 Feb 2023



Three-day Rainfall Total: 11 Feb 2023 to 14 Feb 2023

Figure 4.29. Virtual Climate Station Network (VCSN) multiday rainfall maps for significant storm events that occurred during SOE2025. Upper left – Winter/Spring transition 2021; Upper right – early January 2023; Middle left – mid-January 2023 (ex-tropical cyclone Hale); middle right – January – early February 2023 (Auckland Anniversary 2023); lower left – mid-February 2023 (ex-tropical cyclone Gabrielle). The start date for each composite is from 9am on the first day listed and the end is 9am on the last day listed. The total number of days for the rainfall aggregation is indicated. Each event was associated with significant surface impacts, including flooding. The duration of each storm was determined using cumulative rainfall totals in conjunction with historical reanalysis data (see Appendices 3 and 4) which indicate each event, and the days included in each plot, can be linked to a distinct weather system. We note that each storm may have undergone reinvigoration or subtle transformations through the time when the mapped rainfall occurred. The mapped rainfall dataset used was supplied from NIWA/ESNZ (Zammit et al. 2025).

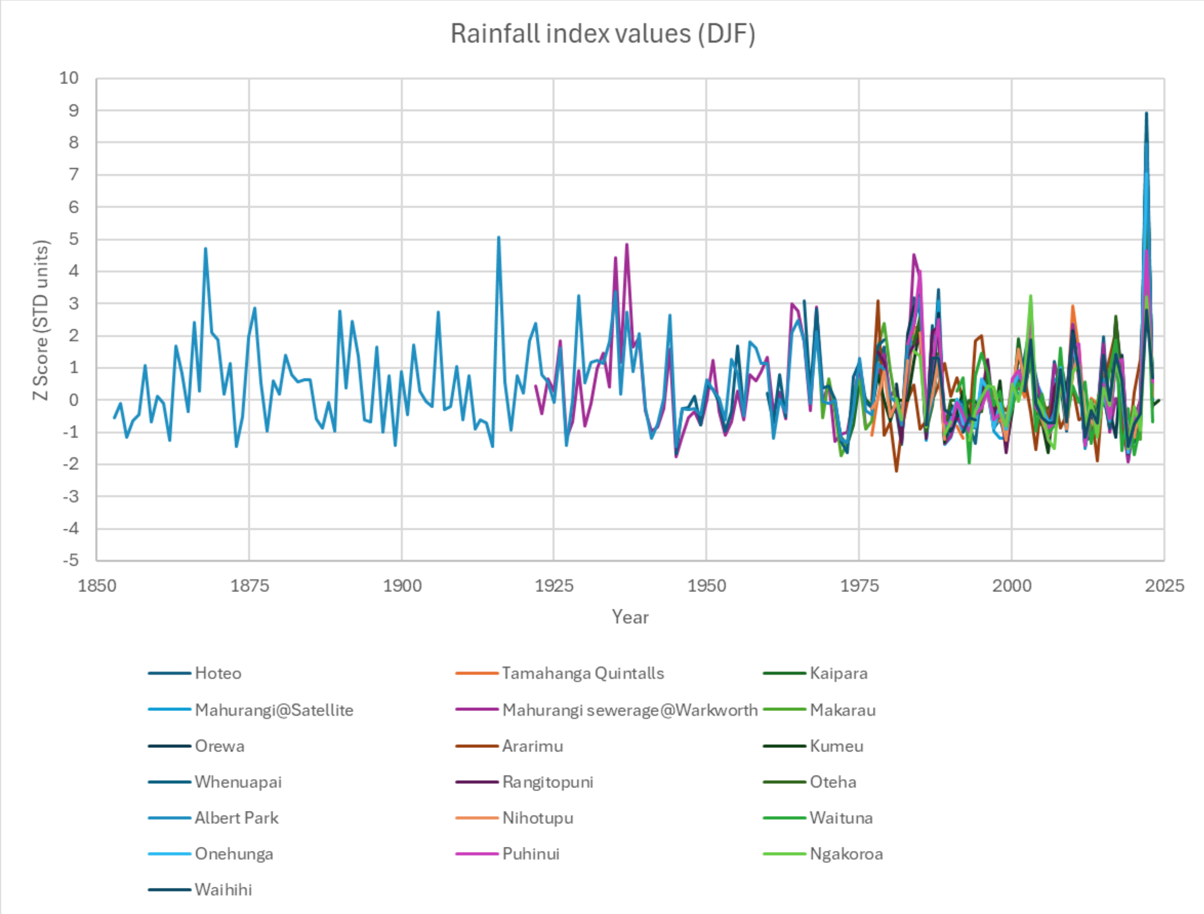


Figure 4.30 Rainfall index values for long-term monitoring sites for summer (December, January, February) rainfall totals. Index values were derived by subtracting the mean summer rainfall from the standard climatological normal amount and dividing by the standard deviation based on the 1991-2020 period. A mean Auckland rainfall index for summer was then made by the arithmetic mean of all available sites for each year (see Figure 5.3 and Figure 5.4 in the Discussion).

The analysis of Auckland Council soil moisture sites that are spaced across the region showed there were acute near-surface water responses to the significant high-intensity short-duration rainfall events that occurred during summer 2022-23. Early in 2023, and in general, the soils across the Auckland region were wet prior to the Auckland Anniversary rainfall event. There was moderate ability of soils to cope with additional rainfall at many of the monitoring sites prior to that event (i.e. they had some capacity), however that capacity was rapidly exceeded due to high rainfall amounts delivered in a short time frame. The quick succession of intense rain events in late January and February 2023 meant that field capacity was reached and exceeded several times, resulting in surface flooding. Soil moisture (%) on a daily time scale across all sites also showed an initial drying response following the early to mid-January rainfall event where soil moisture levels decreased by 10% to 20%. While the relative soil moisture drying in early January was not as significant as what has occurred during a drought, it shows that there was some capacity within the soil to absorb rain that followed. Examples from Mangemangeroa and Mt Albert Grammar illustrate this situation (Figure 4.31).

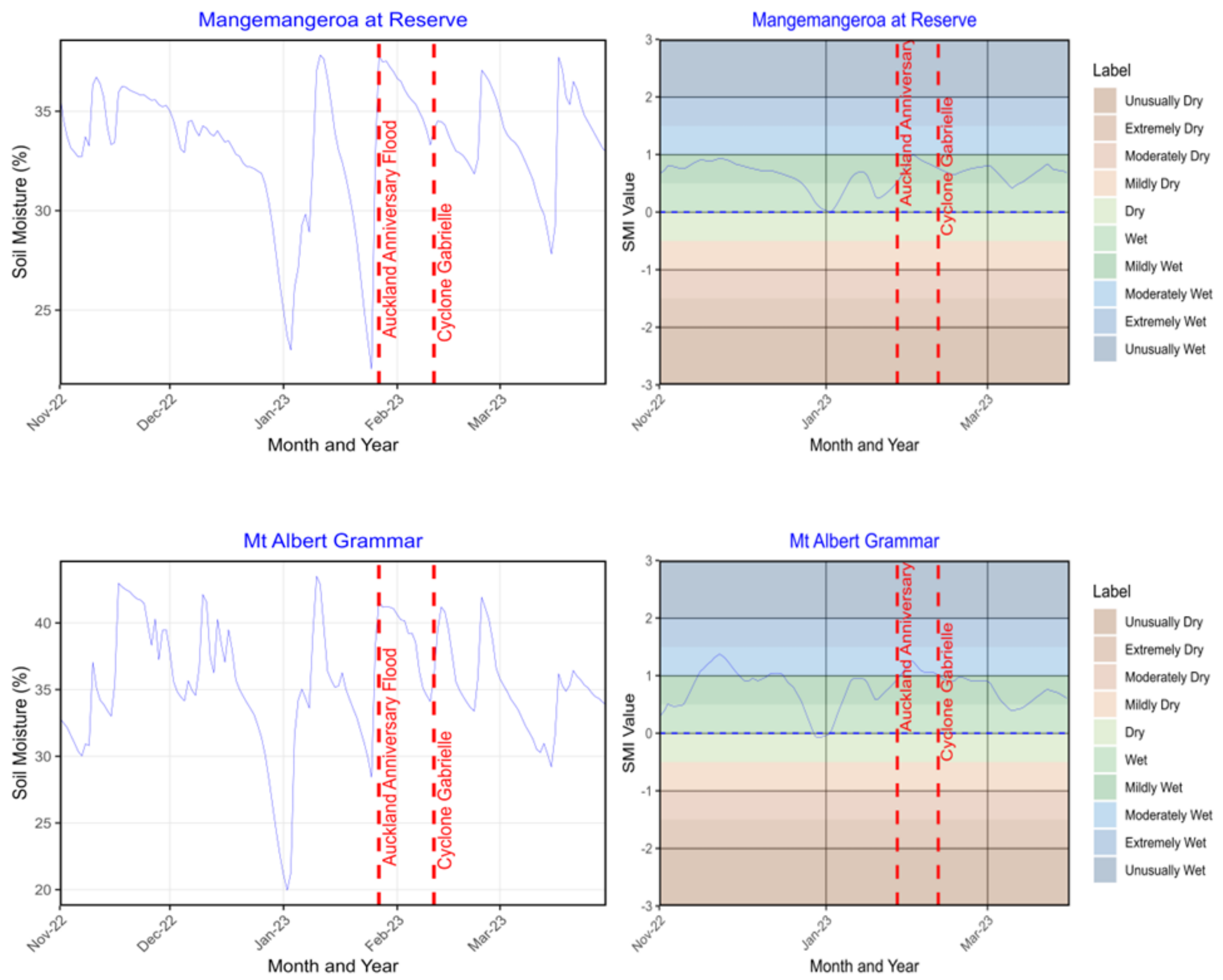


Figure 4.31 (Left panels) Soil moisture (%) at Mangemangeroa (top) and Mt Albert Grammar (bottom) from November 2022 to March 2023. (Right panels). Soil moisture index values Mangemangeroa (top) and at Mt Albert Grammar (bottom) from November 2022 to March 2023.

Monthly groundwater values at selected monitoring sites illustrate that the antecedent very wet conditions in Winter and Spring 2022 influenced the ability for the environment to cope with the significant rainfall received in summer 2022-23. Groundwater reached a relatively high level before summer of 2022-23 at Angle Street but remained extremely high at that location through summer 2022-23 and into autumn 2023. Maraeorahia showed a groundwater level lag with an increase to high levels in February 2023 and peak in May 2023. Quintals showed an acute and extreme high groundwater response in January 2023 but then reached peak levels in May 2023. Revell court showed high groundwater level values in December 2022 and January 2023, and a string of extremely high-water levels relative to the long-term average between February 2023 and June 2023 (peak in March 2023). Extremely high groundwater levels relative to the historical record at Selaks began in February 2023 and persisted through the end of the calendar year. Wooten Court showed antecedent extremely high groundwater levels that onset from November 2022 and remained persistently at extremely high levels starting in January 2023 that lasted uninterrupted until October 2023.

The flow impacts from the Auckland Anniversary event were much larger for most sites in the region than those associated with ex-tropical cyclone Gabrielle. For the Auckland Anniversary rainfall event, 63% (27 of 43) of the flow gauging stations examined in SOE2025 recorded their highest flows on record (Table 4.51). Unsurprisingly, the highest flows were recorded in the largest catchments. We note that this proportion of sites with record high flows may be an underestimation because flow recorders at several sites (Alexandra, Kaukapakapa, Kourawhero, Mahurangi, Motions, Opanuku, Oratia, and Waiau) failed during this event. There was an increase in the 1% AEP for 31 (72 %) sites across the region for the analysis of the full record. High flow extremes across the region ranged from 340 times the mean (Newmarket Stream) to 13 times the mean (Hoteo River).

Flows resulting from Cyclone Gabrielle (14 February 2023) were generally much less than the Auckland Anniversary event, however there were exceptions. The largest catchment (Wairoa River) recorded the highest flow in its 45-year record of 468.2 m3/s, approximately 63 times the long-term mean flow of 7.3 m3/s and 133 times the median flow of 3.4 m3/s.

Table 4.51. Auckland anniversary 2023 flow statistics. Flows are in litres/second.

Site	Maximum	Mean	Median	RBI	Area (km^2)	Type	Group
Alexandra	32733	615	37	0.85	2.64	Urban	1
Awaruku stream	18949	77	18	1.08	1.70	Urban	1
Eskdale Stream	22365	178	46	1.02	3.85	Urban	3
Hoteo River	296731	23152	8302	0.63	268.00	Rural – High	2
Kaipara River	313528	7392	1924	0.78	155.40	Rural – High	2
Kaipatiki Stream	7835	58	16	0.95	1.50	Urban	3
Kaukapakapa	214172	4412	1538	0.87	61.92	Rural – High	3
Kourawhero	177469	4873	1223	0.93	73.59	Rural – High	3
Kumeu	*NA*	*NA*	*NA*	*NA*	2.64	Rural – High	2
Lucas	24359	329	72	1.01	6.26	Urban	1
Mahurangi	241208	4866	1459	0.87	46.90	Exotic forest	3
Mairangi Bay	6868	38	13	0.87	0.60	Urban	3
Mangawheau	104796	1346	619	0.53	30.40	Rural – High	2
Mangemangeroa	10483	142	53	0.71	4.57	Rural – High	3
Meola Creek	39240	783	256	0.54	14.70	Urban	2
Motions Stream	59974	570	294	0.66	7.50	Urban	2
Newmarket	49672	146	14	1.40	5.50	Urban	1
Ngakoroa Stream	6137	146	80	0.47	4.73	Rural – High	2
Oakley Creek	25541	555	220	0.77	12.73	Urban	3
Opanuku	79716	1604	527	0.86	26.50	Urban	3
Opanuku Stream	69605	531	144	0.79	15.45	Rural – Low	3
Oratia	134429	1034	428	0.87	22.88	Urban	3
Orewa	93409	652	159	1.10	9.73	Rural – High	3
Otara	68025	1025	272	0.80	18.90	Urban	3
Oteha River	150185	1120	130	1.22	12.20	Urban	1
Papakura	55430	1928	791	0.55	51.60	Urban	2
Paremuka Stream	7115	42	3	1.41	4.40	Urban	1
Puhinui	63687	462	149	0.83	11.60	Urban	3
Rangitopuni River	160307	2747	1299	0.65	81.50	Rural – High	3
Swanson Stream	136668	1382	462	1.07	22.60	Urban	3
Taiaotea stream	15486	377	17	0.86	2.20	Urban	1
Taiorahi Stream	9485	66	11	0.98	1.00	Urban	1
Tamahunga River	43894	763	181	1.06	8.30	Rural –	1
Tamaki Trib	10958	150	26	1.13	3.05	Urban	1
Te Muri	1307	10	3	0.96	0.30	Rural – High	3
Vaughn Stream	14988	103	30	0.86	2.30	Urban	3
Wairau Creek	26602	91	8	1.42	1.40	Urban	1
Wairau Creek	140216	831	98	1.23	11.10	Urban	1
Wairoa River	468272	7389	3497	0.68	161.00	Rural – Low	2
Waitangi	31145	433	204	0.62	17.60	Rural – High	2
Waiteitei River	182059	6339	1594	0.97	80.60	Rural – High	3
West Hoe	2217	46	34	0.49	0.34	Native forest	2
Whau Stream	27721	373	48	0.87	4.66	Urban	1

5 Discussion

5.1 Rainfall

Auckland Council rainfall observation sites have mean annual, hydrological year and seasonal rain total amounts that exhibit subtle long-term trends; however, most of them are not statistically significant based on the testing used for SOE2025 (see section 4.2.5). For one site located in the northwest of Auckland that shows significant drying (Whenuapai), a reduction in autumn rainfall appears to be the overarching culprit for achieving lower overall hydrological year rainfall totals (Table 4.6). Mahurangi (northeast) also shows a hydrological year rainfall reduction (albeit to a lower significance level) but that is also likely contributed to by lower rainfall during spring months. Caution is needed interpreting the Mahurangi site trends because it is a composite rainfall record. Conversely, the sites that show significant long-term wetting trends are in the southern part of the Auckland region, with increases in winter and spring rainfall (Ngakoroa and Waihihi). These differences show a key example of spatial heterogeneity and complexity of rainfall dynamics for our region.

A long-term shift in regional atmospheric circulation has been established using an analysis of historical atmospheric pressure (Rampal et al., 2022). It indicates a change in the occurrence of typical weather patterns our region experiences, with a high-pressure trend emerging over northern and central New Zealand (see Figure 5.1). An increased high-pressure trend over time is associated with an increased frequency of fine weather days and a simultaneous reduction in 'lows', which are partly responsible for delivering rain to northern and northwestern sites in Auckland. The reduced frequency of weather systems characterised by low pressures positioned to the northwest of the country during autumn (LNW synoptic types; (Rampal et al. 2022)) has occurred across the same time as the autumn rain reduction at Whenuapai. This type of atmospheric circulation change could have contributed to the reduced autumn rainfall amounts for impacted sites on the northern and northwestern margin of Auckland. The strong correlation of rainfall anomalies observed across the region also suggests this type of synoptic weather type change may have contributed to (non-significant) diminishing rainfall trends at other sites.

An overall drying trend is in line with regional climate change projections for Auckland, which indicate an increased frequency of dry days during the 21st century (Lorrey et al. 2018). For the mid-to-late 21st century, climate change projections indicate drier overall conditions for Auckland, with reduced rainfall in spring countering wetter autumn conditions associated with increased rainfall (Pearce et al. 2018). The historical rainfall trends agree with the climate change projections for annual rainfall amounts remaining close to average, but recent variability and rainfall changes at some sites are at odds on seasonal time scales to recently published climate change projections. This suggests the moderate negative (and statistically non-significant) rainfall trends for many sites may still change and eventually align with a projection of wetter autumns in the future. Alternately, if the current trend of autumn drying that has been observed continues, it would mean more significant overall drying could occur for the region if climate change projections of drier spring conditions in the future is correct. We are aware that the latest climate change guidance report for Auckland using CMIP6 downscaled model results show a projection of autumn mean rainfall levels in the future that are similar to present and with more uncertainty than what was made in 2018 using CMIP5 downscaled models (Macara et al., 2025).

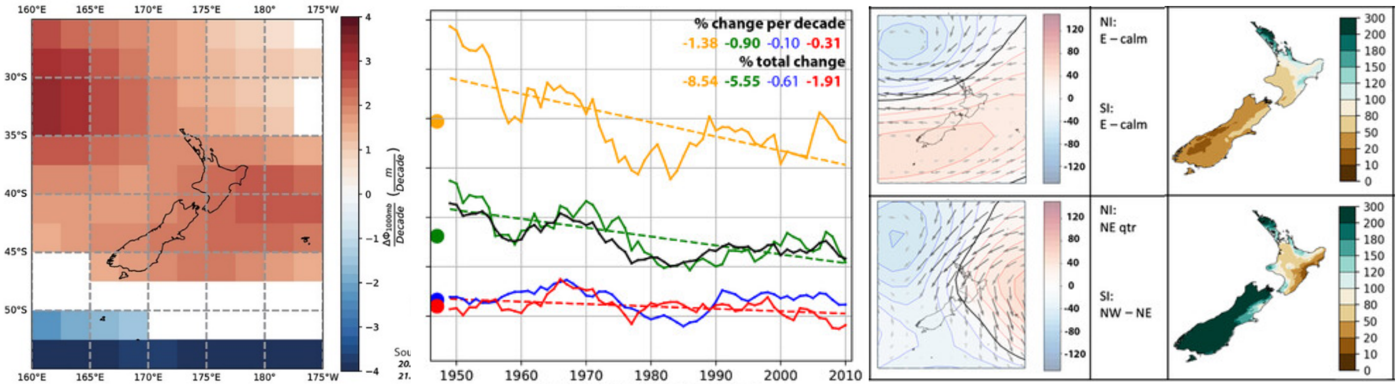


Figure 5.1 (left) Statistically significant trends (all coloured areas) in NCEP—NCAR1 1000-hPa geopotential height (z1000; near surface pressure) gridded data (1 Jan 1948-31 Dec 2020). (Centre) changes in the frequency of occurrence of LNW (low to the northwest) synoptic weather types for New Zealand, showing statistically significant changes during autumn (green line). (right) Atmospheric pressure anomalies for z1000 and winds associated with two variants of the LNW synoptic type, with the spatial pattern of daily rainfall anomalies derived from NIWA VCSN. This shows that northern margin of the Auckland region could see diminished rainfall due to a reduced frequency of occurrence of this type of weather pattern. Reproduced from Rampal et al. (2022) with permission.

The wetting trend observed at the long-term rainfall observing sites along the southern fringe of the Auckland Council observing network may appear to contradict the assertions made about regional drying and synoptic drivers of that change. However, this situation may be due to differences in seasonal rainfall responses and how incident atmospheric flow interacts with topography at a given site. A change in the direction of incident flow, related to the occurrence of specific weather systems that deliver rain to the region, may have meant that more precipitation 'got in' to the southern sites during certain seasons or specific events relative to the past. Additional work is required to investigate both drying and wetting subregional anomalies and trends, because they have relevance for informing water resource management of nearby agriculture production and reticulated storage schemes.

Short-term variability of rainfall averages and rainfall anomalies occurred during the individual seasons included in SOE2025. Statistics for those seasons were calculated with reference to a standard climatological normal period, and they provide a means of evaluating the contemporary hydrological state for Auckland and how it has shifted since SOE2020. For SOE2025, it was much drier in north, west and central for summer on average (63-75% of normal rainfall) despite the occurrence of an extraordinarily wet summer in 2022-23. Conversely, it was significantly wetter overall in the west and south during autumn, despite extremely dry mean conditions during the first three years of the SOE2025 snapshot. This shows the strong influence of single seasons (like autumn 2023) for determining overall short-term climate averages at some sites.

Differences in the rainfall average for some seasons during SOE2025 indicate lower overall rainfall in autumn for most years in SOE2025 occurred relative to SOE2020. Most sites received quintile 1 or quintile 2 rainfall for three of the five years included in SOE2025 snapshot. Repeated lower rainfall during autumn was countered by some exceptionally high rain events during 2021, 2022 and 2023, and the delivery of the rain during those events was spread across multiple seasons. This demonstrates that while interannual and interseasonal rainfall variability is strong for Auckland, important subseasonal rainfall variability also exists on top of the long-term (and emerging) trends and the snapshot changes described above.

The combination of rain events occurring at synoptic weather time scales and the absence of rainfall leading to drought on seasonal timescales highlights the difference (and importance) of observing and analysing rainfall across multiple timescales. It also underscores the overall significance of the recent succession of very dry seasons and years – and that the overall hydrological situation with respect to our regional meteoric water balance in SOE2025 may have been much worse without several distinct, very strong and exceptional rainfall events in the past five years.

5.2 Soil moisture

The short length of soil moisture observations and limited number of sites across the region meant the analysis for SOE2025 was restricted to a snapshot comparison of the most recent 5-year period to the previous 5 years (see section 4.3.2 and 4.3.3.). Aside from the typical seasonal cyclicity that can be expected of soil moisture for the region (with lower values registered in summer and autumn, and higher values during winter and spring), there were some signs of noticeable drying occurring at some sites like Tomarata (across all seasons) and at Hoteo and Mt Albert (in Autumn) relative to SOE2020 (Table 4.9). The 2022-23 hydrological year registered significantly at sites located in the northwest, northeast and eastern part of the region, where above normal soil moisture levels occurred due to the exceptionally high levels of rainfall within that hydrological year during summer (Table 4.15). In particular, the annual and hydrological year soil moisture levels and anomalies for 2022-23 were raised most significantly by what occurred during the summer. In addition to very high soil moisture levels recorded in 2022-23, the opposite was observed for the 2019-20 summer, but with a main difference that the loci of soil moisture reduction appeared to be focused initially on only a couple of sites during spring in the northeast and central part of the region (Table 4.14). We must recognise the spatial limitations with respect to examining the start of this drought event through a lens of soil moisture observations. However, it became much worse during summer across more sites as rainfall became less frequent and temperatures rose. Additional details about the long-term context for both seasons, and for individual site responses to droughts, is expected to emerge as the soil moisture network continues to add observations into the future.

There are relatively few external reference stations in the region for soil moisture, however NIWA does hold some long-term data that are relevant for context, in addition to a modelled soil moisture product produced at a daily time step (VCSN). An analysis of the latter up to about mid-2024 along with a selected Auckland Council site at Ararimu, suggested that the range of variability for soil moisture was getting progressively larger since 2014 as part of a regional expression of contemporary hydroclimatic changes (Lorrey, 2024). In an independent analysis of the Ararimu site, there appears to be an emergence of a short-term pattern with an earlier start to highly variable soil moisture conditions through the last decade. There were also at least six intervals where rapid soil moisture decline occurred over 15- to -35-day periods resulted in soil moisture anomalies in the range of 30-71% of average – which could be classed as ‘dry events’ at a site level. These discrete intervals were not categorised as either a flash dry, flash drought or climatic drought because a larger number of stations across the region were required to make such an assessment.

Analysis of a representative VCSN soil moisture site as a regional drought proxy (Lorrey, 2024) suggests there has been an increase in the number of dry spells and drought conditions for Auckland using that tool. Specifically, there appears to be a near doubling of drought occurrence since 2005 (across all seasons combined) relative to the earliest part of the VCSN record which goes back to 1973 (using a representative VCS centred on Auckland Airport). That analysis also found that Auckland is experiencing very dry conditions that could lead to the development of drought every other year when it used to occur every 5-7 years at some time during spring, summer and autumn. There has also been an increase in dry/drought-like stretches increasing from once in 10 years to about every 3 years during winter.

A key finding from the analysis of the VCSN also indicated that 'dry day accelerator windows' were becoming more common in spring – one of the main instigators of conditions that can lead to rapid soil moisture drying and preconditioning of drought (Lorrey 2024). This signal occurs alongside a well-established temperature rise for the region (which may play an important role on guiding soil moisture deficit), and is consistent with previously summarised (Lorrey et al. 2018; Pearce et al. 2018) and new climate change projections that indicate an increase in the number of dry days during spring with reduced rainfall in that season, as well as an increased frequency, intensity and duration of drought for northern regions of New Zealand (Gibson et al. 2025).

There are many outstanding questions related to soil moisture for the Auckland region, but evidence from SOE2025 shows extremes have recently occurred and that Auckland Council needs to continue to monitor this part of the hydrological system because it has exceptional utility for use in forewarning about the onset of extreme events and widespread impacts. Many outstanding questions can only be answered with continued monitoring from the existing network (which helps us understand buffering capacity for extremes), and additional soil moisture observations to fill current spatial gaps is needed (e.g. understanding the location of drought development and how that changes through time (Zhao et al. 2020)). In addition, the development and calibration of remotely sensed soil moisture proxy observations and soil moisture models that are region-wide in nature (Hamarash, Rasul, and Hamad 2024) are needed for decision making around water sensitive assets like parks and open spaces, as well as domestic and commercial water supplies.

There is an opportunity to use the current soil moisture network as the backbone for enriching knowledge about long-term climate variability and change by harnessing it to develop reconstructions of the recent past when limited observations exist. Future work should continue to analyse the combination of the Auckland Council soil moisture network stations in conjunction with other longer in situ sites (e.g. Pukekohe DSIR) and utilise tools like the NIWA VCSN for a wider initial spatial view of soil moisture, as well as seek to improve on modelling of virtual soil moisture conditions under different types of land cover and soil types. In addition, it is possible to develop modelled soil moisture datasets both forward and backward in time to help understand the range of variations that have occurred and what may unfold with respect to discrete drought events and for identifying their drivers. This type of 'line of sight' process-based view is required to evaluate contemporary subseasonal soil moisture anomalies as well as prepare for events that are anticipated in a warmer future. A robust evidence base will also be required to develop and deliver early warnings about soil moisture impacts that can be derived, in part, from real-time and long-term soil moisture monitoring.

5.3 Rivers

Analysis for SOE2025 has revealed notable changes in the region's hydrological patterns, with pronounced shifts in both high flow metrics. A significant increase in high-flow events has been recorded, with 80% of monitoring sites observing new peak instantaneous flows. These changes are linked to the recent extreme events, including the Auckland Anniversary 2023 storm and ex Tropical Cyclone Gabrielle, which contributed to a marked rise in short-duration, high-intensity rainfall and increased surface runoff. The occurrence of the high rainfall amounts in the 2022-23 hydrological year, within a context of a rare triple dip La Niña that has unfolded close to the end of the SOE2025 period, is expected to have impacted the statistical analysis of high flows and low flows.

Cluster analysis has classified Auckland's catchments into three groups; 13 small (generally urban), 19 mid-sized (mixed), and 11 large (generally rural) types (Figure 4.13). These groups exhibit diverse hydrological responses depending on land use and groundwater contributions. Small urban catchments are especially prone to flash flooding, while large rural ones benefit from greater infiltration and storage capacity. This classification underscores the importance of considering both the physical characteristics and urban development status of catchments when assessing flood risk and is useful when understanding the hydraulics within the catchments.

Frequency analysis undertaken for SOE2025 highlights the sensitivity of flood recurrence estimates to extreme events. The inclusion of the Auckland Anniversary 2023 storm in flood frequency analysis caused over half of the sites to show more than a 10% increase in the magnitude of the 1% AEP for the annual maximum value (Table 4.24. Difference between the high flow frequency analysis for the full length of the record that includes and does not include the Auckland Anniversary 2023 flood event. Amounts are in litres per second.). Sites with shorter or discontinuous records were particularly affected, indicating the importance of long-term, continuous monitoring for reliable flood risk assessment. In contrast, low flow statistics remained largely unaffected by short extreme low flow events, as low flows are shaped more by prolonged dry conditions and baseflow that is more groundwater controlled.

Threshold analysis using the FRE3 indicator (a count of high flow events exceeding three times the median) showed a general increase in event frequency (i.e. average number of events per year), but this was not consistent across analyses that changed the length of observational record. The trends of the number of events above the FRE3 show an association between the catchment type and the trend direction. Increases in the average number of events above the FRE3 were noted at six sites and except for the Kaipara River catchment all increases in FRE3 were in Urban catchments (cluster 1). Decreases in the number of events above the FRE3 were noted in six catchments in, except for the Wairau creek these occurred in native forest or Rural catchments in clusters 2 and 3. While 30 sites saw an increase in SOE 2025 $MALF_7$ compared to the long-term record, a concurrent rise in the number of low-flow events below the $MALF_7$ threshold for SOE2025 implies a growing frequency of hydrological extremes suggesting more frequent high flows but also more frequent low flows. A similar pattern of hydrological extremes can be seen with rainfall and soil moisture patterns suggesting that the changes might be occurring across the wider portion of the hydrological cycle. It has yet to be determined whether human activities or environmental modifications have played a role in those observed changes, but these hydrological changes need to be considered in that context in future SOE assessments.

5.4 Groundwater

For the SOE2025 assessment, we selected the groundwater monitoring bores that had no abrupt temporal heterogeneities and that did not contain sharp shifts related to aquifer management practices (Table 2.4). Despite this predetermined selection of sites, some recent changes at the ends of each record may be incorporated in our analysis and therefore influences from monitoring practices and aquifer management cannot be ruled out. Of the six monitoring sites that qualified for long-term groundwater trend analysis for SOE2025, two showed significant reduction in groundwater level, two had significant positive trends for groundwater level, and two did not have significant trends (Table 4.45). There was significant variability of groundwater levels during the SOE2025 period at all sites (Figure 4.17 - Figure 4.22). We discuss these findings below with a focus on the sustainability of long-term groundwater supply that could be gleaned from the trends analysis and highlight concerns arising from acute groundwater supply responses due to climate variability and the occurrence of extreme seasons like the 2019-20 drought and 2022-23 deluge.

5.4.1. Sites with positive groundwater trends

For the two sites with positive groundwater trends (Angle Street and Wooten Road) the significance of the long-term groundwater level rise is observed for most of the year and seasons (Table 4.45). Angle Street shows a long-term shift from a prolonged groundwater deficit phase to a strong and consistent high-level phase starting in the early 2010s, peaking in the 2020s (Figure 4.19). This suggests the local recharge mechanism for this aquifer has changed to consistent surplus. The rising trend leading into the high-level phase at Angle Street may be attributed in part to increased stormwater soakage through urban development, and this site is known to respond rapidly to rainfall due to the unconfined nature of the aquifer and presence of soakage pits that increase natural infiltration and flow. Soakage systems in the area where Angle Street is located were initially installed in the early 1900s, and about half of them were installed before 1980 at relatively shallow (3- 6 m) depths. Soils in the area are largely volcanic and includes organic-rich volcanic loam (Burns, Dodd, and Hartnett 2013), but some locations have weak packing and admixture with scoria cobbles and boulders that contain air pockets capable of accommodating subsurface water.

Since the introduction of soakage pits across the central urban area of Auckland, it is likely that the Mt Wellington Volcanic Aquifer monitored at Angle Street has progressively drifted toward increasing influences from human activity, and then again more strongly from the 1980s onward due to an increased presence of impermeable surfaces. This type of change could have increased the amount of surface water across the area where monitoring is taking place, whereby the soils and underlying basalt lava channels are relied on to accommodate an increased amount of surface water through soakage pits/systems. Water use within the area also changed within the SOE2025 reporting coverage during late 2022, when a significant water take was paused and the volume abstracted was released back into the aquifer system (Orsman 2024). The impact from this change may have increased the local groundwater level following the drought of 2019-20, and just ahead of the summer 2022-23 period when heavy rainfall occurred.

Wooten Road also exhibited an increasing groundwater level trend (Figure 4.22), but attribution for that change at that site is difficult. Rainfall at the Ngakoroa site (Figure 4.10-Figure 4.11) shows a significant increase over the period when the groundwater level is rising at Wooten Road. The Bombay Volcanic aquifer that the Wooten Road site monitors is unconfined and has minimal lag to rainfall occurrences, which is exhibited by several key drought years showing up in that record (e.g. during the 1994 drought that drove the Auckland water crisis (Fowler 1994) and the most recent 2019-20 drought). A steady precipitation increase over the past few decades along the southern margin of Auckland means it is possible the aquifer underlying Wooten Road has been gradually recharging over time, but additional observations (particularly about land use change and water allocation) is required to test that hypothesis.

5.4.2. Sites with negative groundwater trends

In the situation where groundwater trends show declining water levels and when the variability that is superimposed on those trends aligns with rainfall and soil moisture deficits, there is a concern that groundwater droughts may arise. A groundwater drought is a type of hydrological drought characterised by a sustained period of abnormally low groundwater levels or diminished spring discharge (Tallaksen & Van Lanen, 2004; Mishra & Singh, 2010; Van Loon, 2015). Assessing the severity and distribution of droughts, including groundwater drought, presents considerable challenges. These difficulties primarily arise from the limited availability and nature of groundwater level data (Bachmair et al., 2016; Van Loon et al., 2017), and the fact that groundwater droughts often exhibit spatial and temporal variability (Peters et al., 2006; Mendicino et al., 2008; Tallaksen et al., 2009; Bloomfield et al., 2015). However, there are several occurrences in the representative groundwater level data for Auckland that indicate concern is warranted.

The two sites that had significant negative groundwater level trends (Quintals and Maraeorahia; Table 4.45) show signs that they may be experiencing the combined pressures of increased water abstraction and changing climate conditions. Quintals has a groundwater abstraction limit of 105,000m^3/year in the Auckland Unitary Plan (Auckland Council 2016). At present, the current consent has issued an allocation of 233,738m^3/year on paper. It may be that the full groundwater allocation was not utilised in this area, however, in the absence of comprehensive water take data, over allocation must be considered as one reason why the groundwater level trend may be negative. In addition, Quintals is in the northeast of the region where significant negative rainfall trend has been observed (at the Mahurangi site nearby) for the hydrological year, as well as anomalously low rainfall during spring and summer in SOE2025 (Table 4.2). This change aligns with the time of the year when Quintals shows a significant negative groundwater level trend, so the long-term rainfall reduction cannot be discounted as a contributing factor. However, it should be noted that the trend in the longest rainfall record nearby (Mahurangi @ Warkworth Sewerage) needs to be treated with caution, so further investigation is required.

The decrease in groundwater level at Maraeorahia Road (Table 4.44) could have arisen due to the location of the bore close to the coastal boundary and the location of the bore at the edge of the aquifer rather than within the thicker central part of the Awhitu Kaawa aquifer, making it more susceptible to shorter term climate fluctuations and usage. Rainfall at nearby sites along the southern margin of the Auckland region (Ngakoroa and Waihihi) had the strongest negative rainfall anomalies during the SOE2025 period, and the relative reduction in rain in the most recent five years may have contributed to a decreasing trend for groundwater recharge at that site. The decreasing trend is also a concern at this site as it appears as if there is a concurrent trend toward fewer months of positive groundwater surplus through time during the main recharge season (Figure 5.2).

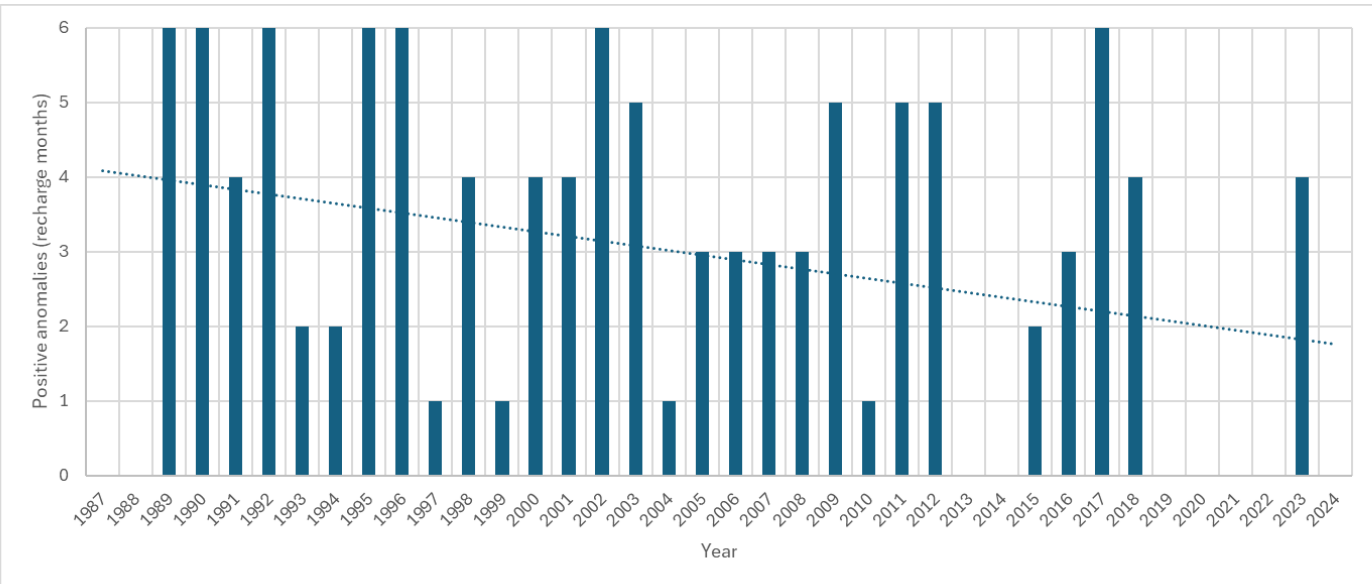


Figure 5.2 Progressively diminished number of months between May and October for each year where positive groundwater anomalies were observed at Maraeorahia. This plot is utilised as a proxy for change in the groundwater recharge season length, which shows a narrowing of the time during the year when positive level values relative to climatology (and recharge) has been occurring.

Almost all the selected sites showed an influence from the 2022-23 event (Figure 4.17 - Figure 4.22); however, the response time and duration of continually positive groundwater levels following seasonally high rainfall was spatially variable. The selected set of groundwater observations further highlights the importance of connecting all the observations across the hydroclimatic network, and maintaining information about water abstraction, in addition to use of aquifers as recharge or stormwater disposal mechanisms.

5.4.3. Limitations of groundwater observations

At present, we do not have enough comprehensive coverage of all the aquifers to support a process-based understanding of how hydroclimatic extremes at both ends of the scale (wet and dry) propagate through the terrestrial water cycle for our region. This is of significant concern with respect to understanding the spatiotemporal characteristics of extreme events, like groundwater droughts, which may be typically delayed and perhaps less intense compared to meteorological droughts (Van Loon, 2015). Numerous catchment and aquifer characteristics can alter meteorological drought signals and influence the eventual spatial and temporal manifestation of groundwater droughts, including the type of land cover, the thickness and hydraulic properties of the soil and unsaturated zone (which affect recharge) over the aquifer, the hydraulic properties of the saturated zone, and the location and hydraulic characteristics of major groundwater discharge zones (Tallaksen et al., 2009; Bloomfield et al., 2015). In the case of the extreme events that occurred during SOE2025, it appears all the selected bores showed an impact from the 2019-20 drought event (Figure 4.17 - Figure 4.22), even in situations where the local groundwater level trend was trending positive. Some of the signatures indicate additional pressure was placed on groundwater resources during particularly dry times that prevailed for much of SOE2025.

Groundwater level data often lack temporal regularity and may contain inaccuracies, and we identified a change in the monitoring frequency for many boreholes across the Auckland region ahead of SOE2025 analysis. The issue of maintaining regular observations was rectified nearly a decade ago with the adoption of telemetry. However, the availability of suitable groundwater level data at timeframes relevant for the systematic evaluation of hydroclimatic extremes (including drought and subpluvials) is often restricted (Van Loon et al., 2017), and this remains the case for the Auckland region with respect to spatial coverage and the range of depths across each aquifer. Nevertheless, the monitoring over the past two SOE reports has been at a high temporal resolution and the observations used in SOE2025 are robust starting point for examining long-term trends and variability related to recent changes and events.

5.5 Extreme seasonal climate conditions

Two of the most hydrologically-extreme summer seasons occurred within the SOE2025 reporting period – the 2019-20 drought and the 2022-23 repeated deluge that was characterised by multiple significant storms (August 2021; January and February 2023). Climate change trends produced for the Auckland region indicate long-term stability or very subtle reduction in annual rainfall, with contrasting rainfall trends for spring (decrease) and autumn (increase) (Lorrey et al. 2018; Pearce et al. 2018). During SOE2025, Auckland experienced widespread drying signatures that were regionally pervasive for multiple years and seasons (Figure 4.3 – Figure 4.6). However, the exceptionally wet 2022-23 hydrological year meant some locations saw a relative swing to a wetter overall short-term climate state in terms of their meteoric water balance (Table 4.5). Reiterating findings from the rainfall analysis, the overarching dry conditions for many parts of SOE2025 would have been more obvious (and much worse) for the Auckland region were it not for the abundant rainfall in the 2022-23 hydrological year.

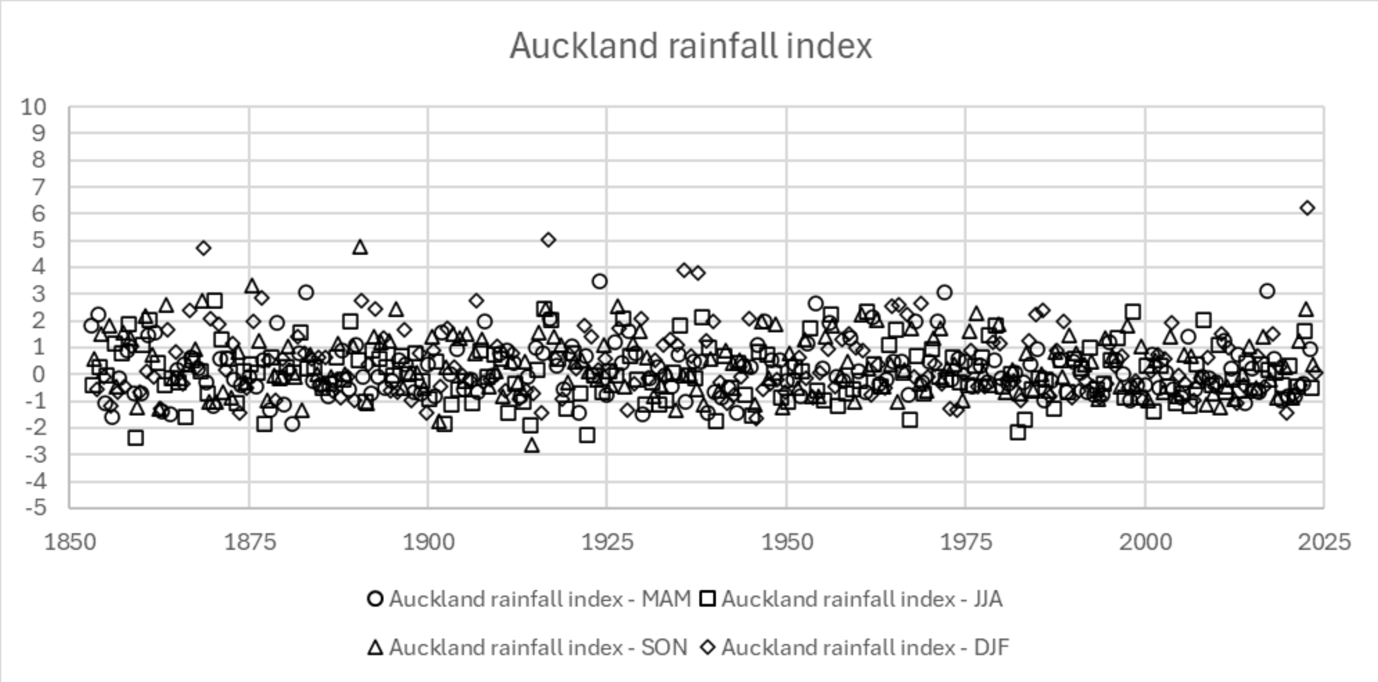
5.5.1. 2019-20 summer drought

Comparison of low rainfall occurrences during SOE2025 to the historical record (Figure 4.23 and Table 4.45) shows the relatively low 2019-20 summer rainfall amounts (and the associated drought) was a significant contributing factor toward the driest summer the region experienced since 1990. The 2019-20 drought has correlatives within the historical record during the 1970s, 1940s, 1920s, 1910s, and in the 1800s. However, it occurred within the 1991-2020 climatological normal period, and so it only receives a quintile 1 rank (qualitatively = very dry) for rainfall amount (Figure 5.3). Nevertheless, this event was probably the most extreme drought to have impacted Auckland during the historical record.

Seasonal climate outlooks issued by NIWA ahead of the 2019-20 drought event and as it unfolded indicated above normal temperatures were likely for the northern North Island, with a signal that the core part of summer and early-to-mid autumn would be characterised by normal or below normal precipitation (see details at https://niwa.co.nz/climate-and-weather/seasonal-climate-outlook). However, that seasonal climate guidance is not spatially or temporally specific enough to action early decisions about water use that could have helped to mitigate the effects of the 2019-20 drought event. In particular, the lack of granularity for seasonal climate outlooks highlights a need for additional regionally focused drought monitoring tools and predictions that are both actionable on local spatial scales and on subseasonal time scales (particularly because of the potential for droughts to now develop rapidly). Part of the basis for developing such tools requires Auckland Council to continue to maintain a high-quality hydrological observation network.

5.5.2. 2022-23 summer deluge

Spring 2022 and summer 2022-23 both lie outside the contemporary climatological distributions for summer rainfall with reference to 1991-2020. Those two recent seasons are categorised as 'extreme' based on their rainfall index values and were also the wettest spring and summer overall for Auckland since 1990 based on mean rainfall index values (Figure 5.3). We observed correlatives for the extremely wet 2022 spring further back in time during the 1960s, the 1920s, 1910s, and in the late 19th century. The exceptionally wet summer of 2022-23 had the highest mean rainfall index value on record dating back to 1853 when continuous regimented observations begin for Auckland (Figure 5.4). A closer look at regional rainfall during the 2022-23 summer season shows large variability for rainfall totals between sites. This is because individual rain events that contributed to high overall seasonal rainfall sums impacted the region heterogeneously (Figure 4.29). Individual storms are inherently transient, with meteorological impacts that change multidimensionally (through time and across space). A clear example is observed for in the exceptional rain total and rain intensities recorded on multi-daily to sub-daily scales for late January 2023 (Figure 4.26), for which much higher rainfall amounts and rain intensities were observed at central and northwestern locations relative to other sites around the northern and southern perimeter of Auckland. This shows the importance of having enough spatial coverage in monitoring rainfall to be able to understand idiosyncratic impacts of storms across the region, including where maximum rainfall occurred and the timing of maximum rainfall and rain intensities at different locations.



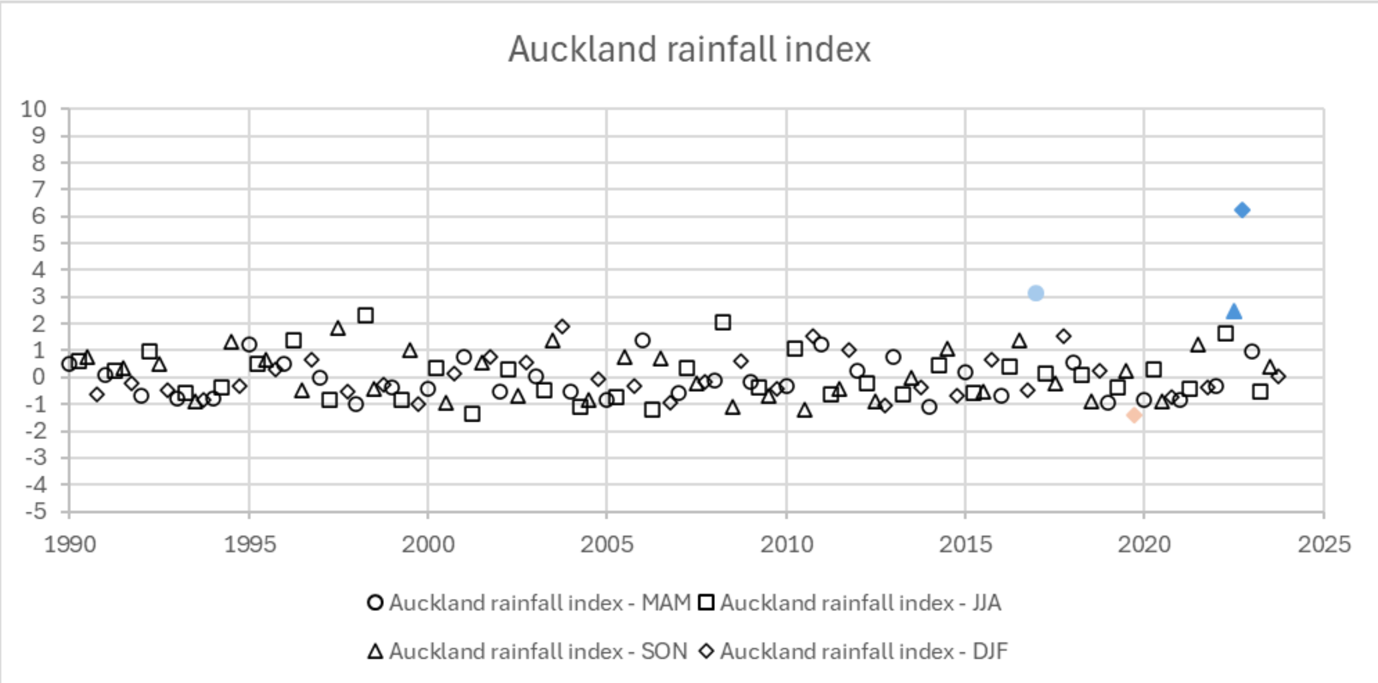


Figure 5.3 Seasonal Auckland mean rainfall index values for 1852-2024 (top) and 1990-2024 (bottom). The very dry summer of 2019-2020 is highlighted in orange, while the extremely wet spring of 2022 and summer of 2022-23 are highlighted in dark blue. The lighter blue circle highlights the 2017 wet autumn when significant rainfall impacted water supplies in the Hunua ranges.

Antecedent soil moisture conditions play an important role in determining whether surface run off occurs during extreme rainfall events like those that happened during early 2023. Dry soils can absorb more rainfall that wet soils; however, there are limitations to the amount of moisture that soils can absorb and retain. Soils overlying shallow groundwater tables can only absorb as much a volume of water as can be stored in the vadose zone during rainfall events (Lebon et al. 2023). Locations where deeper groundwater exists can absorb more water than areas where there is shallow groundwater. In addition to the constraints volumetric capacity places on the absorption potential of soils, the maximum infiltration rate is also a key determinant in how much rainfall can be accommodated at any location (Jia et al. 2024).

Thus, the combination of vadose zone thickness and rainfall intensity are critical to determine when and where surface flooding occurs. Lower intensity rainfall events over thicker vadose zones that can absorb more rainfall helps to reduce sheet flow and attenuate peak flows in streams (Wang et al. 2022), while intense rain events over areas with shallow groundwater are likely to result in increased sheet flow and sharper peak flows in rivers and streams. It may be that a combination of these factors contributed to flood impacts in early 2023.

Although the soils across Auckland showed interannual and seasonal variability over the short length of the observation period (see Table 4.10 - Table 4.15), it did not mean that soils in the region did not have any ability to absorb rainfall when strong rainfall events occurred. For example, the preceding seasons leading into 2022-23 summer were much wetter than normal for Auckland, and this situation likely resulted in reduced volumetric absorption capacity of the soils at depth at many locations, along with relatively higher groundwater tables. The groundwater anomaly plots for selected sites (Figure 4.17 - Figure 4.22) suggest that assertion is likely for multiple locations that represent the situation where groundwater is shallowly positioned with respect to the ground surface. Disposal of stormwater to ground in some locations may have also exacerbated the impact of the rainfall events that occurred in January and February 2023, but an investigation that harnesses stormwater management data as well as soil and rainfall observations is required to confirm this assumption.

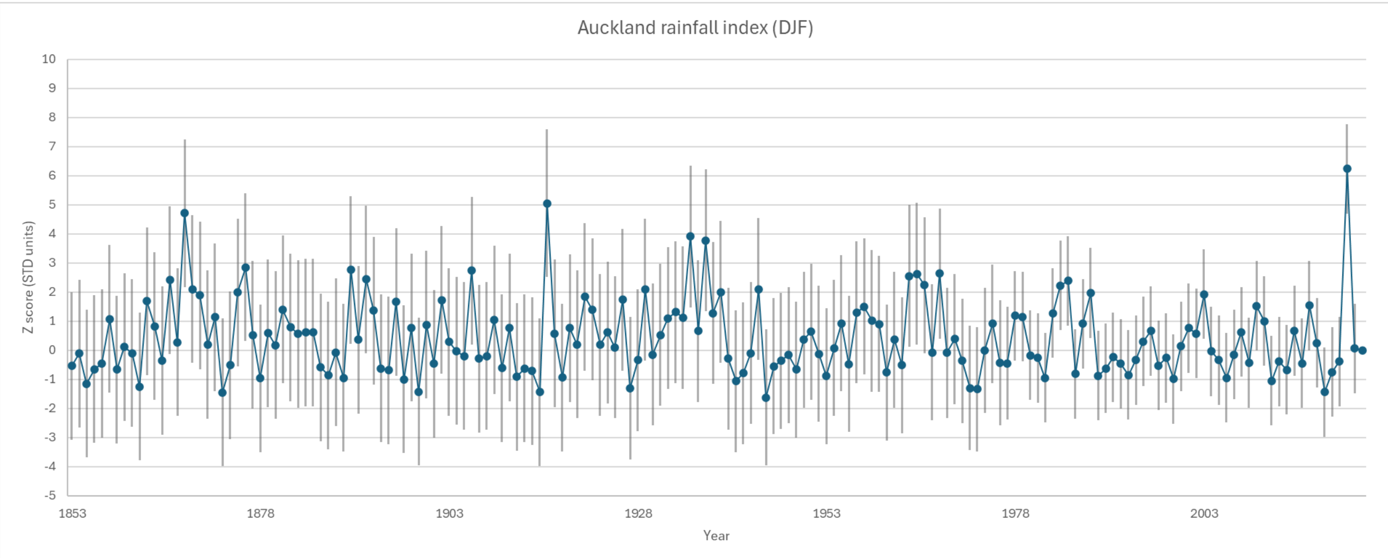


Figure 5.4 Mean rainfall index values for long-term observing sites in the Auckland Council network (See Figure 4.30 for temporal coverage of each site). Error estimates for the mean rainfall index values in this plot are based on an observed relationship for intersite differences (spread) that increase due to relative depreciation of site coverage through time. This plot is meant to be used for discussion purposes that highlight several historical summer seasons that had anomalously high rainfall which deserve further consideration for investigation.

5.5.3. Limitations for understanding extreme rainfall events and their impacts

Evaluating the buffering capacity of soil and groundwater as a dual means of accommodating extreme rainfall (and stormwater) remains a significant knowledge gap and our perspective is highly dependent on the depths that are being monitored. Soil moisture sensors are commonly placed at shallow depths (between 10-35cm below the ground surface), which is relevant for monitoring near-surface water that is available for plant growth. This type of monitoring set up, while useful for estimating impacts on plants, agriculture and for recreational settings, sets up a tendency to observe strong wet-dry soil moisture contrasts that can arise from temperature variability in the upper soil profile. In this situation, where soil moisture within the upper soil profile may appear relatively dry episodically, deeper soil levels may still be saturated and thus a distorted view of the comprehensive soil moisture profile arises.

The intensity of rainfall events, in addition to antecedent full soil profile and shallow groundwater conditions, likely played a role in exceeding the capability for a range of environments to absorb significant rain amounts that occurred during the 2021 and 2023 rainfall episodes. As an example, soils showed an apparent dry signal in the days preceding the impacts of the Auckland Anniversary 2023 rain event (see Figure 4.31), suggesting the absorption capacity may have simply been reduced quickly due to the sheer intensity of rainfall. While that point may be valid, what is not known is whether there was significant saturation at deeper levels within the soil profile (in addition to relatively high shallow groundwater levels) that exacerbated the situation.

An additional example comes from the Selaks groundwater observation site in the Kumeu area, which is prone to episodic flooding. This bore monitors groundwater levels that are approximately 15-20m below the local ground surface. Nearby, the rainfall observations in Kumeu for the late August and early September 2021 rainfall episode registered as the second wettest day on record since 1943 at the time the event happened. More than 208 millimetres fell from 9am on Monday 30 August until 9am Tuesday 31 August, with 201mm of rain falling from Monday night onward. The antecedent local groundwater conditions showed a relative groundwater deficit and capacity 15-20m below the surface for accommodating additional water in the area. Yet floods occurred, meaning local groundwater accommodation space was not able to be accessed and/or utilised instantaneously through natural processes. In 2023, there was a relatively high groundwater level at Selaks ahead of the Auckland Anniversary 2023 floods (in addition to a short and sharp rainfall event in mid-January, followed by the extreme rainfall on 27-28 January). In this situation, with anomalously high shallow groundwater being indicated, the local capacity at depth was probably reduced, and it could have also been expected that surface flooding may have arisen from exceptionally high rainfall.

These points highlight knowledge gaps about soil composition, spatial heterogeneity of soil types and soil water/shallow groundwater interfaces that contribute to a poor and inconsistent understanding of the responses that arise from moderate and large rainfall events for Auckland. The two different antecedent conditions and yet similarity of the outcomes for Kumeu points out that idiosyncratic, local processes play a role in contributing to the hydrological signals at each observing site. As such, additional soil moisture observations and shallow groundwater observations that cover a greater range of depths presently monitored is warranted, and they need to remain fit-for-purpose beyond their initial utility of evaluating water resources.

Soil moisture monitoring in the future should consider the combination of in-situ observations, low-cost arrays of sensors, remote sensing and modelling to increase the spatial density of observations that can support early warnings for surface flooding. Clearly, there is a need for representative ‘sentinel sites’ that have the full range of hydrological observations, from which wider conclusions can be drawn about variability, long-term change and responses to extreme events.

6 Conclusions

Hydroclimatic observations over the SOE2025 period clearly show that the Auckland region experienced one of the most significant periods of hydrological variability and extremes since instrumental observations began in the mid-1800s.

6.1 Rainfall analysis

For rainfall, there has been significant interseasonal and interannual variability with respect to the overall rainfall amounts received during SOE2025 (Figure 4.3 – Figure 4.6), and noticeable spatial heterogeneity for rain received across the region for between SOE2020 to SOE2025 (Figure 4.1 and Figure 2.1; Table 4.5). With respect to the overall rainfall received during SOE2025, it would have been much drier if the significant rainfall during the 2022-23 hydrological year had not occurred. During 2022-23, the quintile-based analysis shows winter (q4 & q5), spring (q5 and extreme levels), summer (mostly extreme levels) and autumn (q4 and q5) (see Figure 4.3-Figure 4.6) counterbalanced and in some cases overrode a succession of drier years that occurred in the early part of SOE2025. The record-low rainfall during summer 2019-20 was likely the most significant drought on record (Figure 4.22 - Figure 4.23; Table 4.47). The rainfall that occurred during the Auckland Anniversary 2023 event also broke multiple sub-daily, daily and multi-daily records (Figure 4.26 – Figure 4.28; Table 4.50).

There were few clear significant linear trends between the rainfall observing sites analysed in this report (Table 4.6), but the extremely high rainfall seasons and years of 2022-23 that are close to the end of the observational record are suspected to have skewed trend analysis. There were also differences in the trends observed for sites in the northwest and southern part of the region, making attribution of the changes to a process difficult. We have presented one hypothesis for the spatial split (see section 5.1), but further analysis is required. The shortness of length for many records cannot be avoided, but they place a significant limitation on what can be attributed to long-term change vs decadal variability at many locations. These identified issues suggest more elegant approaches to the analysis of rainfall change, including the creation of robust composite series and regionally representative indices, are warranted. This also underscores the value of maintaining the rainfall network into the future for the purpose of understanding both short- and long-term changes in precipitation for the Auckland region.

The occurrence of several dry autumn seasons in succession for recent years during SOE2025 are particularly concerning. They can be interpreted simply as a part of climate variability that could be expected, and they may well be related to that. However, this rainfall signature has occurred despite the presence of La Niña for part of SOE2025 (which showed patterns more closely associated with La Niña during 2022-23 than the years just prior). A trend toward drying is consistent with modern changes observed in regional atmospheric circulation (see Figure 5.1). The succession of dry seasons, including successive dry autumns, also occurs at a time when emerging climate change projections (Macara et al. 2025) indicate greater uncertainty for autumn rainfall change relative to previous projections. Overall, above average rainfall conditions were formerly expected in the future for that season based on the CMIP5 projections (Pearce et al. 2018), but the most up-to-date CMIP6 projections now indicate normal rainfall during autumn.

As such, if more seasons like those we experienced in SOE2025 (Table 4.6). tend to occur in the future, the prior climate change projections for the region from 2018 may have overestimated the overall autumn rainfall contribution to balancing out annual and hydrological year averages (Pearce et al. 2018), and thus drier conditions overall could more significant than anticipated. Regardless of whether the observed rainfall changes are short-term variability or a sign of long-term changes to come, Auckland experienced significant impacts from both the recent wet and dry conditions.

This means seasonal climate variability will continue to play a strong role in influencing our rainfall and our regional climate, our water supplies, and there will be impacts that continue to place pressures on our water-sensitive assets like stormwater systems, parks, wetlands and public spaces. The rainfall monitoring network was recently reviewed, and recommendations for modest improvements for the stations that are currently in operation have been made (Judd and Hyde 2025). Beyond those recommendations, additional observing site locations and changing composition of data quality through time are being considered separately.

6.2 Soil moisture analysis

Soil moisture levels registered significant negative anomalies that lasted multiple successive seasons at some locations (Table 4.13 and Table 4.16) related to the 2019-20 drought and showed acute responses due to the overall wet conditions experienced during the 2022-23 hydrological year. Long-term soil moisture observations are not numerous in the Auckland region, but current tools estimating soil moisture deficit from NIWA (now Earth Science New Zealand) indicate that the occurrence of dry intervals and droughts are potentially more frequent, more severe and more commonly extending into spring. One hypothesis is that changes in seasonal rainfall distributions along with an increase in temperatures is helping to drive soil moisture deficits, and this is of significant concern in light of all climate change scenarios (Lorrey et al. 2018; Pearce et al. 2018).

It is also evident that significant variability of soil moisture has increased within the short-term monitoring period captured by the Auckland Council soil moisture monitoring network. At present, the limited number of soil moisture monitoring sites means the current network spatial coverage can be improved on, and this would have utility for informing risks related to declining soil moisture (drought development) and when soil moisture is high (surface flooding).

Current soil moisture monitoring is carried out in accordance with NEMS. Auckland Council follow the standard setup and soil moisture ribbon sensors are installed between 10cm to 35 cm below the surface of the soils. Monitoring of soil moisture within a limited section of the soil profile in this fashion, however, does not allow an understanding of the movement of water within the vadose zone or presence of deep soil moisture content. Thus, we are missing an important perspective that monitoring soil moisture at additional depths could provide which is a more accurate understanding of subsurface conditions. Less than half of the soil moisture monitoring sites are located within urban centres (Figure 2.1).

Therefore, in addition to expanded spatial coverage for soil moisture monitoring, multiple sensors at differing soil depths are recommended additions if possible. The installation of complementary shallow bores at soil moisture monitoring sites would also allow us to better determine the depth to the local groundwater from the surface, which will assist in the understanding of spatially complex vadose zone hydraulics. The spatial distribution of soil moisture monitoring should also consider areas that have seen recurrent problems with surface water flooding, and a more detailed view of soil type spatial variation could help to identify where new monitoring sites should be located for maximum benefit.

6.3 River Flow analysis

Establishing clear relationships between rainfall, runoff, and flow parameters at a catchment level is fundamental to identifying key drivers of flood events. For example, evaluating what proportion of urban development, and where it is situated within the catchment, and how it contributes most significantly to flash flooding can inform both planning and mitigation strategies. Similarly, understanding the behaviour of stormwater infiltration or disposal to groundwater is crucial to grasp where the water ultimately goes and how it interacts with surface flows.

The cluster analysis for the catchments was able to identify situations where disturbance flows (FRE3) appeared to be decreasing for a handful of rural and forested catchments (only one was urban) and increasing for a handful of urban catchments (and only one rural catchment). The lowest annual flow was also assessed and shows 49% of observing sites (18 out of 37 sites) experienced their lowest or equal lowest flow during SOE2025. Of those 18 sites, 13 (72%) experienced their lowest flow or lowest equal flow during the 2019-20 hydrological year when the 2019-20 drought occurred.

The analysis of river flow observations showed significant changes to both high and low flow metrics, where the 1% flood magnitude AEP was exceeded at all sites during SOE2025 with respect to the long-term observational record. Within SOE2025, the largest annual instantaneous maximum flows occurred at 33 of 41 sites (80%). Flow monitoring infrastructure must be resilient to extreme events like high flows. Multiple sites were damaged during the Auckland Anniversary flood event, thus unable to record the peak event flow. After the event, many sites underwent hardening and improvements to increase site resilience and allow better capture of extreme high-level flows in support of long-term monitoring and evaluation of extremes presented in State of the Environment reporting. All flow sites should be regularly assessed against the Annual Exceedance Probability (AEP) flows experienced during events like the Auckland Anniversary 2023 flood, ensuring they are structurally capable of withstanding extreme flood events. Manual flow gauging during high-flow events is important, but limited resources and health and safety concerns only allow high flows to be measured in a few catchments during any one event. Non-contact velocity technologies that support the development of the upper end of the rating curve safely and accurately could be a solution to this issue. The use of concurrent gauging is particularly important to understand how catchments respond to extreme events throughout their course from upper to lower reaches and between catchments (especially during low flow period). Concurrent gaugings enable the identification of river reaches where river water/groundwater exchange occurs through riverbed/groundwater interactions.

Linear trends analysis used multiple starting points through each flow record to evaluate long-term changes (Figure 4.15 and Figure 4.16). This illustrated just how difficult it is to establish significant trends using hydrological observations that include extreme values such as those associated with the 2022-23 summer season. Significant linear trends were observed for the mean annual low flow at multiple sites, but were sensitive to the starting time of the analysis and some of the observed changes were very small with respect to the observing precision and must be interpreted with caution. Of all the sites analysed, Otara was the only one that showed a significant increase in the annual low flow level across all time periods both with and without 2022-23 data included (Table 4.29).

The increasing frequency and intensity of extreme weather and climate events that are impacting flows will significantly complicate the management of stream systems, particularly at both high and low flow ends of the spectrum. Therefore, managing for ecological and environmental aspects is likely to become more challenging.

6.4 Groundwater analysis

Groundwater observations analysed for SOE2025 focused on a selected number of representative sites that did not contain significant heterogeneities for water level changes (i.e. step changes). Significant responses of groundwater levels to seasonal climate events like the 2019-20 drought and 2022-23 summer deluge show some locations for our groundwater monitoring are highly sensitive and rapidly respond to what occurs above ground. All the selected sites exhibited impacts from the meteoric rainfall input (or lack thereof) that was experienced for the extreme summer of 2019-20 and the 2022-23 hydrological year. These records also showed differences in the presence (or not) of a long-term trend (Figure 4.17 - Figure 4.22; Table 4.45).

Attribution of long-term groundwater level rise was made in one case (Angle Street) due to known changes in urbanisation and presence of soakage pits. Similar trend was observed at Wooten Road, but those may be due to a localised influence from meteoric water increases along the southern margin of Auckland (see Section 5.4 for details).

Significant negative trends for groundwater levels at Maraeorahia and at Quintals suggest there could be connections with long-term climate changes, including a narrowing of the recharge season (Figure 5.2), and increased usage and therefore pressure on the aquifers. The trends of groundwater level lowering that were observed at multiple sites were consistent with overuse, however the current availability and/or accessibility to water use data is poor. The ramification for understanding this change relates to water resource allocation, and therefore this aspect of the regional hydrological monitoring requires high-quality water use and consenting data, including water level as well as volume used. Shortening of the groundwater recharge season observed at Maraeorahia also raises the possibility that climate changes, increased intra-annual climate variability and other factors may be at play there, however monitoring the edge of a groundwater system at that location may have also influenced this view about the wider aquifer.

Monitoring multiple boreholes allow the best representation of the aquifer management areas that exist across the Auckland region, and in a spatial array that can represent four-dimensional properties of the aquifer holistically with limited influences from sole users or via edge effects where groundwater level fluctuations could be large and frequent. Ideally, groundwater aquifer monitoring should use at least one bore in the recharge area, one centrally located bore and with bores near the discharge area or down-gradient aquifer boundary areas to represent a more complete view of aquifer condition or state. Further spatiotemporal details about how holistic groundwater aquifer responses occur is desired for future SOE reporting, and so determining ways to homogenise the wider groundwater observation data to account for temporal heterogeneities linked to water use changes is also a worthy goal. This also draws into focus the idea of having ‘sentinel hydrological monitoring sites’ where a full suite of observations maintained by Auckland Council (including equipment like lysimeters and additional soil moisture sensors) are arranged in a way to collectively inform on source to resource to discharge processes more completely.

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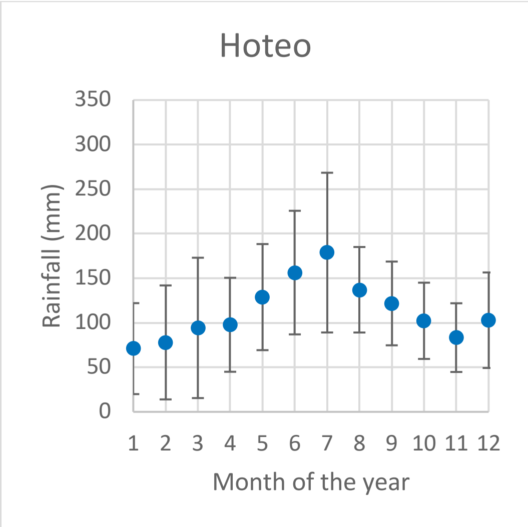
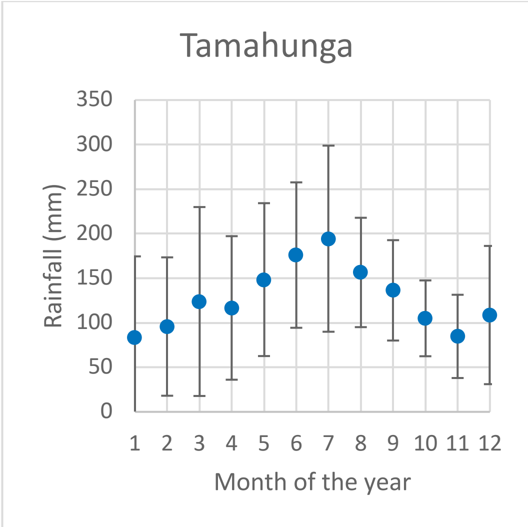
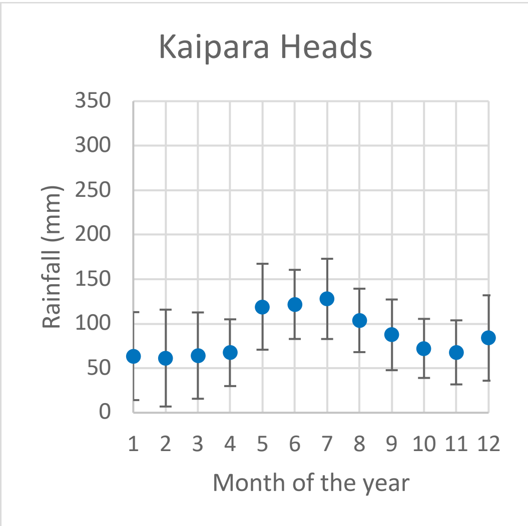
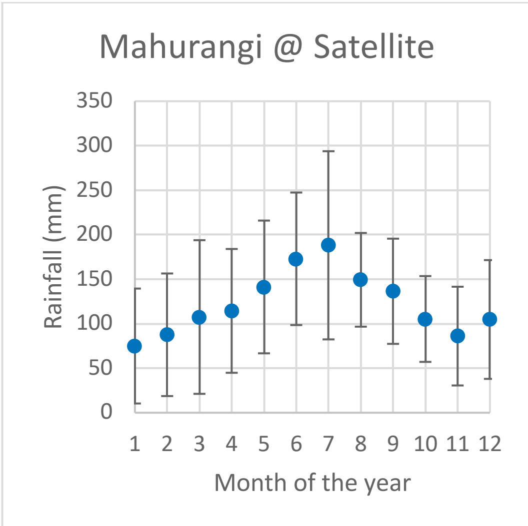
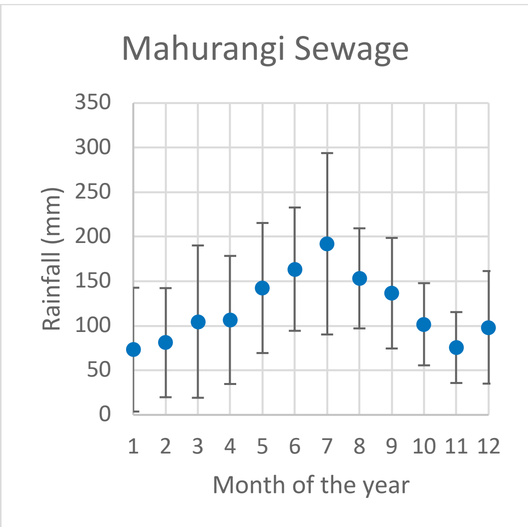
9 Appendix 1 – Rainfall supporting data analysis

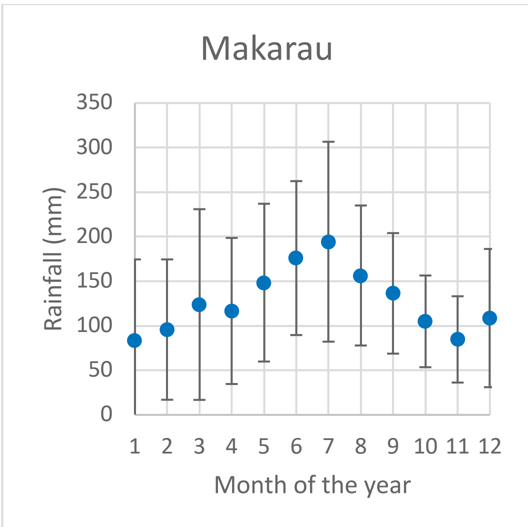


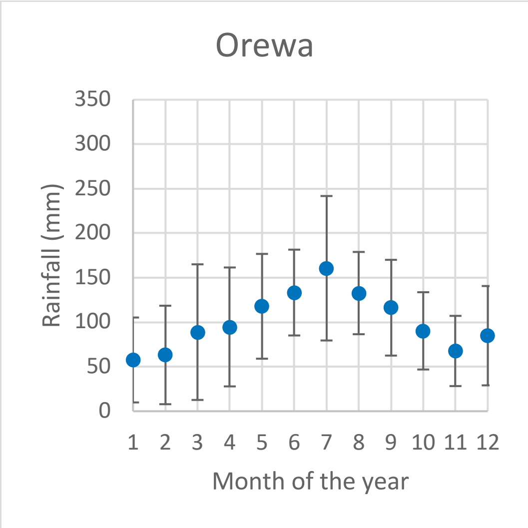


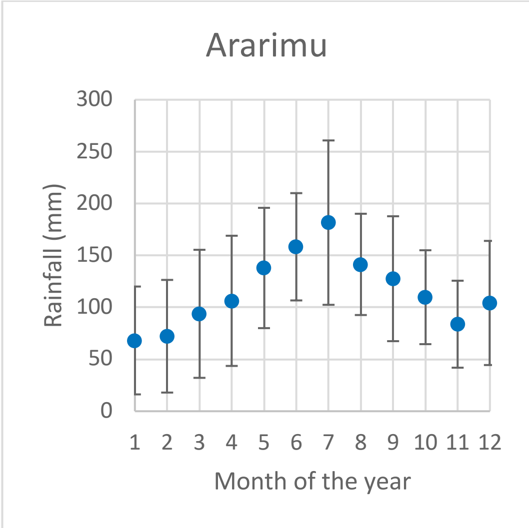









Orewa
Rainfall (mm)
Month of the year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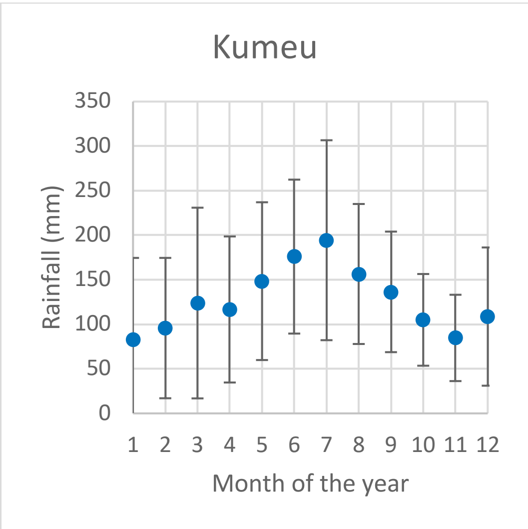
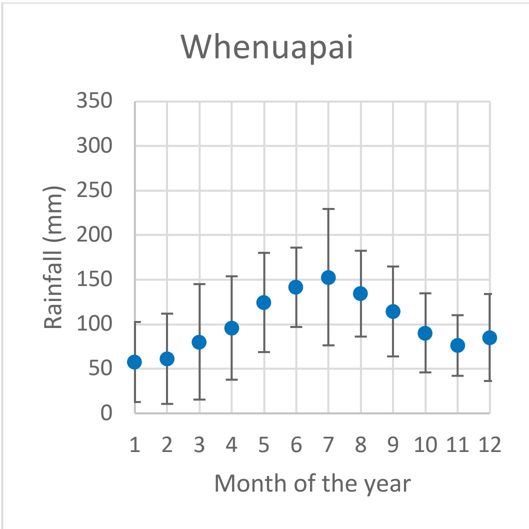
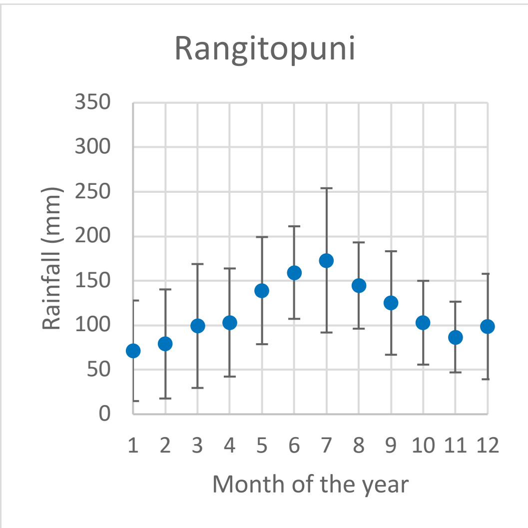
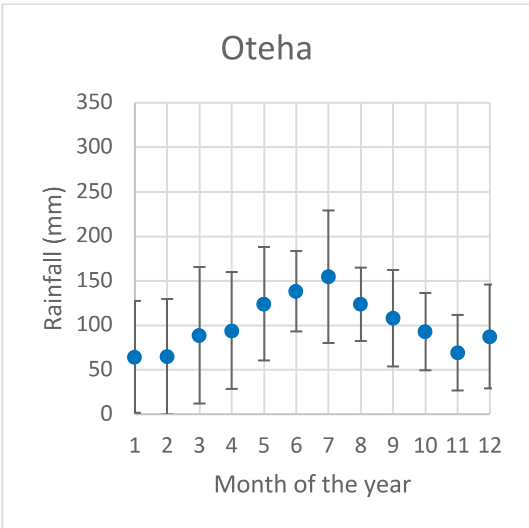
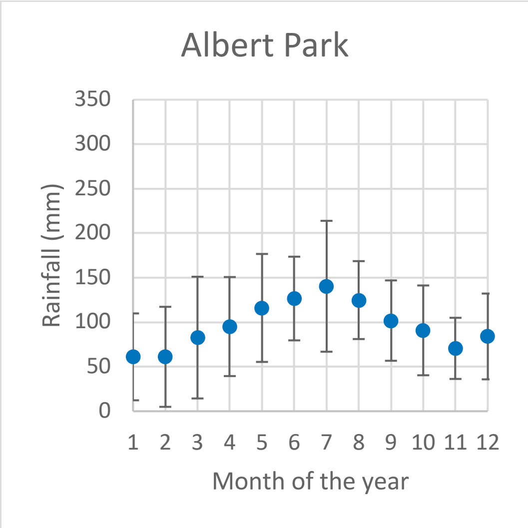
Rainfall (mm)
Month of the year

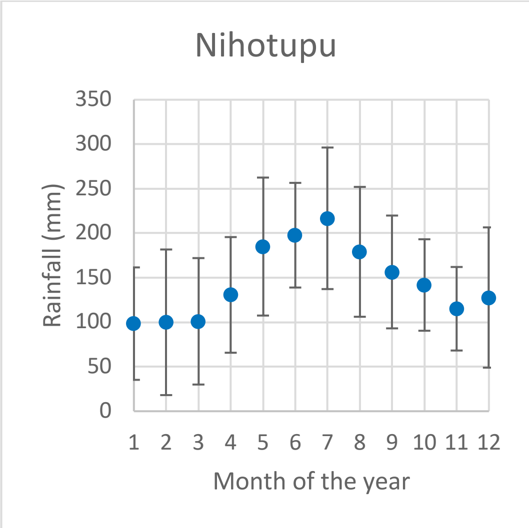

Kumeu
Rainfall (mm)
Month of the year

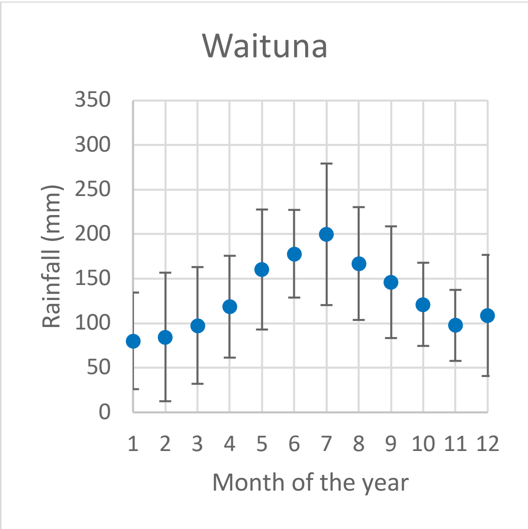

Whenuapai
Rainfall (mm)
Month of the year

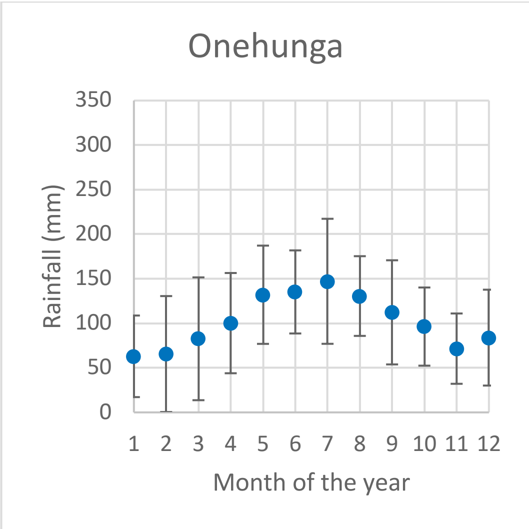

Rangitopuni
Rainfall (mm)
Month of the year

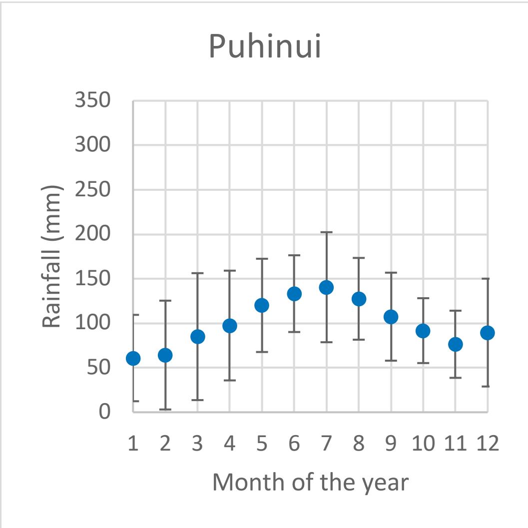

Oteha
Rainfall (mm)
Month of the year

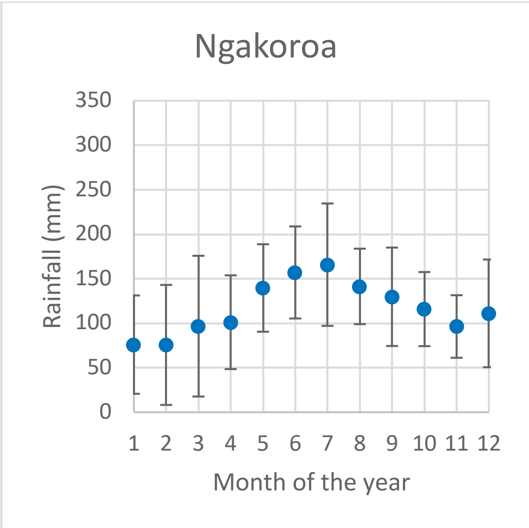

Albert Park
Rainfall (mm)
Month of the year


Nihotupu
Rainfall (mm)
Month of the year


Waituna
Rainfall (mm)
Month of the year


Onehunga
Rainfall (mm)
Month of the year


Puhinui
Rainfall (mm)
Month of the year


Ngakoroa
Rainfall (mm)
Month of the year

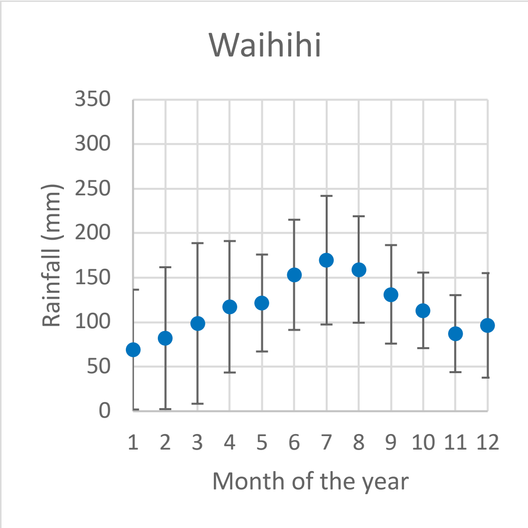


Figure A1.1. Climatological distribution of rainfall through the year for selected Auckland Council rainfall sites based on the 1991-2020 standard climatological normal period. Mean values (blue dots) and the spread (whiskers; 1 standard deviation) are shown for all months (January = 1; December = 12).

10 Appendix 2 – Groundwater supporting data analysis

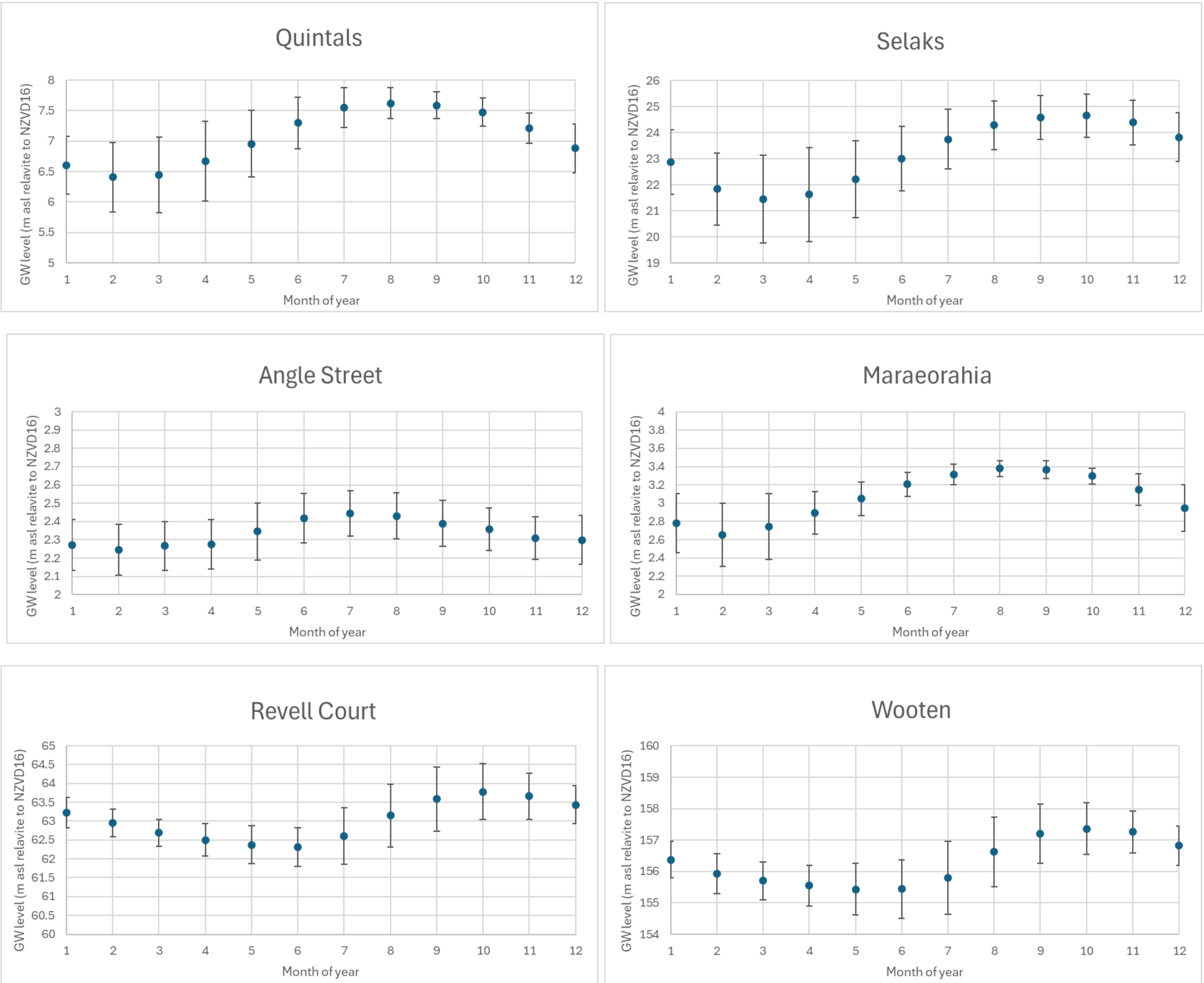


Figure A2.1. Climatological distribution of groundwater levels at six locations across the Auckland Council region based on the 1991-2020 standard climatological normal period. Mean values (blue dots) and the spread (whiskers; 1 standard deviation) are shown for all months (January = 1; December = 12). Elevation of the ground at the observing sites are derived from LINZ 1m LIDAR data (relative to NZVD16) and are as follows: Quintals, 12.29m; Selaks, 35.55m; Angle Street, 3.92m; Maraeorahia 4.09m; Revell Court, 86.30m; Wooten 210.59m.

Table A2.1 Groundwater bore sites not used in the analysis

Site Name	Site Number	Easting	Northing	Aquifer	Total Depth (m)	Casing Depth (m)	Casing Ø (mm)	Record Start	Confinement	Recording	Freq.
Omaha Flats Bore 25	6437021	1756485	5977154	Omaha Waitematā	90	34	100	7/12/1977	confined	automatic	15-minute
Caroline Heights	6437087	1759338	5977414	Omaha Waitematā	188	131	100	31/05/1993	confined	manual	monthly
Waiwera Beachfront Deep	6457041	1752868	5954102	Waiwera geothermal	407		100	30/11/1976	confined	automatic	15-minute
Waiwera Beachfront Shallow	6457097	1752873	5954101	Waiwera geothermal	52	30	100	10/12/1997		automatic	15-minute
Parakai Bore 86	6464007	1728297	5941883	Parakai geothermal	249	100	200	13/06/1984	confined	automatic	15-minute
Rimmer Road	6464089	1726124	5939301	Kaipara sand	63.5	49.5	100	15/04/1997	unconfined	manual	monthly
Waitakere Road #2	6474003	1739082	5927989	Kumeu West Waitematā	150	78	100	5/08/1998	confined	automatic	15-minute
Trigg Road	6475005	1736310	5928959	Kumeu West Waitematā	248	71	100	11/01/1989	confined	manual	monthly
Short Road	6475157	1741716	5929638	Kumeu East Waitematā	242	91.5	100	10/09/1996	confined	manual	monthly
Nick Johnstone Drive	6479007	1778056	5926955	Waiheke West greywacke	88.5	42	100	11/03/2006		manual	monthly
Volcanic Street	6487001	1755313	5915915	Onehunga volcanic	10.5	7	50	14/11/1996	unconfined	manual	monthly
Selkirk Road	6487007	1754021	5917236	Western Springs volcanic	25.5			13/11/1996		automatic	15-minute
Leslie Road	6487009	1754679	5917291	Western Springs volcanic	24.3	18.3	50	13/11/1996	unconfined	automatic	15-minute
Chamberlain Park	6487021	1753511	5918278	Western Springs volcanic				15/06/1998		manual	monthly
PD-13S	6488045	1763376	5915230	Mt Wellington volcanic	23.5	22.5	50	11/12/1991	unconfined	manual	monthly
Alfred Street	6497007	1759789	5912783	Onehunga volcanic	40	24	50	6/06/1989		manual	monthly
Waikaraka Cemetery	6497013	1759920	5911507	Onehunga volcanic	15.9	9.9	50	21/06/1993	unconfined	manual	monthly

Site Name	Site Number	Easting	Northing	Aquifer	Total Depth (m)	Casing Depth (m)	Casing Ø (mm)	Record Start	Confinement	Recording	Freq.
Orakau Avenue	6497015	1757832	5914770	Onehunga volcanic	47.8	41.8	50	14/11/1996		manual	monthly
Amelia Earhart	6497017	1758649	5905851	Mangere-Manurewa Kaawa	50.6	42.6	50	25/03/1997		manual	monthly
Tiwai Road	6497019	1758791	5913752	Onehunga volcanic	58.53	46.53	50	8/04/1997		manual	monthly
Mako Road	6570013	1779254	5927093	Waiheke West greywacke	117	106	25	16/03/2006	confined	manual	monthly
Tawaipareira	6570015	1783160	5925794	Waiheke Central West greywacke	60	53.5	100	12/02/2007	confined	automatic	15-minute
Mt Richmond	6594001	1764001	5911038	Mt Richmond volcanic	42.6	30.27	150	9/08/2001		manual	monthly
Burnside Road	7409001	1777680	5900303	Clevedon East Waitematā	169	154.2	100	10/07/1985	confined	manual	monthly
Bullens Road	7409011	1775849	5899165	Clevedon West Waitematā	75	38.9	100	21/06/1993	confined	manual	monthly
Glenbrook Hall	7417001	1756247	5882259	Glenbrook Kaawa	103.7		115	16/03/1970	confined	manual	monthly
Seagrove Road	7417021	1756024	5889134	Waiau Pa Waitematā	201	97.8	100	8/08/1991	confined	manual	monthly
Waiau Pa Bore 2C	7418003	1758131	5887101	Glenbrook Kaawa	43.8	34.7	200	18/04/1980	confined	manual	monthly
Batty Road	7418013	1763756	5889684	Glenbrook Kaawa	50	41.4	100	20/12/1985	confined	manual	monthly
Ostrich Farm Road #2	7418023	1766027	5885160	Pukekohe Kaawa	47.6	46	80	20/12/1985	confined	manual	monthly
Ostrich Farm Road Observation	7418027	1766016	5885089	Pukekohe Kaawa	84	68	80	20/12/1985	confined	manual	monthly
Tuhimata Road	7419003	1770320	5884982	Pukekohe Kaawa	114.2	67.6	100	3/12/1986	confined	manual	monthly
Fielding Road Sand	7419007	1774443	5890653	Bombay-Drury sand	64	57	100	4/04/1989	semi-confined	manual	monthly
Fielding Road Volcanic	7419009	1774447	5890664	Bombay-Drury volcanic	46.7	16.3	150	4/04/1989	unconfined	manual	monthly
Cooper Road	7419011	1773758	5886862	Bombay-Drury Kaawa	120.6	108.4	100	16/01/1990	confined	manual	monthly
Fielding Road Waitematā	7419013	1774438	5890637	Bombay-Drury Waitematā	273	157	100	24/04/1991	confined	manual	monthly
Karaka #2	7419119	1767829	5892996	Karaka Waitematā	207	91.2	100	12/03/1992	confined	automatic	15-minute
Diver Road	7427003	1756683	5880119	Waiuku Kaawa	218	173	100	27/08/1985	confined	manual	monthly
Pukekohe DSIR	7428043	1765111	5881260	Pukekohe central volcanic	96.3	73	150	26/04/1979	confined	manual	monthly

Site Name	Site Number	Easting	Northing	Aquifer	Total Depth (m)	Casing Depth (m)	Casing Ø (mm)	Record Start	Confinement	Recording	Freq.
Mauku Main	7428047	1760994	5881217	Glenbrook Kaawa	194.7	156	150	17/04/1985	confined	automatic	15-minute
Rifle Range Deep	7428103	1766258	5880972	Pukekohe central volcanic	90	78	50	24/04/1997	confined	manual	monthly
Rifle Range Shallow	7428105	1766250	5880967	Pukekohe central volcanic	42	30	50	24/04/1997	unconfined	manual	monthly
Douglas Road Volcanic	7429013	1766160	5879366	Pukekohe central volcanic	108.2	71	100	6/06/1980	confined	automatic	15-minute

Table A2.2. Groundwater observing sites not used in the formal SOE2025 analysis due to observed temporal heterogeneities.

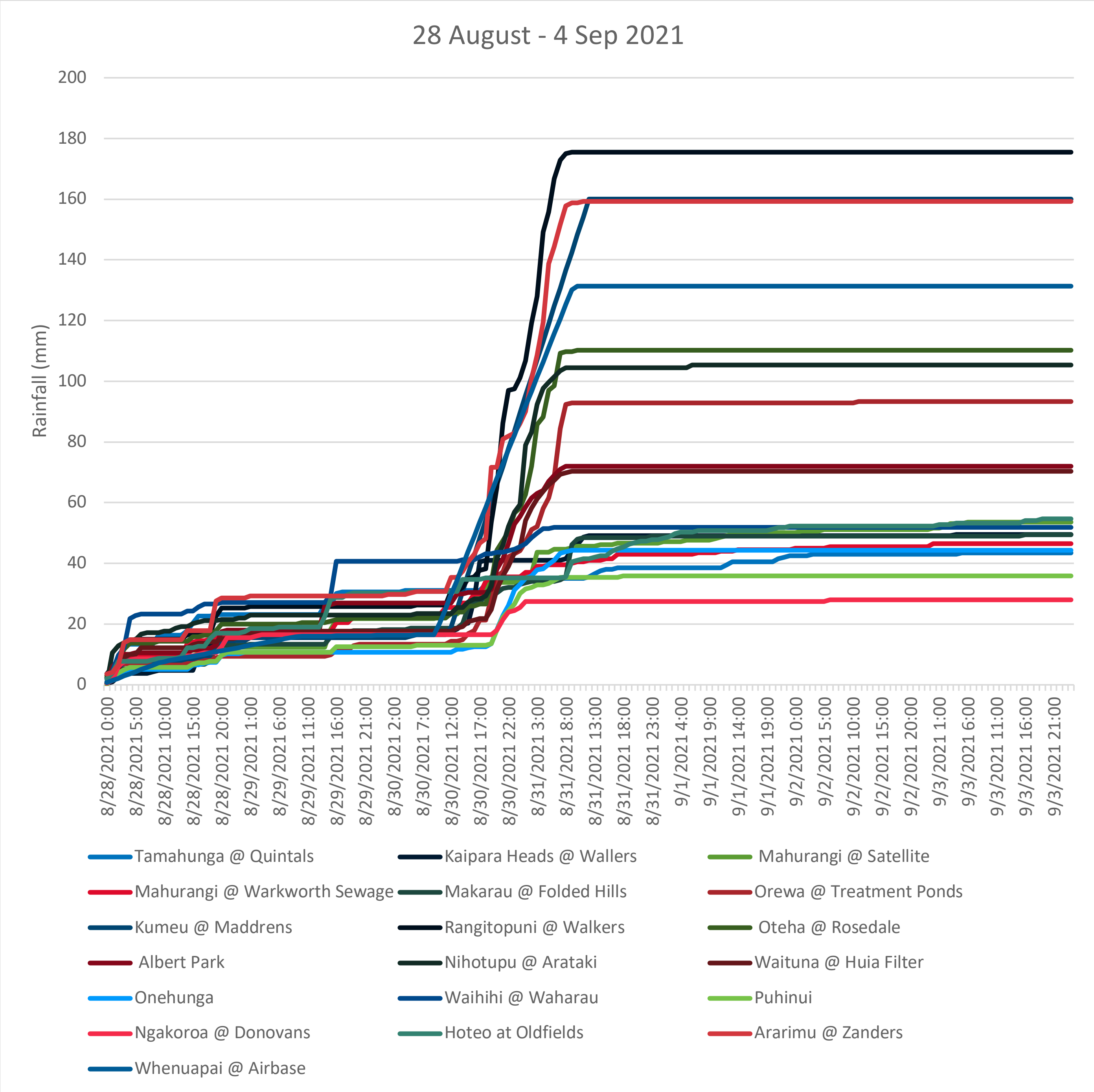
Site Name	Site Number	Minimum	Maximum	Mean	Median	Standard Deviation	Interquartile Range	5th Percentile	25th Percentile	75th Percentile	95th Percentile
Quintals Road Omaha (SOE 2025)	6437005	4.353	11.593	6.767	6.905	0.744	1.222	5.649	6.201	7.423	7.568
Quintals Road Omaha (SOE 2020)	6437005	5.024	7.843	6.924	7.022	0.740	1.215	5.424	6.354	7.568	7.813
Omaha Flats Bore 25 (SOE 2025)	6437021	-0.154	5.025	3.528	4.176	1.389	1.906	0.696	2.658	4.564	4.787
Omaha Flats Bore 25 (SOE 2020)	6437021	0.951	4.911	3.905	4.350	1.101	1.242	1.086	3.470	4.712	4.873
Caroline Heights (SOE 2025)	6437087	0.858	1.779	1.576	1.583	0.135	0.179	1.308	1.510	1.689	1.735
Caroline Heights (SOE 2020)	6437087	-0.773	1.574	0.896	1.310	0.745	1.040	-0.599	0.467	1.506	1.556
Waiwera Beachfront Deep (SOE 2025)	6457041	2.584	3.388	2.950	2.958	0.117	0.166	2.757	2.863	3.029	3.127
Waiwera Beachfront Deep (SOE 2020)	6457041	0.926	2.872	1.690	1.598	0.649	0.934	0.960	1.112	2.046	2.856
Waiwera Beachfront Shallow (SOE 2025)	6457097	2.510	3.237	2.948	2.972	0.128	0.183	2.719	2.861	3.045	3.118
Waiwera Beachfront Shallow (SOE 2020)	6457097	0.931	2.810	1.646	1.549	0.591	0.889	0.958	1.120	2.009	2.800
Parakai 86 (SOE 2025)	6464007	1.873	3.983	2.875	2.860	0.472	0.685	2.126	2.517	3.202	3.743
Parakai 86 (SOE 2020)	6464007	1.639	3.949	2.951	3.081	0.620	0.833	1.678	2.634	3.467	3.748
Rimmer Road (SOE 2025)	6464089	3.447	5.313	4.996	5.037	0.244	0.294	4.458	4.892	5.185	5.248
Rimmer Road (SOE 2020)	6464089	3.823	4.861	4.511	4.566	0.244	0.291	3.947	4.383	4.674	4.817
Waitakere Road #2 (SOE 2025)	6474003	-6.328	24.846	19.968	21.929	5.329	5.381	8.904	18.182	23.563	24.595
Waitakere Road #2 (SOE 2020)	6474003	6.851	28.089	19.156	19.874	4.979	6.684	10.301	16.356	23.040	26.341
Selaks Bore (SOE 2025)	6475003	18.607	26.530	24.679	24.811	1.747	2.856	22.143	23.556	26.411	26.492
Selaks Bore (SOE 2020)	6475003	19.422	26.056	23.885	24.196	1.594	2.611	21.014	22.594	25.205	25.877
Trigg Road (SOE 2025)	6475005	17.816	23.049	21.663	21.777	0.870	1.246	20.369	21.164	22.410	22.732
Trigg Road (SOE 2020)	6475005	20.215	22.006	21.236	21.247	0.475	0.740	20.424	20.856	21.596	21.992
Short Road (SOE 2025)	6475157	15.138	20.501	18.450	18.511	1.276	2.078	16.529	17.312	19.389	20.365
Short Road (SOE 2020)	6475157	10.482	20.282	17.338	18.246	2.515	3.148	12.026	16.035	19.210	20.076
Nick Johnstone Drive (SOE 2025)	6479007	27.763	34.052	30.004	30.052	1.423	2.339	27.907	28.752	31.091	31.852
Nick Johnstone Drive (SOE 2020)	6479007	29.847	32.814	31.124	31.026	0.914	1.673	29.901	30.298	31.971	32.589
Volcanic Street (SOE 2025)	6487001	37.710	41.401	38.707	38.550	0.895	1.578	37.722	37.855	39.433	40.307
Volcanic Street (SOE 2020)	6487001	37.714	39.722	38.408	38.239	0.584	1.085	37.721	37.836	38.921	39.343
Selkirk Road (SOE 2025)	6487007	17.632	21.850	18.954	19.017	0.454	0.550	18.159	18.683	19.233	19.547
Selkirk Road (SOE 2020)	6487007	18.062	19.489	18.983	19.113	0.369	0.531	18.242	18.736	19.267	19.453

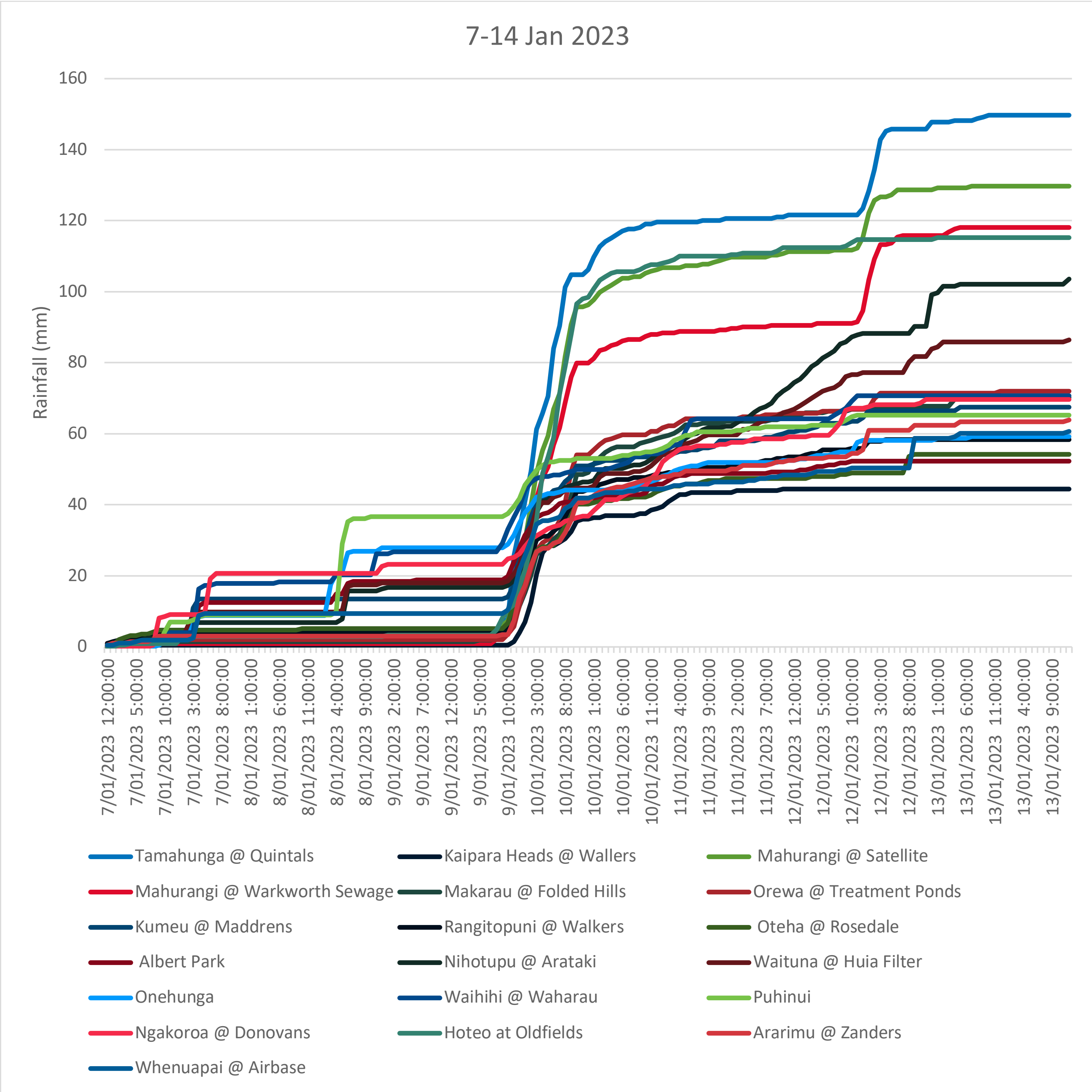
Site Name	Site Number	Minimum	Maximum	Mean	Median	Standard Deviation	Interquartile Range	5th Percentile	25th Percentile	75th Percentile	95th Percentile
Leslie Road (SOE 2025)	6487009	25.790	32.105	27.782	27.866	0.958	1.509	26.284	26.975	28.484	29.163
Leslie Road (SOE 2020)	6487009	25.905	29.187	27.952	28.312	0.878	1.301	26.339	27.336	28.637	29.046
Chamberlain Park (SOE 2025)	6487021	10.075	11.806	11.179	11.264	0.330	0.519	10.606	10.897	11.415	11.557
Chamberlain Park (SOE 2020)	6487021	10.600	11.526	11.138	11.206	0.242	0.389	10.693	10.925	11.314	11.473
PD-13S (SOE 2025)	6488045	17.798	26.611	21.964	21.820	1.600	2.156	20.078	20.716	22.872	24.593
PD-13S (SOE 2020)	6488045	19.560	25.565	21.819	21.638	1.386	1.978	19.877	20.721	22.698	24.203
Alfred Street (SOE 2025)	6497007	2.229	6.272	3.508	3.514	0.430	0.662	2.899	3.141	3.804	4.190
Alfred Street (SOE 2020)	6497007	2.753	4.497	3.392	3.288	0.414	0.677	2.842	3.064	3.741	4.085
Cemetery Bore (SOE 2025)	6497013	1.395	2.298	1.841	1.895	0.215	0.345	1.481	1.648	1.993	2.177
Cemetery Bore (SOE 2020)	6497013	0.986	2.276	1.761	1.776	0.227	0.298	1.395	1.629	1.927	2.053
Orakau Avenue (SOE 2025)	6497015	36.680	44.168	39.581	39.564	2.170	4.068	36.757	37.336	41.404	42.950
Orakau Avenue (SOE 2020)	6497015	36.868	44.043	39.975	39.744	1.661	2.769	37.389	38.590	41.359	42.678
Amelia Earhart (SOE 2025)	6497017	2.248	3.590	3.068	3.171	0.345	0.563	2.434	2.818	3.381	3.464
Amelia Earhart (SOE 2020)	6497017	2.686	3.713	3.276	3.324	0.274	0.411	2.773	3.074	3.485	3.676
Tiwai Road (SOE 2025)	6497019	14.160	18.272	15.747	15.746	0.630	0.595	15.041	15.394	15.989	16.435
Tiwai Road (SOE 2020)	6497019	14.630	17.942	15.807	15.837	0.568	0.537	15.067	15.445	15.982	17.172
Angle Street (SOE 2025)	6498003	2.157	3.006	2.503	2.501	0.131	0.151	2.284	2.424	2.576	2.730
Angle Street (SOE 2020)	6498003	2.343	2.672	2.512	2.511	0.079	0.108	2.376	2.453	2.561	2.634
Tawaipareira (SOE 2025)	6570015	1.182	3.636	2.658	2.782	0.596	0.879	1.540	2.251	3.130	3.474
Tawaipareira (SOE 2020)	6570015	2.016	3.432	2.796	2.771	0.375	0.545	2.088	2.571	3.116	3.350
Mt Richmond (SOE 2025)	6594001	-17.783	-0.778	-4.124	-4.092	2.628	3.386	-6.325	-6.027	-2.641	-0.829
Mt Richmond (SOE 2020)	6594001	-6.906	-2.979	-5.033	-4.815	1.350	2.531	-6.870	-6.523	-3.992	-3.136
Burnside Road (SOE 2025)	7409001	21.592	29.096	26.499	27.000	1.805	2.276	23.162	25.535	27.810	28.793
Burnside Road (SOE 2020)	7409001	23.997	29.670	27.805	28.004	1.243	1.690	25.600	27.017	28.707	29.499
Bullens Road (SOE 2025)	7409011	16.934	23.392	22.069	22.352	1.087	1.142	20.488	21.609	22.751	23.314
Bullens Road (SOE 2020)	7409011	21.145	23.892	22.844	22.863	0.615	0.854	21.620	22.411	23.265	23.820
Glenbrook Hall (SOE 2025)	7417001	7.029	9.433	8.638	8.719	0.471	0.644	7.713	8.345	8.989	9.323
Glenbrook Hall (SOE 2020)	7417001	7.594	9.093	8.290	8.317	0.369	0.445	7.656	8.112	8.557	9.007
Seagrove Road (SOE 2025)	7417021	2.420	5.987	4.299	4.474	0.826	1.133	2.721	3.802	4.934	5.267

Site Name	Site Number	Minimum	Maximum	Mean	Median	Standard Deviation	Interquartile Range	5th Percentile	25th Percentile	75th Percentile	95th Percentile
Seagrove Road (SOE 2020)	7417021	2.886	5.512	4.555	4.658	0.639	0.881	3.342	4.140	5.021	5.443
Waiau Pa Bore 2C (SOE 2025)	7418003	-1.402	14.229	9.232	10.479	3.598	4.692	2.471	7.149	11.841	13.480
Waiau Pa Bore 2C (SOE 2020)	7418003	8.994	14.216	12.439	12.659	1.176	1.781	10.459	11.608	13.389	13.977
Batty Road (SOE 2025)	7418013	17.738	22.865	22.033	22.082	0.701	0.742	21.488	21.707	22.449	22.763
Batty Road (SOE 2020)	7418013	21.877	23.167	22.515	22.523	0.361	0.469	21.926	22.278	22.747	23.100
Ostrich Farm Road #2 (SOE 2025)	7418023	19.564	22.120	20.297	20.298	0.394	0.479	19.741	20.043	20.522	20.745
Ostrich Farm Road #2 (SOE 2020)	7418023	19.613	21.824	20.507	20.496	0.421	0.486	19.887	20.240	20.726	21.067
Ostrich Farm Road Obs (SOE 2025)	7418027	19.371	20.961	20.426	20.460	0.344	0.539	19.937	20.163	20.702	20.922
Ostrich Farm Road Obs (SOE 2020)	7418027	19.883	21.105	20.522	20.533	0.332	0.540	19.979	20.261	20.801	21.020
Tuhimata Road (SOE 2025)	7419003	22.495	24.308	23.545	23.676	0.509	0.659	22.641	23.246	23.905	24.264
Tuhimata Road (SOE 2020)	7419003	23.057	24.672	23.968	23.997	0.401	0.613	23.275	23.664	24.276	24.563
Fielding Road Sand (SOE 2025)	7419007	4.524	12.520	9.355	9.608	1.990	3.416	5.926	7.599	11.015	12.101
Fielding Road Sand (SOE 2020)	7419007	5.611	12.463	9.521	9.622	1.795	3.163	6.767	7.939	11.102	12.131
Fielding Road Volcanic (SOE 2025)	7419009	13.924	16.139	15.010	14.927	0.693	1.259	14.031	14.403	15.662	15.971
Fielding Road Volcanic (SOE 2020)	7419009	13.672	16.339	15.213	15.269	0.717	1.285	14.120	14.608	15.893	16.272
Cooper Road (SOE 2025)	7419011	11.731	18.950	16.658	17.048	1.619	2.047	13.127	15.845	17.892	18.718
Cooper Road (SOE 2020)	7419011	13.663	27.049	18.322	18.009	2.303	2.015	15.328	16.950	18.965	22.906
Fielding Road Waitemata (SOE 2025)	7419013	11.040	12.593	11.823	11.912	0.421	0.598	11.161	11.538	12.137	12.460
Fielding Road Waitemata (SOE 2020)	7419013	11.388	12.510	12.031	12.068	0.312	0.522	11.483	11.775	12.298	12.444
Karaka #2 (SOE 2025)	7419119	2.647	4.998	3.962	4.081	0.631	1.088	2.863	3.431	4.519	4.785
Karaka #2 (SOE 2020)	7419119	3.441	5.069	4.376	4.457	0.465	0.785	3.532	3.984	4.769	4.992
Divers Road (SOE 2025)	7427003	2.130	13.897	11.111	12.204	3.144	2.724	3.723	10.410	13.133	13.796
Divers Road (SOE 2020)	7427003	4.953	13.441	11.407	12.207	2.209	2.142	6.043	10.812	12.953	13.361
Maraeorahia (SOE 2025)	7427005	0.485	2.965	2.156	2.326	0.538	0.782	1.059	1.805	2.588	2.758
Maraeorahia (SOE 2020)	7427005	1.385	2.826	2.358	2.463	0.417	0.641	1.569	2.063	2.704	2.801
Pukekohe DSIR (SOE 2025)	7428043	46.517	50.799	48.999	48.983	0.605	0.453	47.804	48.861	49.314	49.732
Pukekohe DSIR (SOE 2020)	7428043	48.553	51.133	49.829	49.728	0.731	1.178	48.734	49.231	50.409	51.011
Mauku Main (SOE 2025)	7428047	24.308	27.905	26.608	26.687	0.733	0.931	25.114	26.217	27.148	27.632
Mauku Main (SOE 2020)	7428047	25.761	28.237	27.287	27.406	0.585	0.880	26.243	26.867	27.747	28.109

Site Name	Site Number	Minimum	Maximum	Mean	Median	Standard Deviation	Interquartile Range	5th Percentile	25th Percentile	75th Percentile	95th Percentile
Rifle Range Deep (SOE 2025)	7428103	43.467	50.459	47.366	47.606	1.934	3.207	44.172	45.804	49.010	49.866
Rifle Range Deep (SOE 2019)	7428103	44.709	51.079	49.193	49.362	1.134	1.503	47.427	48.492	49.995	50.714
Rifle Range Shallow (SOE 2025)	7428105	54.442	58.511	56.425	56.507	1.156	1.770	54.592	55.484	57.254	58.009
Rifle Range Shallow (SOE 2019)	7428105	55.535	59.178	57.562	57.797	0.931	1.317	55.818	56.884	58.201	58.898
Revell Court (SOE 2025)	7429011	61.232	64.256	62.687	62.578	0.804	1.409	61.492	61.975	63.384	64.010
Revell Court (SOE 2019)	7429011	61.808	64.781	63.344	63.320	0.752	1.276	62.081	62.721	63.997	64.462
Douglas Road Volcanic (SOE 2025)	7429013	48.490	52.381	50.429	50.453	0.892	1.235	48.748	49.818	51.053	51.847
Douglas Road Volcanic (SOE 2019)	7429013	49.029	52.547	51.050	51.194	0.959	1.459	49.393	50.335	51.794	52.421
Wooten Road (SOE 2025)	7510005	154.866	159.409	156.941	156.846	1.300	2.207	155.039	155.808	158.015	158.888
Wooten Road (SOE 2019)	7510005	154.232	158.807	156.935	156.874	1.019	1.793	155.663	156.099	157.892	158.536

11 Appendix 3 – Rain event supporting data analysis (cumulative rainfall)




7-14 Jan 2023
Rainfall (mm)
160
140
120
100
80
60
40
20
0
7/01/2023 12:00:00
7/01/2023 5:00:00
7/01/2023 10:00:00
7/01/2023 3:00:00
7/01/2023 8:00:00
8/01/2023 1:00:00
8/01/2023 6:00:00
8/01/2023 11:00:00
8/01/2023 4:00:00
8/01/2023 9:00:00
9/01/2023 2:00:00
9/01/2023 7:00:00
9/01/2023 12:00:00
9/01/2023 5:00:00
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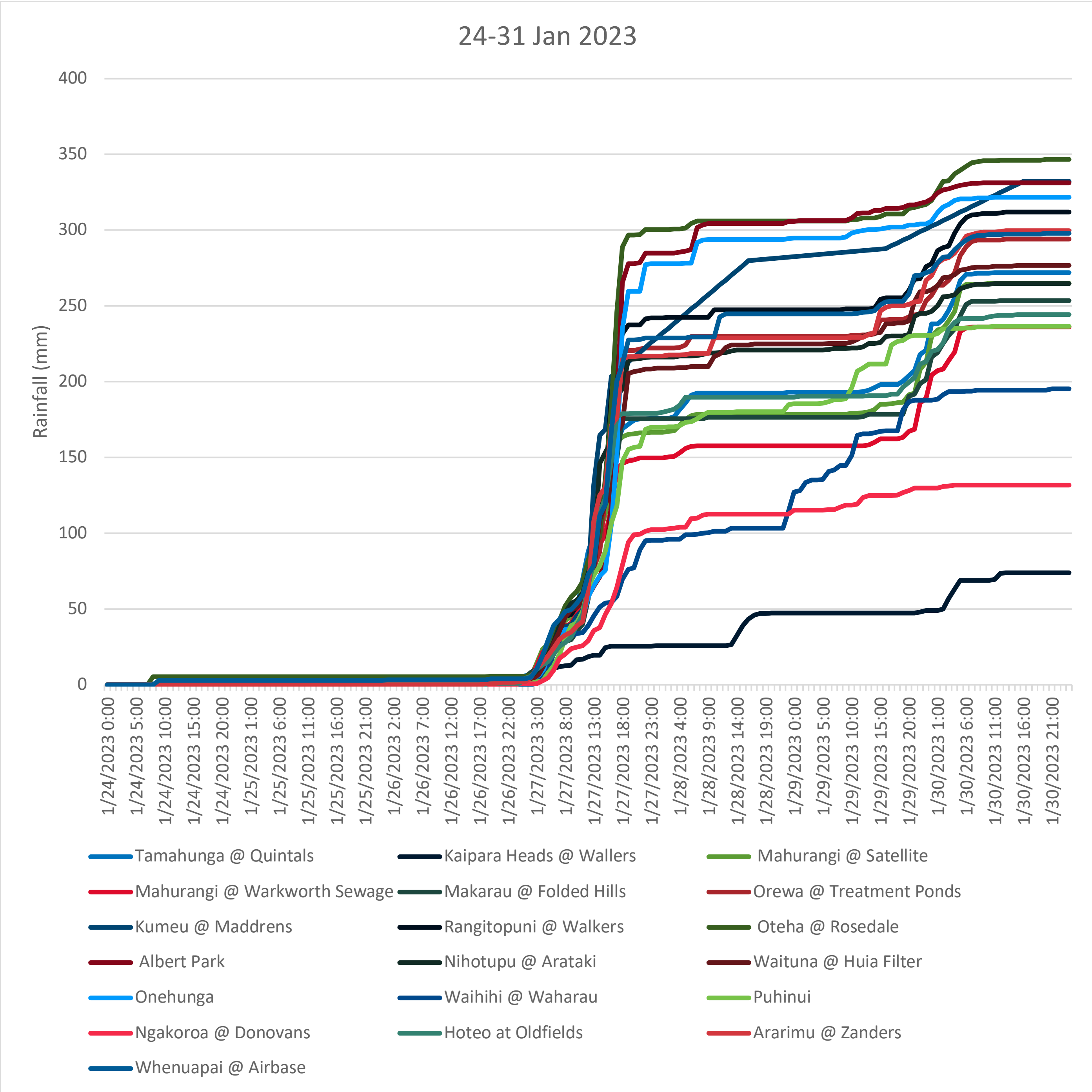
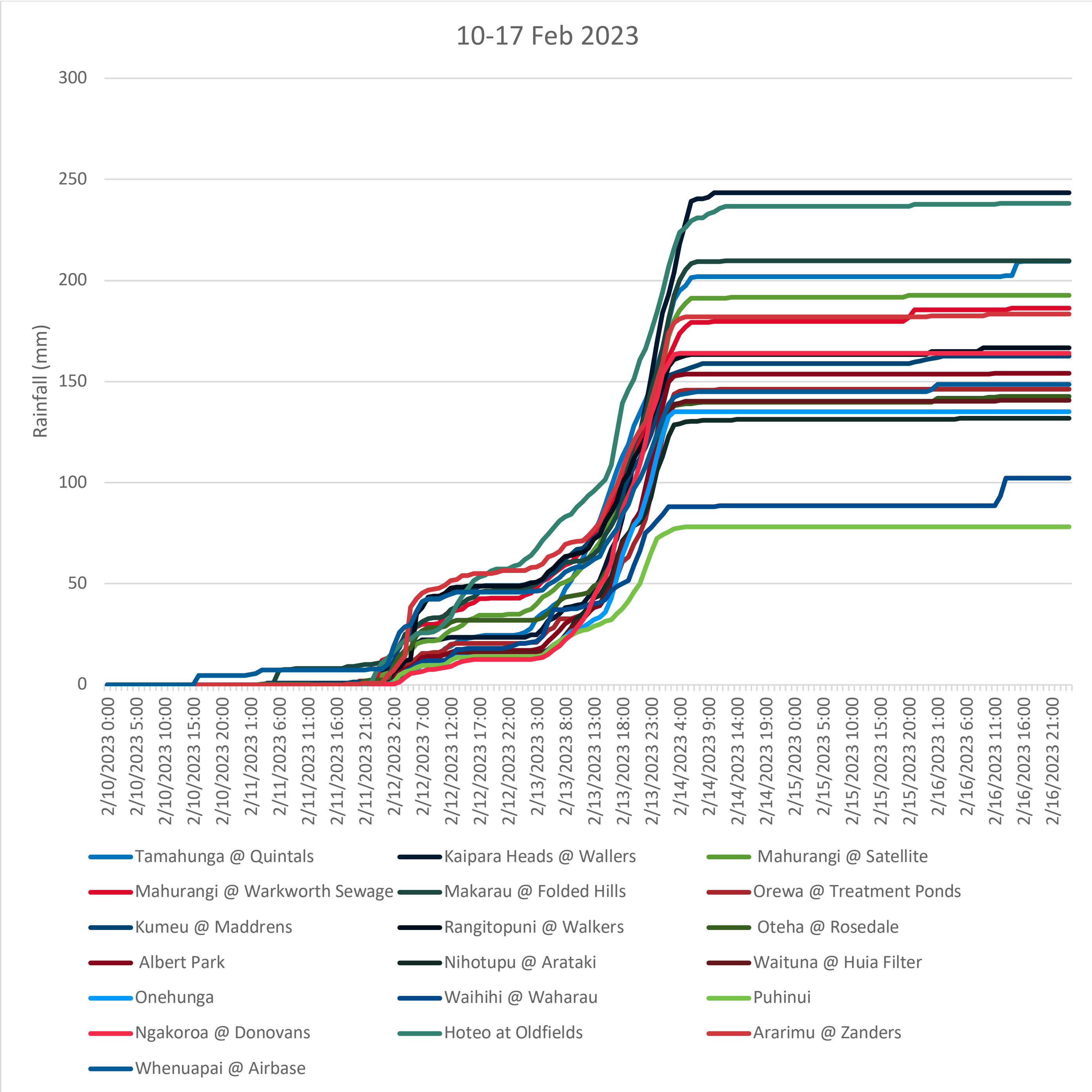
13/01/2023 1:00:00
13/01/2023 6:00:00
13/01/2023 11:00:00
13/01/2023 4:00:00
13/01/2023 9:00:00
Tamahunga @ Quintals
Kaipara Heads @ Wallers
Mahurangi @ Satellite
Mahurangi @ Warkworth Sewage
Makarau @ Folded Hills
Orewa @ Treatment Ponds
Kumeu @ Maddrens
Rangitopuni @ Walkers
Oteha @ Rosedale
Albert Park
Nihotupu @ Arataki
Waituna @ Huia Filter
Onehunga
Waihihi @ Waharau
Puhinui
Ngakoroa @ Donovans
Hoteo at Oldfields
Ararimu @ Zanders
Whenuapai @ Airbase



24-31 Jan 2023
Rainfall (mm)
400
350
300
250
200
150
100
50
0
1/24/2023 0:00
1/24/2023 5:00
1/24/2023 10:00
1/24/2023 15:00
1/24/2023 20:00
1/25/2023 1:00
1/25/2023 6:00
1/25/2023 11:00
1/25/2023 16:00
1/25/2023 21:00
1/26/2023 2:00
1/26/2023 7:00
1/26/2023 12:00
1/26/2023 17:00
1/26/2023 22:00
1/27/2023 3:00
1/27/2023 8:00
1/27/2023 13:00
1/27/2023 18:00
1/27/2023 23:00
1/28/2023 4:00
1/28/2023 9:00
1/28/2023 14:00
1/28/2023 19:00
1/29/2023 0:00
1/29/2023 5:00
1/29/2023 10:00
1/29/2023 15:00
1/29/2023 20:00
1/30/2023 1:00
1/30/2023 6:00
1/30/2023 11:00
1/30/2023 16:00
1/30/2023 21:00
Tamahunga @ Quintals
Kaipara Heads @ Wallers
Mahurangi @ Satellite
Mahurangi @ Warkworth Sewage
Makarau @ Folded Hills
Orewa @ Treatment Ponds
Kumeu @ Maddrens
Rangitopuni @ Walkers
Oteha @ Rosedale
Albert Park
Nihotupu @ Arataki
Waituna @ Huia Filter
Onehunga
Waihihi @ Waharau
Puhinui
Ngakoroa @ Donovans
Hoteo at Oldfields
Ararimu @ Zanders
Whenuapai @ Airbase



10-17 Feb 2023
Rainfall (mm)
300
250
200
150
100
50
0
2/10/2023 0:00
2/10/2023 5:00
2/10/2023 10:00
2/10/2023 15:00
2/10/2023 20:00
2/11/2023 1:00
2/11/2023 6:00
2/11/2023 11:00
2/11/2023 16:00
2/11/2023 21:00
2/12/2023 2:00
2/12/2023 7:00
2/12/2023 12:00
2/12/2023 17:00
2/12/2023 22:00
2/13/2023 3:00
2/13/2023 8:00
2/13/2023 13:00
2/13/2023 18:00
2/13/2023 23:00
2/14/2023 4:00
2/14/2023 9:00
2/14/2023 14:00
2/14/2023 19:00
2/15/2023 0:00
2/15/2023 5:00
2/15/2023 10:00
2/15/2023 15:00
2/15/2023 20:00
2/16/2023 1:00
2/16/2023 6:00
2/16/2023 11:00
2/16/2023 16:00
2/16/2023 21:00
Tamahunga @ Quintals
Kaipara Heads @ Wallers
Mahurangi @ Satellite
Mahurangi @ Warkworth Sewage
Makarau @ Folded Hills
Orewa @ Treatment Ponds
Kumeu @ Maddrens
Rangitopuni @ Walkers
Oteha @ Rosedale
Albert Park
Nihotupu @ Arataki
Waituna @ Huia Filter
Onehunga
Waihihi @ Waharau
Puhinui
Ngakoroa @ Donovans
Hoteo at Oldfields
Ararimu @ Zanders
Whenuapai @ Airbase

12 Appendix 4 – Rain event supporting data analysis (synoptic maps)

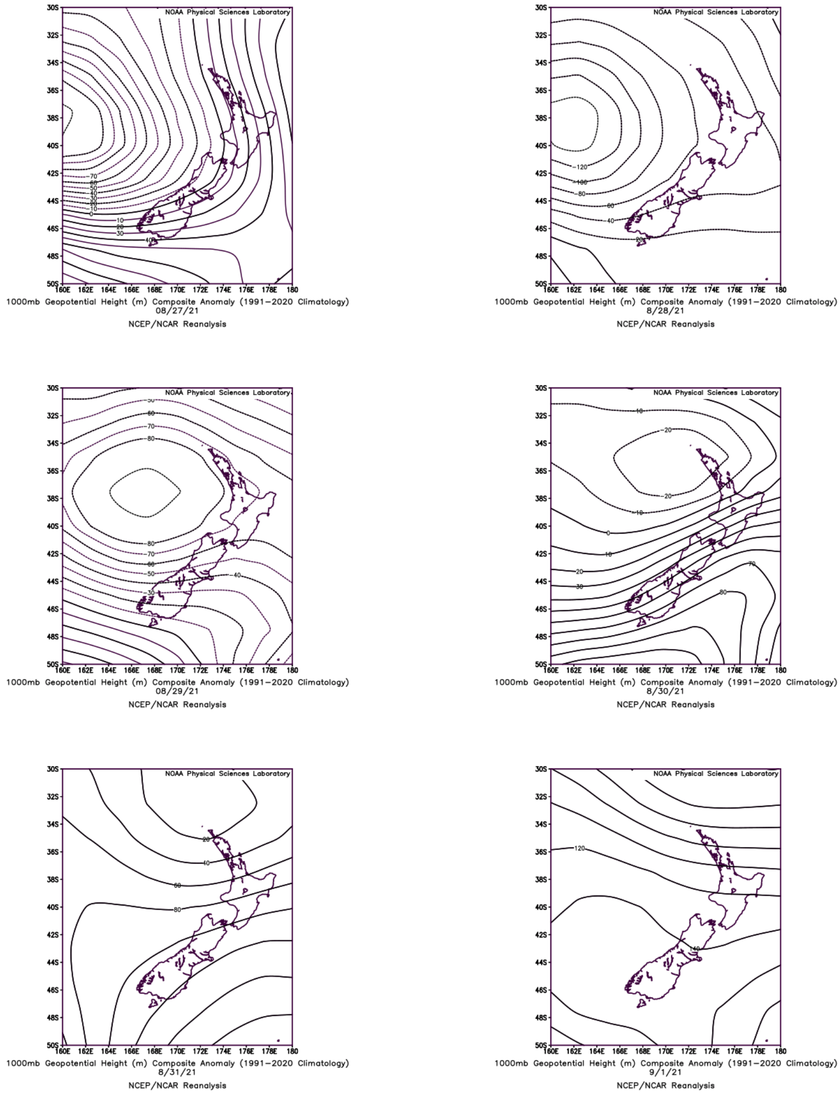


Figure A4.1. Progression of daily synoptic weather patterns for New Zealand during the late winter/early spring 2021 period when a significant rainfall event occurred for Auckland. The patterns show near surface geopotential height at the 1000hPa level (z1000) as a close approximation for mean sea level pressure patterns. Plots use NCEP1 reanalysis data and are courtesy of NOAA Physical Sciences Laboratory plotting tools at https://psl.noaa.gov/data/composites/day/.

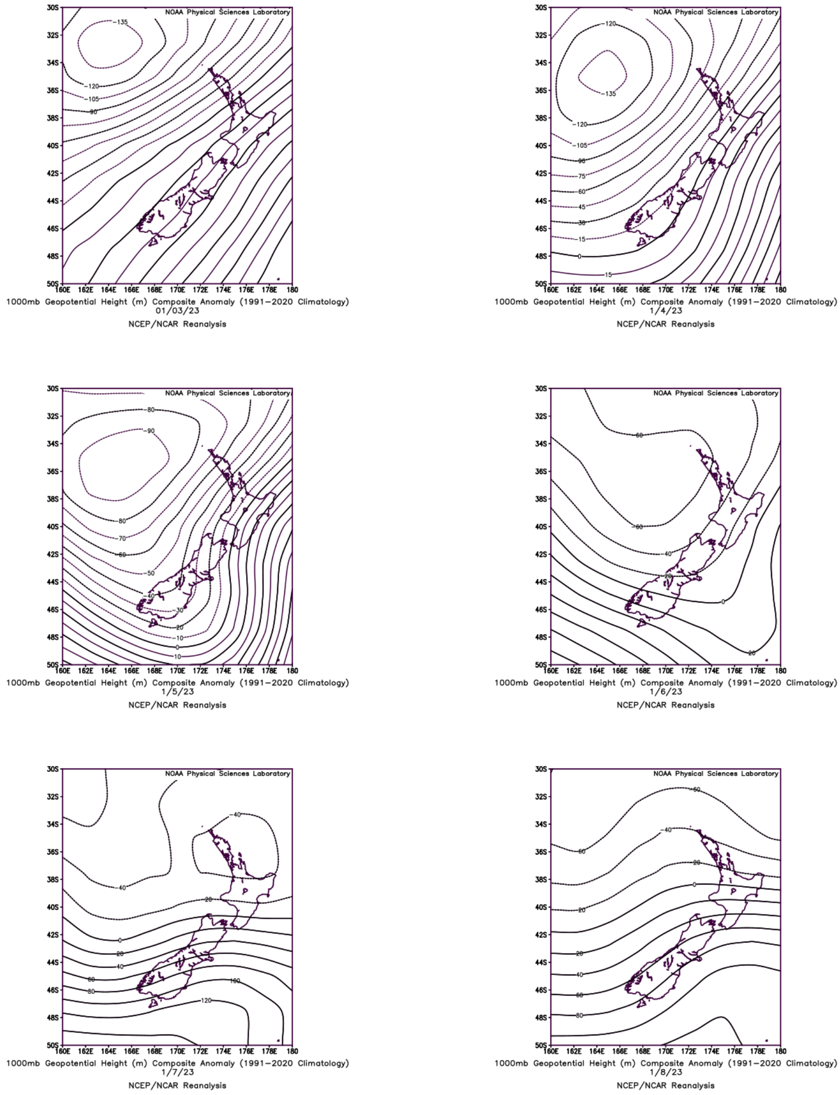


Figure A4.2. Progression of daily synoptic weather patterns for New Zealand during 3 – 8 January 2023 period when a significant rainfall event occurred for Auckland. The patterns show near surface geopotential height at the 1000hPa level (z1000) as a close approximation for mean sea level pressure patterns. Plots use NCEP1 reanalysis data and are courtesy of NOAA Physical Sciences Laboratory plotting tools at https://psl.noaa.gov/data/composites/day/.

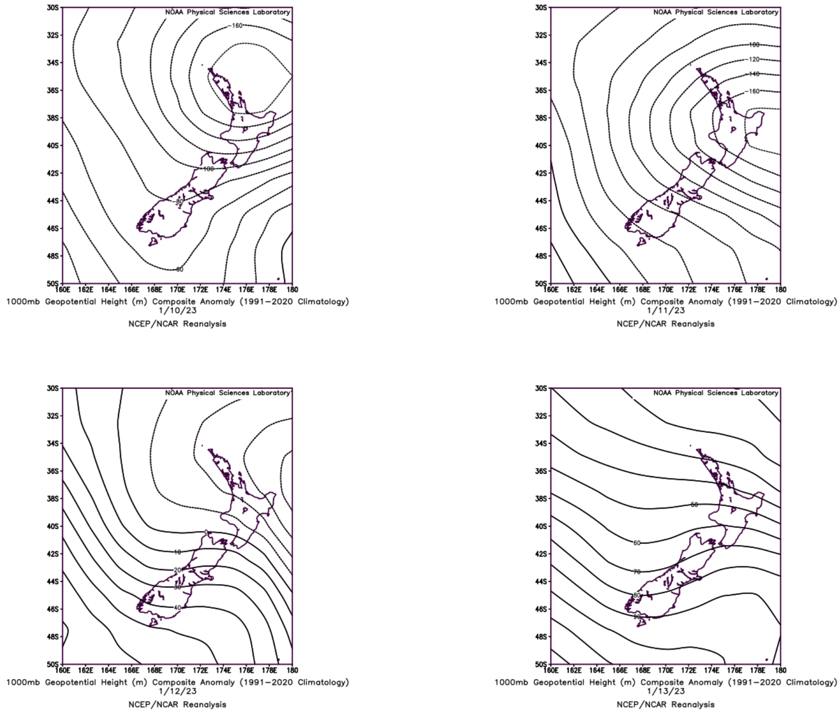


Figure A4.3. Progression of daily synoptic weather patterns for New Zealand during the 10 – 13 January 2023 period when a significant rainfall event occurred for Auckland associated with ex tropical cyclone Hale. The patterns show near surface geopotential height at the 1000hPa level (z1000) as a close approximation for mean sea level pressure patterns. Plots use NCEP1 reanalysis data and are courtesy of NOAA Physical Sciences Laboratory plotting tools at https://psl.noaa.gov/data/composites/day/ .

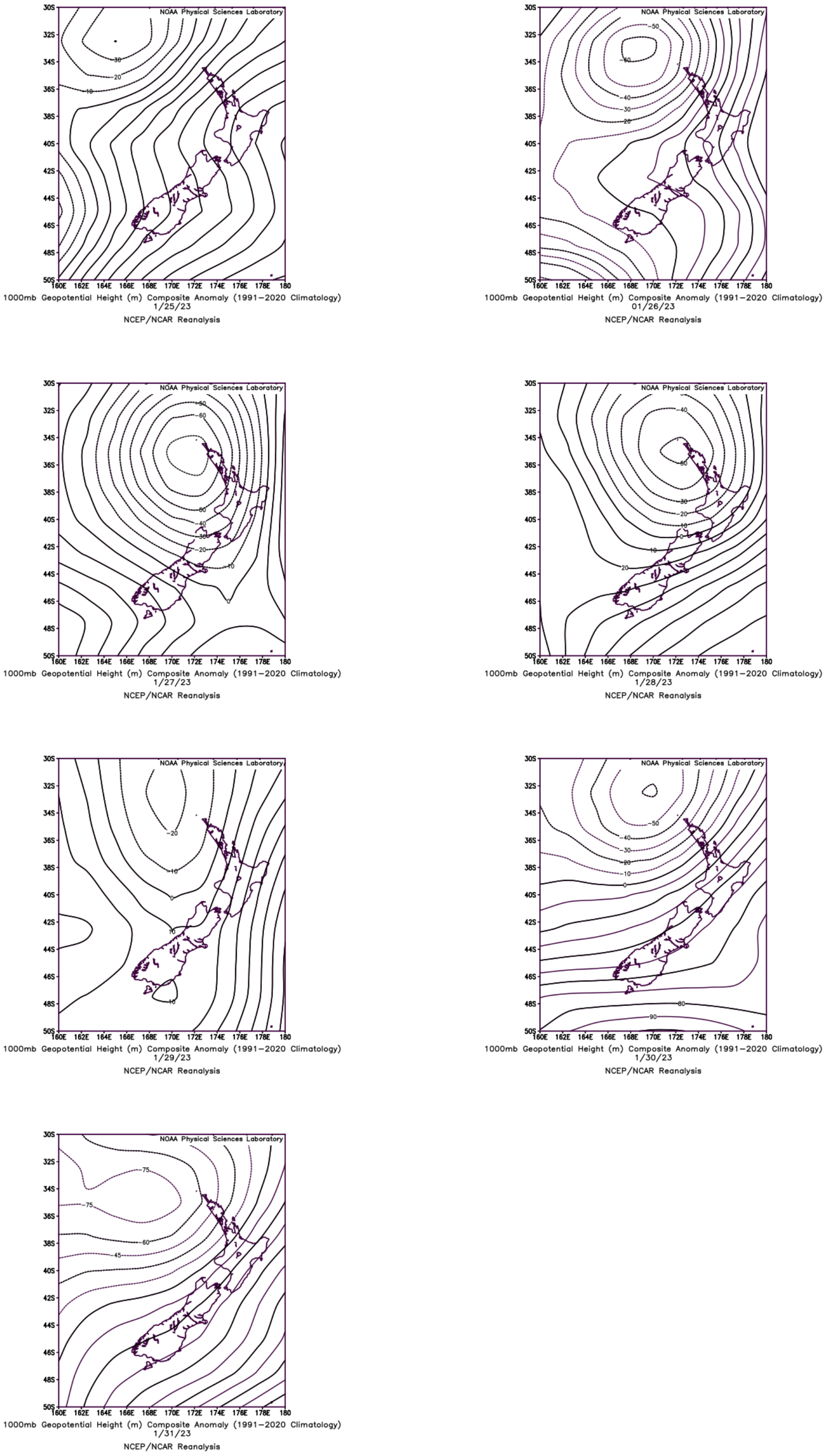


Figure A4.4. Progression of daily synoptic weather patterns for New Zealand during the 26 January – 1 February 2023 period when a significant rainfall event occurred for Auckland during the Anniversary Weekend. The patterns show near surface geopotential height at the 1000hPa level (z1000) as a close approximation for mean sea level pressure patterns. Plots use NCEP1 reanalysis data and are courtesy of NOAA Physical Sciences Laboratory plotting tools at https://psl.noaa.gov/data/composites/day/.

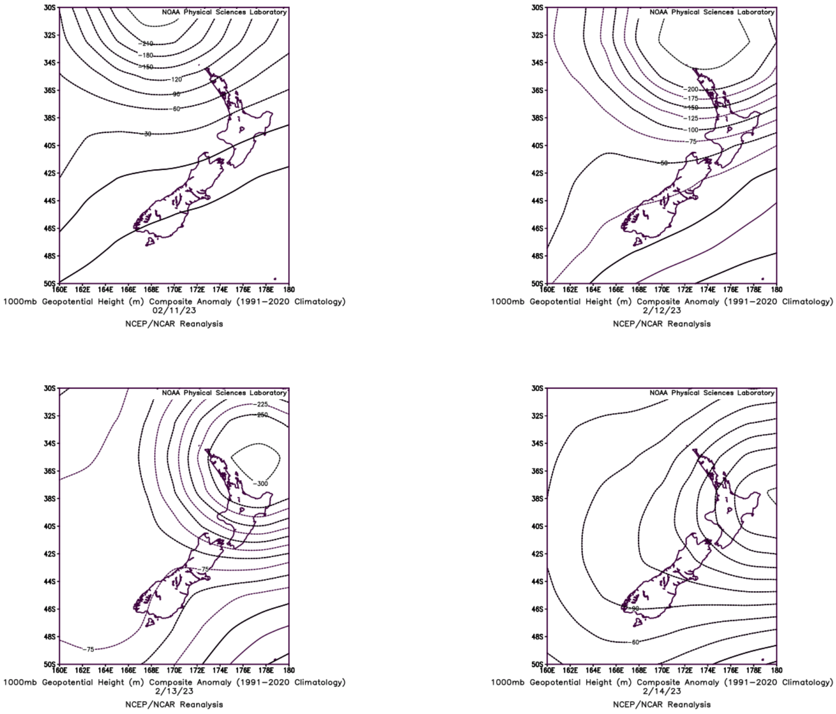


Figure A4.5. Progression of daily synoptic weather patterns for New Zealand during the 11 – 14 2023 period when a significant rainfall event occurred for Auckland associated with ex tropical cyclone Gabrielle. The patterns show near surface geopotential height at the 1000hPa level (z1000) as a close approximation for mean sea level pressure patterns. Plots use NCEP1 reanalysis data and are courtesy of NOAA Physical Sciences Laboratory plotting tools at https://psl.noaa.gov/data/composites/day/.

Find out more:
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