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Trends in Hydrology and Water Resources

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Waikato REGIONAL COUNCIL Te Kaunihera ā Rohe o Waikato

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Disclaimer

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Executive Summary

This report presents an analysis of hydrological data in the Waikato region as part of the State of Environment (SOE) reporting programme. The environmental data relating to hydrology and water resource utilisation held at the council was reviewed for availability and reliability and analysed to determine trends in the data.

Waikato Regional Council measures hydrological variables across the region and receives additional data from resource consent holders on how much water they use under their authorisations to take water. Much of this dataset is available to the public in a timely manner and is used to understand how wet or dry current conditions are, for example to assess river levels and flows in relation to floods or low flow conditions when water takes are restricted. However, State of Environment reporting is a more comprehensive way to communicate the dataset, which allows the analysis of long-term patterns in the data.

A further issue is that a comprehensive analysis of the region's water allocation and use data has never previously been undertaken. As pressure increases on the region's water resources, it is important to understand historic water allocation and use patterns.

The hydrological variables evaluated in this report include rainfall, evapotranspiration, groundwater levels, streamflow and water use. The analysis and reporting focused on the low flow aspects of hydrology as this is more relevant to water resource management. Due to the breadth of the hydrological dataset, the nature of the analysis is exploratory, with the intent to find and describe patterns.

For rainfall and evapotranspiration, a spatially complete interpolated dataset was used to place recent conditions in a historical context from the 1960s until present. Annual streamflow and groundwater levels were assessed to determine any direction of trend and confidence in the assessed trends for the most recent climate normal period of 1991 to 2020. Water use records are not available for all authorisations, therefore a large exercise in estimating water use based on available records was undertaken. The result of this analysis is a dataset of water use that extends from 1968 to 2021.

The data shows an overall declining trend in annual rainfall since 1960, with each decade being drier than the previous one, and a corresponding increase in potential evapotranspiration from the 1990s to 2020. This has resulted in a reduction in mean river flows and allocable flow, particularly during summer. Although groundwater resources at regional level have a similar proportion of declines and increases in groundwater level, localised groundwater level depletions were detected and overall, where detected there is a stronger confidence in the decreases in groundwater level trends.

The report emphasises the increasing pressure on the water resource system as water availability decreases, while the demand for water increases due to population and industrial growth. There has been a decline in annual low flow at most sites which reflects the combined effect of climate and increased water usage. The Tongariro Power Scheme's cross-regional import of water from the Wanganui River has increased the mean flow of the Waikato River, but many major catchments are now nearly fully or over-allocated, making prioritisation and competing water uses critical management issues. The report discusses the implications of these trends on water quality, instream values, and wetland values, emphasizing the need for readiness for regional policy direction in anticipation of increasing pressures.

This report represents the first formal systematic attempt to estimate water use for the Waikato region. While substantial progress has been made, there is large potential for improvement in the methodology. There are a number of unexplained patterns in the analysed timeseries. There is value in further investigations to improve understanding of climatic and hydrological processes, and possibly identifying further data issues and resolutions. The underlying dataset

that was analysed for this report is large and issues with data quality were identified during the process despite Council's quality assurance processes. This highlights a benefit of this work, data issues have been identified and resolved, and other avenues of review recommended, for example reviewing details of older consents to confirm details.

1 Introduction

Waikato Regional Council (WRC) runs programmes to measure hydrological variables at key monitoring locations and receives data from consent holders[1]. The collected information is used internally to provide guidance for evidence-driven sustainable management of the regional freshwater resource. Moreover, the council is obligated to monitor, record and report on the state of the regional environment under the Resource Management Act (1991), section 35. Therefore, all environmental data collected is considered public knowledge and is available upon request[2]. The majority of this data is presented electronically through websites, such as the Waikato Data Portal[3], Environmental Data Hub[4] and LAWA[5], and is available close to real-time.

Although data is available to the public through various channels, State of Environment (SOE) reporting is a more comprehensive way to communicate regional environmental datasets. It enables highlighting significant patterns in the data and provides narratives from the scientists' perspective. WRC science has decided to publish a series of SOE reports that cover a variety of environmental topics based on the council's accumulated data. This report is part of the series and provides a narrative for the available water quantity data. This hydrology SOE report serves as a starting point to explore valuable data-driven regional knowledge.

This report examines data associated with the regional hydrology in the Waikato Region and human influence on the regional hydrology. Changes in the hydrology impact ecosystems and water resource availability. To manage water resources, it is necessary to understand past, present, and future water availability, which is becoming increasingly important due to the effects of climate variation and change on various components of the hydrological cycle.

1.1 Objective and Research questions

The main objective for publishing the SOE report series is to "show and tell" the available dataset kept in the council database. The more specific objectives of this report can be described in the form of following research questions:

1. What are the key components of the hydrological cycle in the Waikato region, including natural pathways of water and human influences on water movement?
2. What datasets are available to detect changes in the hydrological cycle in the region?
3. Are there any significant patterns in the hydrological variables that the community should be aware of, and if so, what is the explanation for these patterns?
4. Are there any explainable causal relationships among the hydrological variables?
5. What is the uncertainty and reliability of the data used, and what are the limitations of the interpretations presented in this report? Can the findings suggest future research directions?

Overall, the goal of this report is to identify patterns that will stimulate further targeted research in the region, as well as contribute to discussions on water resource management.

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[1] The list of variables is given in section 3.1.

[2] There are some commercially sensitive information submitted by consent holders that require pre-approval by submitters before dissemination; but the hydrological variables measured by the council can be obtained freely by the public community.

[3] Waikato Data Portal website https://data-waikatolass.opendata.arcgis.com/

[4] Waikato Environmental Data Hub webpage https://www.waikatoregion.govt.nz/environment/envirohub/

[5] Land Air Water Aotearoa (LAWA) website https://www.lawa.org.nz/explore-data/waikato-region/

1.2 Scope

This report outlines trends in both the supply (rainfall, groundwater level, and streamflow) and demand (water use) of freshwater resources in the Waikato Region. The hydrological variables evaluated in this report include rainfall, evapotranspiration, groundwater level, water use, and stream flow. While this report presents an overall trend in annual hydrology, it emphasises low flow hydrology over high (storm) flows as it is more relevant to water usage.

This SOE report is exploratory in nature and aims to uncover meaningful patterns in the collected data. The report provides a narrative of the available data and demonstrates some examples of how the data can be analysed. However, the analysis presented in this report is not exhaustive, and other analyses can be conducted to explore the dataset further.

All datasets had varying degrees of uncertainties and limitations, but the water use data had a much higher level of uncertainty and anomalous behaviour. Although efforts were made to correct the data within the project's timeframe, comprehensive data cleaning and correction could not be undertaken at this stage. Interpretations of the datasets, along with their limitations and caveats, are discussed wherever relevant in the body of the report and are summarised in section 5.3 and 5.1.

2 Study Area Description

2.1 Waikato Region

2.1.1 Population and Economy Growth

The Waikato region is one of the 16 regions of New Zealand and is home to approximately 10% of the country's population. The population of the region is growing at a similar rate to the national average, although growth has been faster in the Waikato and Waipa Districts and Hamilton City (Table 1). Agriculture has been the primary focus of the region's economy, but there are other large-scale industry sectors such as mining and food processing factories (Infometrics 2022). The iron sand mines on the West Coast of the region are an example of heavy industry in the region. The demand for water in the region has increased due to growth in both population and industry.

Table 1. Population of territorial authority districts[6]. The growth rate was evaluated as compound growth rate[7].

Year	1996	2001	2006	2011	2016	2021	Growth (% per decade)
Waikato District	52,000	53,700	59,500	65,400	72,600	86,700	23%
Hamilton City	113,500	121,200	134,800	145,600	160,800	179,100	20%
Waipa District	38,400	40,000	43,700	47,700	52,200	59,800	19%
Thames-Coromandel District	25,400	25,800	26,700	27,200	29,100	33,300	11%
Taupō District	31,600	32,500	33,400	34,300	36,800	41,000	11%
Matamata-Piako District	30,300	30,300	31,200	32,400	34,200	36,800	8%
Hauraki District	18,550	18,000	18,300	18,650	19,700	22,000	7%
Otorohanga District	9,960	9,590	9,310	9,500	10,150	10,800	3%
South Waikato District	25,800	24,200	23,200	23,300	24,100	25,600	0%
Waitomo District	10,000	9,780	9,680	9,590	9,580	9,710	-1%
Waikato Region	358,800	368,100	388,700	412,400	442,100	500,100	14%
New Zealand	3,732,000	3,857,700	4,133,900	4,350,700	4,609,400	5,090,200	13%

[6] The data was obtained from the tool called Infoshare, which is provided by Statistics New Zealand. https://www.stats.govt.nz/

[7] The decade rate was calculated using this formula. Decade growth rate = (Population in 2021 – population in 1996)$^{(10/25)}$ – 1.

The agricultural sector, particularly dairy farming, is a major industry in the region. At the national level, dairy cattle headcounts have been increasing, while the numbers of other stock types such as beef cattle, sheep, and deer have been steadily decreasing. The Waikato region has followed the same trend as the national average, but the growth rate of dairy cattle has been slower than the national average. The numbers of beef cattle, sheep, and deer have been decreasing at a similar rate to the national average. This implies that the Waikato region's water demand is increasing, particularly for the dairy industry.

Table 2. Change in livestock count of the region[8]. Counts are in thousands. Rounded to the nearest fifty thousand.

Area	Livestock	1991	1996	2001	2006	2011	2016	2021	Growth (% per decade)
Waikato	**Dairy Cattle**	1,250	1,550	..	1,750	1,800	1,850	1,800	13%
	Beef Cattle	750	750	..	650	500	500	600	-7%
	Sheep	4,000	3,350	..	2,700	1,850	1,650	1,550	-27%
	Deer	150	150	..	150	100	50	50	-26%
New Zealand	**Dairy Cattle**	3,450	4,150	..	5,150	6,150	6,600	6,200	22%
	Beef Cattle	4,650	4,850	..	4,450	3,850	3,550	3,950	-5%
	Sheep	55,150	47,400	..	40,100	31,150	27,600	25,750	-22%
	Deer	1,150	1,200	..	1,600	1,100	850	800	-10%

2.1.2 Hydrology Overview

The Waikato Region has a temperate, with the typical pattern of dry summers and wet winters. Post-tropical cyclones can affect the Coromandel Peninsula, which is located at the northeastern end of the region, resulting in extreme rainfalls. The orographic effect plays an important role in the spatial distribution of rainfall, with lower rainfall in low-altitude areas and higher rainfall in high-altitude areas. In the Waikato region, rainfall is the predominant form of precipitation, with occasional hailstorms and frequent fogs reported throughout the area (Chappell 2013). Snowfall is generally limited to high-altitude zones south of Lake Taupō. We have chosen to use the term rainfall as a replacement for precipitation throughout this report.

The spatial pattern of annual rainfall for the latest climate normal[9] period (1991-2020) is shown in Figure 1. The influence of topography on the rainfall pattern is evident, with lower annual rainfall on the Hauraki plains and in the Hamilton and Reporoa basins, and higher rainfall in the western ranges, Coromandel, and the mountainous areas of the Central Plateau (Chappell 2013).

[8] The data was obtained from the tool called Infoshare, which is provided by Statistics New Zealand. https://www.stats.govt.nz/
[9] A climate normal is the average condition computed for a 30-year period (World Meteorological Organization 2017).

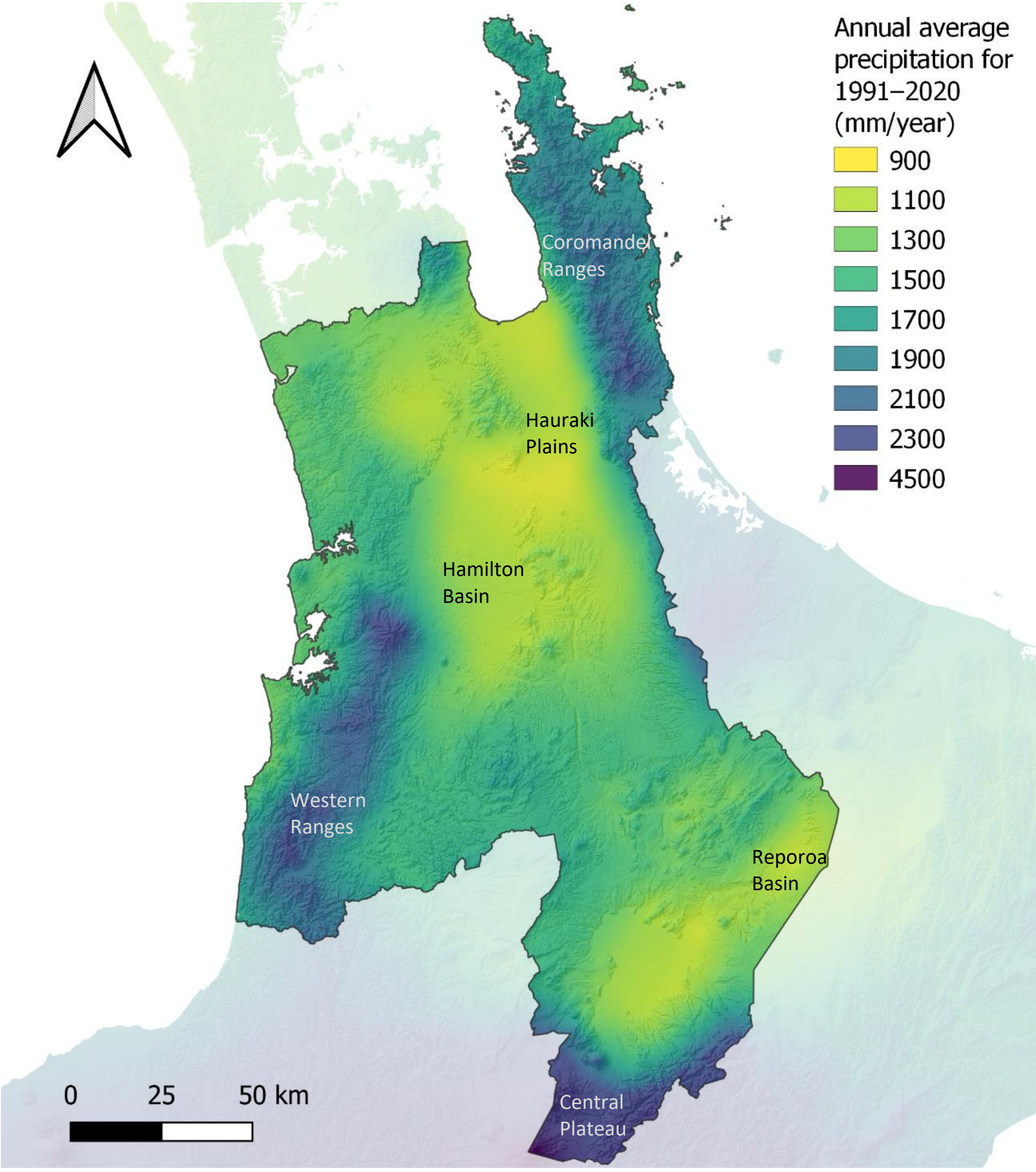


Figure 1. Estimated rainfall for the Waikato region on a 0.05° latitude/longitude grid (approximately 5km) for the latest climate normal period (1991–2020). Data source: VCSN.

The Waikato Region accounts for approximately 27 billion cubic metres (6.1%) of New Zealand's surface water flow (Collins et al., 2015). While in 2014, the estimated volume of groundwater held in the Waikato Region's aquifers was 35 billion cubic metres, the second-highest regional volume (Moreau and Bekele, 2015). The region contains approximately 40,000 kilometres of river stream length out of New Zealand's more than 425,000 kilometres (Snelder and Biggs, 2002, v2.5). The Waikato River, New Zealand's longest river, flows for 425 kilometres from the slopes of Mount Ruapehu north-west to the Tasman Sea at Port Waikato. Lake Taupō is the largest lake in New Zealand, covering an area of approximately 616 square kilometres.

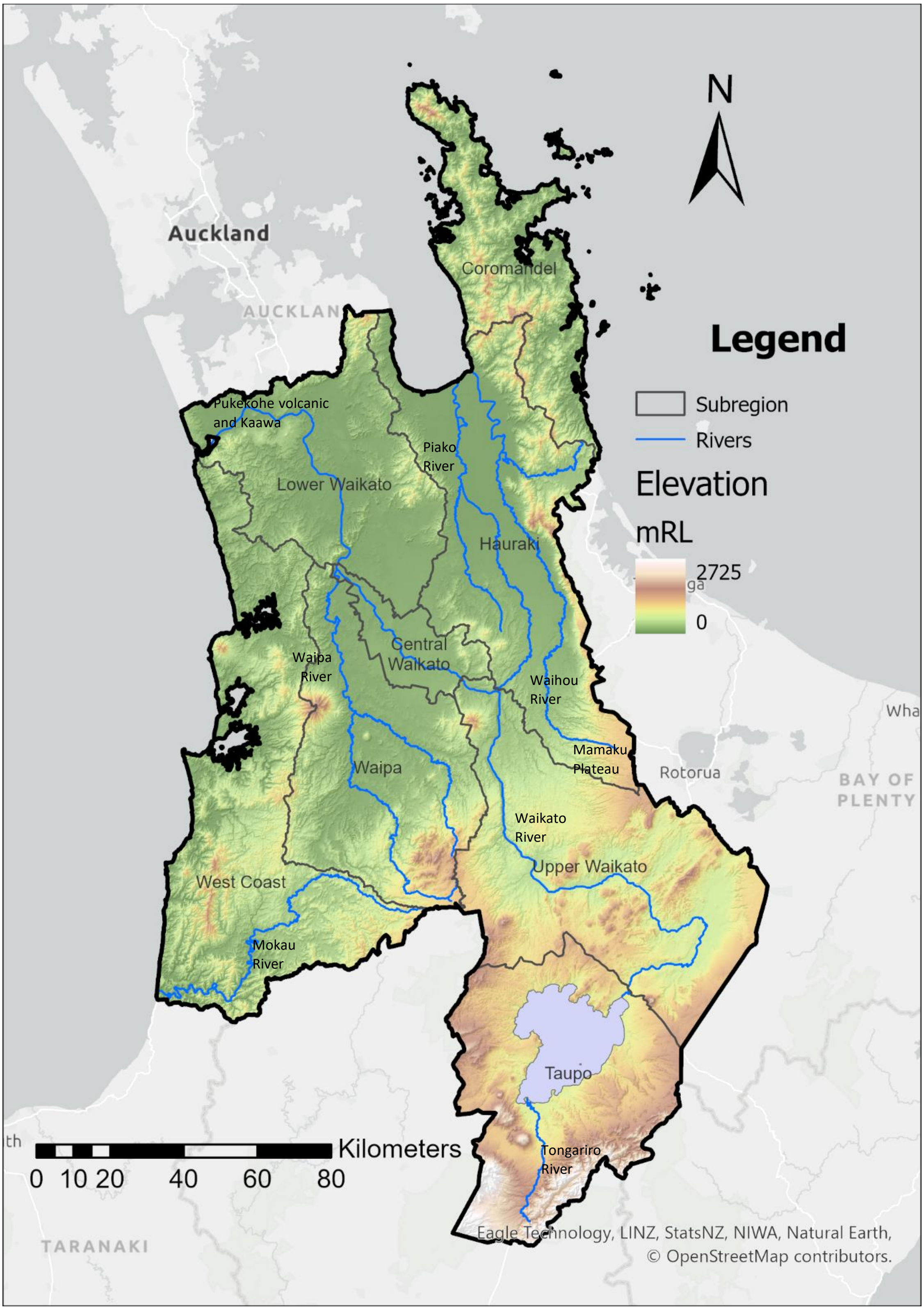


Figure 2. Elevation and subregions of the Waikato Region.

There are four major river catchments in the region that discharge to the sea: Waikato River, Piako River, Waihou River, and Mokau River. These four river catchments cover 79% of the region's land area (see Table 3).

The Waikato River catchment is the largest of all, covering the Upper, Central, and Lower Waikato and Waipa subregions, as shown in Figure 2. Lake Taupō receives inflows from many tributary catchments around it, with the Tongariro River being the largest contributing tributary flowing from the south (see Figure 2). The Tongariro River is a modified waterbody with additional flow introduced by cross-regional aqueduct and pipe network that collect and transport runoff from Mount Tongariro outside of the region. This hydrological modification is called the Tongariro Power Scheme (TPS), and its objective is to increase the water available for hydropower generation in the Tongariro catchment as well as the downstream Upper Waikato subregion. Further details about the scheme and the resulting hydrological modification are provided in Section 2.2.1.

Table 3. Catchment Areas of major River catchments.

Catchment Description	Area (km^2)	Area (% of region)
Waikato River at mouth	14,460	59%
Waihou River at mouth	1,980	8%
Piako River at mouth	1,480	6%
Mokau River at mouth	1,440	6%
Total	**19,350**	**79%**
Waikato Region	24,580	100%

Lake Taupō and the Upper Waikato catchments are sources of electrical power for the national grid. The Lake Taupō zone is geologically active and has large-scale geothermal power plants. The Waikato River begins at the outlet of Lake Taupō, where a control gate regulates the lake level and generates power. From there, the river flows through the Upper Waikato subregion, collecting further inflows from tributaries. A series of eight hydro-dams were constructed along the mainstem of the Waikato River in the Upper Waikato subregion to provide power for the national grid. The Upper Waikato subregion is also home to many small- and large-scale agricultural activities, as well as large industrial centres in Tokoroa. The generation of power and other abstractive uses pose challenges in managing competing demands for instream versus out-of-stream uses of the water resource.

The Waipa and Central Waikato subregions are collectively known as the Hamilton Basin (see for example Lowe 2010) and are home to many small-scale farms and industries. Industries and farms in the area rely on groundwater and run-of-river water. The area also has vegetable and fruit growers, as well as small-scale dairy farmers. Major population centres such as Hamilton, Cambridge, and Te Awamutu are also major users of water. Ranges that enclose the Hamilton Basin (e.g. Hakiramata, Taupiri) have a narrow outlet for the Waikato River at Taupiri. This creates a low-energy environment upstream where alluvial plains of pumice, rhyolite and other material have formed during depositional periods as recently as 17,000 years ago. Since then, the Waikato River has been downcutting through these deposits. Low-lying areas in the basin are often characterised by bogs and swamps, requiring artificial drain network.

The Lower Waikato subregion is characterised by shallow peat lakes and the internationally significant RAMSAR Whangamarino wetland, while a series of volcanic mountains define its northern boundary. The fractured basalt volcanic domes and geology of the area offer the potential for large groundwater yields. The northern end of the subregion is where groundwater is most utilised in the region. The Kaawa aquifer, which provides very deep and clean groundwater, is also located in this subregion. Recently, many kiwifruit farms have established in the area, and the population is rapidly growing, leading to urbanisation. A challenge in this subregion is the competing use of productive lands versus urban areas. The Waikato River is close to full allocation, and this imposes a question of whether the provision by the Waikato River allocation limit can sustain the long-term strategic growth of the population and urbanisation. Auckland sources a portion of its municipal demand from the Waikato River in this subregion, representing a cross-regional export of water that is discussed in section 2.2.2 of this report.

The Hauraki subregion contains two main rivers that discharge into the Firth of Thames, a coastal waterbody shared with the Auckland region. The Piako River catchment covers the western half of the Hauraki subregion, while the Waihou River catchment covers the eastern half. The Piako River catchment has low topography and low specific discharge compared to other parts of the region, leading to frequent restrictions for water users due to low flow alarms. The allocation status of the Piako River catchment is over the allocation limit[10], and the council has declared its intention to reduce the allocation level below the allocation limit by 2031. On the other hand, the Waihou River has sustained baseflow due to the large recharge in the Mamaku plateau located at the southeastern end of the catchment. Dairy farming is the key industry in this subregion, and the current management issue is nutrient discharge into the Firth of Thames and the lower reaches of the two rivers, which can cause algal blooms and depletion of oxygen, leading to massive fish kills. The Kopuatai peat dome is another internationally significant wetland that receives attention from the council and other government agencies.

The Coromandel subregion is characterised by its mountainous terrain and coastal villages, with primary sources of drinking water being rain harvested water and groundwater. The catchment areas of the rivers in this subregion are smaller and there is limited storage in the soil, leading to flashy river flows with a fast response to storm events such as Cyclone Gabrielle in February 2023. As discussed in later sections, the Coromandel subregion receives a large amount of rainfall annually and is frequently affected by post-tropical cyclones. As a result, the stream habitat has adapted to these significant variations in flow.

The West Coast is another mountainous subregion that has several smaller streams and river catchments. The largest of these is the Mokau River, which is depicted in Figure 2. A unique feature of this area is its karst topography, which is the result of marine deposits in the stratigraphic sequence. The population and farming density are lower than in other parts of the region, resulting in generally lower allocation pressure on the water bodies (see section 4.1.2).

2.1.3 Water allocation principles and issues

The protection of instream values is the basis to the water allocation practice in the region. Eels and migratory fish reside in all rivers, highlighting the importance of providing fish passages to maintain continuous habitats. In addition, in-river trout fishing is a significant factor. The allocation scheme is also influenced by a chain of nationally significant hydropower schemes in the Waikato River. Due to the boggy nature of the Hamilton Basin and Hauraki Plains, mudfish protection issues often arise in urban development situations.

To protect the instream values, the Waikato region has established minimum flows, and primary and secondary allocable flows for approximately 350 major catchments. The minimum flow represents the flow that the regional plan aims to keep in the stream or river. When river/stream flows fall below the minimum flow level, water users are required to reduce or cease water take[11]. The level of restriction imposed is determined by the purpose of the water take and the allocation pressure in the catchment. Allocable flows are divided into two allocation bands: primary and secondary allocable flows. Sensitive river bodies only have primary allocable flow, while rivers with greater resilience receive discretionary additional secondary allocation with more stringent water take restrictions. Key allocation pressure thresholds were defined from these two allocable flow levels: 70% of primary allocable flow, primary allocable flow, and secondary allocable flow. As the cumulative allocation grows past these thresholds, more and more stringent rules are applied when considering water take consent applications. The Waikato region accounts for and regulates allocation levels every month of the year, with January having the highest allocation and July the lowest. While allocation levels fluctuate throughout the year (as shown in Figure 32), the allocation limits defined as primary and secondary allocable flows remain constant. Further information about allocation pressures is presented in section 4.1.2.

When applying for a water take consent, water users must provide detailed information about the purpose of water use. This information is used to categorise how much water is used for

[10] Detailed discussion about allocation pressure is made in section 2.1.3.

[11] In the event of below-minimum low flow conditions, municipal water takes are mandated to reduce the intake by 15%. Other water takes in lightly allocated catchments are required to reduce the intake by 50%. For heavily allocated catchments, water extraction for purposes other than municipal and animal drinking takes must cease entirely. Water takes for human and animal drinking may continue even in these events.

each specific purpose in the region. Three levels of water use purpose categories have been defined and are expressed in the database, allowing for regional statistics to be prepared under these categories. The list of the categories is presented in Table 15 in the Glossary section.

The Waikato water allocation system considers groundwater takes as equivalent to surface water takes at most places. This is based on the basin aquifer morphology, where all recharge must emerge back up to the surface before discharging out of the basin. Typically, these basins have a gorge with a narrow neck that water flows through, and there are several major basin outlets that follow this pattern, such as Upper Waikato basin with an outlet at Karapiro, Waihi basin with an outlet at Karangakake, Hamilton basin with an outlet at Taupiri, and Mangatawhiri basin with an outlet at Mercer. As a result, groundwater takes from inland aquifers are included in the surface water allocation accounting, reflecting the conceptual understanding that these takes would ultimately lead to a reduction in surface water flow where the re-emergence occurs. In contrast, groundwater takes from coastal aquifers are not included in the surface water allocation accounting, where most groundwater flows directly to the sea without re-emerging to surface water bodies.

As a result, groundwater takes within inland aquifers are added in the surface water allocation accounting, reflecting the conceptual understanding that the groundwater takes would ultimately result in reduction in surface water body somewhere downstream. On contrary, groundwater takes from coastal aquifers that capture the groundwater flow to the sea without such re-emergence to surface water body are not added in the surface water allocation accounting.

Many catchments in the region are already and will soon be experiencing allocation issues. For example, the Waikato River is nearing its allocation limit. Once the catchment reaches full allocation status, any new applications for water take will be put in a waiting queue until some allocable flow is released from an expiring consent. This situation is particularly concerning because the three districts with the highest population growth rates are situated within the Waikato River catchment, which is already allocated up to 90% (Table 10). This imposes a rigid constraint on the region's growth, exacerbated by a climate trend that is diminishing water availability in the river. Additionally, there are other catchments where secondary allocable flow status has been exceeded, necessitating the implementation of clawbacks as outlined in the Regional Policy Statement by a specified target date. The implications of climate change and over-the-limit allocation status on allocation practices are further examined in section 5.3.2.

2.2 Cross-regional Flows

2.2.1 Tongariro Power Scheme - Cross-regional flows

The Tongariro Power Scheme (TPS) is a hydroelectricity project located at the southern end of the region (Figure 3). The scheme includes two primary diversions that take water from water bodies outside of the region and transfer it through a canal and tunnel system to generate electricity before draining into Lake Taupō. From there, the water flows down the Waikato River and is utilised for subsequent electricity generation before ultimately reaching the sea. The western diversion brings water from tributaries of the Whanganui catchment, while the eastern diversion brings water from tributaries of the Whangaehu, Rangitikei, and Tongariro catchments. These catchments are shown in Figure 3. The water captured by the scheme is used to generate electricity at two main points: Rangipo Power Station and Tokaanu Power Station, before it is discharged into Lake Taupō via the Tokaanu tailrace.

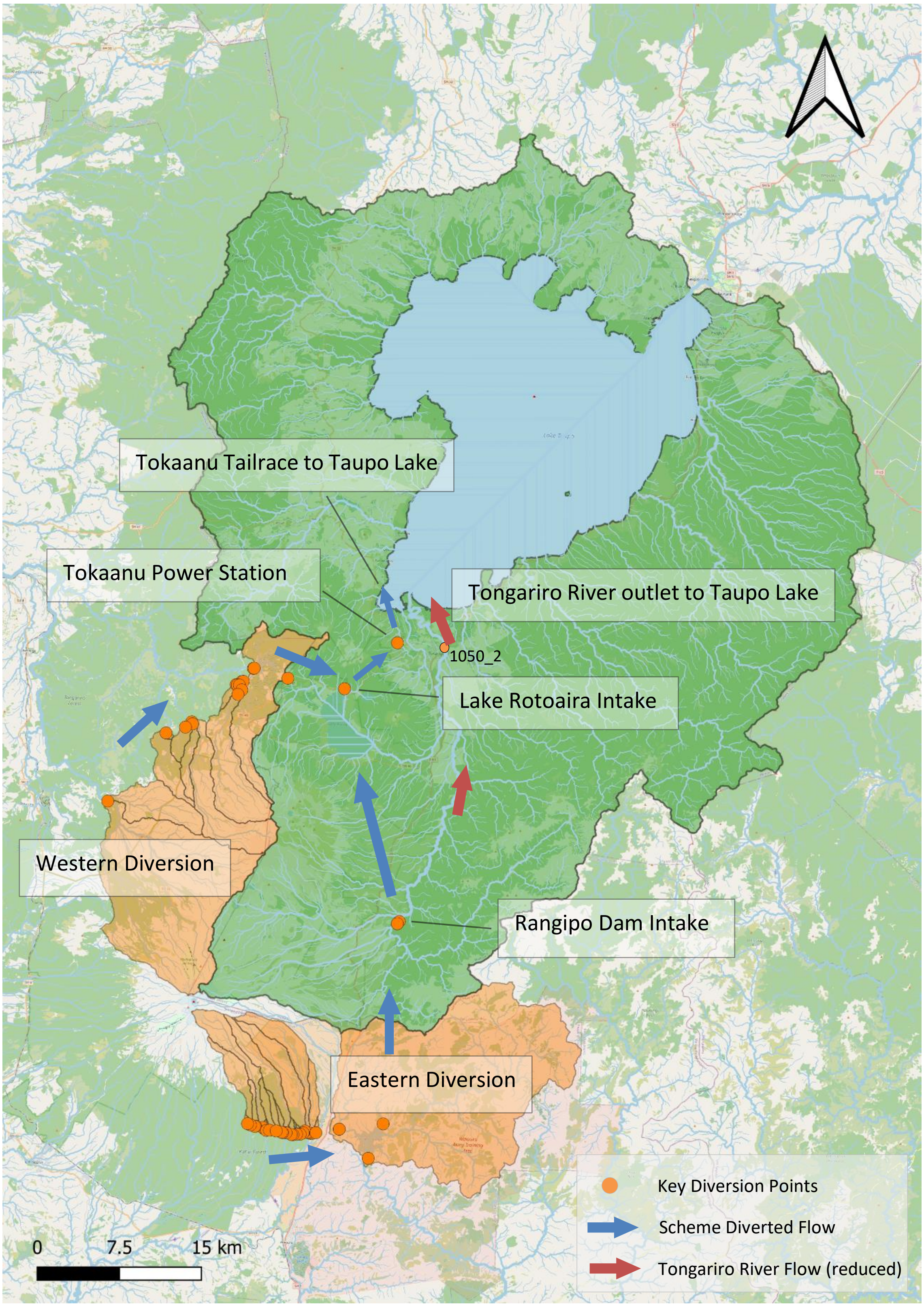


Figure 3. Tongariro Power Scheme catchments (orange polygon) and structures (orange dots). The natural catchment of Lake Taupō is shown in green. 1050_2 is the flow recorder at the outlet of the Tongariro River to Lake Taupō.

The total inflow from the Manawatu-Wanganui region is the sum of the eastern and western diversions[12]. A seasonal pattern is observed in the daily inflow time-series, as shown in Figure 4. The cross-regional inflow reaches its maximum in winter, peaking either in August or September, with a flow of up to approximately 50 m^3/s. The cross-regional inflow then declines to less than 5 m^3/s during summer. The long-term mean annual flow shows a slight downtrend, demonstrated by orange curve in Figure 5. The decline was faster during the 1990s, but the rate

[12] Genesis Energy, the operator of the Tongariro Power Scheme, provided the combined daily timestep data.

has slowed down since 2000. Similar trend was experienced by Annual Low Flow (ALF; see section 3.2.2) as well. The mean flow of the cross-regional inflow between 1991 and 2020 was 26.3 m^3/s. The range of seasonal fluctuation over the record has remained almost constant.

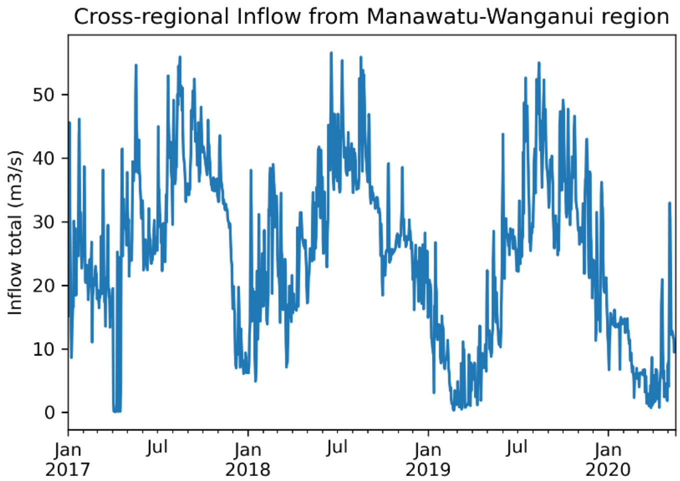


Figure 4. Cross-regional Daily inflow from Manawatu-Wanganui region. A snapshot of the recent three years. Seasonal fluctuation is visible.

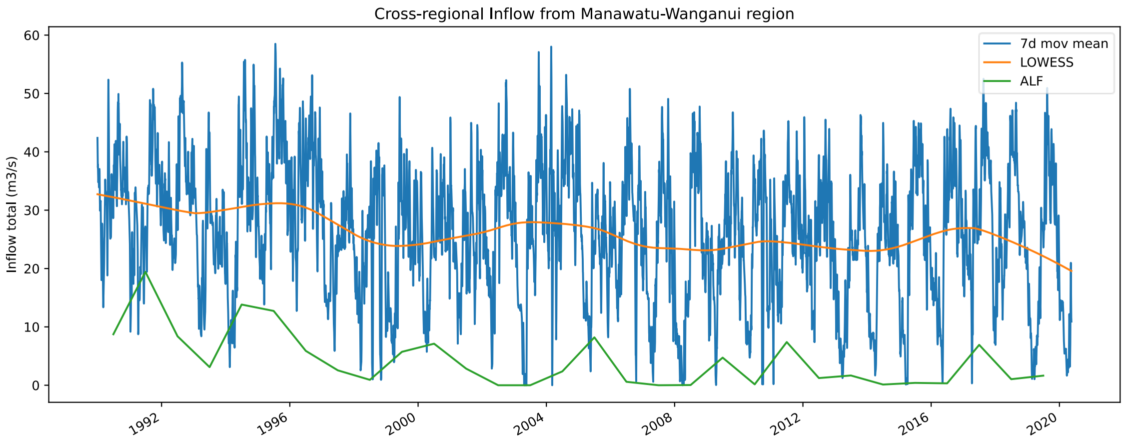


Figure 5. Long-term Trend in Cross-regional inflow. The LOWESS curve was fitted to the 7-day moving average (blue).

The implementation of the TPS diversion began in 1971 and resulted in significant downstream flow changes. The Tongariro River was impacted by both extra water from the cross-regional inflow and the reduction caused by diversion of some of its flow to Lake Rotoaira, which provides head and flow to the Tokaanu Power Station (Figure 3). While the extra water is introduced into the Tongariro River catchment through the Eastern diversion, the imported water, along with a portion of the natural river flow, is diverted to Lake Rotoaira at the Rangipo dam. Figure 6 shows the change in the river flow downstream of the Rangipo diversion. The hydrograph from 1971 and earlier shows natural recession periods after rainfall events. However, hints of unnatural recession periods started to appear in late 1972, probably due to the beginning of the Rangipo diversion (shown in the orange rectangle in Figure 6). The hydrograph shows that the unnatural flatlining of the minimum flow routinely occurs afterwards, as demonstrated in the examples from 1980 and 1994. The Tongariro River's management includes maintaining a minimum low flow. For example, the flow record in 1980 indicates a cut-off flow level of approximately 25 m^3/s. All but the minimum flow of 25 m^3/s was diverted to Lake Rotoaira. The implementation of the Tongariro Power Scheme diversion led to a reduction in the annual mean flow of the Tongariro River from 53.2 m^3/s to 31.6 m^3/s, a drop of approximately 20 m^3/s (Figure 7).

Despite the reduction in flow in the Tongariro River, the TPS has increased the downstream flow of water bodies by introducing additional water into the region. This increase in outflows from the Taupō Lake outlet is demonstrated in Figure 8 and Figure 9. The year of change was 1972, and from this year, shifts in ALF and annual mean flow were evident. The grey vertical lines in the figures indicate the timing of the Taupo Control Gate and TPS commencements, while the green horizontal lines represent the Q_5 levels of the respective time periods[13]. Q_5 before 1970 was 23.1 m^3/s and Q_5 after 1971 was 62.5 m^3/s, resulting in a shift of 39.4 m^3/s. This shift contrasts against the lack of Q_5 shift after Taupo Control Gate commencement. Therefore, net effect of the regional import of water is observed in a rise of the Q_5 by approximately 40 m^3/s at Taupo Control Gate (Figure 8). Similarly, the annual mean flow exhibited a comparable pattern, where TPS commencement caused a shift in annual mean flow of around 22.9 m^3/s (=150.5–127.6; Figure 9). Two observations can be made. Firstly, the effect of the TPS was more substantial for low flows than for mean flows. Secondly, the increase in annual mean flow in 1971 inferred from Figure 9, 22.9 m^3/s, is similar in magnitude to the measured mean annual flow rate of the import from outside the region, 26.3 m^3/s.

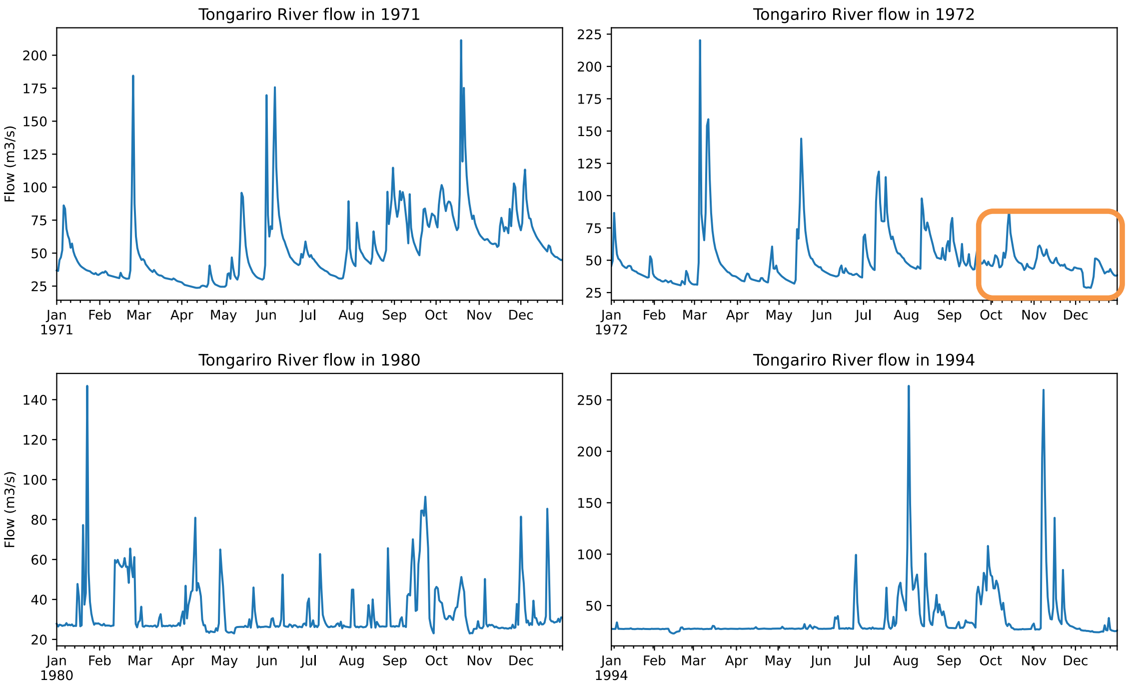


Figure 6. Natural and modified Tongariro River flow at long-term flow monitoring station, 1050_2[14]. See Figure 3 for the location of the flow monitoring station.

[13] Q_5 is a flow statistics called five-year return low flow derived from 7-day moving average flow. The specific method is described in section 3.2.2. Also see Glossary for the definition.

[14] The location ID can also be identified in Figure 16.

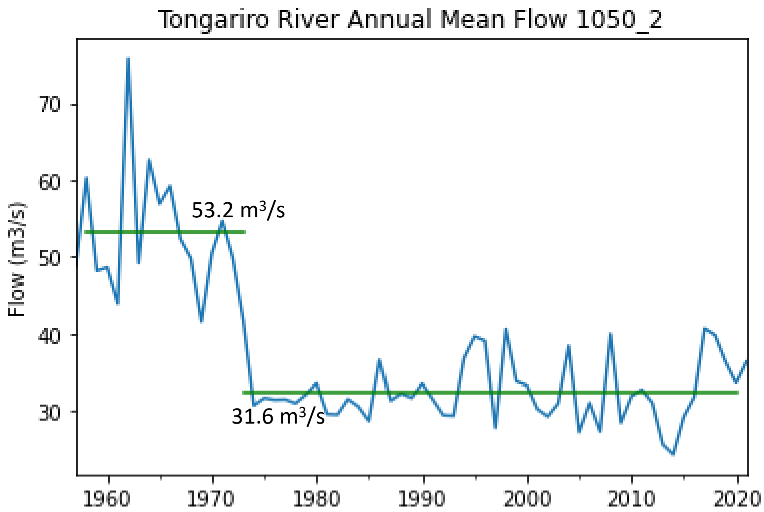


Figure 7. Long-term Annual Mean Flow of Tongariro River at 1050_2. Green lines are mean flows of the respective periods.

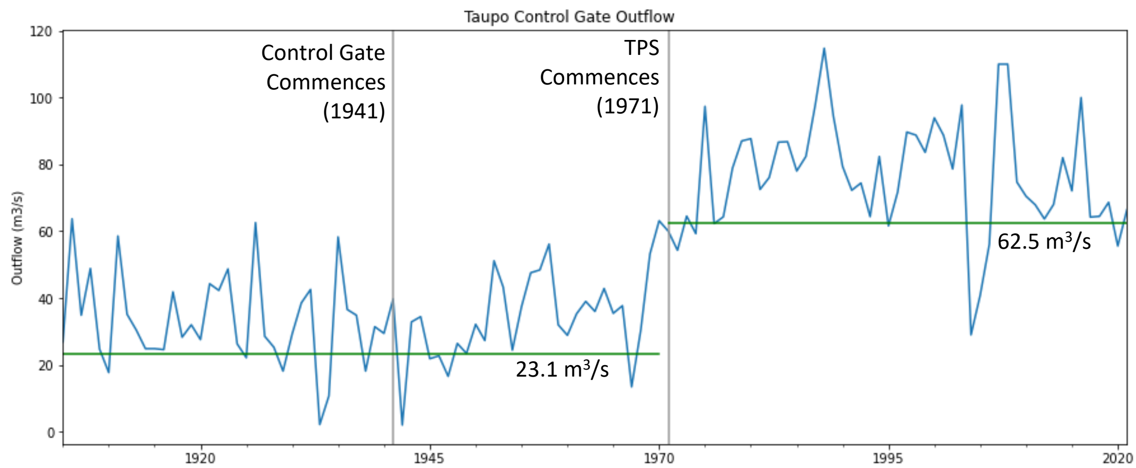


Figure 8. Long-term Annual Low Flow (ALF) at Taupō Control Gate Outflow (1131_127[15]). Green lines are estimated Q_5 of the respective periods.

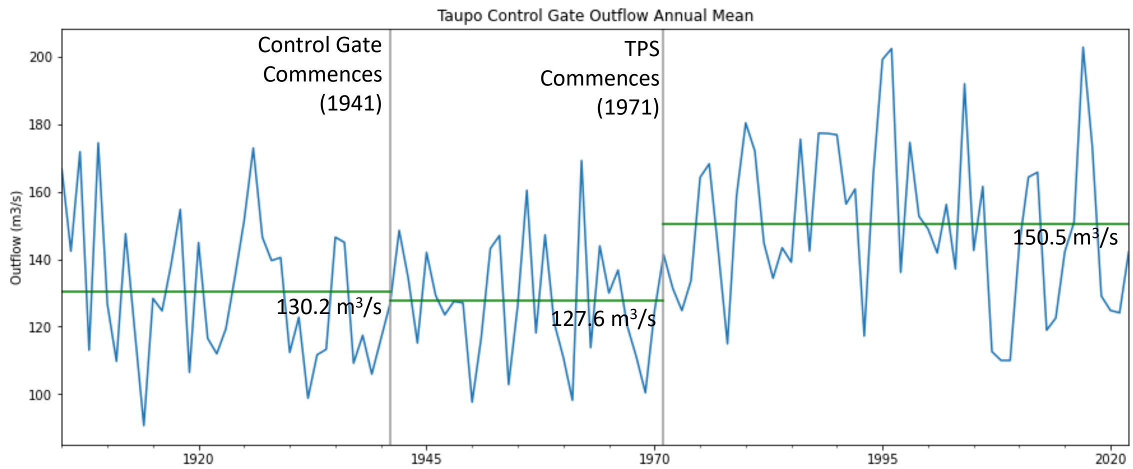


Figure 9. Shift of Annual Mean flow at Taupō Control Gate, an implication of TPS. Green lines are mean flows of the respective periods.

2.2.2 Auckland water supply - Watercare

Watercare is a publicly owned company that provides water and wastewater utility services to the Auckland region. The company is authorised to abstract up to 175,000 m^3/d (equivalent to 2 m^3/s) from the Waikato mainstem since 1997. This abstraction represents up to 11% of the

[15] The location ID can be identified in Figure 16.

allocable flow from the mainstem abstraction point alone, compared to the total allocable flow limit of the entire river catchment, which is currently 18.7 m^3/s. In addition to the mainstem abstraction, there are two other abstraction points within the catchment of the Waikato River, and more freshwater is abstracted from the dammed reservoirs built in the upstream tributaries (Mangatangi and Mangatawhiri). The storage capacities of these two reservoirs are 35.3 GL and 16.2 GL, respectively[16]. A summary of these water take activities is provided in Table 4.

Table 4. Watercare Abstraction Points within Waikato Region.

Water Source	Consent Number	Abstraction Location ID	Maximum Daily Rate (m^3/d)
Mangatangi	AUTH122099.01.02	3105_1	123,000
Mangatawhiri	AUTH123496.01.01	459_1	123,000
Waikato River	AUTH960089.01.05	1131_381	175,000

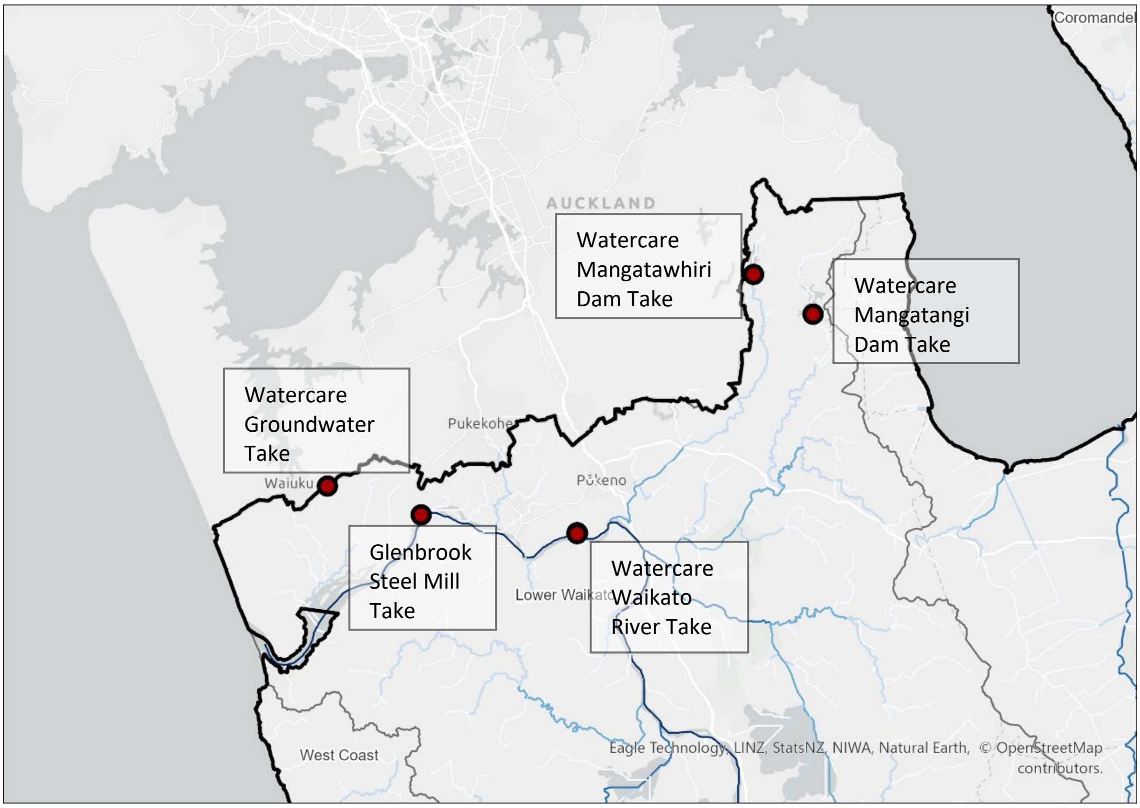


Figure 10. Water abstraction points for Auckland Export. Four out of the five locations are related to Watercare municipal supply.

The Waikato mainstem abstraction began in 1997, but electronic records of the water take time series are only available from 2014. Previous water take records were reported in annual reports and were not included in this analysis. Based on the record from 2014, Watercare's strategy has been to use the Waikato mainstem abstraction as a backup supply to its reservoirs, taking Waikato mainstem water when there is not enough water in the reservoirs (as shown in Figure 11). The top of the green area in Figure 11 represents the total daily export volume from the three sources of water, while the blue area represents the export from the Waikato mainstem abstraction point near Mercer.

In the years 2014, 2015, and 2016, the reservoirs experienced dry conditions, resulting in limited water production. As a result, the Waikato mainstem take was increased to its maximum consented rate to compensate for the shortfall. During the wetter years between 2017 and

16 Watercare's dams – supplying water to Auckland. Watercare Brochure. https://wslpwstoreprd.blob.core.windows.net/kentico-media-libraries-prod/watercarepublicweb/media/watercare-media-library/dams/water_supply_dams_auckland_brochure.pdf

2019, the pressure on the Waikato mainstem abstraction point was relieved, but the rate had to be increased again in the winter of 2019. The summer of 2020 was exceptionally dry, and although the abstraction rate at the mainstem decreased in the summer of 2022, the total export to Auckland remained within the range defined by two grey horizontal lines. Figure 11 displays the breakdown of the water supply source load, indicating that the Mangatangi reservoir supplied more water to Auckland than the Mangatawhiri reservoir.

It was identified at later stage of the project timeline that there were two freshwater export activities to the Auckland region that were not included in the analysis presented in Figure 11. Watercare takes groundwater in Waiuku, commenced in 2017 (AUTH135970.01.01), with a consented maximum rate of 1,680 m^3/d. This take was decided not to be added in the analysis as the size of the take was relatively small and did not significantly impact the overall picture presented in Figure 11. The second activity was the surface water take for the Glenbrook steel mill (AUTH141708.01.01) with a consented maximum rate of 30,000 m^3/d. This take was located near the mouth of the river in the tidal zone and was also relatively small compared to the municipal take for the Auckland region.

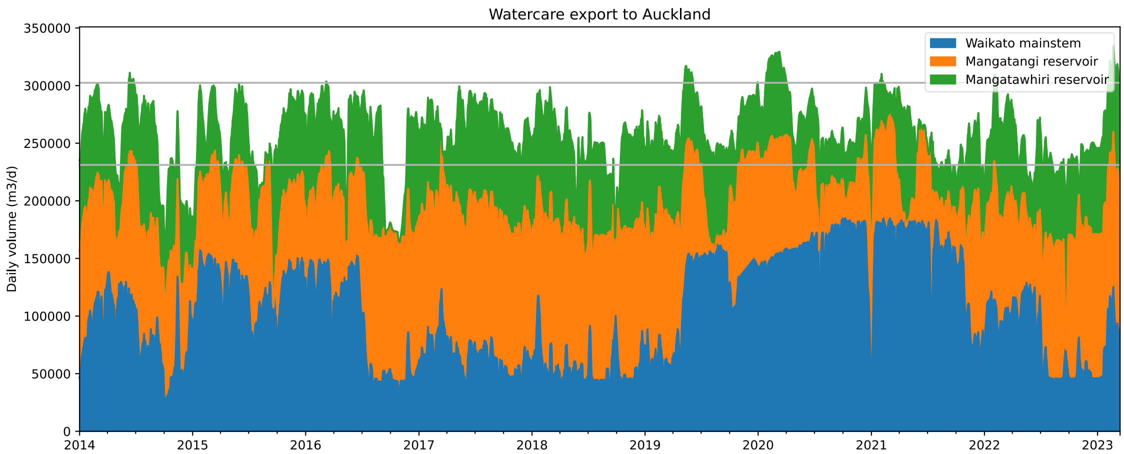


Figure 11. Watercare cross-regional export history 2014-2022. Legend identifies the sources of water supply.

2.2.3 Other shared water resources

While direct water imports and exports between regions are readily apparent, regional hydrology may also interact through shared aquifers, which can extend beyond surface water catchment boundaries. While it is difficult to accurately quantify the flux, technical discussions are underway towards better understanding and management of these shared resources. Due to the difficulty of quantifying the flux, the potential cross-regional fluxes through the shared aquifer were not included in the analyses of this report. The Pukekohe volcanic and Kaawa aquifers are shared with the Auckland region, while the Mamaku plateau ignimbrite aquifer is shared with the Bay of Plenty region. The locations of these aquifers can be found in Figure 2.

3 Data and Methodology

3.1 Data

The following section outlines the data that is available for hydrological analysis, including its duration, spatial coverage, and reliability.

3.1.1 Rainfall and PET

Rainfall is the primary hydrological variable that influences catchment hydrological processes. While the distribution of rainfall stations provides adequate spatial coverage of the region, the stations have varying operation periods and are situated at different elevations. Estimating the rainfall at a location between two weather stations is a common challenge in hydrology. The typical distance between weather stations is 20-30 km as shown in Figure 12.

The National Institute of Water and Atmospheric Research (NIWA) has developed the Virtual Climate Station Network (VCSN)[17], which provides an interpolated weather record product covering the entire New Zealand at 5km grid points (Macara *et al.* 2020). The VCSN provides daily records of key weather variables at each grid point, including rainfall, potential evapotranspiration (PET), maximum and minimum temperatures, and solar radiation. The virtual points at which the interpolated weather variables were estimated are interchangeably called VCSN agents and VCSN nodes in this report.

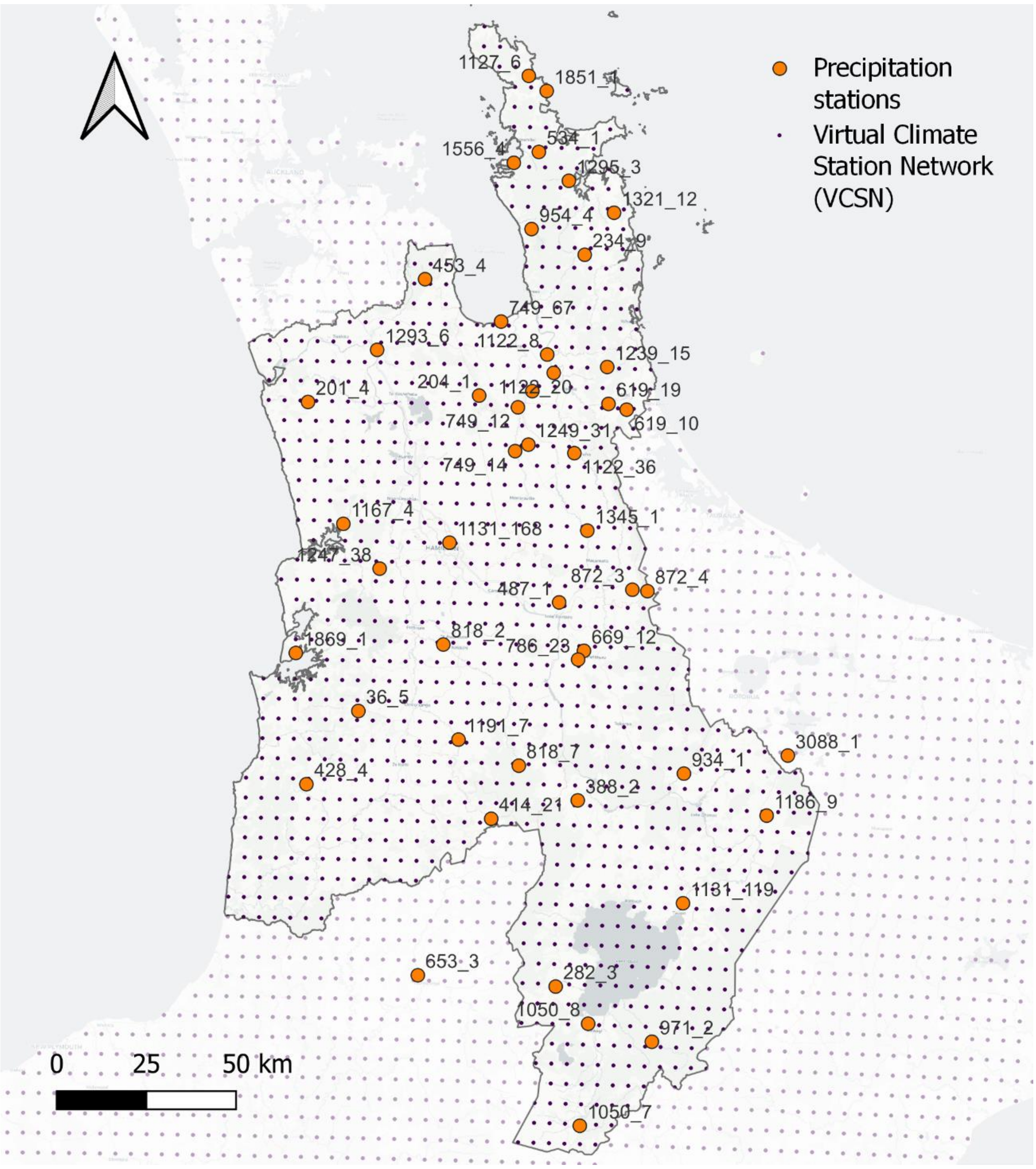


Figure 12. VCSN station network and rainfall stations in the Waikato region.

[17] https://niwa.co.nz/climate/our-services/virtual-climate-stations

The VCSN estimates meteorological values through spatial interpolation of observations (detailed method in Tait et al. (2006) and Tait and Woods (2007)). While there are some limitations to the interpolation products, as noted by Tait et al. (2012), the VCSN dataset offers several advantages, including a long and continuous record spanning back to 1960 and complete spatial coverage. Although the accuracy of absolute values predicted by the dataset may not always be reliable, its comprehensive spatial and temporal coverage facilitates trend analysis in both time and space. For instance, it enables reliable comparisons between different regions or decades at specific locations.

This report analysed the long-term trend of rainfall and PET records from VCSN. The PET record supplied by VCSN was used in this report (Macara et al. 2020). In New Zealand, potential evapotranspiration is calculated assuming grass cover and the term is used in place of reference crop evapotranspiration. For brevity, we refer to it as PET in this report.

3.1.2 Water takes and use

The water metering practice started to become prevalent in the decade of 2000-2010 in Waikato; larger water users were the first ones to adopt, and the adoption of the practice trickled to smaller users, so the adoption count has increased consistently since 2000 (Figure 13). It was common to find water metering records that cover only a part of the durations of consents, if not missing, even in modern consents post-2010. The coverage was generally better for recent, large water users; conversely, the data coverages were worse as size of the consent got smaller and the exercised dates were older.

The regional council's consents database has kept a record of the maximum allowed take rates since 1969, when the first consent was issued. This historic record was used to extrapolate the actual water use prior to 2000, when water metering was introduced (see section 4.1.2 for the description of the detailed method). For modern water take consents without water meters, the extrapolation method was also used to estimate the actual water use.

The allocation system adopted in the Waikato Regional Council tracks primarily the sums of net takes. Net take is a concept used when there is a return flow to the environment after the water was taken. The allocation account will then regard the net take, which is the difference between the average daily take rate at the abstraction point and the average return flow rate. For example, water taken for hydropower generation will be accounted zero net take because all water will be returned to the river. Another example is the municipal takes for cities and towns; they are accounted using net take concept because they return water to rivers after treatment at sewage treatment plants. The consent record system (the electronic accounting system) will record and account the net take components of the water takes, which are the difference between the take rates and return flow rates.

A consequence of this way of allocation record keeping was that some water take rates reported by water meters appeared larger than the maximum consented rates. The water meters report back what was taken at the abstraction point. The data about the return flows were not reported back to the council thoroughly as water takes. In this report, when actual water takes were assessed, consideration on return flow was not made. Not including return flows in actual water take analysis is a shortcoming impacting all analysis based on actual water take data from water meters in this report. The discussed impact of the water takes on the stream flows are mostly likely over-estimates, especially where there are large municipal takes in the catchment.

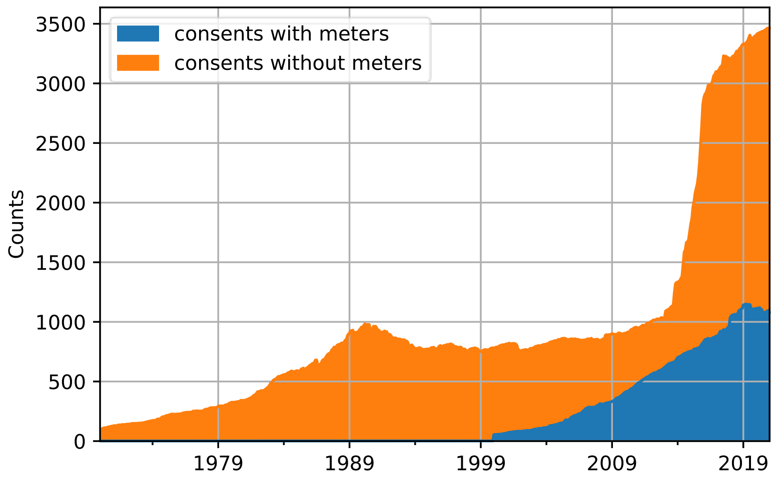


Figure 13. Number of Consents with and without water meters.

There is another uncertainty around the actual water take data. These are all submitted data from consent holders. Although efforts were spent on spotting and removing anomalous behaviours in the data, authors could not assure the quality of the actual water take dataset. Some of obviously erroneous behaviours in the data include:

- Water meter data with value exceeding 100 times the consented maximum take rate;
- Sudden spikes or steps in values both in positive and negative directions; spikes could be results of noises in telemetry transmission network or changes in reported units (L/d vs m^3/d); and
- A gap in data followed by a large value; the large value could be the accumulated value over the period of the gap. This typically happened when meter reading was not reported for prolonged period and a reading was made and reported at the end of the period.

Although these poses huge uncertainty in the used dataset, the cleaning of these erroneous water meter data was kept out from the scope of this SOE report project, because of the time constraints allocated to the project.

3.1.3 Groundwater Level

There were 1,702 bores that had at least one groundwater (GW) level measurement. Among these, 327 bores had records with duration equal to or greater than 15 years. The distribution of bores with long-term records are evenly distributed across the region because most of the long-term groundwater monitoring sites are maintained by the council – council staff visit these monitoring sites regularly to measure the water levels.

Trend analysis was carried out over the recent climate normal period of 1991–2020 and the bores with data spanning less than 30 years or record were not included in the trend analysis.

Groundwater levels experiences seasonal fluctuation and examples of the intra-annual fluctuations can be seen in the long-term data. Median intra-annual fluctuation was 0.9m. There were locations where the intra-annual fluctuation was as little as 0.2m. There were bores where the intra-annual level fluctuation was 16m (Figure 15). All regional bores with a data frequency greater than 4 records per year were included in creating the cumulative frequency plot in Figure 15. For each included bore, the series of annual fluctuations were calculated by subtracting the minimum level from the maximum level of each year. For instance, a bore with 16 years of high-frequency level data would have yielded 16 annual fluctuation values. All annual fluctuation values from all bores were collected, and the cumulative frequency plot was generated to illustrate the distribution of the region's annual fluctuation.

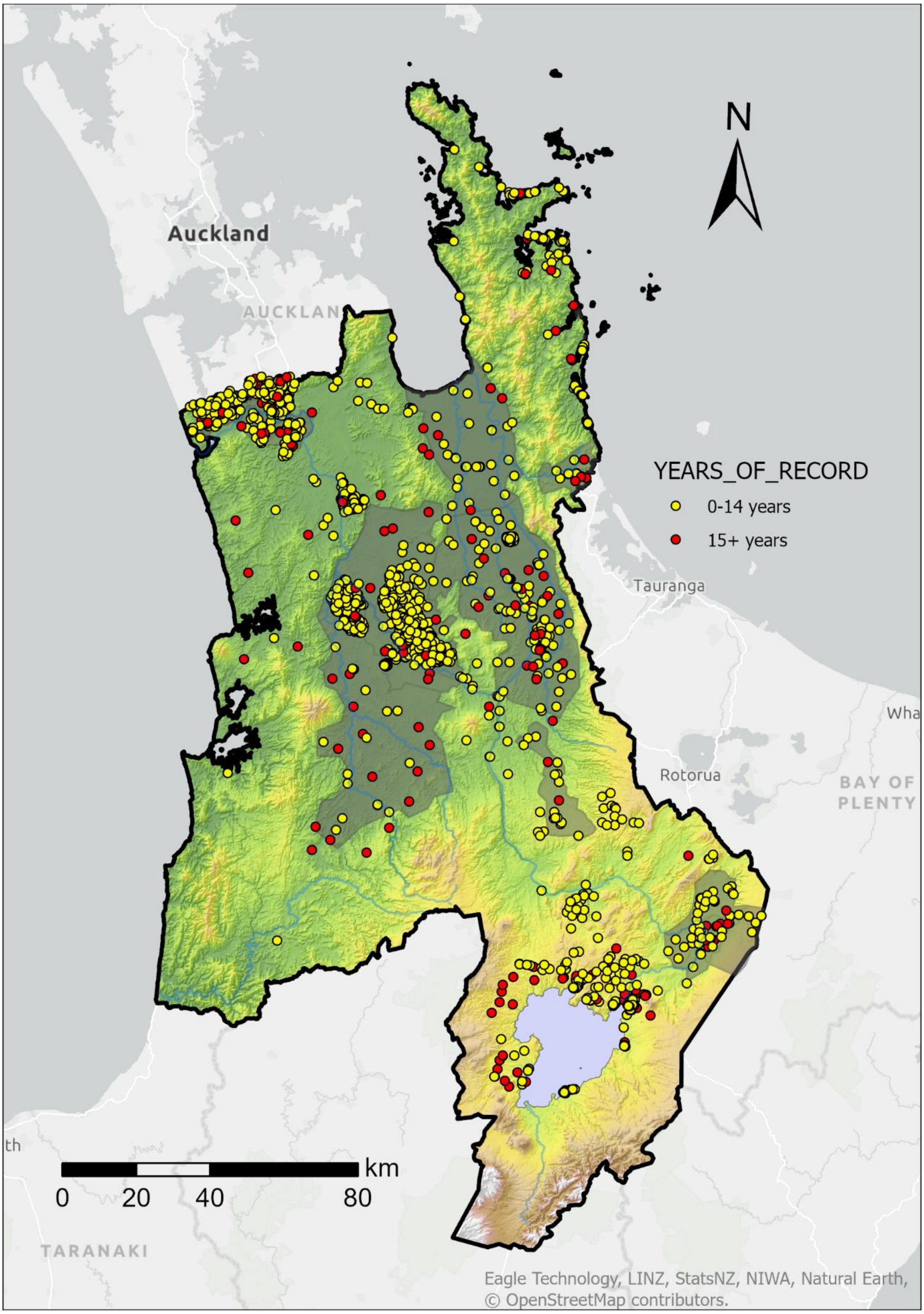


Figure 14. Locations of bores with Groundwater level data. Shaded area are the GW allocation management zones. Red circles are long-term monitoring locations.

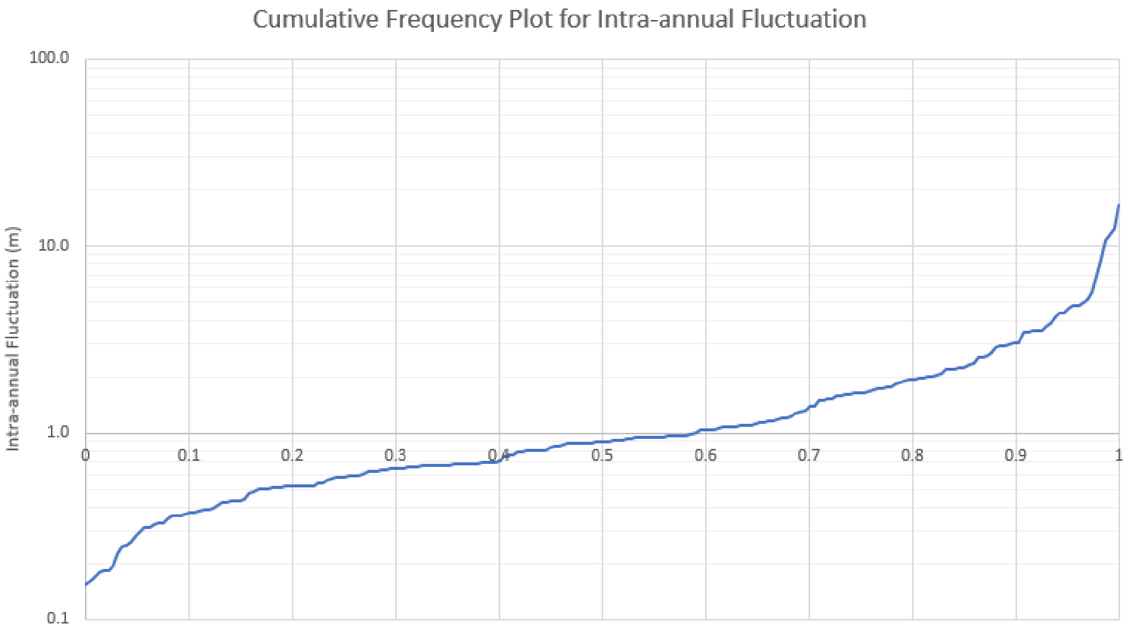


Figure 15. Cumulative frequency plot of intra-annual groundwater level fluctuation. The x-axis represents the probability of exceedance for the intra-annual fluctuation.

3.1.4 Stream and River Flow

There are two types of flow measurements available in the region: discrete spot gauging and continuous flow recording. For this analysis, only data from the continuous flow recorders were used to derive flow statistics and trends. Spot gauging data could have been used to extend the statistics to cover smaller tributaries and improve spatial resolution, but it was left out of scope due to project time constraints.

To observe summer water availability, flow recorder sites with more than 30 years of continuous records were analysed. There were 58 flow recorder sites with continuous flow records spanning more than 30 years. Figure 16 displays the locations of the long-term active flow stations used in the subsequent assessment. These continuous flow sites typically record flow rate measurements at 5-minute or 15-minute intervals. Daily mean flow records were used for the trend analysis in this study.

Data from the continuous flow stations are actively used to manage water intake during low flow periods. An automated system sends alerts for both high flow and low flow, allowing community and flood asset operators to respond. Other uses of the data include updating flow statistics used for water allocation.

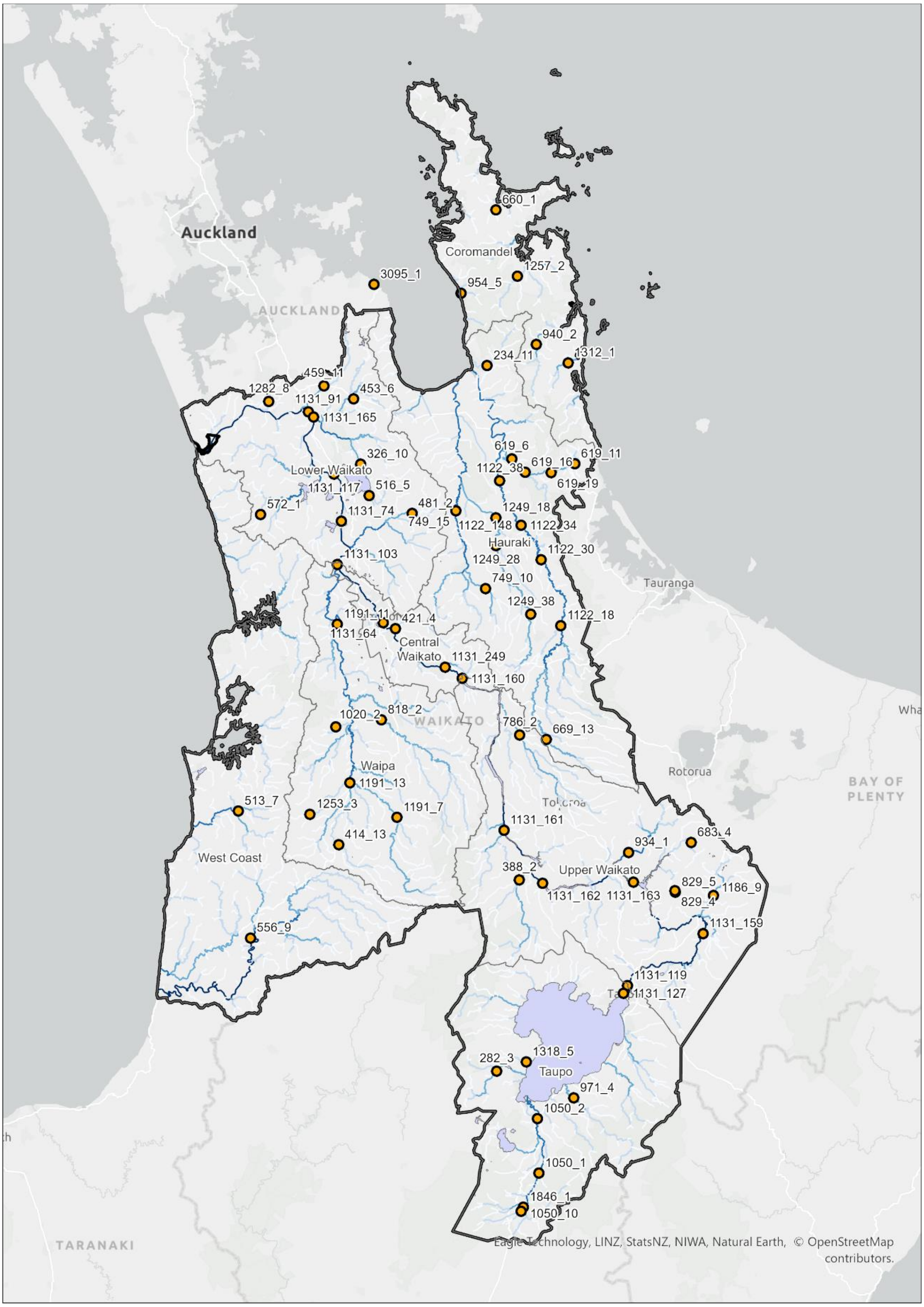


Figure 16. Location of flow recorder stations that are currently active with 30 years or greater of record.

3.2 Methodology

3.2.1 Estimation of water usage

As discussed in section 3.1.2, the metering of actual water take began in 2000. Coverage was not complete, but even with partial coverage, the data provides a general pattern of actual water use at the regional level. An extrapolation of water use behaviour was made from the available water meter data. The aim of the extrapolation was to create a system that produces a catchment-wide history of water use, filling the data gaps from existing information on a pro rata basis. The catchment-wide history of water use is an indicator of how quickly the community in the catchment is growing. The catchment-wide history estimation is also a precursor step towards the naturalisation of the flow statistics; this aspect will be explained in section 3.2.2.2. All historic water take consents, except for non-consumptive takes, were included in this extrapolation process. The objective was to estimate the actual water usage for all past consents. For each consent that existed in the historical records, the water usage history was generated using one of the following methods, depending on the level of data coverage:

- **Method A:** The ideal situation occurs when a water take consent has a metered record that covers the entire duration of the consent, enabling the data to be used without any modification.
- **Method B:** If a consent has a metered record that does not cover the entire duration of the consent, a four-step process was undertaken. Step one, a 7-day moving average was applied to the reported daily water take rates within the available data period. Step two, for each hydrological year of the record, the highest water take rate of the year based on the 7-day moving average was determined; this forms an annual timeseries called the *annual peak rate*. For example, if the available timeseries spans 4 years, 4 values would compose the annual peak rate timeseries. Step three, the median of the annual peak rates was evaluated, and this value was named *average annual peak water use*. Step four, the duration of consent that was not covered by water metered data was filled with this average annual peak rate. Figure 17 displays selected examples of the results of the extrapolation performed using this method; those consents with partial water meter data coverage. The 7-day moving average smoothing is performed to ensure that the data processing aligns with the method used to evaluate the annual low flows (ALF) and Q_5. This smoothing also helps to suppress any unintended spikes in the raw data, such as mistakes in meter readings or telemetry noises.
- **Method B:** If a consent has a metered record that does not cover the entire duration of the consent, a four-step process was undertaken. Step one involved applying a 7-day moving average to the reported daily water take rates within the available data period. Step two involved determining the highest water take rate for each hydrological year based on the 7-day moving average, resulting in an annual timeseries called the *annual peak rate*. For example, if the available timeseries spans 4 years, there would be 4 values in the annual peak rate timeseries. Step three involved evaluating the median of the annual peak rates, which was referred to as the *average annual peak water use*. Step four involved filling the duration of the consent not covered by metered water data with this average annual peak rate. Figure 17 displays selected examples of the results of the extrapolation performed using this method for consents with partial water meter data coverage. The 7-day moving average smoothing is performed to ensure alignment with the method used to evaluate the annual low flows (ALF) and Q_5. This smoothing also helps suppress any unintended spikes in the raw data, such as errors in meter readings or telemetry noise.
- **Method C:** For permits without any associated water meter data, a four-step process was undertaken. The main strategy of this process was to use the concept of "similar" consents based on subregion and water use purpose. *Average peak utilisation levels* were evaluated to translate the knowledge learnt from similar consents with the same water use purpose. Step one involved evaluating the *average annual peak water usage* for each permit with water meter data in the region. The method used to calculate the average annual peak water usage in Method B was repeated but for all consents with any data. Step two involved consolidating the consents with water meter data into a table per subregion and per water use purpose. An example table for Waipa subregion is shown in Table 5. In the summary table, the subregional total of the average annual peak water use, evaluated in step one, is recorded in a column labelled Actual (m^3/d), while the subregional total of consented maximum daily rates is recorded in a column labelled Consented (m^3/d). Step three involved calculating the average peak utilisation level per water usage purpose per subregion, using the following equation:

$$[\text{Average peak utilisation level}] = \frac{[\text{Average annual peak water use m}^3/\text{d}]}{[\text{Maximum consented daily rate m}^3/\text{d}]}$$

In Step four, the analysis then examines each consent without any water meter data. The analysis examines the water use purpose of the consent under consideration and estimates the likely average annual peak use by multiplying the consented maximum daily rates and the average peak utilisation level of the corresponding water use purpose from the subregion summary table. This design was decided because all historic consents had records of consented maximum daily rates, even in absence of water meter data. This rate is assumed to be pumped every day throughout the duration of the consent that does not have water meter data. It is important to note that this assumption is likely to overestimate the actual water use, as consent holders would not necessarily pump at the peak rates at all times. This limitation has affected the historical water usage presented in section 4.2, where certain subregions appear to have higher water extraction levels in the period before 2000 compared to the period after 2000 (e.g. Figure 65). Further methodological improvements are required in generating the historical water usage data. It is important for the reader to recognise this limitation and consider the water usage history information presented in this report as preliminary finding at this stage. The uncertainty inherent in water use history construction is also discussed in section 5.1.2 as well.

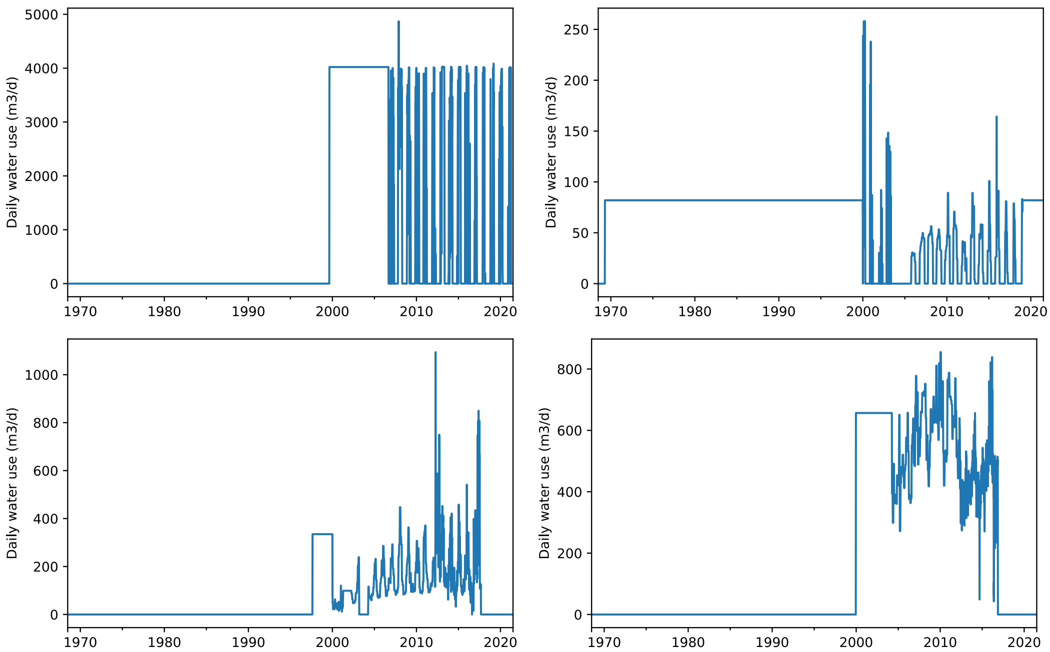


Figure 17. Selected Examples of Water use Extrapolation Results in case of Partial Meter data Coverage.

Table 5. Average Peak utilisation as an intermediate calculation step. Example of Waipa catchment.

Water Use Purpose		Actual (m^3/d)	Consented (m^3/d)	Ratio
Primary	**Secondary**			
Agriculture	**Irrigation**	56,662	100,100	0.566
	Shed wash	159	295	0.538
	Stock water and shed wash	2,727	3,696	0.738
Domestic & Municipal Water Supply	**Drinking water Supply - Domestic, rural or urban**	202,981	279,900	0.725
Horticulture/market gardening	**Irrigation**	2,533	9,360	0.271
Industry (Others)	**Washing**	2,075	1,320	1.572
Industry (Quarry/mining)	**Factory/industry processing**	89,923	24,890	3.613
Recreation	**Irrigation**	568	840	0.676

Certain water use purpose categories showed apparent anomalies where actual water usage exceeded the consented maximum rate. The anomaly was not necessarily the result of non-compliance, extracting more than consented maximum, but rather due to the representation of net take in consent conditions. Net take is the amount taken from water body less the return flow. For the industry (other) washing purpose, the typical washing scenario involved truck washing, while the quarry/mining industry washes aggregates before shipping. The water used for washing is returned to the water body after sediments are settled in ponds. The water meters usually capture only the amount abstracted from water bodies. Since most of the water is returned to the water body after washing, the net water usage is typically smaller than what was measured at the water meter.

The water usage history described above pertains to surface water take, which has a more direct impact on river flows. In contrast, the impact of groundwater takes on river flows is slower and more diffuse throughout the year due to the attenuating nature of groundwater storage. Therefore, a yearly basis was used to construct the history of groundwater usage. For each groundwater take consent, if it had a daily water usage record, the record was summarised into the total annual groundwater usage for each hydrological year (Figure 18). Since the impact of the groundwater takes on downstream surface water bodies is typically delayed[18], the calculated total annual groundwater usage was accounted for in the following year. The same approach was applied to old groundwater take consents without any water usage records, like the surface water take analysis described earlier. A simplistic approach was taken and the total water use was calculated as simple arithmetic sum of groundwater takes and surface water takes. Using a simplistic arithmetic approach to represent the effect of groundwater takes on surface water flows is a significant simplification, and therefore, the findings from the actual water use estimate should be used for indicative purposes only.

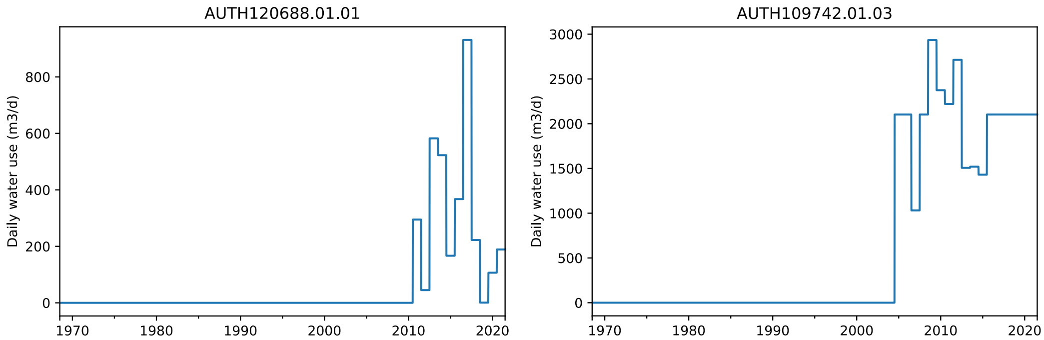


Figure 18. Examples of water use extrapolation for Groundwater takes.

The procedure up to this point was the gap filling of the historic water use record for each surface and groundwater take consent. The catchment-wide water use history was calculated by adding these individual consent water use records within the catchment boundary of interest. The catchment-wide growth histories in water uses are reported at regional (section 4.1.2) as well as subregional levels (section 4.2).

3.2.2 Low Flow Statistics ALF and Q_5

In the realm of water supply management, one important aspect of interest is the level of dryness in a catchment during the driest times of the year. This is because the demand for water is at its highest during this time for both natural ecosystems and communities. Key statistics used in managing water usage at the Waikato Regional Council are the Annual Low Flow (ALF) and Q_5. The ALF is an annual time series that records the lowest flows achieved in a hydrological year[19], while Q_5 is a statistic that is derived from the ALF and reflects how the river would flow during an extreme low flow condition with a return period of approximately 5 years.

[18] this effect is called stream depletion.
[19] Hydrological year is the year starting on 1 July and ending on 30 June of the subsequent year.

ALF represents how dry the river and the catchment were in general for the given particular year, whereas the Q_5 represents the expected the extreme dryness of the catchment. ALF is a result of combined effects of weather conditions such as rainfall and evapotranspiration pressures as well as the soil moisture retention of the catchments and consumptive water use. It is well suited indicator statistics in reporting the state and trend of the dryness of the given catchments and water resource availability. For this reason, the Waikato region uses ALF and Q_5 as low flow statistics in minimum flow setting, and water take allocation. Minimum flow targets and allocable flows are defined as percentages of the flow statistic Q_5, as outlined in Table 3-5 of the Waikato Regional Plan[20].

3.2.2.1 Method for ALF

To evaluate ALF for this report, the daily mean flow record at each long-term flow recorder station was smoothed by applying a 7-day moving average. For each hydrological year, the lowest value achieved by the 7-day averaged flows was identified. This results in an annual time-step timeseries called the 7-day Annual Low Flow (7dALF), which the report will simply refer to as Annual Low Flow (ALF) hereafter. For example, a flow recorder with a record duration of 45 years will have an ALF timeseries of 45 values.

This report discusses two types of ALF: modified and naturalised ALF:

- Modified ALF is the ALF directly evaluated from the observed timeseries at the flow recorders. Although the evaluation itself is simpler, this ALF represents the combined result of weather conditions, catchment geomorphology, and changes in water use. If the procedure described in the previous paragraph is applied to the observed data straight from the flow recorder, the resulting ALF will be the modified ALF.
- Naturalised ALF is the expected ALF if there was no abstractive water use in the catchment. It is calculated by adding the long-term water use timeseries back to the observed daily flow timeseries, and then ALF was evaluated. The region has only recently begun recording water use, so the long-term water use records had to be synthesised from behavioural patterns per industry and water use consents. The method used to synthesise the long-term water use history is described in section 3.1.2 of the report. The synthesised long-term daily timestep water use was added to daily river flow data, creating naturalised daily flow. The council's consent database contains estimates of permitted activity water takes, which are associated with flow recorder locations and key allocation catchment outlets. These permitted activity rates have also been added to the river flow timeseries. Then, the ALF evaluation process, starting from applying a 7-day moving average, was applied to the naturalised daily flow timeseries. The analysis of the catchments affected by dams and weirs was excluded in this report, as it requires additional steps beyond simply adding back water abstraction.

The difference between the modified and naturalised ALF provides the basis for a novel analysis that distinguishes between the impacts of climate change factors and water use on long-term changes in low flows. This represents an interesting contribution of this report to the local body of knowledge. The analysis procedure will be described in section 3.2.4 of the report.

3.2.2.2 Method for Q_5

The Q_5 is a statistical measure that represents the lowest flow a river is expected to have on average once in every five years, based on the 7-day annual low flow (ALF). There are two types of ALFs used to calculate the Q_5: modified and naturalised ALF (section 3.2.2.1). As a result, two Q_5s are calculated from these two ALFs. In the past, before the Variation 6 of the regional plan became effective in 2012, the modified Q_5 was utilised to establish minimum flow and allocation levels. However, the region is progressively transitioning towards the utilisation of naturalised

[20] https://www.waikatoregion.govt.nz/council/policy-and-plans/regional-plan/

Q_5 in its practices to comply with the updated Regional Plan. When Q_5 is evaluated, the most recent 30-year ALFs are considered.

To calculate the Q_5, a statistical method called *frequency analysis of extreme values* was used. This involves sorting the ALF values from largest to smallest and fitting a cumulative Weibull distribution curve (Stedinger *et al.* 1992). The 20-percentile is then determined from the curve, which represents the expected frequency of occurrence of a flow that is as low as or lower than the Q_5 value. This occurs once every five years on average. The distribution curve fitting is necessary because the position of the 20-percentile does not always coincide with the data point, so interpolation is needed. Fitting the curve enables the overall trend of the ALF to be reflected in evaluating the 20-percentile, not just the two data points neighbouring the 20-percentile position. The selection of different distribution curves had a negligible impact on the analysis as the 20-percentile value fell between the available data points. This is different from flood frequency analysis, where distribution curves are utilised to estimate return events such as 20-, 50-, or even 100-year events, beyond the scope of the available data. The selection of a distribution curve is a significant factor in determining the magnitude of the return events.

The naturalised Q_5, which is derived from the naturalised ALF, is an extension of the reconstruction of the actual water use history. This is because the naturalisation is achieved by adding the estimated actual water use history to the observed flow timeseries before subjecting it to frequency analysis of extreme values. The resulting Q_{5nat} at selected long-term flow recorder stations is presented in Table 12. The reported Q_{5nat} will be incorporated in future allocation practices.

3.2.3 Trend analysis

Trend analysis was conducted on the available hydrology data with the main aim of describing the long-term changes experienced in the region. Whenever possible, reasons for the observed changes were provided, but the primary focus was on presenting the data itself.

3.2.3.1 Annual Rainfall and PET

The trend analysis for rainfall and PET was conducted using a descriptive approach, with a visual focus in presenting the findings. The exhibition of the analysis proceeded by displaying one panel of the figure followed by the next, accompanied by commentaries explaining key patterns found in the graphics.

To better visualise the trends, the concept of deviation from the climate normal over the period of analysis was used. For example, the first trend analysis (Figure 20) focused on the rainfall record at Ruakura in Hamilton. This site is a regional representative located in the centre of the region and has a long rainfall record spanning 116 years, from 1907 to present. The total rainfall over each calendar year[21] was determined, and the average annual rainfall over the full record was calculated. The annual rainfall deviation from the average value over the 116-year period was plotted as a bar chart. Each bar indicated whether a particular year was wet or dry based on the full record average value. The cumulative value of the deviation from the average was plotted as a line, demonstrating the slower pattern or clustering of the wet-dry year cycles.

The same concept of deviation from the climate normal was applied to the spatial analysis presented in the subsequent figure, Figure 21. In this case, the climate normal was evaluated as the average annual rainfall over the available data coverage of the VCSN from 1961 to present. The spatial pattern of the deviation from the climate normal value was visualised to identify the areas that experienced drier conditions compared to other areas. The spatial pattern was visualised per decade to illustrate the slower long-term changes over time. The concept of

[21] The calendar year runs from January to December.

deviation from the climate normal proved useful also in identifying the key season that contributed the most to the change in the latest decade (Figure 22).

The subsequent set of panels focused on the annual rainfall and PET values and how they changed over time. To better visualise the temporal changes, the annual rainfall and PET values were aggregated over seven large subregions, as shown in Figure 2. When aggregating at the subregion level, the time series at all VCSN nodes within each subregion were averaged with equal weights. The subregions were Coromandel, Lower Waikato, Hauraki, Upper Waikato, Central Waikato, West Coast, and Taupō. The Central Waikato region is sometimes referred to as the Hamilton-Waipa zone in Waikato, following the names of the hydrologic basins used in hydrologic literature. The resulting trend was visualised in Figure 23 and Figure 24. To observe the smoothed, long-term behaviour of the variables, the aggregated annual rainfall and PET values were smoothed with LOWESS using a smoothing factor that removed year to year fluctuations. LOWESS is a widely used time series smoothing algorithm and, in this work, it was evaluated using a Python scientific package. The mathematical formulation for LOWESS can be found in the work of Cleveland and Devlin (1988).

A way of summarising the pattern in the number of trend plots in Figure 23 and Figure 24 was calculating the rate of changes in annual rainfall. The rate of change in annual rainfall was calculated based on the values read from the LOWESS curve. The result was presented in Table 7. Two distinct periods were selected for analysis. The first period covers the entire duration of data coverage, from 1961 to 2020. The second period, from 1991 to 2020, represents more recent decades. By comparing the rate of change between these two periods, it was determined whether the rate of change has increased in the more recent period. If the rate of change in the 1991-2020 period is greater than the long-term rate of change in the 1961-2020 period, it concludes that the rate of change is accelerating. This way, numerical evidence could be produced to confirm or oppose the general sentiment that recent decades have been drier. The choice of the year 1991 was based on an observation of a change in trend direction for PET, and it was intended to find out whether this change in trend, or a corresponding acceleration, was also observable in annual rainfall. Table 7 was visualised in a map (Figure 25), so that it highlights the subregion experiencing the most rapid annual rainfall change.

3.2.3.2 Driest 90-day period

It is the dry spells of the year that the water supply resources are put in stress. Therefore, the next analysis focused on identifying trends in dry spell severity, which is critical for addressing water supply concerns during this period of heightened demand. This was accomplished by identifying the driest 90-day period of each hydrological year and tracking changes in rainfall and evapotranspiration.

To identify the driest 90-day period for rainfall in a given hydrological year, a 90-day moving total was calculated at each VCSN node, and the lowest moving total of the hydrological year was selected. Dry spell analysis was performed using the hydrological year to ensure that the driest 90-day event is positioned in the middle of the year under analysis, thus avoiding the double counting of a single severe event in two consecutive years. The change in severity of the dry spells was represented by plotting the total rainfall depth received during the driest 90-day period of each year (Figure 28). It is worth noting that the timing of the dry spells, i.e., the 90-day period of least rainfall each year, varied from year to year. This approach differs from tracking fixed three-month periods to represent a particular season, such as December to February, to represent summer. However, the methodology used in this study is similar to analysing extreme flood events, where the duration and severity of the storm event are first determined. The only difference is that dry spell events last longer than a few days. The 90-day duration was selected to capture key trends and patterns in dry spell severity over the study period, and other event durations exhibited similar patterns to those identified in the 90-day dry spell analysis presented in this report.

Following the same methodology used for annual rainfall and PET analysis, a LOWESS curve was fitted to the total rainfall received during the driest 90-day period each year. To divide the observation period of 1972 to 2020, the year 1990 was selected from the same reason discussed in section 3.2.3.1. The analysis was conducted for each node in the VCSN, and several example plots are shown in Figure 28. To determine the rate of change during the representative period of 1990-2020, the slopes were calculated by reading the values on the LOWESS curve at 1990 and 2020. For instance, in the Hauraki (27739) plot, the total depth (mm) values on the orange trendline were read at year 1990 and 2020, yielding 141 mm and 76 mm, respectively. This represents a –46% change over the 30-year period[22]. This calculation was repeated for all VCSN nodes in the Waikato Region, and a spatial map was generated to display the percentage changes observed during this period (Figure 30).

The same analysis was repeated for PET. The simple 90-day moving average was calculated and the highest moving average of each year was plotted (Figure 29). Higher average PET values in the plot means drier 90-day period. It is noted that the timing of the driest 90-day period based on PET may different from the driest 90-day period, however, the approximate occurrence is expected to be similar. The same rate of change analysis over 1990-2020 was done and the percentage change mapped (Figure 30).

The same approach was applied to PET analysis. A simple 90-day moving average was calculated, and the highest moving average of each hydrological year was plotted (Figure 29). Higher average PET values in the plot indicate a drier 90-day period. It should be noted that the timing of the driest 90-day period based on PET may differ slightly from the driest 90-day period evaluated from rainfall, although the approximate timing is expected to be similar. The rate of change analysis over the period of 1990-2020 was repeated, and the resulting percentage change was mapped (Figure 30).

3.2.3.3 Water allocation and usage

The subsequent theme addressed in the report is water allocation and use. In addition to regional climate drivers, human water use and modifications also contribute to the pressures on water resources. There are several ways in which human activities exert pressure on water bodies, such as water abstraction, in-water earthworks like dredging and damming, and the introduction of sediments that alter the hydraulic and geomorphological properties of water bodies. There have been previous attempts to investigate the impact of changing land use (and land cover) on both low (Mourot *et al.* 2021; Yao and Palmer 2022) and high flow hydrology (Waikato Regional Council 2010). This section of the report presents the most readily available information on water use from the council database, including information on water allocation and actual use.

Information on regional water use has been collected since 1969, even prior to the RMA's implementation. This information was obtained through consent processes and recorded in a consent database (section 3.1.2). These records contain information on the maximum consented take rates, which industries obtained consent and for what purposes the water was used. More recently, the council has implemented an automated water allocation accounting system known as the Water Allocation Calculator (WAC). The WAC provides an automated summary of allocation levels based on the data captured for individual consent records and is available for approximately 350 catchments, with updates made on a daily basis. However, a limitation of this system is that the summary is overwritten daily, and only the allocation summary for the day being viewed is available. To obtain the catchment summary for a past day, data manipulation and synthesis is required to replicate the calculation procedure used in the WAC.

[22] = (76-141)/141

Section 4.1.2 begins with an overview of the current allocation status across various catchments, as presented in Figure 31 and Table 10. This information enables an assessment of allocation pressures by comparing the allocation levels against two allocation limits - primary and secondary - providing a comprehensive view of the stresses on water bodies due to water use. The month-by-month fluctuation is visualised in Figure 32, while Figure 31 shows the spatial pattern of allocation pressure in January and July, highlighting the pressure on catchments when the allocation is at its highest and the reduction in pressure in July.

The estimated growth of the total regional maximum consented take rates was presented. When this growth history was synthesised, a python script was written to loop through each day starting from 1 January 1968 to 31 December 2022 and active consents on the day were identified by referencing the commencement and end dates. The sum of the maximum consented rates of all active consents of the day was calculated and plotted (Figure 32). For the summary, a simple arithmetic summation was made, after removing any duplicates in the record. This summary did not replicate some complicated business logic incorporated in WAC, for example, grandparenting agreement made with dairy shed water users. The summary values presented in Figure 32 does not match one on one to the summary portrayed by WAC but it shows the pattern that demonstrate the consistent growth of water allocation in the region. One can regard the allocation growth summary represented in this report as an indicative representation of regional growth in water take allocation, an approximation of more accurate representation of WAC outputs. Although the current work simplified the summary calculations for sake of demonstration, future works may include implementation of all business logic in WAC in the historic reconstruction.

The actual water use growth history was synthesised using the methodology outlined in section 3.2.1, with Figure 33, Figure 34 and Figure 35 generated using the same approach. The breakdown of major water use sectors enabled identification of the sectors that drove the largest growth during different decades. The water use purposes identified in the consent database[23] were used to categorise the water uses into four main categories: Agriculture, Municipal, Industry, and Other. The "other" sector comprises consents that do not fall under the three main categories, such as those related to ecology maintenance and flood management. Consents with no readily available sector or water use purpose information were all added to the "other" sector category. The same method and Python code were used to generate the water use history graphs for subregion analysis (section 4.2), but with varied spatial scopes. It is important to note that there are larger uncertainties associated with the actual water use estimates, particularly for the estimates from the pre-water metering era before 2010. There is room for improvement in reducing these uncertainties, and this aspect is left for future investigations (section 6.1.2). An extension of the long-term historic reconstruction of actual water use is the evaluation of naturalised Q_5, Q_{5nat}. This report includes an evaluation of Q_{5nat} (as reported in Table 12) as a partial fulfilment of the 5-year update routine of Q_5 for ongoing council allocation practice.

3.2.3.4 River flow and groundwater

To gain an overview of the relationship between rainfall and flow in the Region's rivers a single standardised rainfall timeseries was compared to a single standardised flow timeseries. The annual rainfall was averaged for all 1006 VCSN stations in the Waikato region to compute a region wide annual rainfall timeseries, that was then standardised using equation 1. The standardised flow series was obtained by

i. selecting all flow stations (n=17) with 50 years or more of record and with records to the end of 2020,
ii. calculate the annual flow series for each the selected flow stations,
iii. apply **Equation 1** to each of these annual flow series to get a standardised flow series for each station, and finally,

[23] The exhaustive listing of the water use purposes expressed in the database can be found in Glossary, under Primary, Secondary and Tertiary water use purposes.

iv. average the standardised flow series to obtain the region standardised flow series.

Equation 1

$$z = \frac{X - \mu}{\sigma}$$

Where X is the observation (rainfall or river flow), μ is the mean, and σ the standard deviation. Then the average of the standardised flow timeseries was compared to the standardised rainfall timeseries.

The rainfall has been exceptionally low during the latest climate normal period, raising concerns about reduced recharge and resulting changes in groundwater (GW) levels and resulting river flows. Therefore, trend analysis was performed using the LWP Trends Library version 2102 (available at https://landwaterpeople.co.nz/pdf-reports/), which was designed for water quality trend analysis by Land Water People (LWP) using the R statistical package (R Core Team, 2020). The magnitude of the trends was computed using the Sen slope (Sen, 1968), which is calculated as the median of all possible pairwise slopes in each timeseries. The Sen slope reports the overall change for the time-period of interest represented as monotonic trend. It is noted that some changes may be the result of a step change, or best represented as non-monotonic trend. However, the reporting of the Sen slope is still useful to indicate the overall change for the analysis period. The statistical significance of the trends was calculated using the Mann-Kendall test ($p \leq 0.05$).

The trend assessment results were assigned categories of confidence that the trend direction is correct (Table 6) following Snelder et al. (2022). All trend directions are reported regardless of the confidence as they are informative in relation to the regional situation for river flow and groundwater.

Table 6. Level of confidence categories for assessing confidence in trend direction.

Level of confidence in assessed trend direction	Value of C
Highly likely	0.95 to 1.00
Very likely	0.90 to 0.95
Likely	0.67 to 0.90
Uncertain	0.50 to 0.67

3.2.4 Contribution of climate and water use to ALF

A preliminary analysis of the change in annual low flows (ALF) over the past few decades, as reported in section 4.1.4.1, revealed that most rivers exhibited a common pattern of increasing ALF until the 1990s, followed by a decline. There are two types of ALF that can be evaluated, based on the water use history of the catchment upstream of flow recorders: modified ALF and naturalised ALF (as described in section 3.2.2.1). The modified ALF represents the low flow response to a combination of climate, physical characteristics of the catchment, and water use, while the naturalised ALF represents the low flow response to climate drivers and physical characteristics only. The difference between the modified and naturalised ALFs indicates the extent of the impact of water use on the observed decline in river flow. Generally, the trend in local climate determined the overall trajectory of low flows, while growth in catchment-wide water use added pressure to low flows.

Based on this idea, a novel approach was developed to assess the relative contributions of the two primary drivers[24]. The modified and naturalised ALFs were plotted together. Figure 19 gives an example assessment using the Ohinemuri at Karangahake flow recorder data[25]. LOWESS

[24] While physical catchment characteristics such as soil water holding capacity also affect low flows, they are expected to change more slowly than climate and water use. Therefore, this work focuses on the two primary factors: climate and water use.

[25] To locate the site, please refer to Figure 16 and look for 619_16. The Ohinemuri River is situated in the north-eastern part of the region.

curves were drawn over the plotted ALFs, one for the modified ALF and one for the naturalised ALF. The LOWESS curves removed the year-to-year fluctuations, allowing for the calculation of changes in trend. The change was defined as the difference between the maximum value achieved in the LOWESS curve and the LOWESS value in 2020. The timing of the maximum values may differ slightly in the LOWESS curves of the modified and naturalised ALFs. By subtracting the two changes, one can isolate the low flow response from the abstracted water use alone. In this real-life example, the LOWESS curve value on the modified ALF decreased by 0.23 m^3/s from 1990 to 2020, while that on the naturalised ALF experienced only a decrease of 0.12 m^3/s.

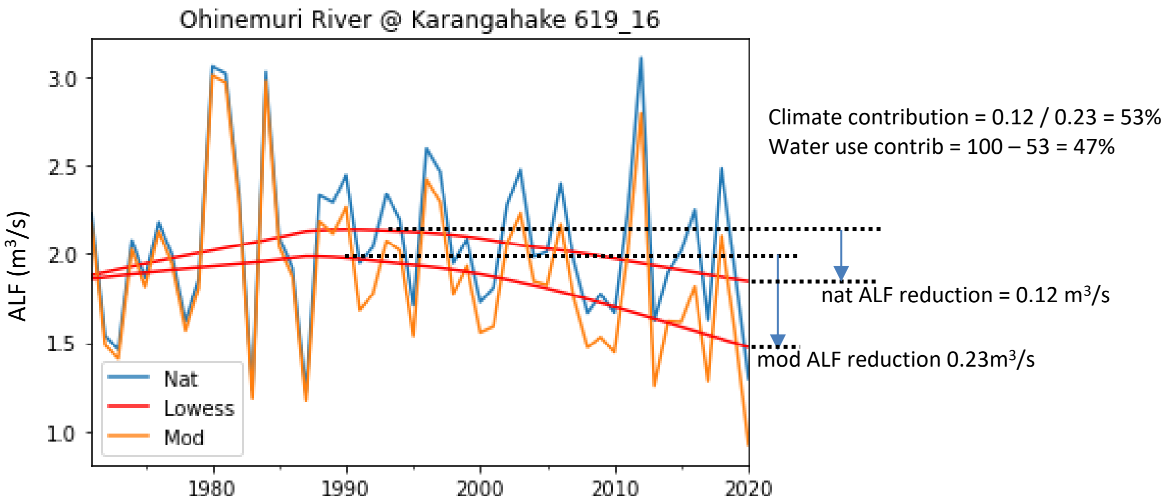


Figure 19. An example of water use vs climate contribution assessment in ALF trend plot. Mod ALF refers to the modified annual low flow, which represents the observed flow. Nat ALF refers to the naturalised annual low flow, which is adjusted by adding the estimated catchment-wide water use. See section 3.2.2.1 for details.

In this case, the response of the LOWESS curve value to the climate change was a reduction of 0.12 m^3/s, which accounted for 53% (=0.12/0.23) of the overall decrease in the modified ALF. Therefore, the analysis concludes that 53% of the observed reduction in stream flow can be attributed to local climate change, while the remaining 47% can be attributed to the increase in abstracted water use in the catchment. The graph also reveals that the gap between the two red LOWESS curves widens over time, indicating a growth in water use. The gap between the two red LOWESS curves provides insight into the water use growth over the period. Similar analyses were conducted for other long-term flow recorder sites, and their results are presented in Section 4.2 of this report.

Certain flow recorders were excluded from the analysis due to their significant influence from artificial structures, such as weirs, dams, and flood management assets. The minimum flows observed at these recorders are a result of artificial controls that are not necessarily related to climate changes or water usage. Therefore, it is inappropriate to directly compare the trend analysis of ALF at flow recorders located downstream of these major artificial structures with other flow recorders free of such influence. Future investigations may include determining the proportion of the influence contributions resulting from changes in the operation and design of these artificial structures.

4 Results

4.1 Regional

4.1.1 Climate: rainfall and reference evapotranspiration

4.1.1.1 Annual

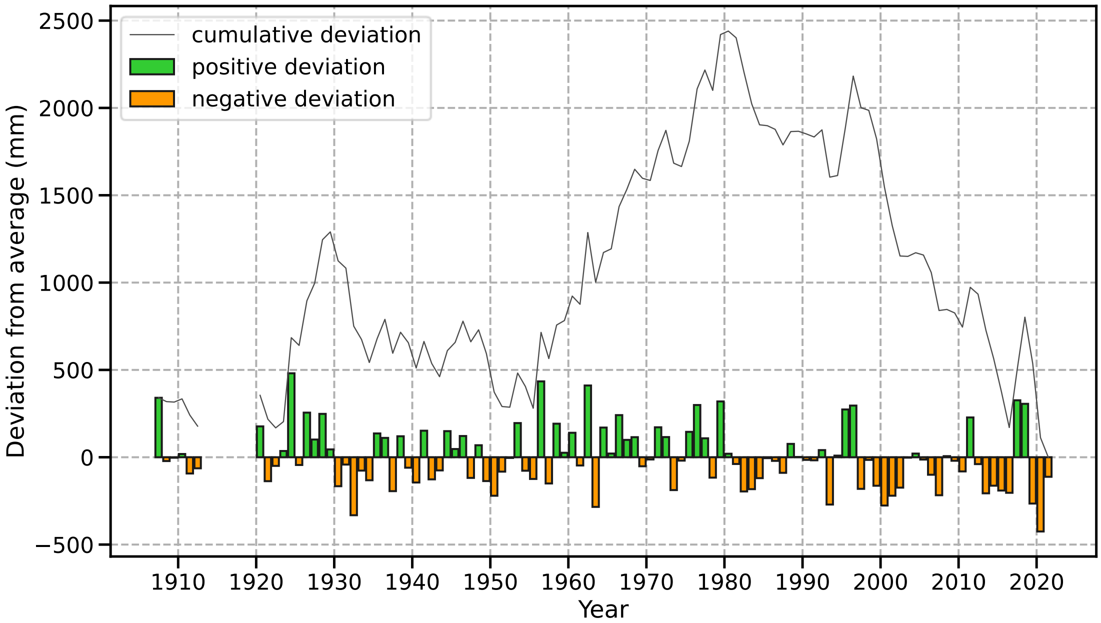


Figure 20. Waikato at Ruakura rainfall, deviation from full record average.

The analysis of long-term annual rainfall for the Ruakura raingauge, located near Hamilton, is presented in Figure 20. Although the record has a large data gap between 1913 and 1919, several observations can be made. The period from 1930 to 1955 shows relatively stable rainfall, with a flat cumulative deviation indicating that the rainfall during this period is close to the average of the full record. The subsequent period from the mid-1950s to 1980 is wetter than average, while the period from 1980 to present is drier than the full record average, with a further decrease in rainfall since 2000.

Figure 21 compares the average rainfall in the Waikato region for each decade from 1961 to 2020 to the long-term average from 1961 to 2020. The graph shows a general pattern of drying across the region, with the first two decades being the wettest on average. The most recent decade (2011-2020) was the driest, and this pattern was consistent across the region. Although the VCSN record used for this analysis only starts in 1961, it does align with the observed rainfall pattern at Ruakura, which has records dating back to 1907.

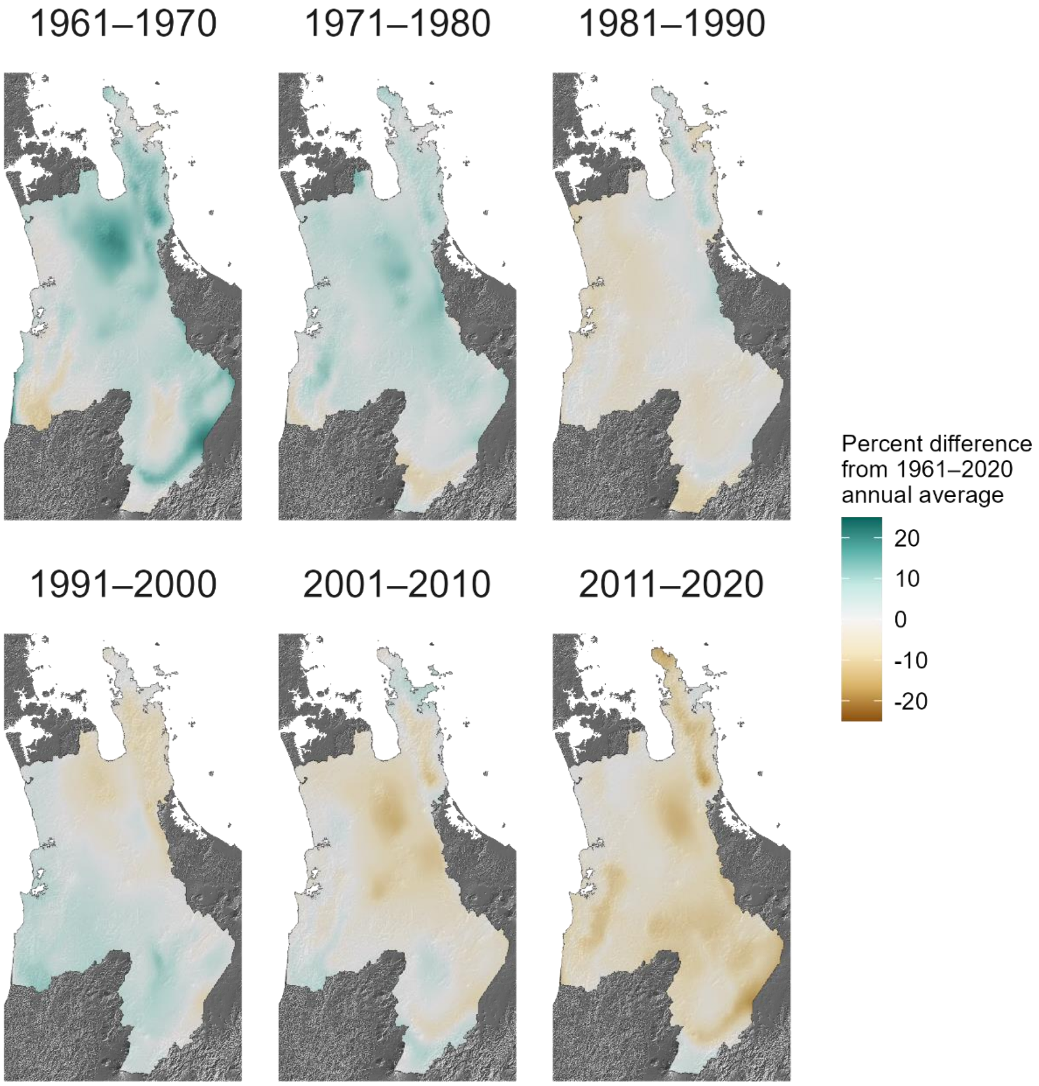


Figure 21. Decadal rainfall as percent difference from the long-term (1961-2020) annual average. Data source: VCSN.

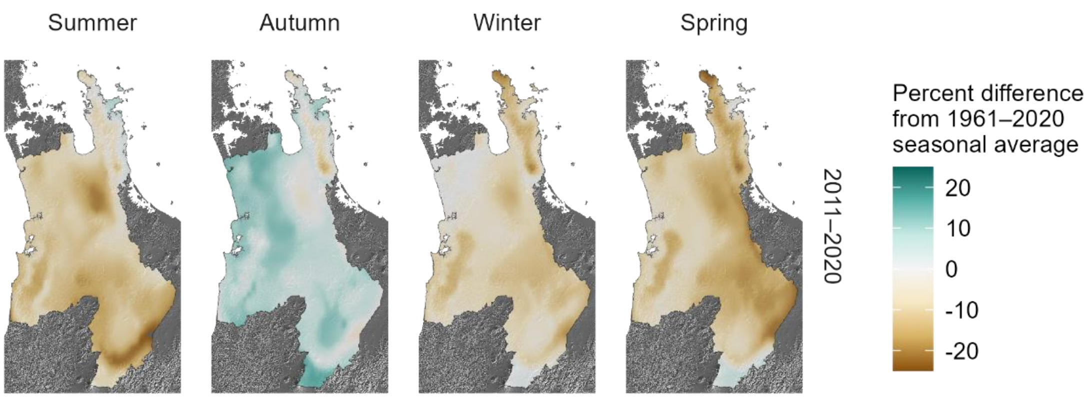


Figure 22. Seasonal rainfall for the decade 2011-2020 as a percent difference from the long-term seasonal averages (1961-2020). Data source: VCSN.

Although the most recent decade has been notably drier, there are discernible patterns within the seasons, as depicted in Figure 22. Specifically, autumn has become generally wetter (with the exception of the Coromandel), spring has become drier, and summer even more so. Meanwhile, winter is generally drier, but there is more variation in this trend in the northwest and south of the region.

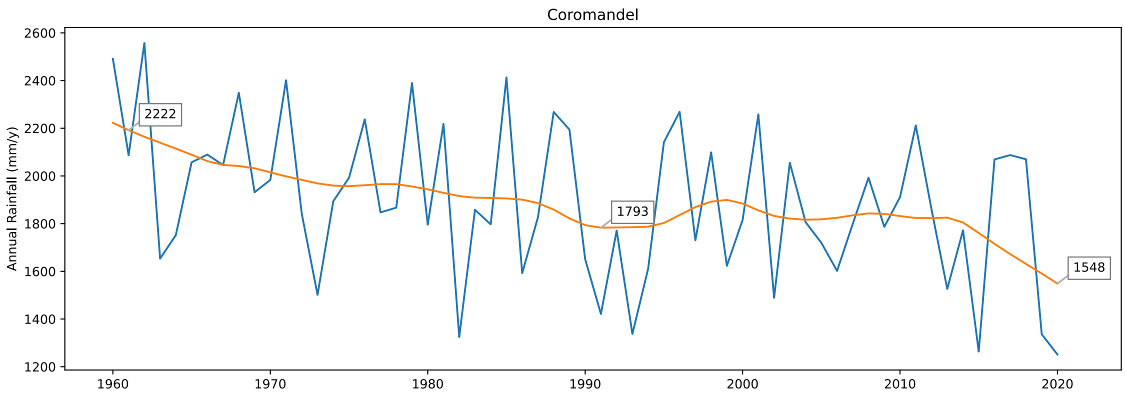
The Coromandel, Lower Waikato, and Hauraki subregions experienced a significant decline in average annual rainfall between 1961 and 2020 (Figure 23). These three subregions had a reduction in average annual rainfall ranging from 26% to 30% over the analysis period, as shown in the first three items in Table 7. Among these, the Coromandel subregion showed the most significant decline, with a reduction of 30% over the analysis period (the first item in Table 7). The rate of decline was faster during the first three decades (1961-1990) compared to the later period in these three subregions.

Table 7. Decline in Annual Rainfall. Moving Average = Orange lines in Figure 23 and Figure 24. The two rightmost columns are spatially represented in Figure 25.

Subregion	Moving average 1961 (mm)	Moving Average 1991 (mm)	Moving Average 2020 (mm)	Change in moving average between 1961 and 1991	Change in moving average between 1991 and 2020	Change in moving average between 1961 and 2020
Coromandel	2222	1793	1548	-19%	-14%	-30%
Lower Waikato	1436	1336	1044	-7%	-22%	-27%
Hauraki	1450	1343	1069	-7%	-20%	-26%
Upper Waikato	1329	1481	1138	+11%	-23%	-14%
Hamilton-Waipa[26]	1469	1639	1324	+12%	-19%	-10%
West Coast	1635	1881	1546	+15%	-18%	-5%
Taupō	1543	1673	1468	+8%	-12%	-5%

In general, the northern subregions[27] consistently experienced a decline in annual rainfall in both the earlier (1961-1991) and later (1991-2020) periods. In contrast, the central to southern subregions[28] saw an increase in annual rainfall in the earlier period followed by a decline, as depicted in Figure 24. This pattern of increase followed by decline made the central to southern subregions appear to have a close-to-neutral trend over the 60-year period.

However, focusing on the later 30-year period, the decline in annual rainfall was widespread across all subregions, with the Upper Waikato subregion experiencing the greatest decline of 23% (Table 7). The Lower Waikato was the next subregion that experienced a significant decline of 22%. Figure 25 visualises the severity of the declining trend during both periods and identifies the subregions that experienced the greatest changes in rainfall.



[26] Hamilton area is alternatively called Central Waikato.
[27] The top three items in Table 7.
[28] The bottom four items in Table 7.

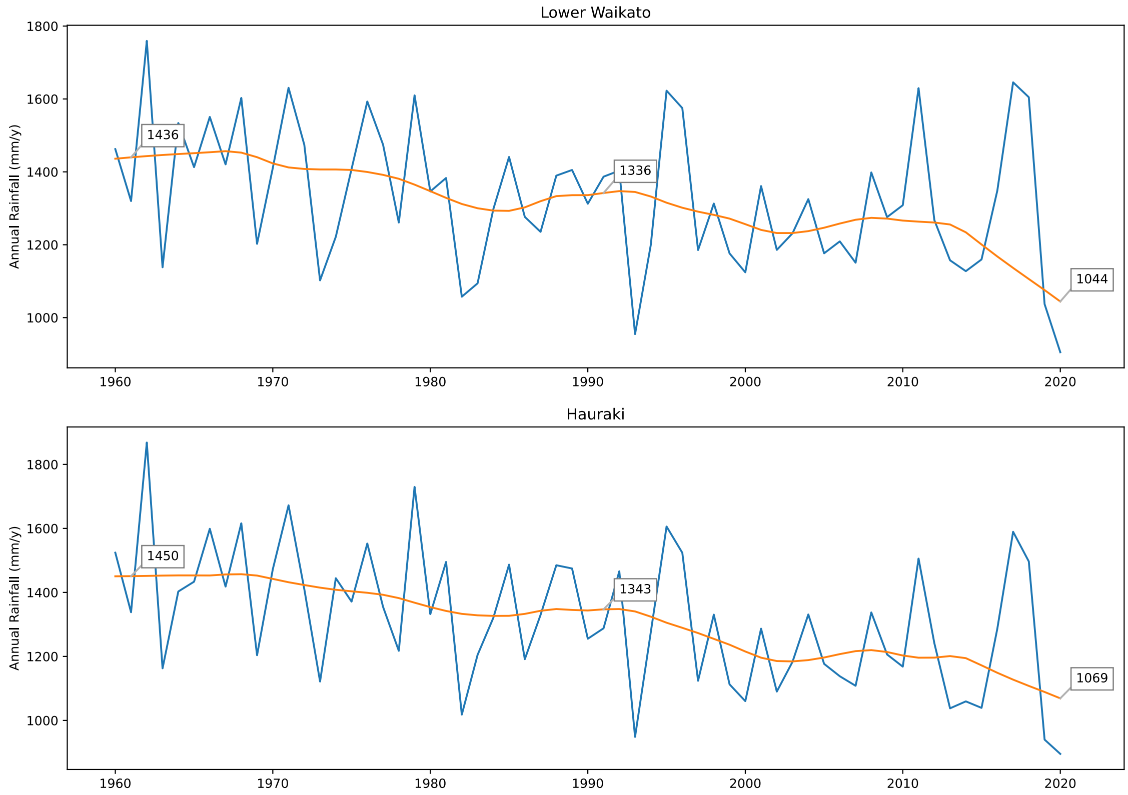


Figure 23. Subregions that experienced declining annual rainfall. Blue = Annual total rainfall. Orange = moving average by LOWESS.

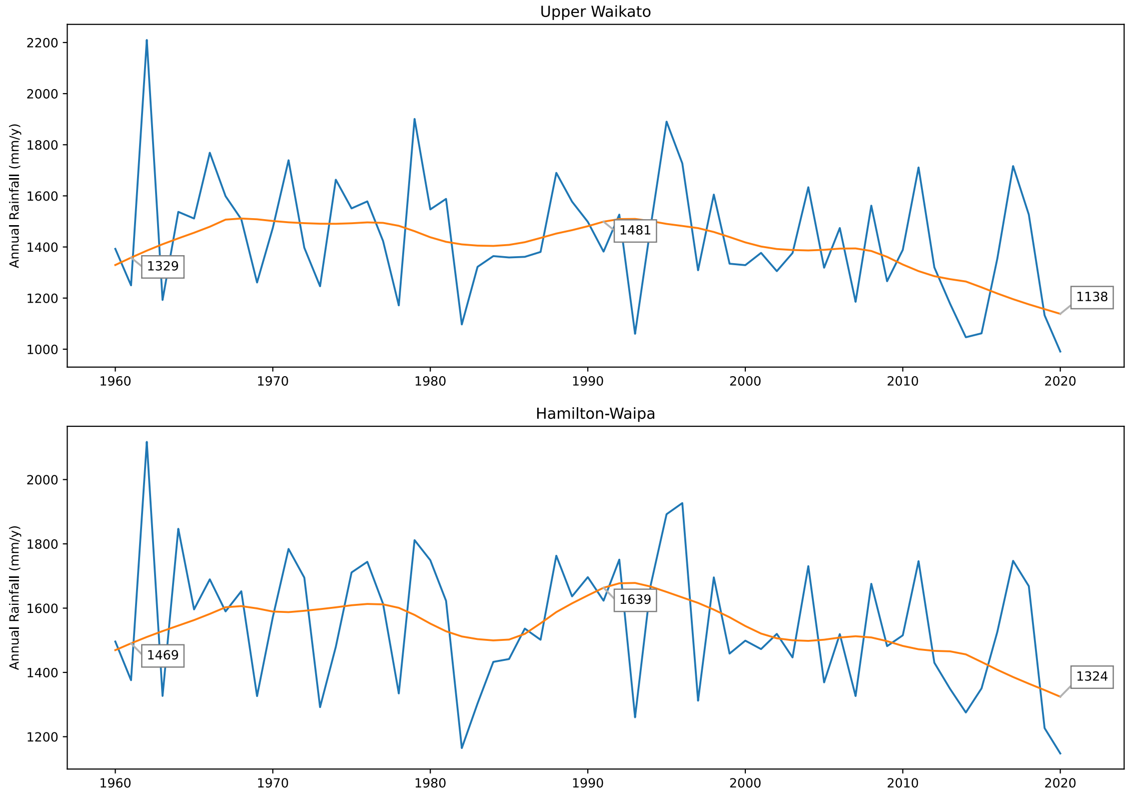


Figure 24. Subregions that experienced weaker declining trend in annual rainfall.

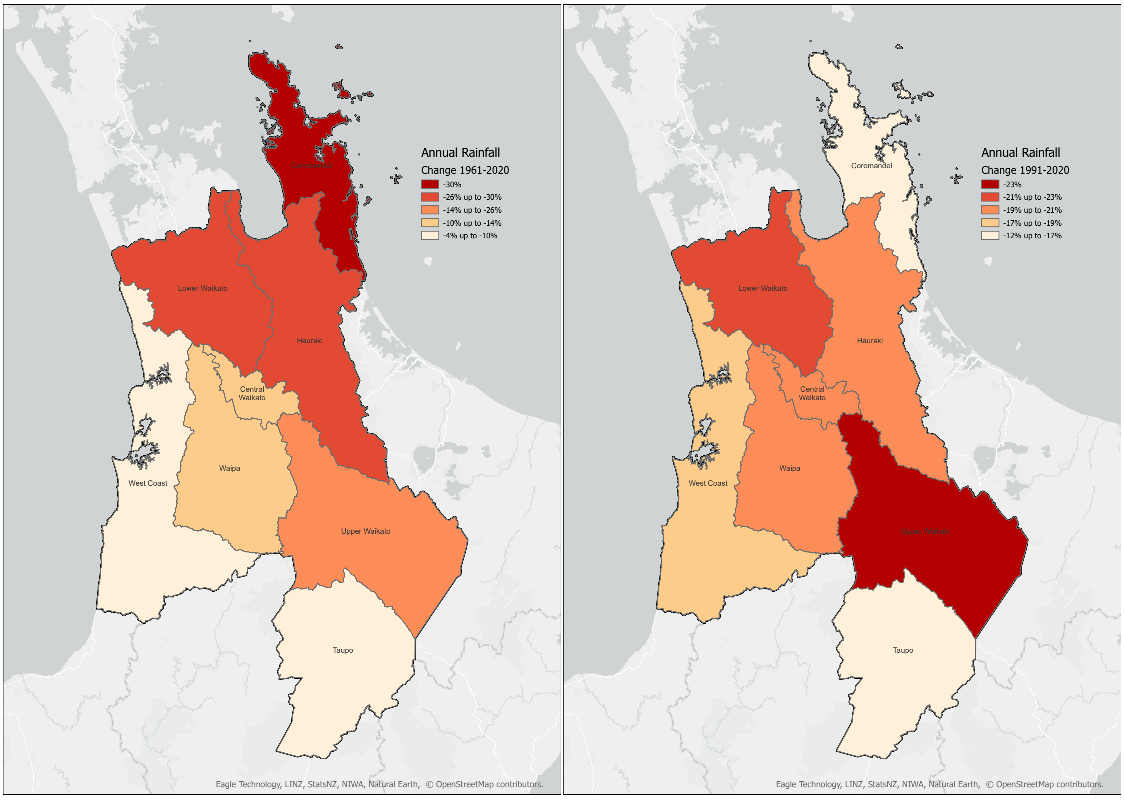


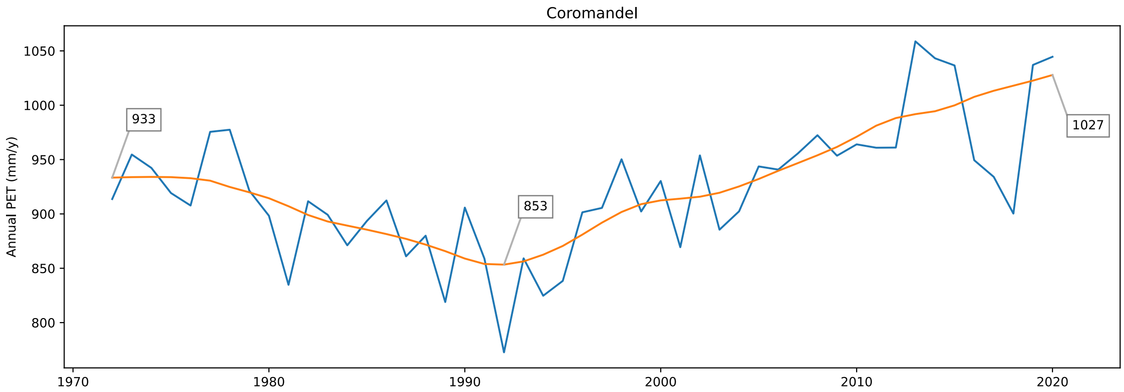
Figure 25. The subregions experienced the most decline in annual rainfall.

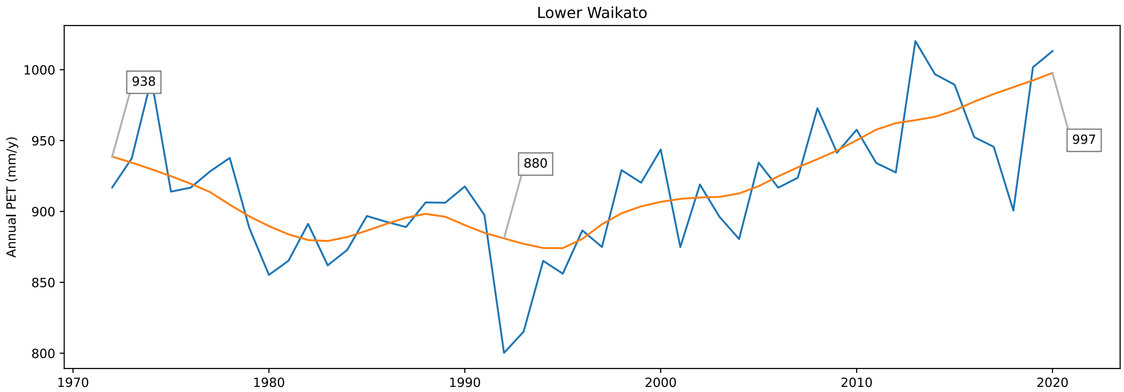
The evapotranspiration is another climate driver that determines the dryness of the region. Evapotranspiration is a result of combined effect of variety of factors including solar radiation, temperature, wind speed and humidity. The variable called Potential Evapotranspiration (PET) was chosen to represent the degree and trend of evapotranspiration occurring in the region. See section 3.1.1 and 3.2.3.1 for the definition of the variable and the method employed in its analysis.

The trend reversal pattern with the pivot point occurring in 1992 is the most prominent observable pattern in the long-term annual PET data. Despite a decline in the early period between 1972 and 1990 and a sharp decrease in 1992, followed by a steady rise, there was an increase in PET across all subregions throughout the entire analysis period from 1972 to 2020 (Table 8). The analysis period can be classified into two distinct periods based on this trend reversal: the earlier period from 1972 to 1992, which experienced a decline in annual PET, indicating wetter conditions, and the latter period from 1992 to 2020, which showed an increase in PET, leading to drier years. The division into distinct periods is visually demonstrated in Figure 26.

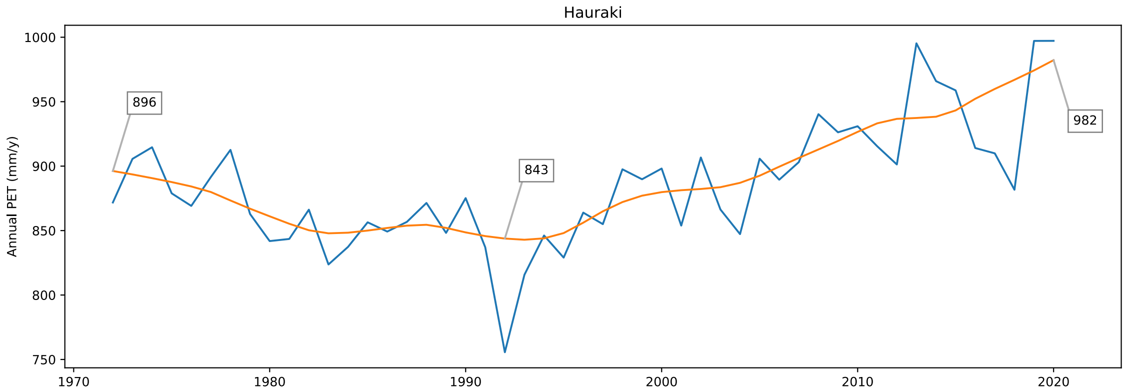
Table 8. Change in Annual PET. Moving Average = Yellow lines in Figure 26. This table is spatially represented in Figure 27. The red shade signifies high increase, and the green shade signifies reduction in PET.

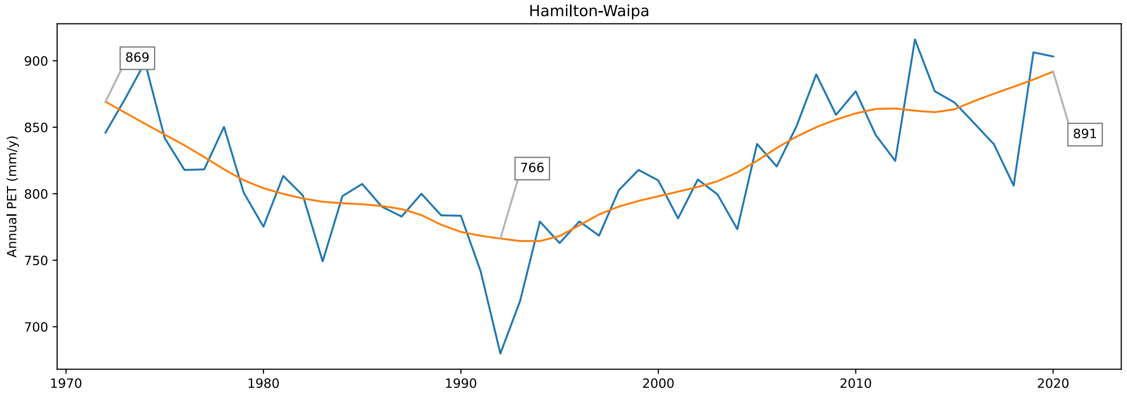
Subregion	Moving average 1972 (mm)	Moving Average 1992 (mm)	Moving Average 2020 (mm)	Change between 1972 and 1992	Change between 1992 and 2020	Change between 1972 and 2020
Coromandel	933	853	1027	-9%	+20%	+10%
Lower Waikato	938	880	997	-6%	+13%	+6%
Hauraki	896	843	982	-6%	+16%	+10%
Upper Waikato	837	757	919	-10%	+21%	+10%
Hamilton-Waipa[29]	869	766	891	-12%	+16%	+3%
West Coast	877	778	890	-11%	+14%	+1%
Taupō	765	668	855	-13%	+28%	+12%

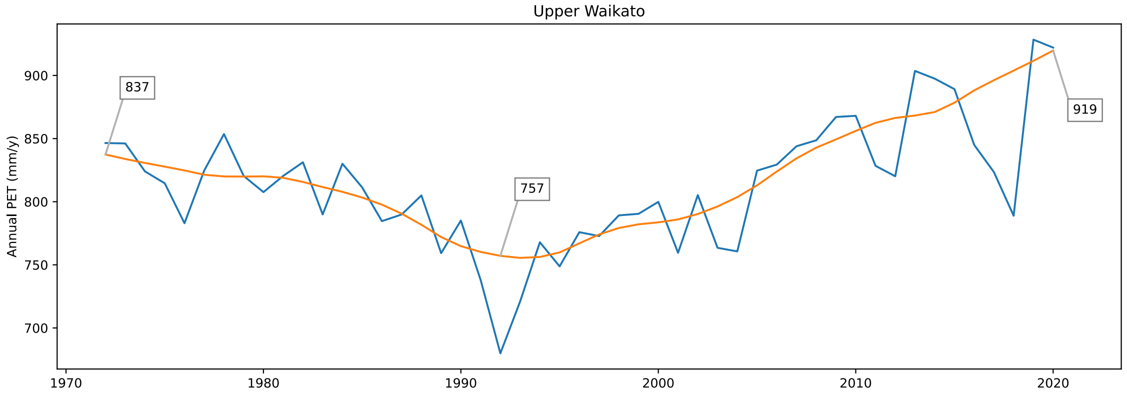


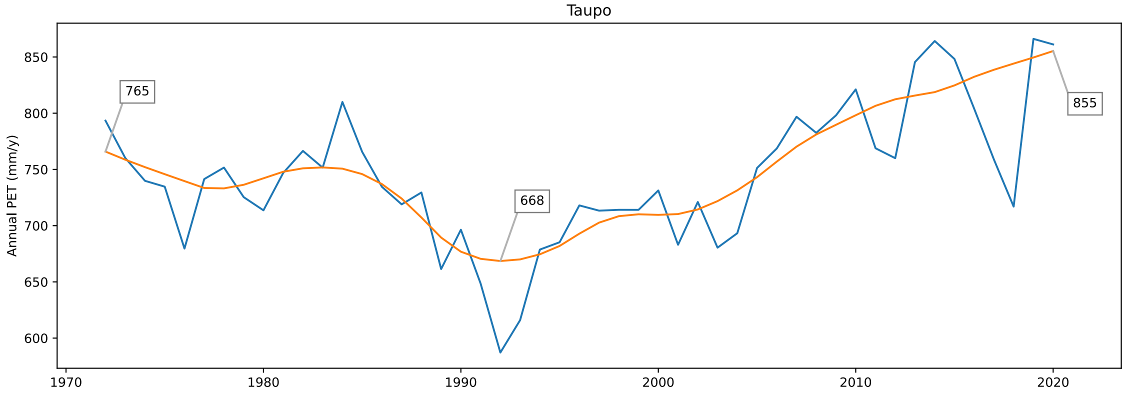


[29] Hamilton area is alternatively called Central Waikato.


Hauraki
Annual PET (mm/y)
896
843
982


Hamilton-Waipa
Annual PET (mm/y)
869
766
891


Upper Waikato
Annual PET (mm/y)
837
757
919


Taupo
Annual PET (mm/y)
765
668
855

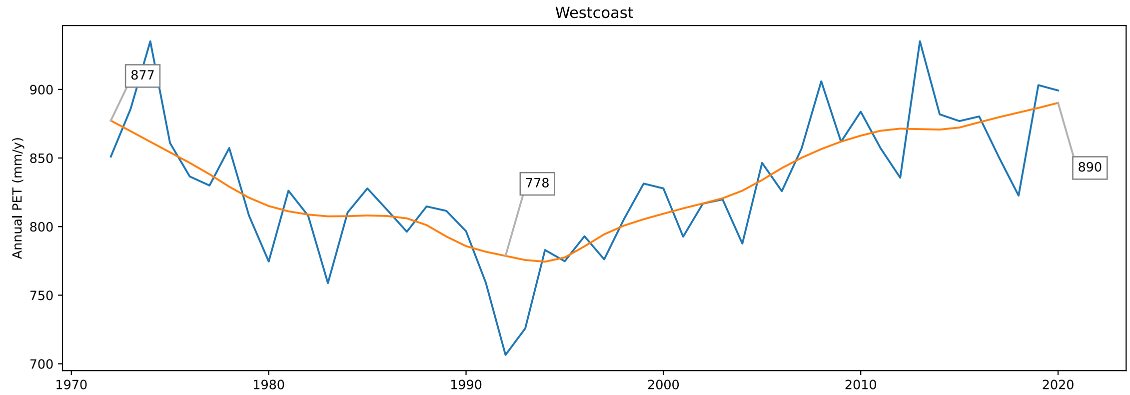


Figure 26. Change in annual PET in subregions of the Waikato Region, 1972-2020.

Although the trend reversal pattern was evident across all subregions, the degree of change varied among them. In terms of spatial distribution, the eastern subregions demonstrated a higher increase in annual PET throughout the entire analysis period between 1972 and 2020. However, when the analysis is focused on the modern decades of 1992-2020, the southern subregions, specifically Upper Waikato and Taupo, exhibited a greater increase in PET over the past three decades (Figure 27).

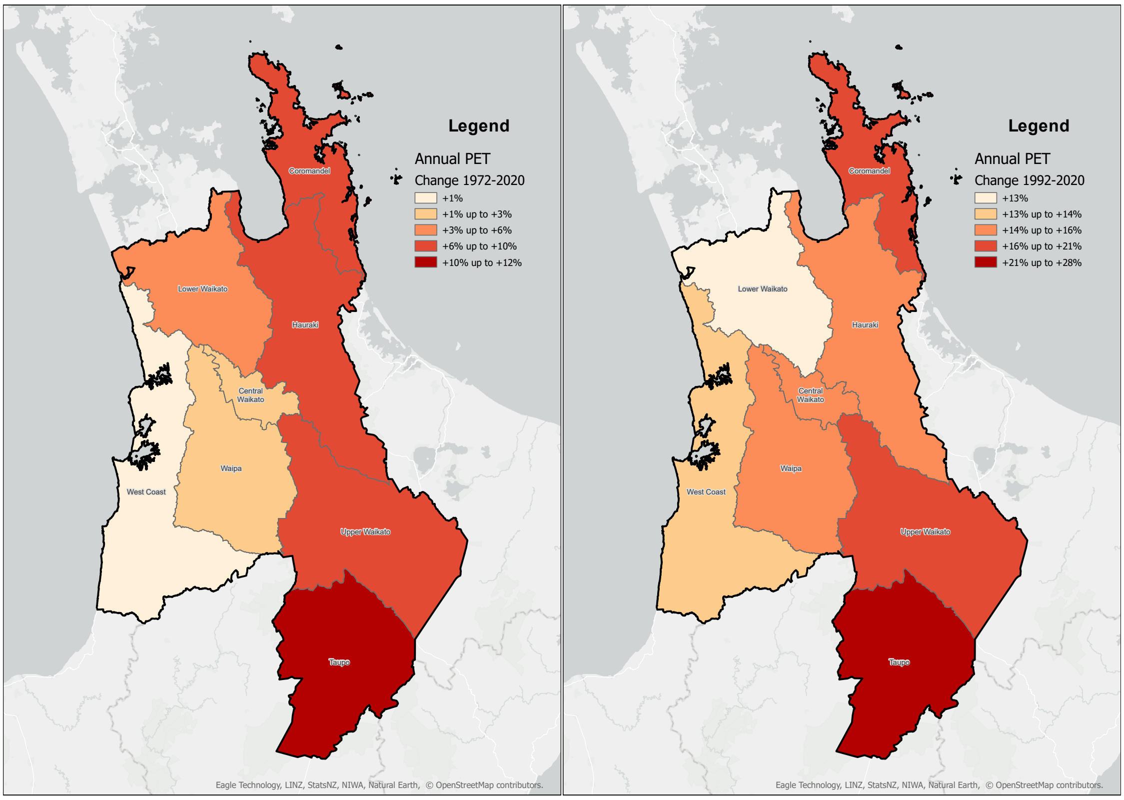


Figure 27. Changes in annual PET in subregions of the Waikato Region, 1972-2020 and 1992-2020.

Up until this point, rainfall and potential evapotranspiration (PET) have been separately analysed. However, the dryness of a given area is influenced by a combination of these two variables. The rainfall surplus over PET, which represents the difference between annual rainfall and annual PET, is a helpful indicator of the combined change in these two climate drivers. For instance, in 2020, the Coromandel subregion had an annual rainfall of 1548 mm and a PET of 1027 mm, resulting in a rainfall surplus over PET of 521 mm (as shown in Table 9). While Coromandel experienced the highest annual PET in the region, Taupō had the lowest PET at 855 mm. Nonetheless, the rainfall surplus over PET for Taupō was 613 mm, and despite having significantly lower PET than Coromandel, the dryness indicated by the rainfall surplus was similar due to their difference in annual rainfall.

During the investigation period of 1972-2020, all subregions experienced a decrease in rainfall surplus over PET (Table 9). Lower Waikato had the lowest rainfall surplus in terms of absolute numbers, followed by Hauraki and Upper Waikato subregion. These three subregions experienced the most significant change during the recent decades of 1992-2020, and they had the lowest rainfall surplus over the entire analysis period. It is noteworthy that Lower Waikato and Hauraki encountered an 80-90% reduction in rainfall surplus, indicating that these areas require greater attention in terms of water supply security. Notably, these two subregions have large highly allocated catchments (section 4.1.2; Figure 31). The Coromandel subregion reported the most significant reduction in rainfall surplus, with a decrease of 768 mm. Despite this, it is not as concerning from a water security standpoint as Lower Waikato and Hauraki because Coromandel had a high initial rainfall surplus, and the water demand density is low in the subregion.

Table 9. Change in Annual Rainfall Surplus over PET. This is an indicator of dryness. Rainfall surplus over PET = Annual Rainfall – Annual PET.

Subregion	Rainfall Surplus 1972 (mm)	Rainfall Surplus 1992 (mm)	Rainfall Surplus 2020 (mm)	Change 1972-1992 (mm)	Change 1992-2020 (mm)	Change 1972-2020 (mm)	Change 1972-1992	Change 1992-2020	Change 1972-2020
Coromandel	1289	940	521	-349	-419	-768	-27%	-45%	-60%
Lower Waikato	498	456	47	-42	-409	-451	-8%	-90%	-91%
Hauraki	554	500	87	-54	-413	-467	-10%	-83%	-84%
Upper Waikato	492	724	219	+232	-505	-273	+47%	-70%	-55%
Hamilton-Waipa	600	873	433	+273	-440	-167	+46%	-50%	-28%
West Coast	758	1103	656	+345	-447	-102	+46%	-41%	-13%
Taupō	778	1005	613	+227	-392	-165	+29%	-39%	-21%

4.1.1.2 Driest 90-day period

The water resource in the region typically experiences the highest level of stress in late summer and early autumn, at the end of the dry spell period. During these times, the demand for water is at its highest while the availability of resources is at its lowest. This section focuses on dry spell hydrologic conditions, which are more relevant to water resource availability than annual averages. While various lengths of dry spells can be analysed, a 90-day duration was chosen for analysis, as detailed in section 3.2.3.2.

Across all representative locations in the region, the rainfall depth within the driest 90-day period of the year has shown a decreasing trend over the analysis period from 1961 to 2020, similar to annual rainfall (as illustrated in Figure 28). The graphs' titles contain a five-digit code[30] that identifies the agent ID numbers in VCSN, while the orange line represents the smoothed LOWESS trend line of the fluctuating graph. The severity of dry spells increased in terms of received rainfall, particularly during the later half of the analysis period from 1990 to 2020. Prior to 1990, there were no common trend directions among subregions, but all subregions have experienced a decreasing trend in rainfall since then. While Coromandel experienced the smallest decrease, it had an exceptionally dry 90-day period in 2020, with only 50 mm of rainfall over the 90-day period when the average was around 200 mm.

[30] The five digit identifier is called agent number.

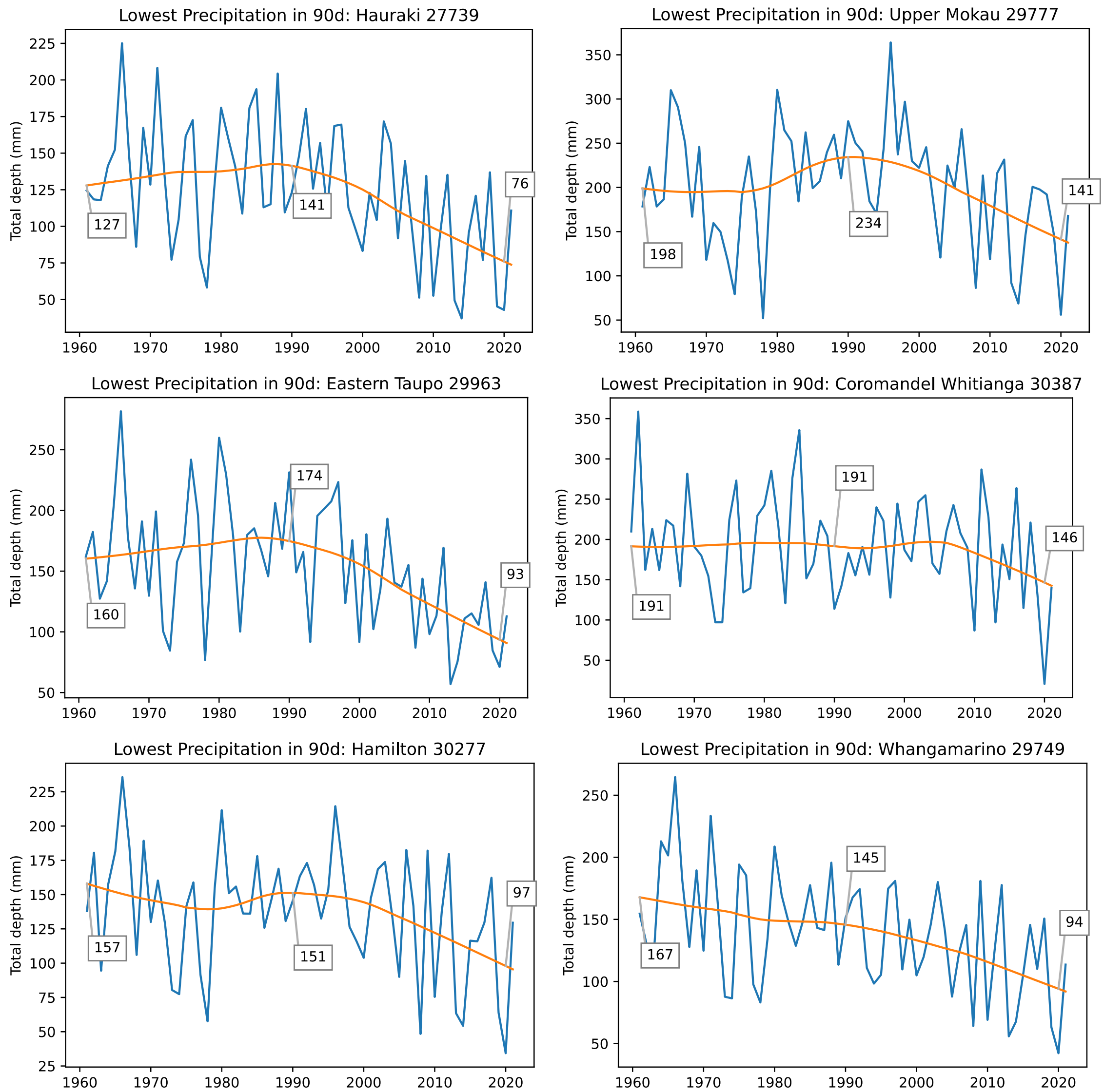


Figure 28. Rainfall received during the driest 90-days of the year at selected locations in the Waikato Region. The locations were mapped in Figure 30.

Similar trend reversal behaviour is observed in the 90-day dry spell PET as in annual PET (section 4.1.1.1). The turning point around in 1992 is observed. On average, the summer PET was in decreasing trend during 1972-1992 at every location of the region (Figure 29). From 1992, the trend reversed, and the summer PET increased steadily at every location of the region. The trend reversal behaviour was ubiquitous at everywhere in the region. For example, based on the orange trendline, the Hauraki (agent no 27739) region experienced an increase of average summer PET from 4.1 mm/d to 4.7 mm/d during 1992-2020. This is an increase of 15% in average summer PET. The Taupō area experienced the fastest increase in the average summer PET; a VCSN node in Eastern Taupō (agent no 29963) experienced an increase from 3.8 mm/d to 4.4 mm/d during 1992-2020, which was an increase of 16%.

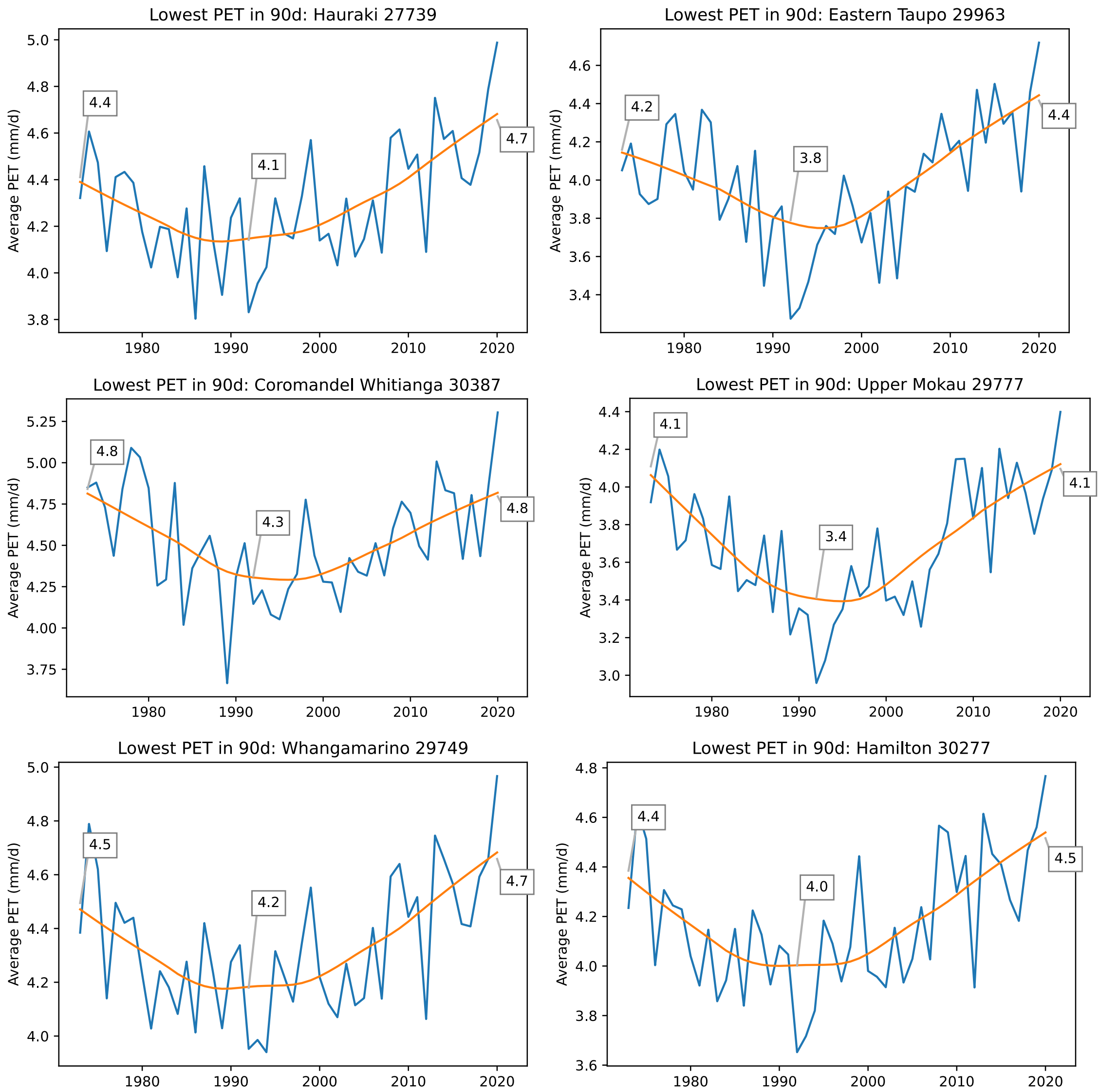


Figure 29. Average PET during the driest 90-days of the year. The locations were mapped in Figure 30.

The left panel of Figure 30 displays a map illustrating the spatial distribution of changes in dry spell rainfall over the 1990-2020 period. The dry spell changes were calculated separately for each of the VCSN agent nodes, and then interpolated using Kriging. The Hauraki Plains, Upper Mokau, and eastern parts of the Taupō catchment experienced the most significant decline in rainfall during this period, with typical reductions of up to 50%. The Coromandel area had the least reduction, with a decrease between 10% and 20%. Throughout the region, the severity of dry spells has consistently increased, with an average decrease of 40% in rainfall during 90-day dry spells. This indicates that, on average, the driest 90-day period of the year in 2020 received 40% less rainfall than it did in 1990 when averaged region-wide.

The right panel of Figure 30 shows that the spatial distribution of percentage change of 90-day dry spell PET. The PET increased at all locations between 1992 and 2020, with a minimum increase of 7%. The median increase was 14%, and most locations showed an increase of 12-20%. The southern end of the Taupō catchment experienced the greatest increase, with up to 55% greater PET. The northern part of the region did not experience as much of an increase in summer PET. In general, high-altitude, mountainous areas experienced greater increases in PET between 1992 and 2020.

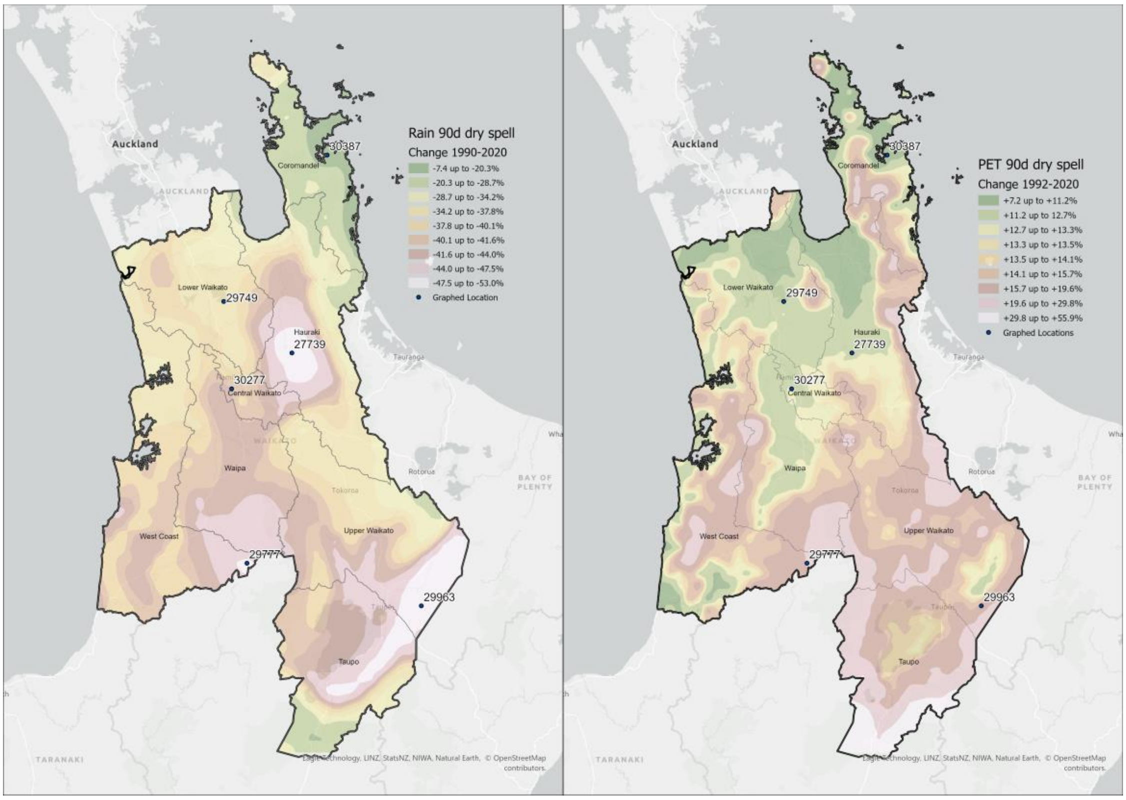


Figure 30. (LEFT) Percentage change in 90-day dry spell rainfall during 1990-2020. (RIGHT) Percentage change in 90-day dry spell PET during 1992-2020. Circles are the example location plotted in Figure 29.

4.1.2 Water allocation and use

Another factor that contributes to pressure on water bodies is human water use, specifically the extraction of water from them. The allocation levels serve as an indicator of the pressure experienced by the surface water bodies. Figure 31 illustrates the allocation levels of catchments in January and July, which are representative of maximum and minimum allocation pressures of the year. The Waikato Regional Council has implemented the allocation system that separately regulates allocation month by month, where the water users must specify in which months they are going to use water. In summer, represented by January, the water demand is high, and there are many consents related to seasonal irrigation. Consequently, the allocation pressure is higher during summer. The classification used in the map reflects the key allocation pressure thresholds that controls how the regional plan treats water take consents: 70% of primary allocable flow, primary allocable flow, and secondary allocable flow. Catchments that appear red, which are over-secondary allocable flow category, are considered over-allocated, and their allocation levels must be reduced below the allocation limits. The Piako River, Whangamarino River, and Pokaiwhenua Stream catchments are experiencing heavy allocation pressure. Some small headwater catchments also show high allocation pressures, typically due to municipal water extraction from springs. Table 10 provides an overview of the allocation pressures on major river catchments.

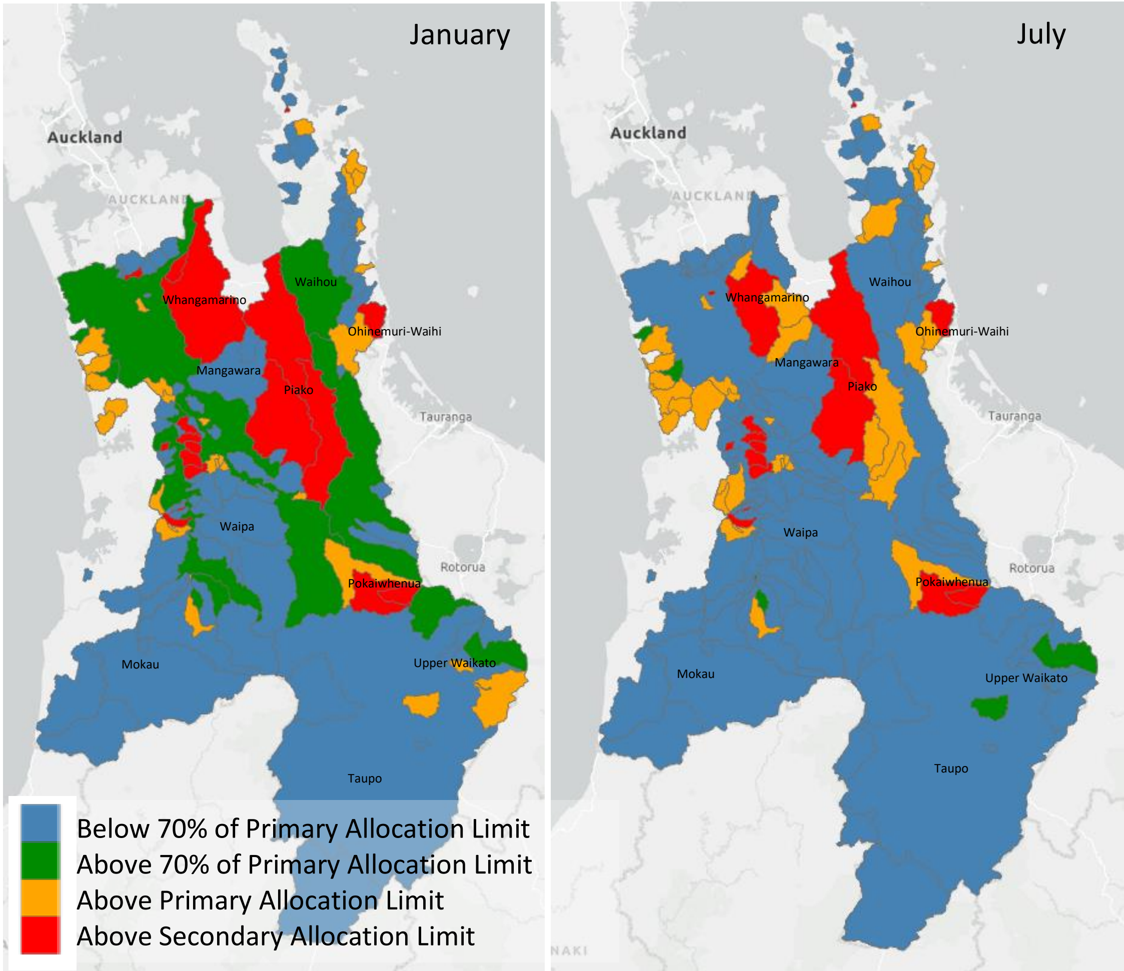


Figure 31. Allocation pressure in January and July. The Piako and Whangamarino catchments have very high allocation pressure.

Table 10. Allocation Status of key River catchments. Snapshot was taken on 5 May 2022.

WAC ID	CATCH_DESC	Area (km²)	Primary Allocable limit (m³/s)	Secondary Allocable limit (m³/s)	January Allocation (m³/s)	July Allocation (m³/s)	Allocation pressure %
397	Waikato River at CMA	14,410	18.793	0	16.765	12.524	89%
227	Waikato River at Karapiro Dam	7,838	7.400	0	6.439	2.587	87%
168	Waikato at Reids Farm	3,449	6.135	0	0.725	0.690	12%
339	Waipa River at Waikato confluence	3,093	1.560	3.120	1.499	1.015	32%
232	Waihou River at mouth	1,976	2.414	4.827	2.343	1.191	32%
237	Piako at mouth	1,481	0.638	0	0.968	0.804	152%
230	Mokau River at mouth	1,444	0.612	1.224	0.151	0.151	8%
120	Ohinemuri at Karangahake	285	0.173	0.346	0.296	0.278	57%
228	Kauaeranga River mouth	128	0.070	0.139	0.134	0.134	64%
-	Total of 5 rivers[31] at mouths	19,439	22.527	6.19	20.361	14.804	71%

The increase in water usage contributes to additional pressure, further reducing stream flows, in addition to the impact of climate drivers. The period of highest water demand coincides with the time of year when water availability is at its lowest. As a result, the critical time for water resource pressure analysis is during the summer months when the highest demand and lowest availability intersect. Consequently, the allocation practice in the Waikato Region is based on low flow statistics, specifically the Q_5, which refers to the 5-year return low flow. The regional allocation volume has consistently increased over the years until 2015 and has plateaued since then (Figure 32). The seasonal fluctuations observed in Figure 32 since 2012 are a result of the new allocation accounting system that considers monthly allocations.

[31] Fiver major rivers that have mouths to the sea: Waikato River, Waihou River, Piako River, Mokau River and Kauaeranga River

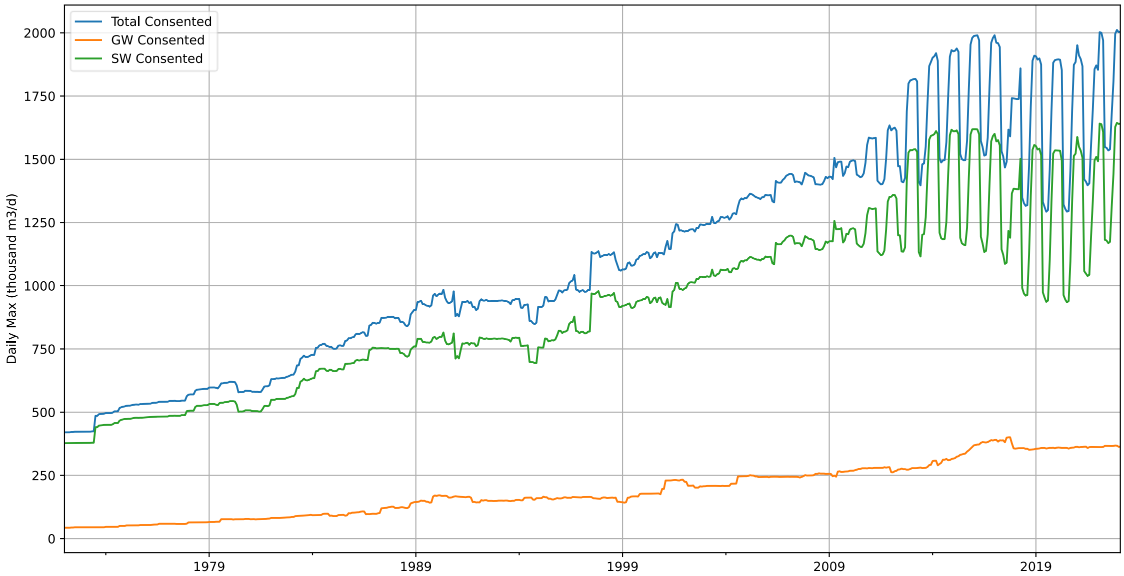


Figure 32. Growth of Total Region-wide Water Allocation. Sum of consented maximum daily rates.

The pressures were measured in terms of allocation levels, which are the maximum rates at which water users are permitted to extract water. However, the actual water usage is typically lower than the allocated rates. The region-wide historic actual water use was estimated from partial coverage of water metering, following the method described in section 3.2.1. The historic water use was broken down into ground water and surface water abstraction; and into four major water use categories, agriculture, municipal, industry and others.

The estimated total rate of groundwater abstraction has grown rapidly from the beginning of the recorded period until 1990, declined until 2013, and then increased again (Figure 33). Industrial uses have been the largest abstractor of groundwater since the beginning of the recorded period. Examples of the first industries to abstract groundwater include the Fonterra factory at Matangi, the paper mill at Kinleith, and the Waharoa Industrial Park; all of which began in 1969. Regional industrial groundwater abstraction increased until 2000 (Figure 33). Municipal and agricultural abstraction followed a similar pattern of growth until 2000, but declined until the early 2010s.

The estimates before 2000 is not as accurate as the estimates after 2000, when the water metering was introduced to the region (Figure 33). The estimated water take before the introduction of water metering was based on the total consented volume and utilisation ratio (section 3.2.1). However, estimation after the 2000s are deemed more reliable, as more of the estimated rate are based on direct measurements of water take. Municipal GW takes have remained constant since 2010, while agricultural GW takes have increased significantly since the early 2010s (Figure 33). Other GW takes (denoted by the red area) include ecological and recreational takes, such as golf course irrigation. Consents that were not classified under modern water use categories were classified as "others" during the database migration process from the old archives. The highest recorded regional GW abstraction rate peaked at 125,000 m^3/d (equivalent to a flow rate of 1.45 m^3/s).

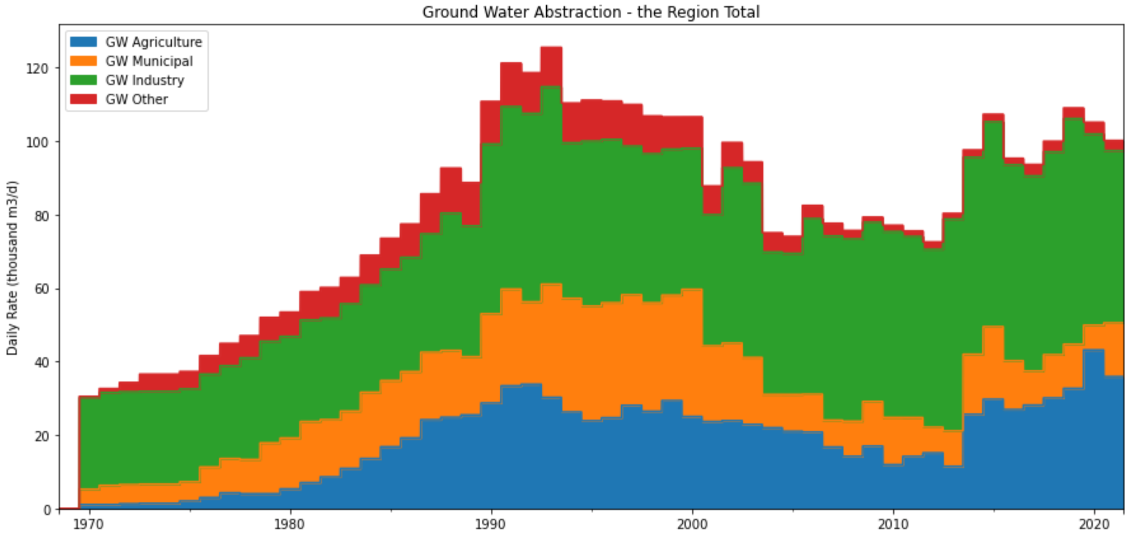


Figure 33. Estimated Groundwater use history in the Waikato Region 1968-2021.

The largest SW use category in the region is agricultural use, as shown in Figure 34. This encompasses the irrigation of pastures and horticultural crops, as well as stock welfare. Irrigation constitutes the largest water use within the agricultural sector and has consistently been the largest water user since the beginning of the record. However, a significant shift occurred in 1998 with the introduction of the Watercare take, which involved the abstraction of water from the lower Waikato for drinking water in Auckland. This marked a notable change, as agricultural and municipal water use became comparable in size in the early 2010s, but agricultural abstraction has increased significantly since then. Municipal SW take has not experienced significant growth since the introduction of the water take for Auckland in 1998. Although there was a marked increase in industrial use in 2001, water use has remained relatively stable. The other use category comprises ecological and recreational uses and excludes hydropower generation and flood management pumping. Geothermal water takes were included in the graph and were summed in the industry category.

Overall, both surface water (SW) and ground water (GW) abstraction have grown since the start of the consent record in 1968 (Figure 35). SW abstraction experienced a significant increase when Watercare began abstracting water for Auckland in 1997. The growth of water abstraction has accelerated since 2013, primarily due to an increase in agricultural use. In terms of volume, the region's water use heavily relies on SW extraction. The maximum regional total surface water use reached approximately 900,000 m^3/d, whereas the maximum regional total GW use was around 125,000 m^3/d in the most recent decade. The average peak combined water use between 1992 and 2022 was 1,025,000 m^3/d, equivalent to a flow rate of 11.9 m^3/s. To get a sense of scale of the water use, it can be compared against the sum of the January allocation in the five major rivers, 20.4 m^3/s, which is the current level of peak allocation (Table 10). This roughly indicates that the combined peak water abstraction rate was approximately 58% of the maximum consented take rate in the region[32]. Seasonal fluctuations began to appear in the record starting in 2010 due to increased water metering in the region, which provided more detailed water usage data. For a more in-depth analysis of water usage trends at a sub-regional level, see section 4.2.

[32] Calculated as 11.9 divided by 20.361.

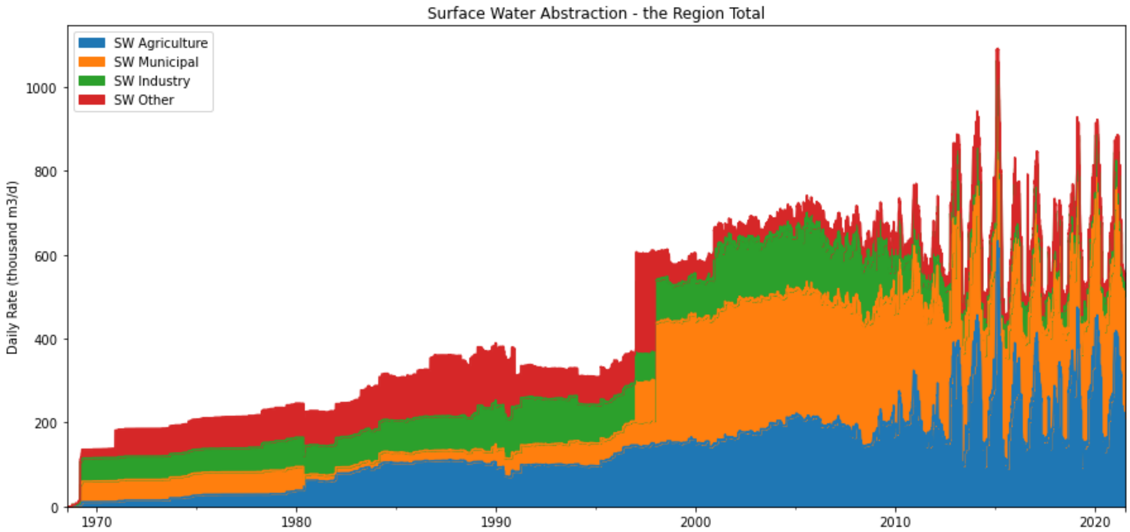


Figure 34. Estimated Surface water use history in the Waikato Region 1968-2021.

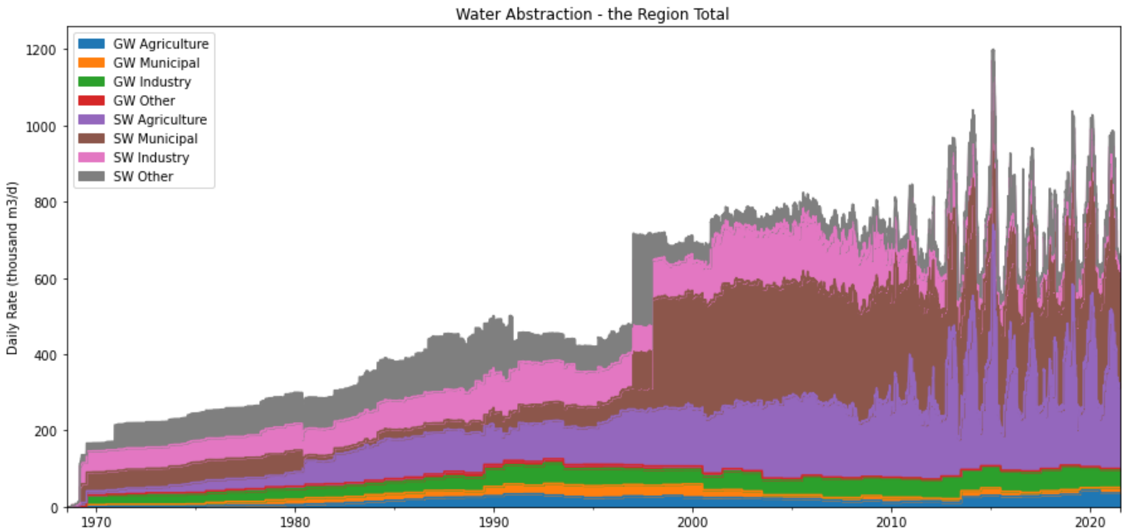


Figure 35. Estimated Total water use history in the Waikato Region 1968-2021.

4.1.3 Groundwater

Over the recent climate normal period of 1991–2020, there were similar numbers of bores with increasing and decreasing trends in water levels (see Figure 36). Out of the 237 long-term monitoring bores with at least 15 years of data, only 78 had data spanning the entire 30-year period. Unlike rainfall, potential evapotranspiration (PET), and river flows, which had a prevalence of trend in one direction, groundwater levels did not exhibit a consistent trend direction in the assessed bores. However, it is noted that there is higher degree of confidence in the decreasing trends, with the highest proportion of bores having a highly likely decreasing trend. While a decline in groundwater levels is expected in response to reduced rainfall and increased PET, the bores at different locations responded differently. The cause of this inconsistency was not investigated but is left as a subject for future study.

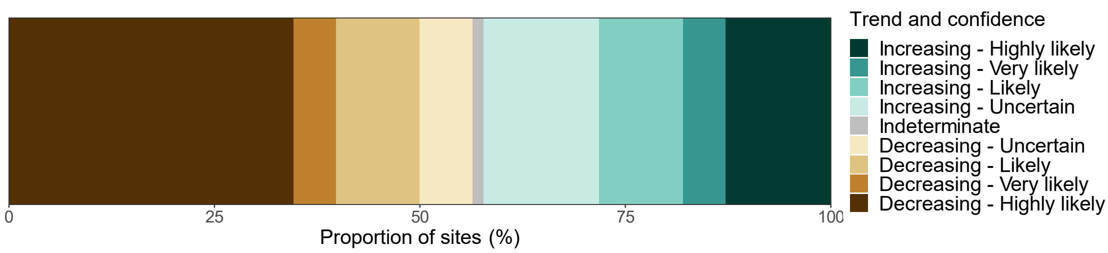


Figure 36. Proportion of trends by direction and confidence in groundwater over 30-year climate normal (1991–2020) for 79 stations.

Spatially, the bores used in the 30-year trend analysis were located around major groundwater production centres, as depicted in Figure 37. The spatial distribution of analysed bores covers the eastern half of the region, while bores with sufficient data for trend analysis are scarce in the western part of the region. This raises the question of whether the mixed trend found in the previous paragraph is representative of the entire region. The depth of bores was not assessed in relation to the trends and confidence.

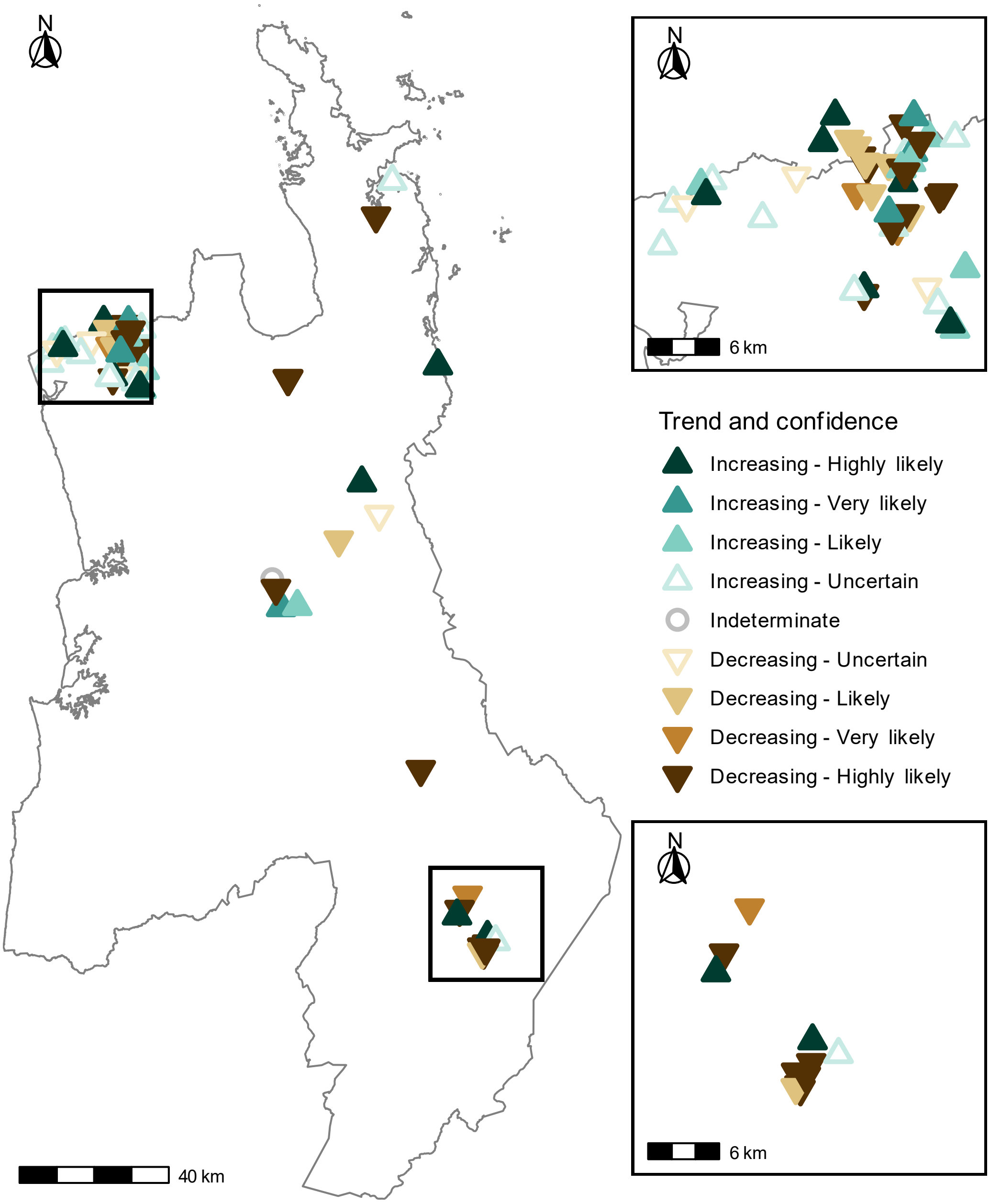


Figure 37. Trends in groundwater over 30-year climate normal (1991–2020) for 79 stations. Inserts show zoomed in area of northern and southern part of the region.

4.1.4 River flow

4.1.4.1 Annual Low Flow (ALF)

Observed or Modified Annual low flows (Mod ALF[33]) are a response to weather conditions during dry spells and water usage. The graph panels in Figure 38, Figure 39, and Figure 40 show the annual low flows (blue lines) at continuous flow monitoring stations that have been operational between 1980 and 2020. The red LOWESS curve shows the trend of the average annual low flow

[33] Observed or Modified ALF is what is observed at flow recorder stations. This is the annual low flow before naturalisation.

fluctuations. The majority of the red LOWESS curves in the flow monitoring stations show a common pattern of the annual low flows being steady or growing slightly until the mid-1990s, then clearly declining since then. For those that do not show a trend reversal, the long-term trend direction is downward. This pattern is similar to the trend reversal pattern found in dry spell climate variables, such as rainfall and PET, as described in section 3.2.3.2.

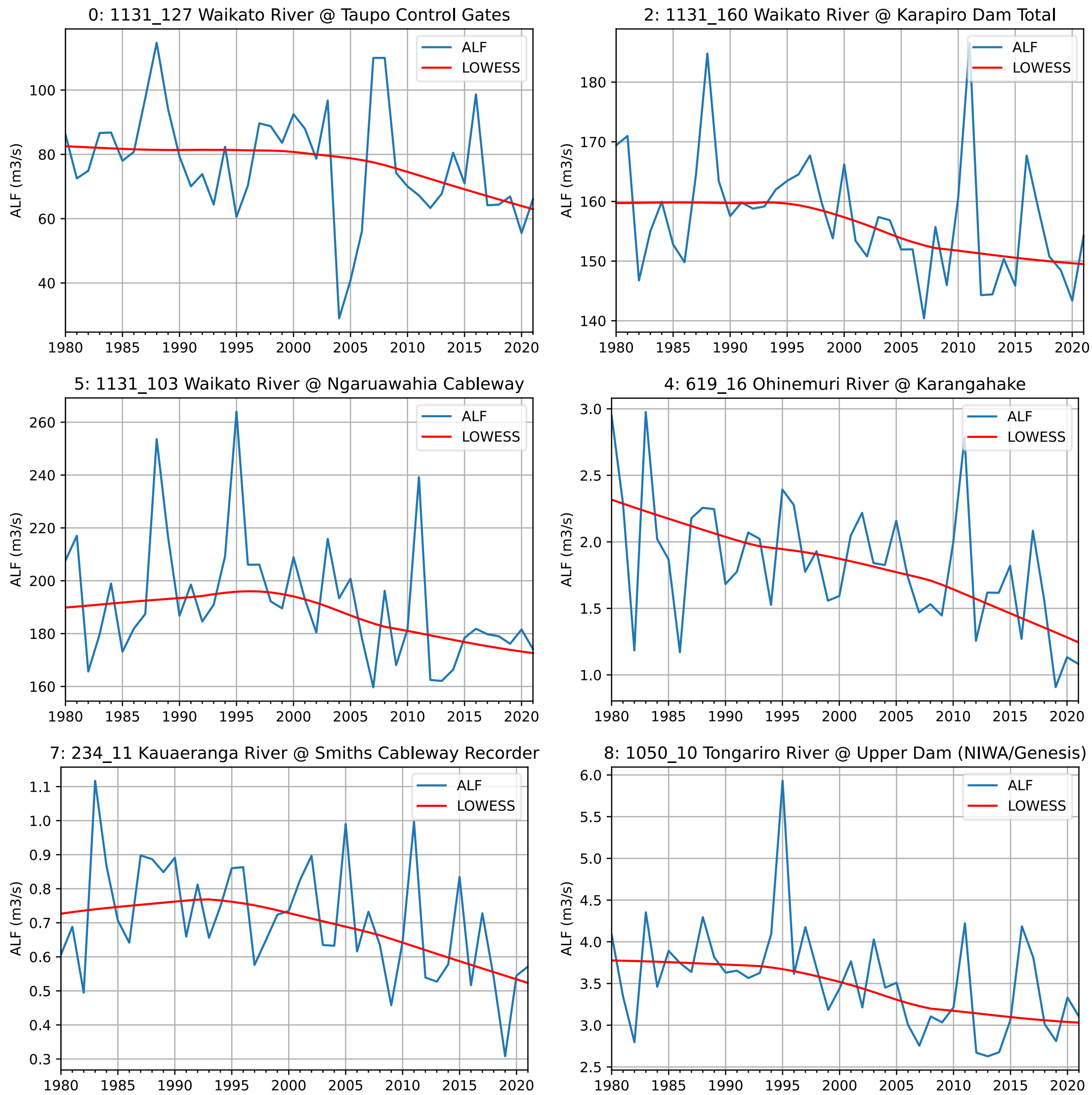


Figure 38. History of Annual Low Flow 1980-2020 – Panel 1. Downward trend is detected at most locations since 1990s.

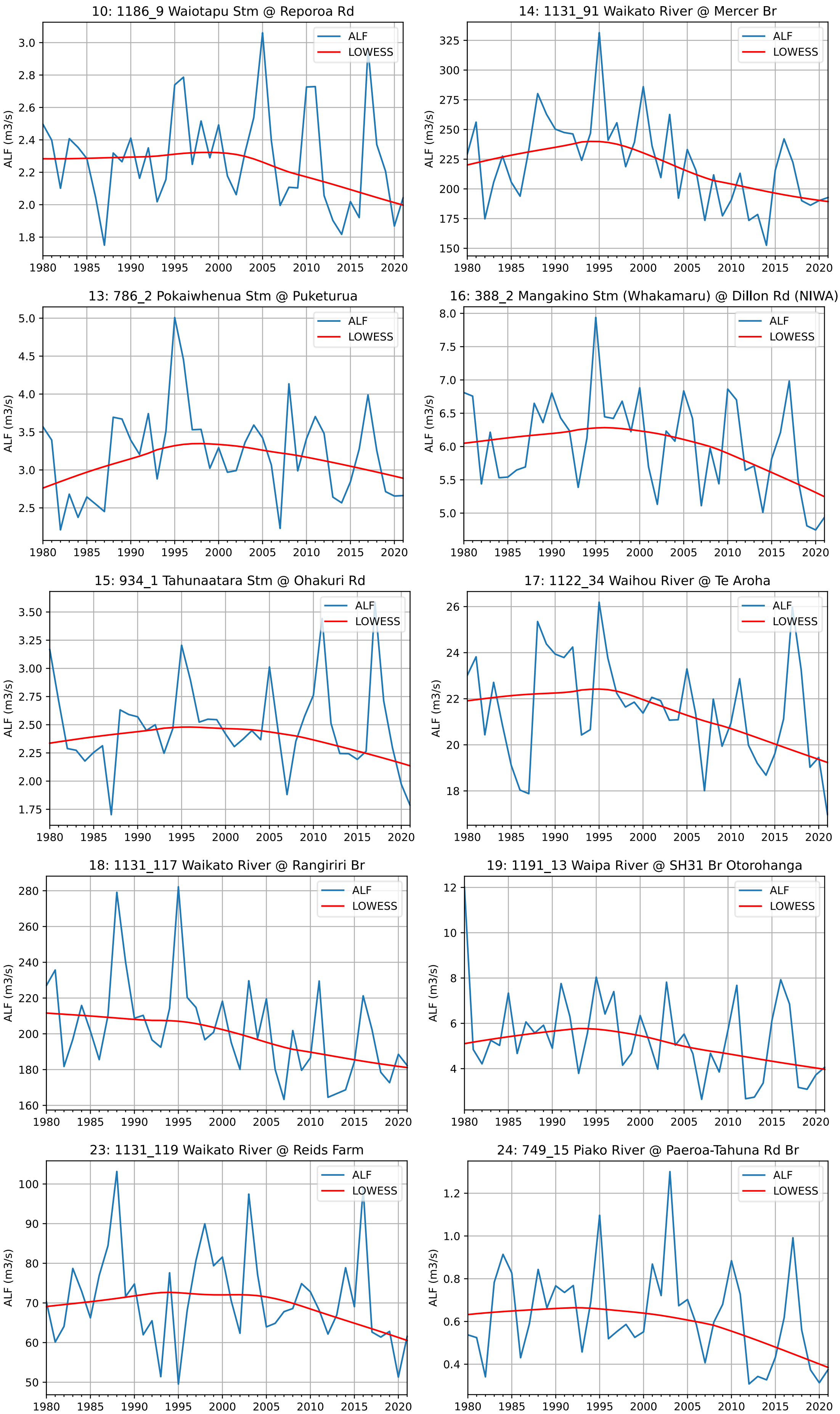


Figure 39. History of Annual Low Flow 1980-2020 – Panel 2. Downward trend is detected at most locations since 1990s.

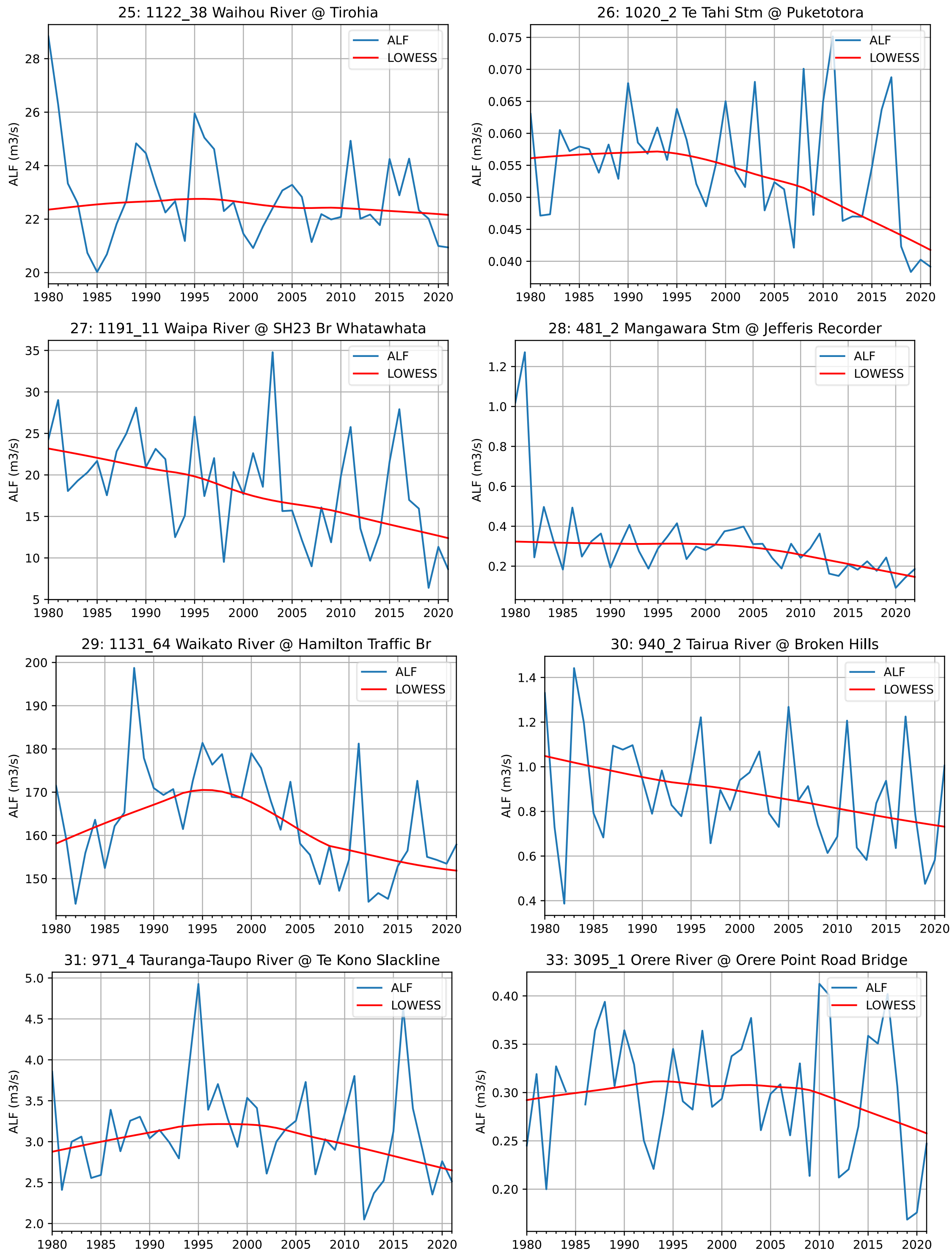


Figure 40. History of Annual Low Flow 1980-2020 – Panel 3. Downward trend is detected at most locations since 1990s.

While most catchments experienced declines in the period from 1990 to 2020, there were variations in the rate of change. Table 11 presents the percentage of flow changes from the baselines in 1990 and 2020, highlighting catchments that experienced significantly faster changes than others. The column titled "Rate of change 1990-2020" reports the rate of change experienced over the 30-year period, while the column titled "Rate of change 2010-2020" reports the rate of change experienced over the recent 10-year period. The rates reported in the second column were greater for all reported catchments, indicating that the rate of change accelerated at all locations in the recent decades. Mangawara Stream at Jefferis was the catchment that experienced the fastest change, followed closely by the Piako River at P-T road and the Tapu River[34]. In terms of spatial trends, catchments in the northern parts of the region

[34] To locate these locations, refer to Figure 16 on the map by using the station ID.

experienced a greater rate of decline than the southern parts. Section 4.2 revisits these values to determine the extent to which local climate change or growth in catchment-wide water abstraction affected these values.

Table 11. Changes in mod ALF experienced in various catchments.

Station Name	Station ID	Rate of Change 1990-2020 (per decade)	Rate of Change 2010-2020 (per decade)
Mangawara Stream at Jefferis	481_2	-16%	-32%
Piako River at P-T road	749_15	-14%	-31%
Tapu River at Tapu-Coroglen Rd	954_5	-25%	-30%
Waitoa River at Upper Piako	1249_38	-12%	-22%
Kauaeranga River at Smith	234_11	-11%	-17%
Waipa River at Otewa	1191_7	-12%	-16%
Mokau River at Totoro Bridge	556_9	-13%	-16%
Piako River at Kiwitahi	749_10	-10%	-15%
Ohinemuri River at Karangahake	619_16	-8%	-14%
Tairua River at Broken Hills	940_2	-8%	-13%
Waitoa River at Mellon Rd	1249_18	-5%	-12%
Waipa River at Honikiwi	1191_13	-8%	-11%
Waipa River at Whatawhata	1191_11	-10%	-10%
Mangaokewa Stream Te Kuiti Pump Station	414_13	-6%	-9%
Waiotapu at Reporoa	934_1	-3%	-6%
Mangakino at Dillon Rd NIWA	388_2	-4%	-6%
Marokopa River at Falls	513_7	-5%	-6%
Otamakokore at Hossack Rd	683_4	-3%	-5%
Tahunaatara at Ohakuri Rd	786_2	-2%	-3%
Puniu River at Pokuru Bridge	818_2	-3%	-3%

4.1.4.2 Annual flow

Annual average flow data reveals a similar decline pattern since 1961. Comparing the average standardised values for each year indicates a strong relationship between annual rainfall and river flows (Figure 41). The overall trend of declining rainfall from 1961 to 2020 is also reflected in the river flow time series. There was a notable reduction in rainfall and river flows following 1981, followed by an increase until the mid-1990s, before a sustained decline in both rainfall and river flow until the end of the analysis period. In 2020, the lowest rainfall on record for the analysis period coincided with the lowest recorded average river flows.

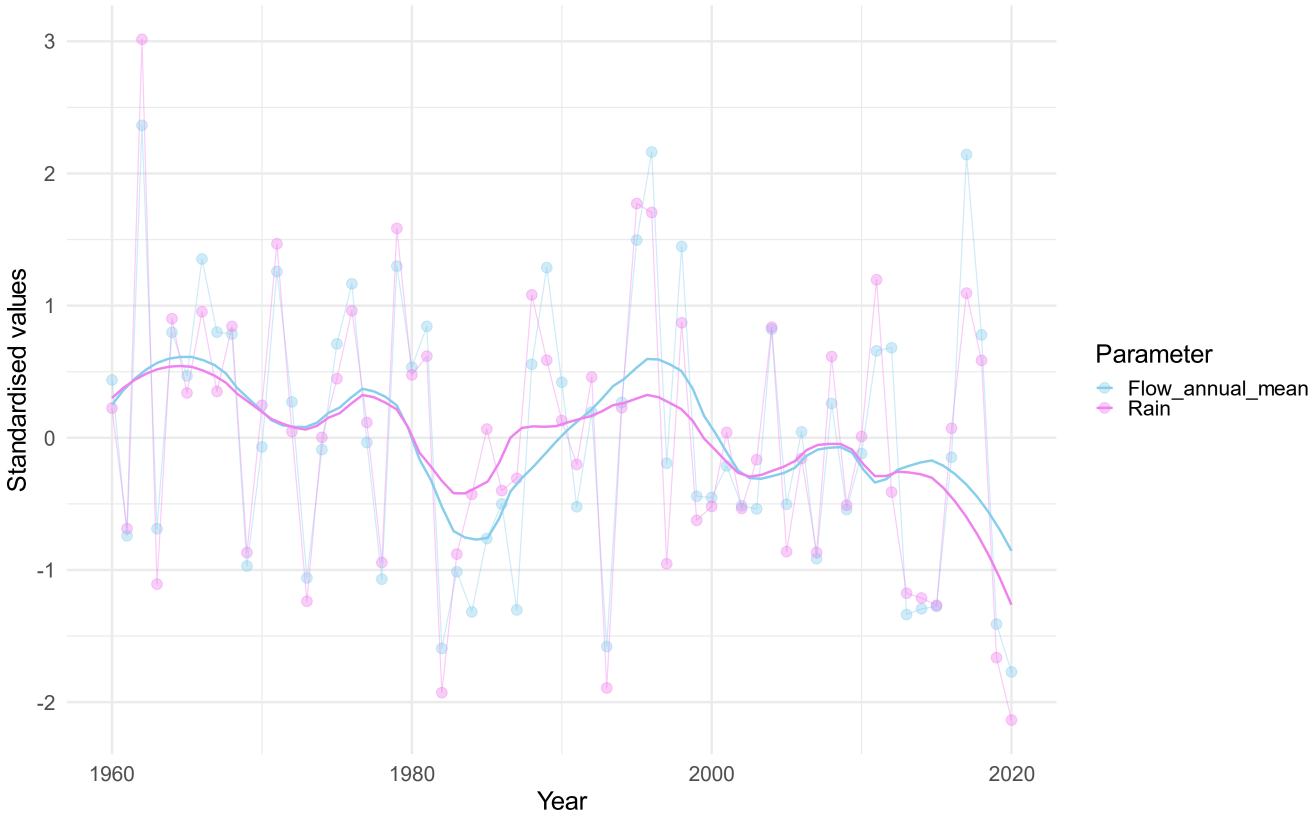


Figure 41. Changes in standardised annual average rainfall (pink) and standardised annual average riverflow (blue) (n = 17). LOWESS curves. Data Source: VCSN (rainfall) and measured flow.

The trend and associated confidence in trend of annual average flow timeseries were assessed for the most recent climate normal period of 1991-2020 (Figure 43). The analysis revealed a region-wide reduction in annual average streamflow over this period. Although three stations recorded an increase in Sen slope, the confidence in this increase in annual average flow over the period of analysis was “uncertain”. Furthermore, no stations had a Sen slope of zero or no trend. Out of the remaining 59 stations, 46 showed statistically significant decreasing trends, with a confidence in the trend direction that likely or higher confidence, which is in line with the reported decline in rainfall and increase in potential evapotranspiration. This finding is not unexpected.

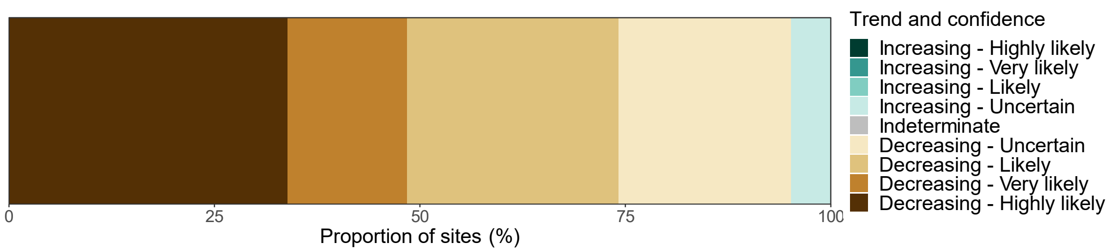


Figure 42. Proportion of trends direction in annual average flow over 30-year climate normal (1991–2020) for 62 stations.

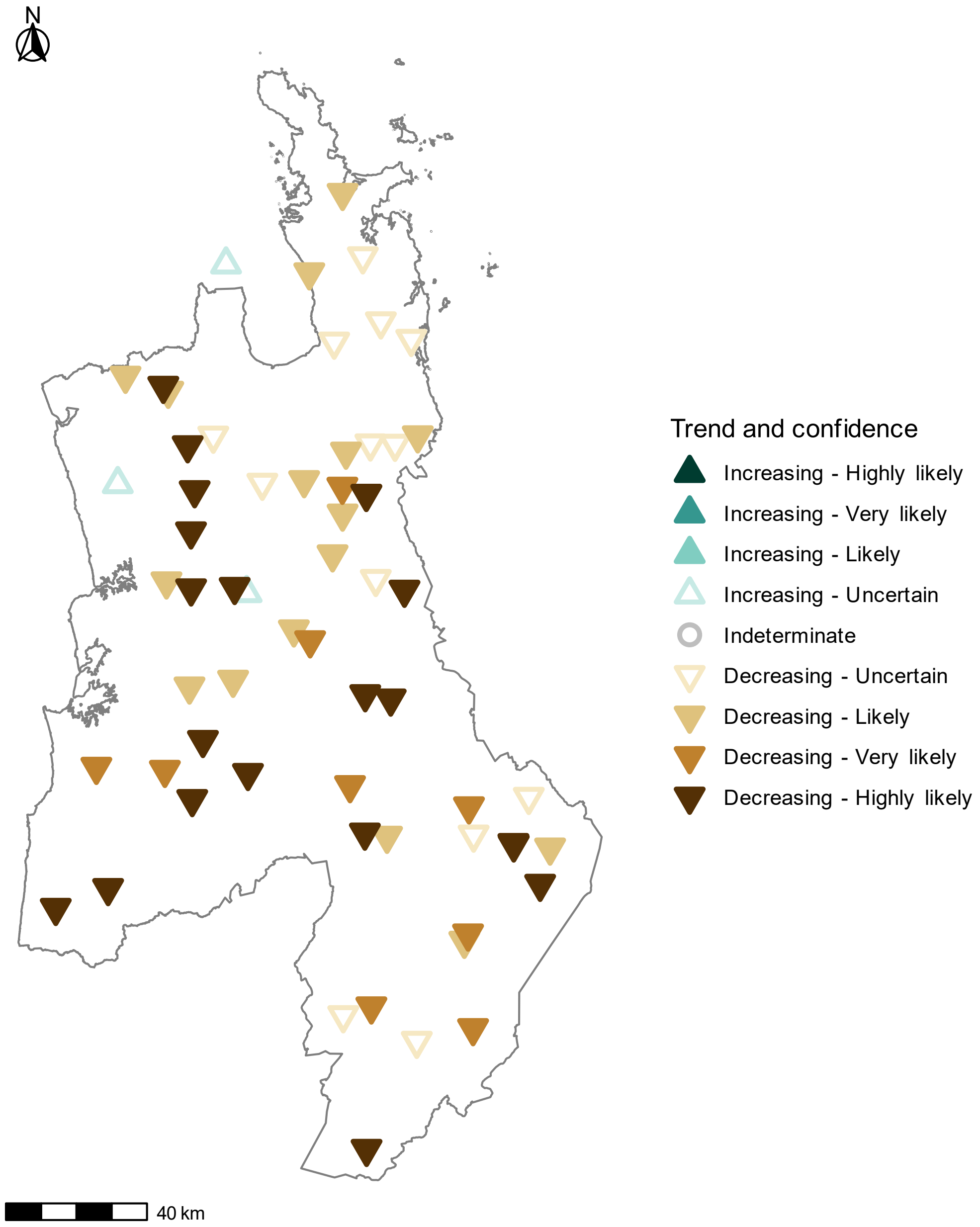


Figure 43. Trends in annual average flow over 30-year climate normal (1991–2020) for 62 stations.

4.1.4.3 Q_{5nat} at long-term flow recorder sites

One useful outcome that can be derived from analysing water use history and long-term low flow (ALF) timeseries is the naturalisation of Q_5 statistics, which are a key indicator of water resource availability. The Waikato Regional Council (WRC) has a policy of updating Q_5 statistics to reflect changes in instream flow conditions and water availability driven by climate change. This enables the WRC to respond to changes in climate and ensure that water resources are managed sustainably. To naturalise Q_5 statistics, a frequency analysis of the annual low flows was conducted, incorporating estimated water use data (see section 3.2.2.2 for details). The resulting statistics are known as naturalised Q_5. For this study, naturalised Q_5 only at flow recorder locations were evaluated, and the summary of the results is presented in Table 12. The naturalised Q_5 values are used to set minimum flow and allocation limits for each catchment. Catchments that show a positive change from the previous Q_5 estimate will have increased primary and secondary allocable flows, as well as increased minimum flows. The percentage changes in Q_5 estimates in the rightmost column of the table can be examined to gain understanding of the implications of this update on allocation practices. Catchments influenced by dams and weirs were excluded from the analysis.

Comparing the current Q_5 values to previous measurements provides insight into the rate of change of Q_5 and its impact on allocation pressures. The rightmost column of Table 12 shows the relative change in allocable flows resulting from this Q_5 update. Some catchments will have higher allocable flows, with increases of up to 27%, while the catchment with the largest reduction will experience a decrease of 13% in allocable flow. Another implication of the Q_5 change is a shift in the minimum flow, which is the level at which water use restrictions are triggered. Catchments with an increase in Q_5 will have their restriction triggers set at a higher level. The "Previous Q_5 Year" column indicates when the previous Q_5 measurement was taken. In most cases, the measurements were taken five years ago, but in two catchments, it has been longer since the last update.

Table 12. Summary of Q_5 naturalisation at key allocation catchments.

WAC ID	Name	Q_{5mod} (m^3/s)	Q_{5nat} (m^3/s)	Subregion	Previous Q_5 value (m^3/s)	Previous Q_5 Year	Change
146	Pokaiwhenua at Puketurua	2.889	**3.722**	Upper Waikato	2.924	1993	27%
123	Waihou at Tirohia	21.729	**22.757**	Waihou	20.352	2018	12%
141	Mangaonua at Dreadnought	0.763	**0.821**	Central Waikato	0.760	2017	8%
158	Otamakokore at Hossack Rd	0.644	**0.662**	Upper Waikato	0.640	2017	3%
147	Oraka at Pinedale	1.992	**2.002**	Waihou	1.945	2018	3%
129	Waitoa at Mellon Rd	0.788	**1.124**	Piako	1.097	2018	2%
140	Waihou at Okauia	18.704	**19.095**	Waihou	18.731	2018	2%
160	Tahunaatara at Ohakuri Rd	2.283	**2.32**	Upper Waikato	2.287	2016	1%
166	Tairua at Broken Hills	0.683	**0.686**	Coromandel	0.680	2017	1%
143	Puniu at Pokuru Bridge	2.879	**2.973**	Waipa	2.970	2017	0%
120	Ohinemuri at Karangahake	1.484	**1.734**	Waihi Basin	1.731	2018	0%
121	Ohinemuri at Queens Head	0.485	**0.652**	Waihi Basin	0.652	2018	0%
163	Waiotapu at Reporoa	2.028	**2.078**	Upper Waikato	2.094	2019	-1%
162	Mangakino at Dillon Rd NIWA	5.484	**5.54**	Upper Waikato	5.596	2005	-1%
242	Piako at Kiwitahi	0.138	**0.172**	Piako	0.173	2018	-1%
150	Tapu at Tapu-Coroglen	0.138	**0.138**	Coromandel	0.140	2017	-1%
170	Wharakawa at Adams Farm	0.259	**0.259**	Coromandel	0.265	2017	-2%
153	Marakopa at Falls	1.383	**1.388**	Westcoast	1.447	2017	-4%
159	Mangaokewa at Te Kuiti Pump Station	0.77	**0.8**	Waipa	0.840	2017	-5%
127	Mangawara at Jefferies	0.198	**0.208**	Lower Waikato	0.220	2017	-5%
171	Kauaeranga at Smith	0.557	**0.57**	Coromandel	0.600	2017	-5%
156	Waipa at Otewa	1.58	**1.599**	Waipa	1.701	2017	-6%
179	Whakapipi at SH22	0.078	**0.113**	Lower Waikato	0.121	2020	-7%
149	Waipa at Honikiwi	3.564	**3.819**	Waipa	4.130	2017	-8%
165	Mokau at Totoro Bridge	3.524	**3.646**	Westcoast	3.980	2017	-8%
138	Waipa at SH23 Br Whatawhata	12.155	**13.268**	Waipa	15.011	2017	-12%
240	Waitoa at Waharoa control	0.15	**0.197**	Piako	0.226	2018	-13%

4.2 Subregions

This section presents an individual examination of each subregion, reporting trends in water use and low flow. In catchments with high allocation pressures, water use may significantly contribute to the change in annual low flows. To separate the impact of climate change from that of water use on annual low flows, a novel approach was used (for detail see section 3.2.4). The section is presented in an encyclopedic style, allowing readers to easily locate and reference information specific to their region of interest. The overview of subregions and the flow stations included in the analysis can be found on the map in the Figure 44.

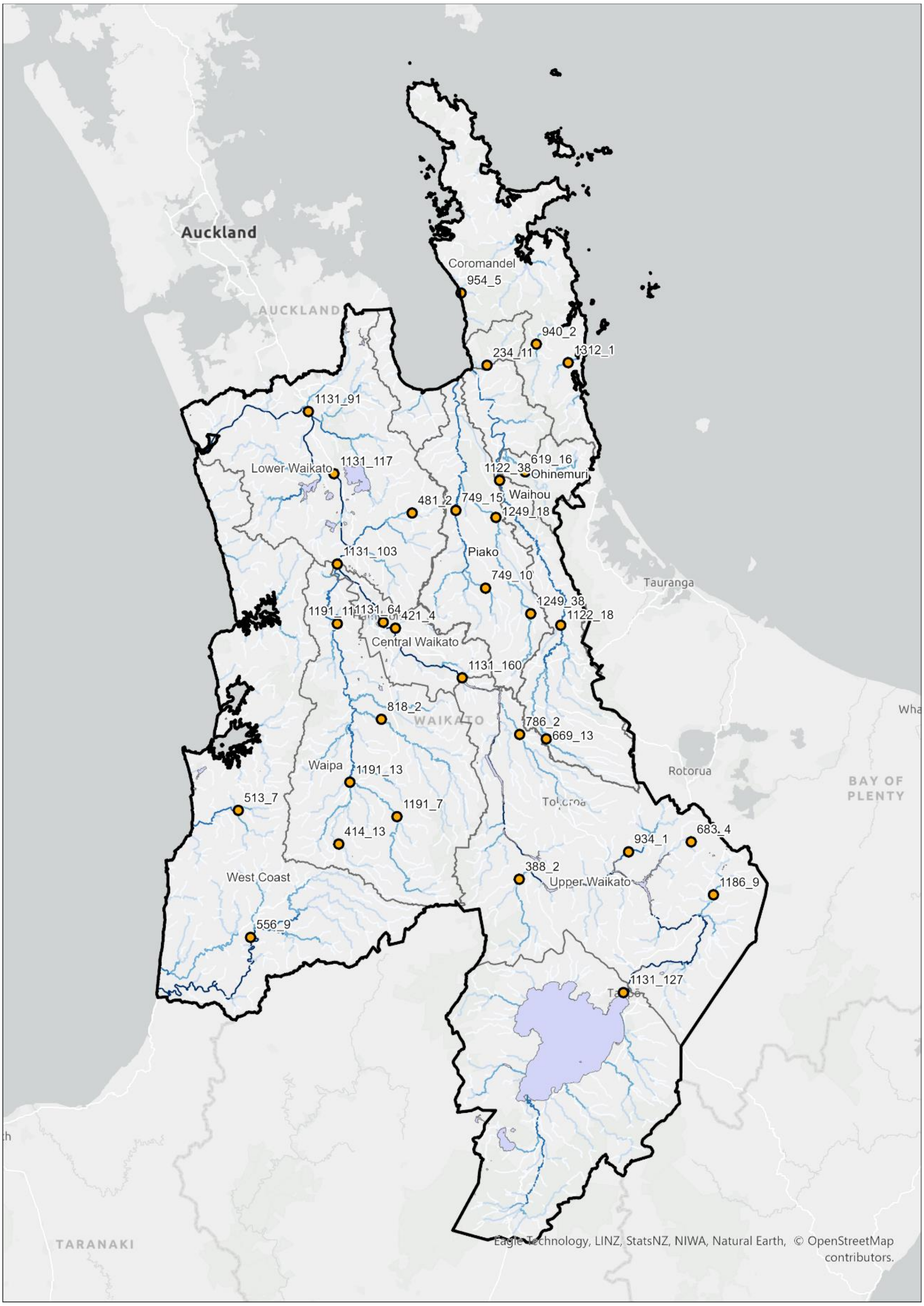


Figure 44. Flow stations examined in the analysis of subregion low flow.

4.2.1 Waikato River

4.2.1.1 Trend in water use

Groundwater (GW) usage steadily grew until 1990, after which it remained relatively stable (Figure 45). While reliance on GW for municipal purposes decreased in 2000, industrial GW usage increased to fill the gap. Agricultural GW usage also increased sharply in the mid-2010s.

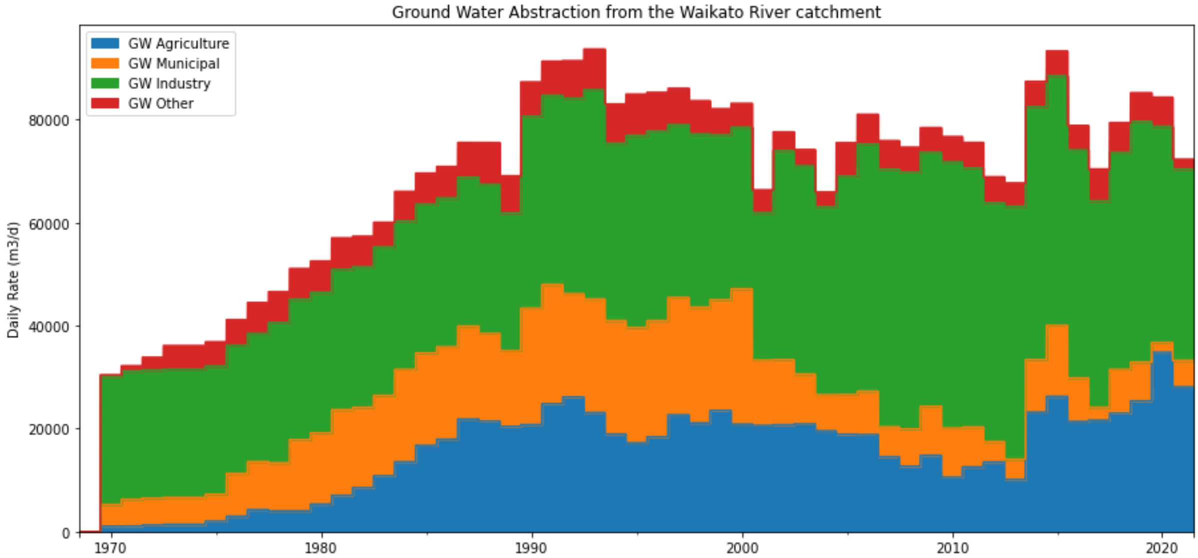


Figure 45. Estimated Groundwater use history in Waikato River CMA catchment 1968–2021.

Surface water (SW) usage increased in steps (Figure 46), starting with the introduction of the Auckland water take and step increases in industrial usage in the 1990s, followed by agricultural increases in 2001 and 2010. The rate of SW usage remained steady after the last step change in agricultural use in 2010. The highest recorded combined GW and SW usage in summer was 920,000 m^3/d in 2014 (Figure 47), equivalent to a rate of 10.7 m^3/s. As of 1 April 2022, the total allocation of the Waikato River was 16.8 m^3/s in January.

The utilisation level, which is the ratio between actual peak water usage and the total allocated water (consented plus permitted), reached a maximum of 64% in 2014. The average peak utilisation for the period 2010-2020 was 55%.

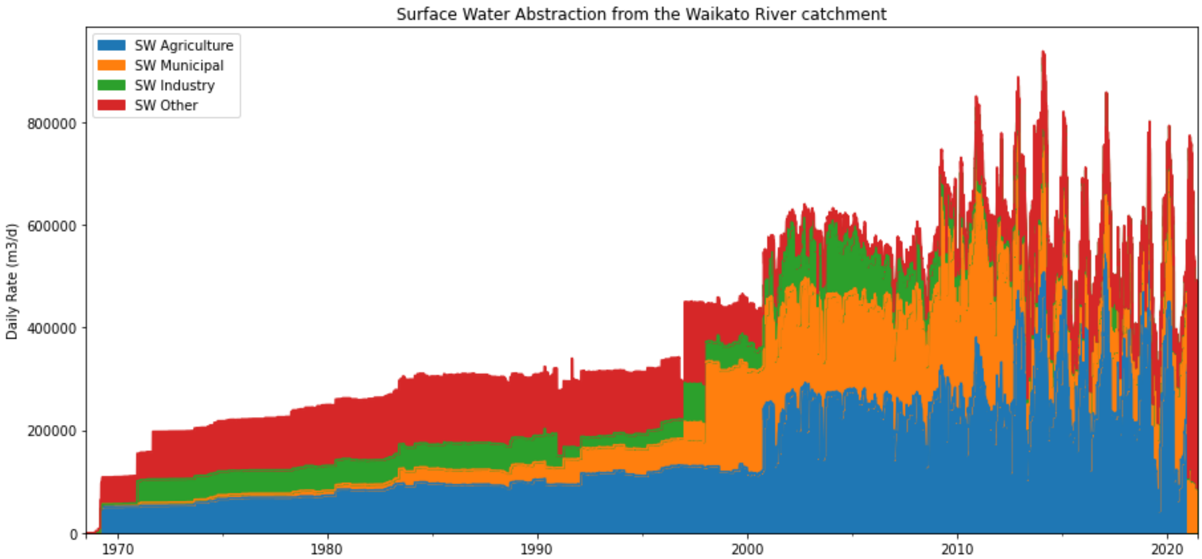


Figure 46. Estimated Surface water use history in Waikato River CMA catchment 1968-2021.

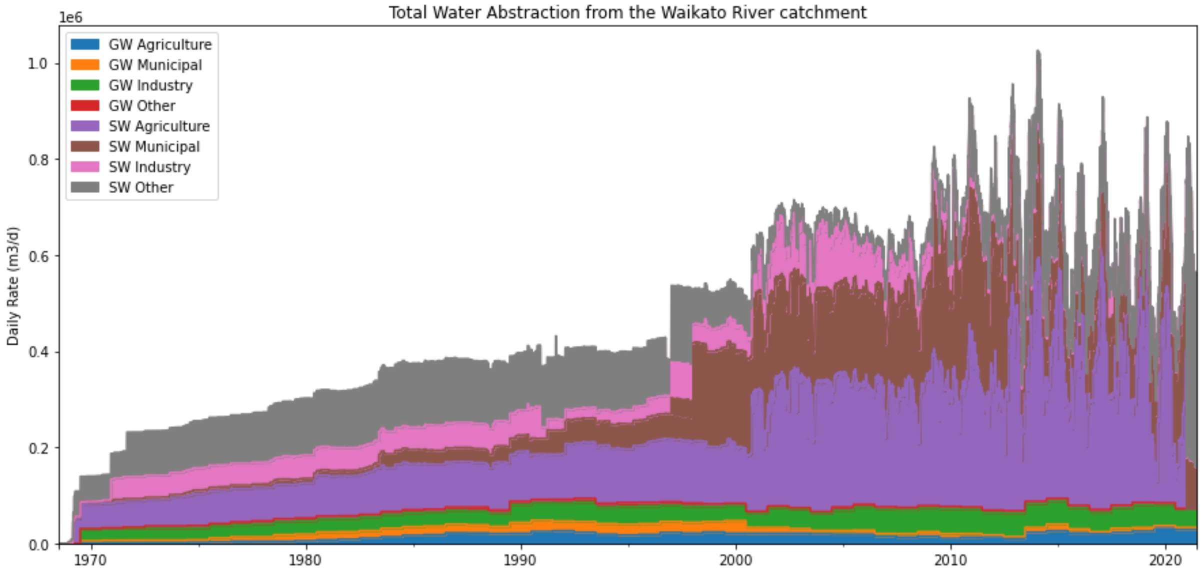


Figure 47. Estimated Total water use history in Waikato River CMA catchment 1968-2021.

4.2.1.2 Trend in Annual Low Flow (ALF)

Despite the impact of hydrodams operation, the mainstem flow monitoring stations of the Waikato River continue to reflect the catchment's overall wetness trend. Hydrodam releases are artificially controlled and are heavily influenced by electricity demand and price. Naturalisation of river flows influenced by dams requires daily inflow and outflow data and the data was not readily available for all hydrodams in Upper Waikato subregion. The naturalisation including the effect of hydrodams will be done in future hydrology SOE report.

However, consent conditions set important management targets, including the maintenance of reservoir minimum and maximum levels. In case of excess flows from upstream tributaries, dams will release more water than usual, while in cases of anticipated lower inflows due to rain and upstream tributary flow, the dams will release less water. Thus, these flow signals are indicative of the upstream tributary catchments' water flow. As previously discussed in section 4.1.4.1, the Waikato River's mainstem flow monitoring stations follow a common pattern of increasing trend up until the mid-1990s, followed by a decline trend since then (Figure 48).

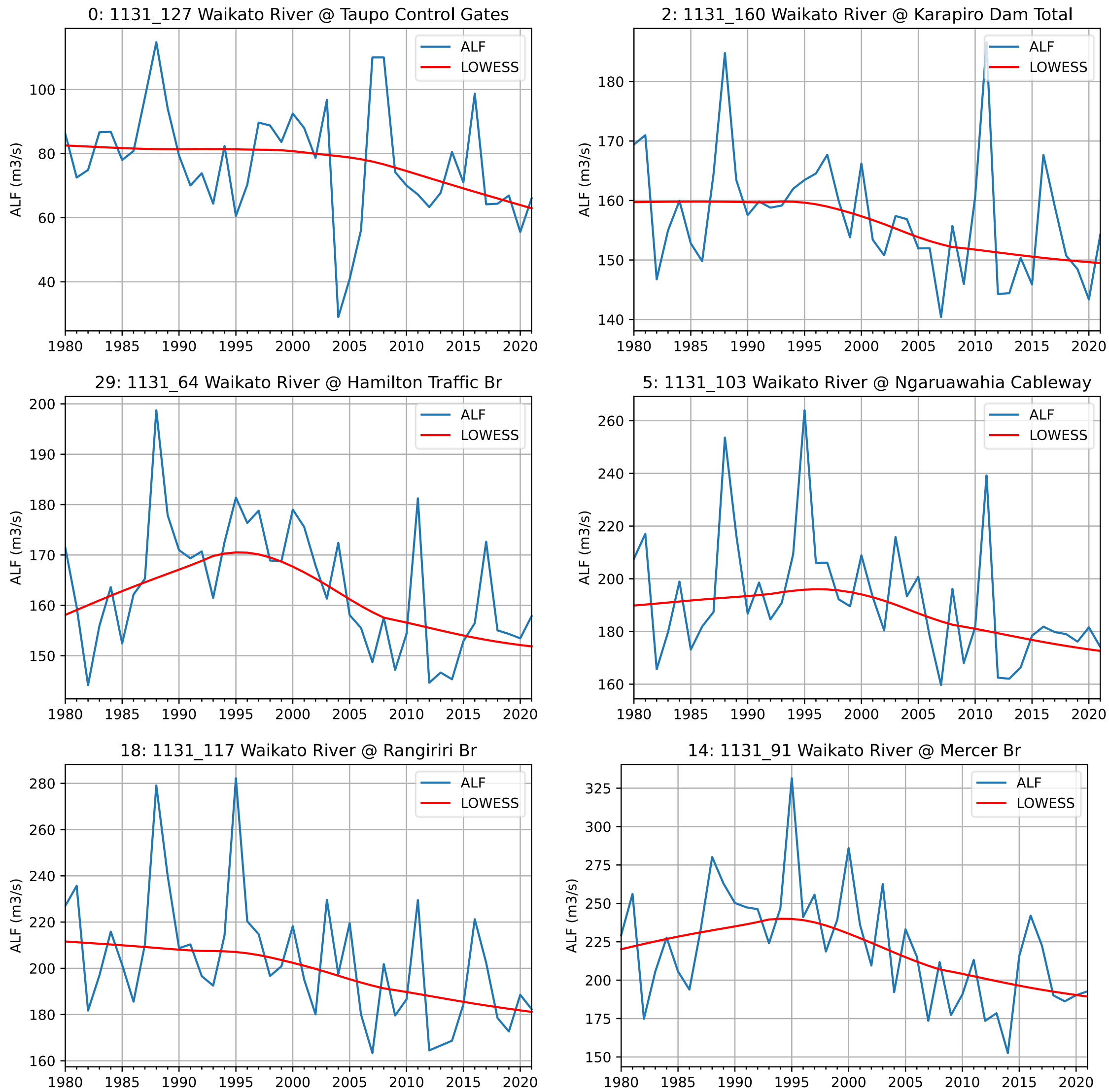


Figure 48. Trend in mod ALF in Waikato mainstem flow monitoring stations. They are organised from upstream Taupō Lake outlet down to Mercer.

4.2.2 Waihou

4.2.2.1 Trend in water use

Groundwater use in this catchment began in the late 1980s and remained relatively steady until the mid-2000s, with industry being the dominant user (Figure 49). Agricultural use experienced a step change in 2014, while municipal groundwater take were minimal. Surface water take for agricultural use remained steady. All other use types remained steady from 1990 onward, apart from agriculture. Overall, the catchment experienced two step changes in total water use: the first occurred with the introduction of industrial use in 1990, and the second with the introduction of large groundwater takes in 2014. Further analysis may be needed to fully understand the factors driving these changes.

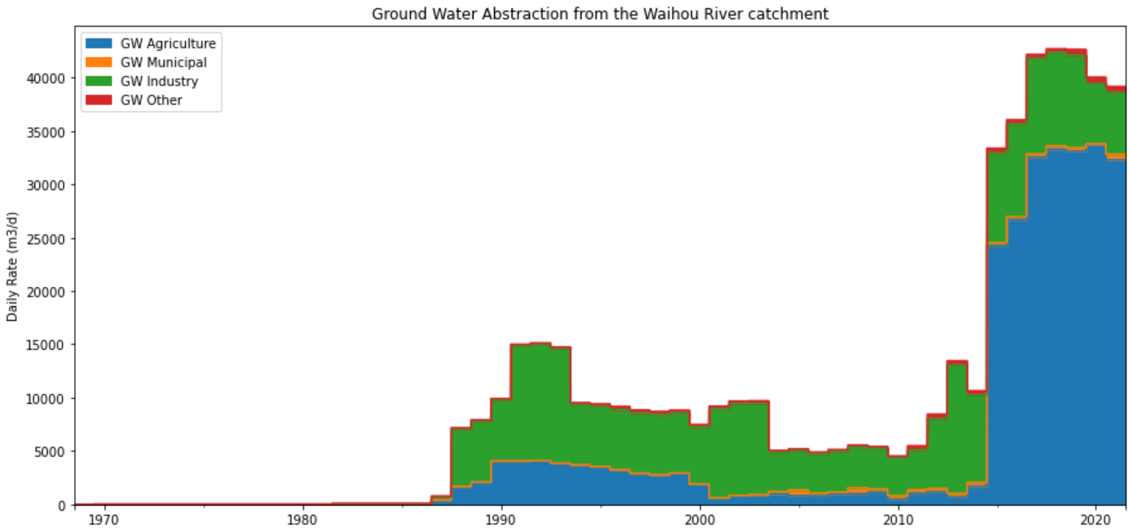


Figure 49. Estimated Groundwater use history in Waihou River catchment 1968-2021.

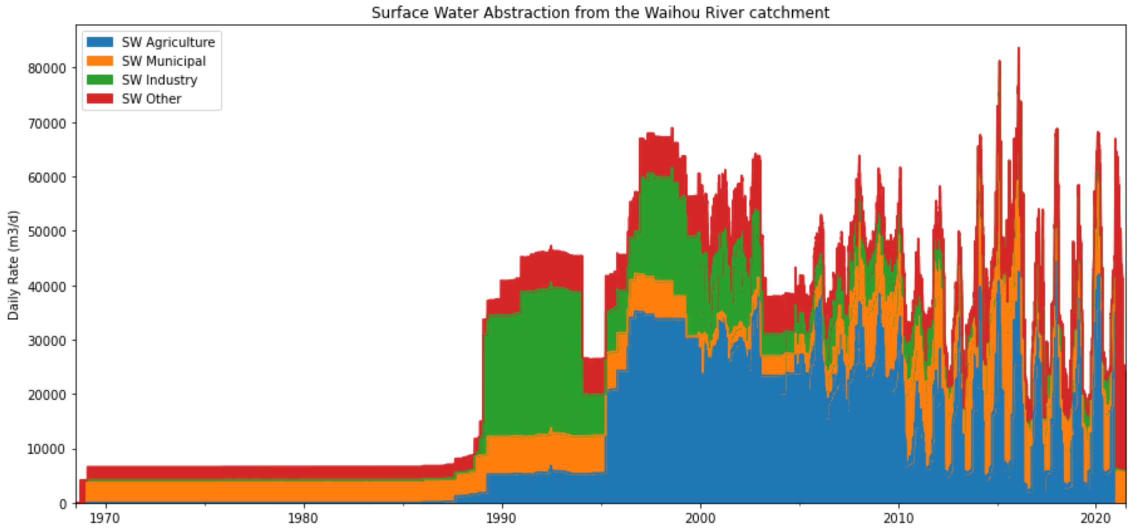


Figure 50. Estimated Surface water use history in Waihou River catchment 1968-2021.

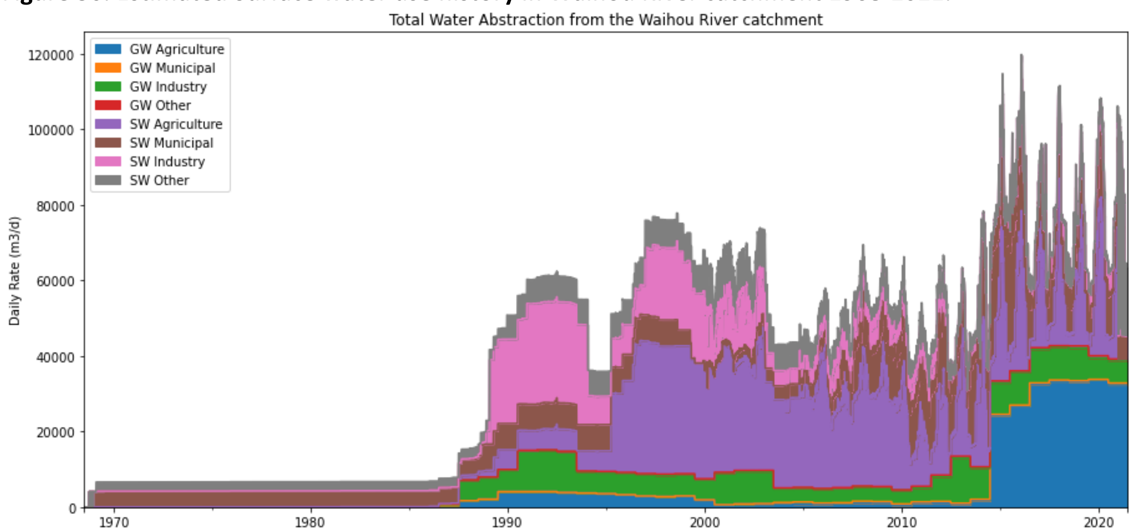


Figure 51. Estimated Total water use history in Waihou River catchment 1968-2021.

4.2.2.2 Trend in Annual Low Flow (ALF)

At the Waihou River in Okauia (1122_18; Figure 52), there was a common trend of ALF increasing until 1998 and declining since then. The flow rate declined by 2.0 m^3/s between 1998 and 2020, at a rate of 4.5% reduction per decade, and by 0.9 m^3/s between 2010 and 2020, which is 4% reduction per decade. This means the rate of decline was slowed down in the recent decade. Climate change was likely responsible for most, if not all, of this decrease, as there has been little to no increase in summer water abstraction since 1998, indicated by the parallel LOWESS curves shown in the figure.

Similarly, the Oraka Stream at Pinedale (669_13; Figure 52) exhibited the common regional pattern of ALF increasing until 2002 and declining since then. The flow rate decreased by 0.24 m3/s between 2002 and 2020, a 5.5% reduction per decade, and by 0.9 m^3/s between 2010 and 2020, a 7% reduction per decade. The rate of change accelerated in the latest decade. Climate change was responsible for 98% of this reduction, as there has been little to no increase in summer water abstraction since 2002, indicated by the parallel LOWESS curves shown in the figure.

Meanwhile, at Waihou River in Tirohia (1122_38; Figure 52), there was a neutral trend of ALF over the past three decades. The ALF remained steady even when other parts of the region experienced very dry summers. One notable pattern in this graph is the significant step change in ALF in 1980. The Waihou River underwent a change in its climate situation during the 1980s, and the major growth in water use in this catchment only began in 1990. However, the data at this location showed a different pattern from the other two representative sites above (1122_18 and 669_13), and this flow recorder site is less reliable for low flow measurements. As such, the trend identified at this flow recorder location should be considered with less weight than the other two reported above. Further investigation is needed to determine the cause of the different behaviour observed at this location compared to the other two.

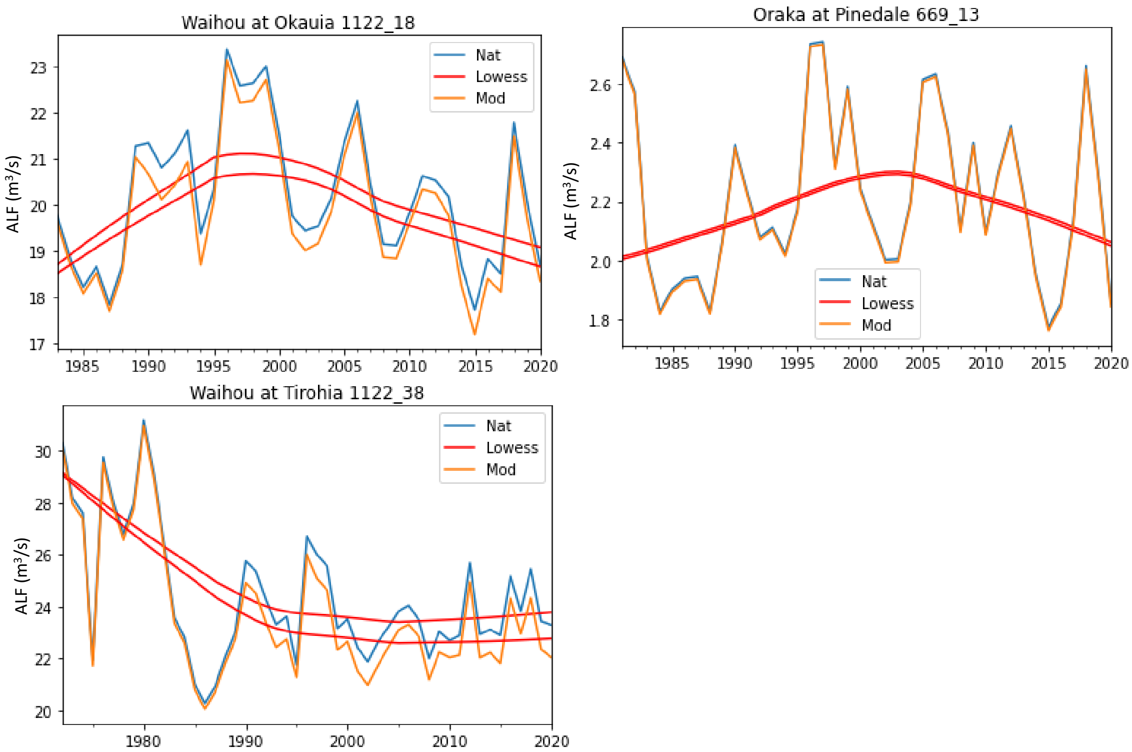


Figure 52. Relative contributions towards Annual Low Flow Trend at key nodes in Waihou River catchment.

4.2.3 Piako

4.2.3.1 Trend in water use

Groundwater takes in this catchment were consented as early as the 1970s, but major growth began in the mid-1980s (Figure 53). Industry was the first sector to use groundwater, followed by agriculture and then municipal. In the graph, agricultural groundwater takes appear to have a step change in 2015, but this was a result of mass registration of the dairy shed wash takes in the consent database from that year. Before mass registration, the dairy shed wash groundwater take was regarded as a permitted activity and not captured in the council consent database. It is expected that agriculture was the main sector that utilised groundwater in this catchment before 2015. The combined groundwater take is estimated to be around 60,000 m^3/d.

Industry and agriculture are the two major sectors that used surface water takes. Water metering began around 2005 in this catchment, and the spikey pattern in the water use graph demonstrates the timing of water metering (Figure 54). The average peak actual surface water take in the recent decades is around 25,000 m^3/d. Groundwater takes dominate water supply in this catchment.

The most recent peak water takes (groundwater and surface water take) were around 78,000 m3/d, calculated as the average of the five latest peak values after the step change in GW in 2017 (Figure 55). As of 2022, the January allocation rate was 0.9358 m^3/s, equivalent to 80,850 m^3/d (see Piako at mouth entry in Table 10). Compared to the catchment-wide January allocated rate, the average utilisation level was 96% (=78,000/80,850). This level of utilisation is significantly higher than other catchments[35], primarily because of the dammed take at Torepatutahi reservoir for Morrinsville township. The allocation footprint of the dammed water take is lower than the actual water take as it collects high flow during storms to sustain the water supply. In the Waikato region, the allocation footprint reflects the alteration introduced to low flow regimes. Damming and supplementing the water supply by collecting high flow during storms effectively reduces pressure on low flows.

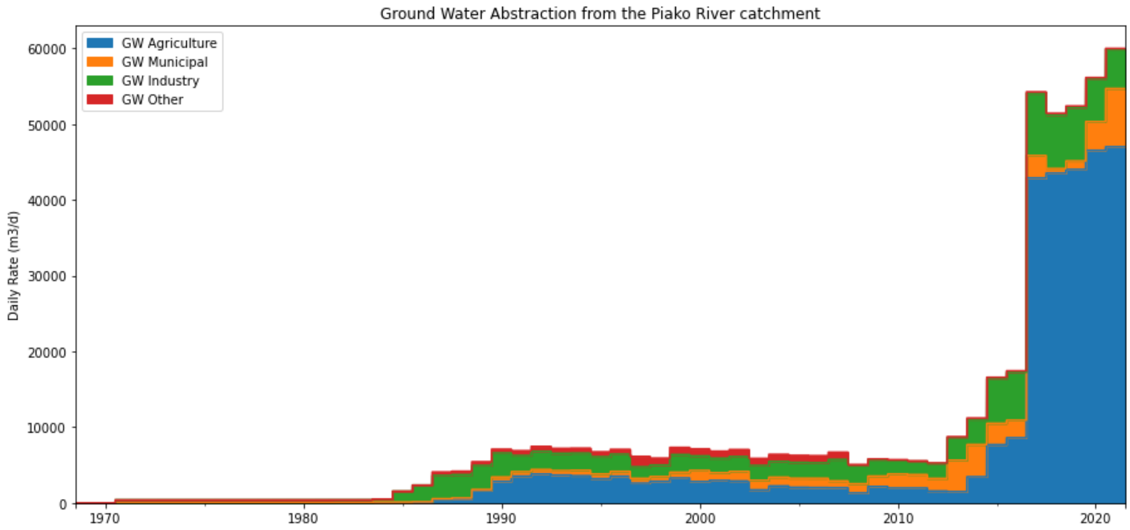


Figure 53. Estimated Groundwater use history in Piako River catchment 1968-2021.

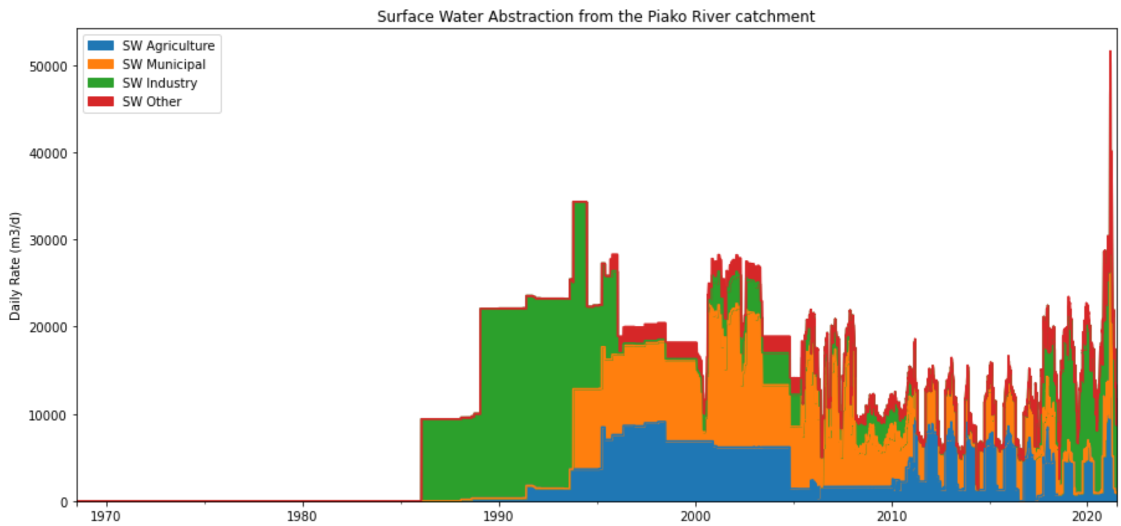


Figure 54. Estimated Surface water use history in Piako River catchment 1968-2021.

35 Typical values range between 40-50% in other catchments.

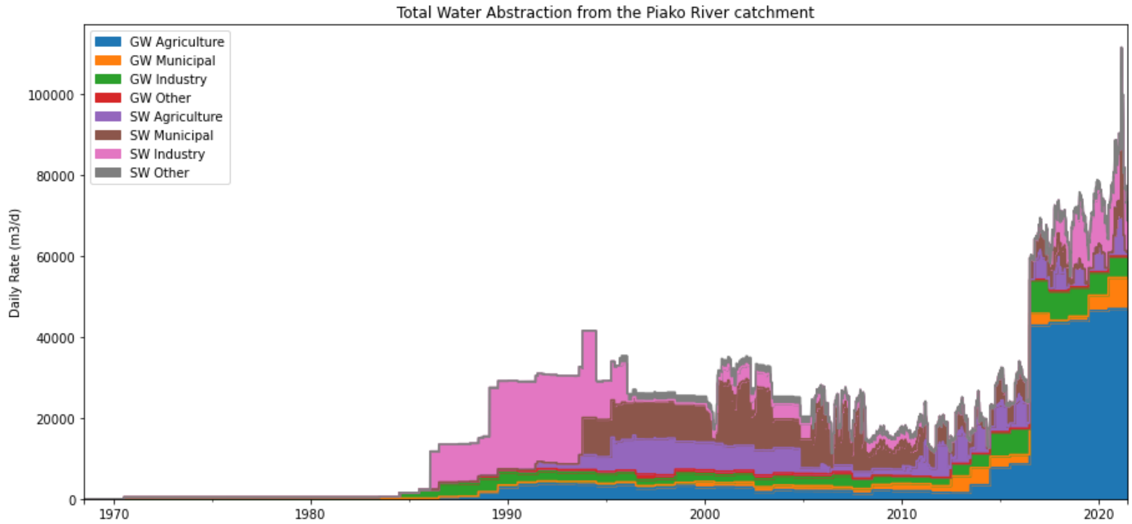


Figure 55. Estimated Total water use history in Piako River catchment 1968-2021.

4.2.3.2 Trend in Annual Low Flow (ALF)

The Piako River at Kiwitahi (749_10; Figure 56) exhibited the typical regional pattern of increasing ALF until 1993 followed by a decline. The year 2020 recorded the lowest ALF in the last 30 years. The rate of decline was 0.05 m^3/s between 1993 and 2020 (-10% per decade), and 0.03 m^3/s between 2010 and 2020 (-15% per decade). The rate of decline accelerated in the recent decade. Climate change was responsible for 94% of the decline in this catchment over the last 30 years, while only 6% could be attributed to water take.

The Waitoa River at Upper Piako (1249_38; Figure 56) showed a declining trend since the beginning of the flow record in 1985. The rate of water take was significant compared to the ALF, as shown by the large gap between the orange and blue lines on the graph. The modified ALF declined by 0.08 m^3/s between 1990 and 2020 (-12% per decade) and 0.04 m^3/s between 2010 and 2020 (-22% per decade). The decline accelerated drastically in the recent decade. Climate change contributed 50% to the decline, while water abstraction growth contributed 50% between 1990 and 2020. If the analysis was focused on the most recent decade, the contribution from water use grew to 60% in the latest decade, reflecting an accelerating increase in water abstraction. The water use is the dominant factor in declining low flow in this catchment.

The Waitoa River at Mellon Rd (1249_18; Figure 56) showed a mixed behaviour that differed from other catchments in the region. The modified ALF increased up to 2005 and declined thereafter, while the naturalised ALF showed the opposite pattern: starting from a high value, reaching a minimum in 2006, and then increasing again. The water take rate was significant in this catchment compared to the ALF, heavily influencing the naturalisation. For example, in 1990, the abstraction rate added to the modified ALF was 0.7 m^3/s, which was 70% of the observed, modified ALF of the year. The pattern in the naturalised ALF contradicted the regional pattern of rainfall and evaporation, suggesting that the catchment was getting wetter in the latest decade, 2010-2020. However, the data and analysis for the Mellon Rd catchment need to be interpreted with caution, and further analysis is required to determine if there was a potential over-estimation in the actual water take rate. The rate of decline of the modified ALF was 0.16 m^3/s between 2005 and 2020 (-5% per decade) and 0.13 m^3/s between 2010 and 2020 (-12% per decade). The declining rate of modified ALF accelerated in the recent decade. The contribution of climate change versus water take pressure could not be determined due to the strange pattern observed in the naturalised ALF at this catchment. Nevertheless, the water take pressure has been consistently high in this catchment, and it grew even higher in the latest decade, 2010-2020.

The Piako River at P-T road (749_15; Figure 56) is impacted by a dammed take, making the naturalisation more complex than other catchments with direct surface water takes. Due to time constraints, the effect from the damming was not naturalised for this catchment, and only the modified ALF was presented in Figure 56. The modified ALF exhibited a fast-reducing trend since 1993, with the rate of decline accelerating from 2008. The rate of decline of the modified ALF was 0.29 m^3/s between 1990 and 2020 (-14% per decade) and 0.18 m^3/s between 2010 and 2020 (-31% per decade). The ALF in this catchment has been declining at an alarming rate and the rate has been accelerating in the recent decade.

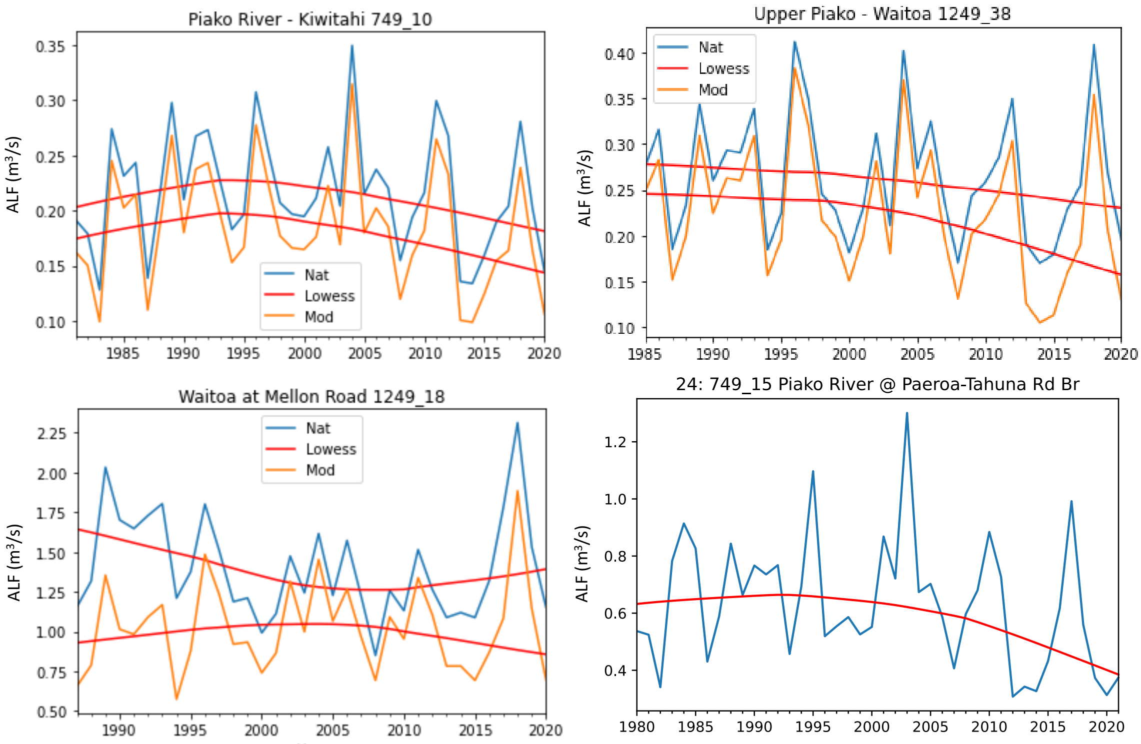


Figure 56. Relative contributions towards Annual Low Flow Trend in Piako River catchment.

4.2.4 Upper Waikato

The Upper Waikato area is defined as the collection of tributary catchments downstream of the Taupō outlet and upstream of the Karapiro dam. The trends of dry spell stream flows were investigated by examining the Annual Low Flows (ALF) of the five main tributary catchments whose flows were measured by flow recorders. These catchments contribute to the flow of Upper Waikato hydro-reservoirs.

4.2.4.1 Trend in water use

The Upper Waikato area has a long history of water abstraction, with consent records dating back to 1968. Groundwater takes under consents started with municipal and industrial use in 1969 (Figure 57). The use of groundwater by industry remained steady, while reliance on groundwater for municipal purposes declined from the year 2000. Agricultural use of groundwater started to increase in the 2010s, although total groundwater use has remained steady since the 1980s.

In terms of volume, surface water utilisation was around ten times greater than groundwater use (Figure 58). Surface water use began for industrial purposes in the early years, but agricultural usage steadily increased from as early as 1980. There was an explosive growth in agricultural surface water use in the year 2000, with another wave of growth in 2013. Since 2000, agriculture has remained the primary sector for water abstraction in this subregion. Industries phased out their use of surface water in 1990 but continue to rely on groundwater (Figure 57 and Figure 58).

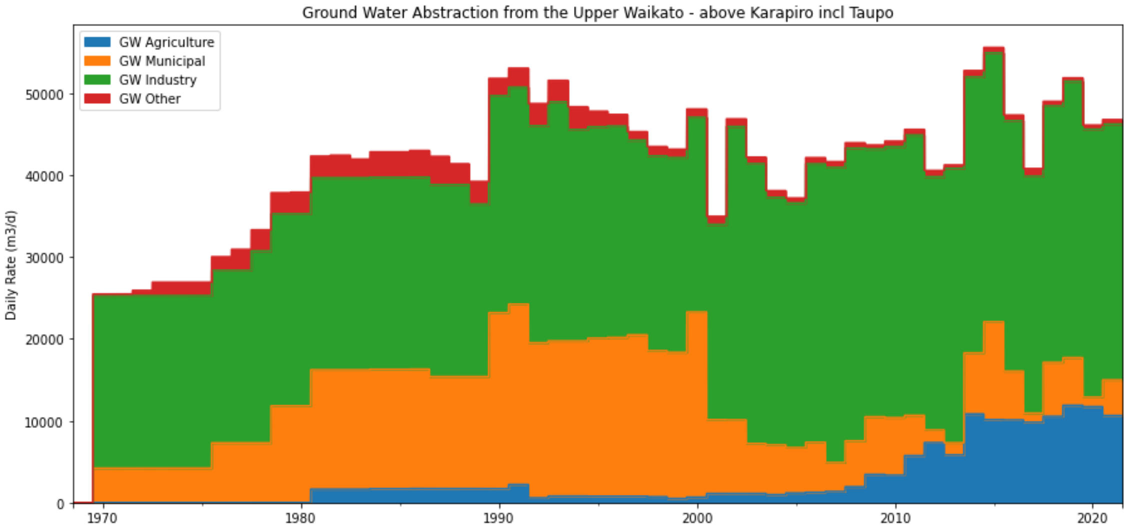


Figure 57. Estimated Groundwater use history in Upper Waikato 1968-2021.

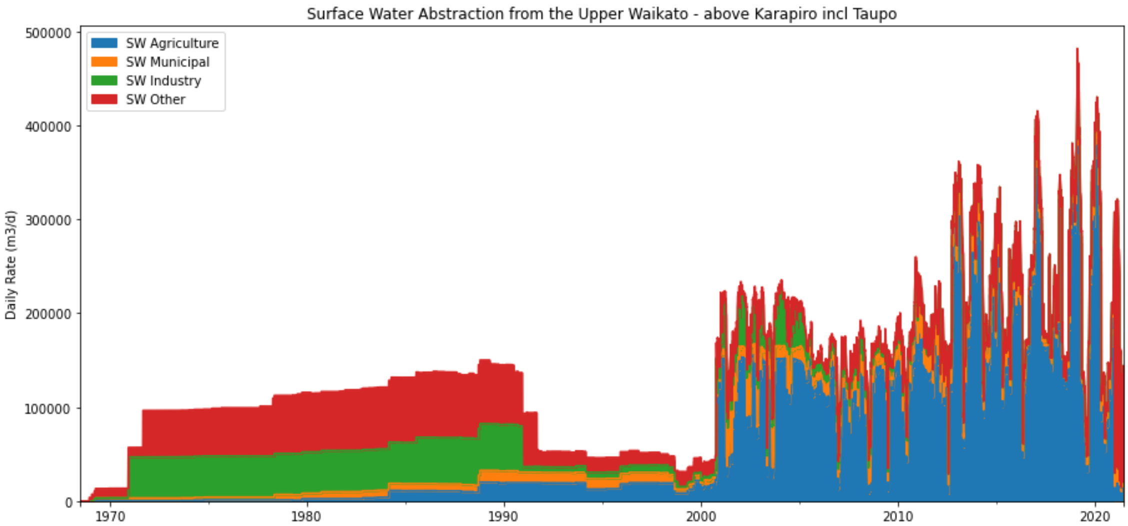


Figure 58. Estimated Surface water use history in Upper Waikato 1968-2021.

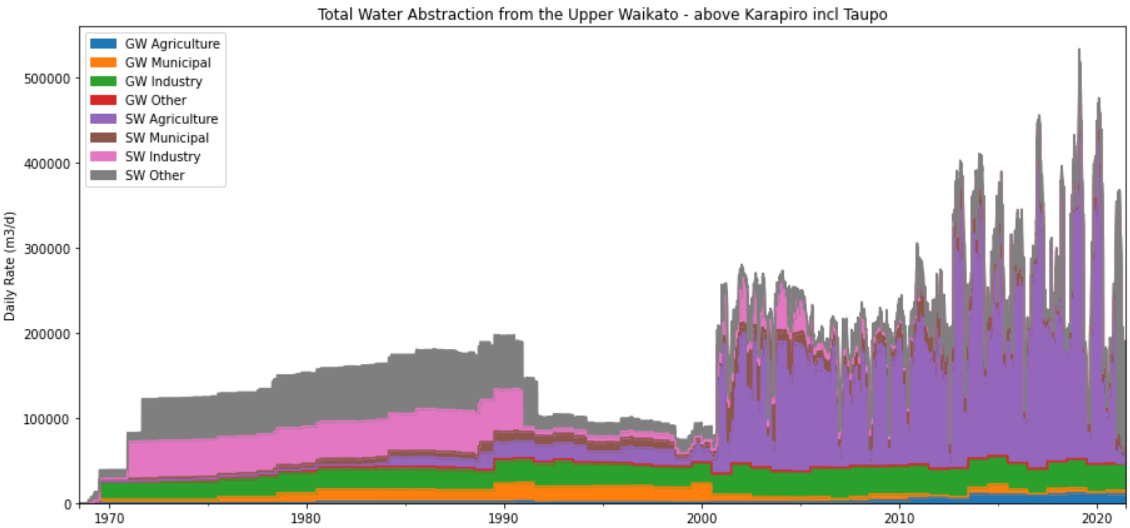


Figure 59. Estimated Total water use history in Upper Waikato 1968-2021.

4.2.4.2 Trend in Annual Low Flow (ALF)

Otamakokore at Hossack flow recorder (683_4; Figure 60) initially experienced an increasing trend in ALF until 2002, after which the ALF began to decline. The lowest ALF recorded was in 1988. On average, the modified ALF declined at a rate of 0.06 m^3/s between 1995 and 2020 (-

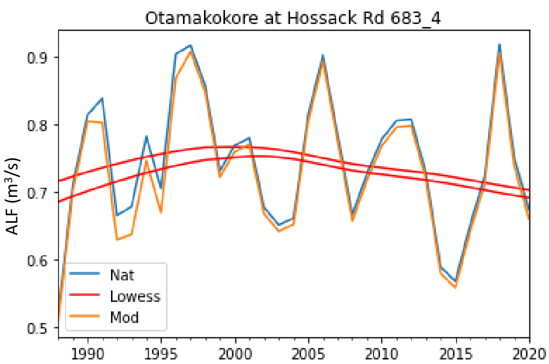
3% per decade) and 0.03 m^3/s between 2010 and 2020 (-5% per decade). The rate of decline accelerated in the recent decade. Climate change was the main if not only contributor to this decline, accounting for approximately 100% of the change. Summer water take did not increase significantly in this catchment over the past 25 years, and this is reflected in the two red parallel LOWESS curves in the graph.

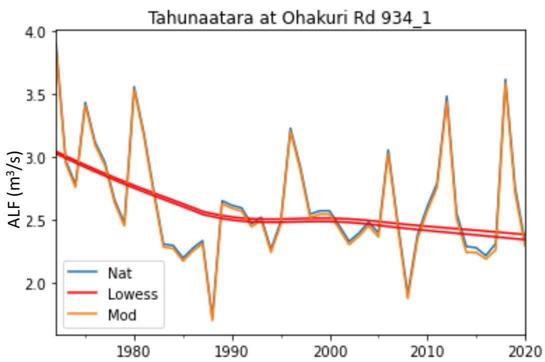
Pokaiwhenua Stream at Puketurua (786_2; Figure 60) is heavily influenced by a take for the Kinleith paper mill. The water take has been growing, as indicated by the widening of the two red LOWESS curves since the beginning of the flow record. The naturalised ALF has been slightly increasing after adding the water use correction, while the modified ALF showed a weak declining trend. The direction of climate change in this catchment appears to be an increase in summer wetness, as indicated by the increase in naturalised ALF. However, the observed flow has been declining. The mixed outcomes hindered drawing a robust conclusion about the relative contribution of climate change and water use. A more in-depth assessment of the water use history is required. The need for further analysis is stated in section 5.3.

Waiotapu Stream at Reporoa (1186_9; Figure 60) has experienced a consistent decline in ALF since the 1970s. Summer water take has been growing, as indicated by the widening of the gap between the two LOWESS curves over time. The rate of decline in the modified ALF was 0.24 m^3/s between 1998 and 2020 (-3% per decade) and 0.13 m^3/s between 2010 and 2020 (-6% per decade). Climate change was responsible for 92% of the decline between 1998 and 2020.

Tahunaaratara Stream at Ohakuri Road (934_1; Figure 60) has consistently experienced a decline in ALF since start of the flow record. The rate of decline in the modified ALF was 0.16 m^3/s between 1990 and 2020 (-2% per decade) and 0.07 m^3/s between 2010 and 2020 (-3% per decade). Recent decades experienced faster decline in mod ALF. The climate driver was responsible for 89% of the decline over the period of 1990-2020.

Mangakino at Dillon Rd (388_2; Figure 60) exhibited the typical regional pattern of increasing ALF until 1998 and declining thereafter. The rate of decline was 0.60 m^3/s between 1998 and 2020 (-4% per decade) and 0.33 m^3/s between 2010 and 2020 (-6% per decade). In 2020, the catchment experienced the lowest ALF since 1972, and water use has significantly increased in the latest decade, as indicated by the widening of the two red LOWESS curves. Climate change was the primary contributor to this decline, accounting for 73%, while the remaining 27% could be attributed to the growth in water use.





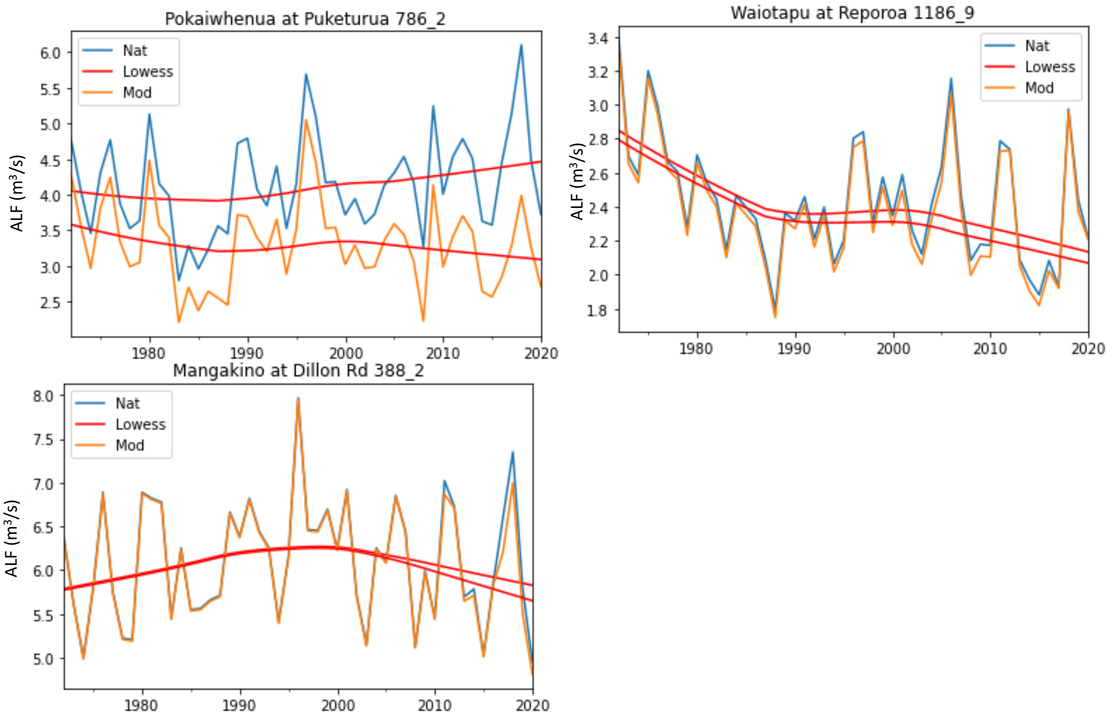


Figure 60. Relative contributions towards Annual Low Flow Trend in Upper Waikato.

Overall, the subregion experienced a decrease in modified ALF at an average rate of 5% per decade in the latest decade (Table 13). On average, 66% of this decline can be attributed to climate change, while the remaining 34% can be attributed to the growth in water take. The catchment total value was calculated using the following equations:

- Contribution % of catchment total = Total climate contribution (m^3/s) / ALF2010 / average ALF change.
- Total climate contribution (m^3/s) = Sum of ALF2010 x Change in ALF x climate change contribution % of each row.

Table 13. Summary of change in mod ALF of Upper Waikato catchments over the past decade.

WAC ID	Catchment Name	Mod ALF 2010 (m^3/s)	Mod ALF 2020 (m^3/s)	Change in mod ALF in 2010-2020 decade	Climate change contribution %[36]	Water use contribution %[37]
158	Otamakokore at Hossack Rd	0.73	0.69	-5%	100%[38]	0%
160	Tahunaatara at Ohakuri Rd	2.42	2.35	-3%	89%	11%
146	Pokaiwhenua at Puketurua	3.22	3.09	-4%	-	-
163	Waiotapu at Reporoa	2.20	2.07	-6%	92%	8%
162	Mangakino at Dillon Rd NIWA	5.99	5.65	-6%	73%	27%
	Upper Waikato Trib Total	14.55	13.85	-5%	66%	34%

4.2.5 Waipa

The Waipa River, a major tributary to the Waikato River, was analysed to identify the trend of the Annual Low Flows (ALF) at five flow recorder sites. The Waipa River catchment does not have any major reservoirs that are managed by dams.

4.2.5.1 Trend in water use

Water takes in the Waipa River were first consented in 1968, with both groundwater and surface water use growing slowly but steadily until 1992. In that year, there was a significant increase in

[36] This column is a summary of values copied from the text.
[37] This column is a summary of values copied from the text.
[38] The calculated value of 100% indicates that the impact of water use on ALF is very minimal for this catchment.

surface water take by the municipal sector (Figure 61 and Figure 62). Since then, total water take has remained roughly steady, with surface water use slowly declining from 2000 due to a reduction in the municipal sector. The apparent step change in groundwater take by the agricultural sector in 2015 was due to the registration of numerous dairy shed uses in the consenting records. Prior to 2015, surface water was the main source of water supply, but from that year onwards, the share of groundwater use has grown to around 50% of the total water use. Agricultural use is the primary purpose of water take in this subregion. Figure 63 illustrates these trends.

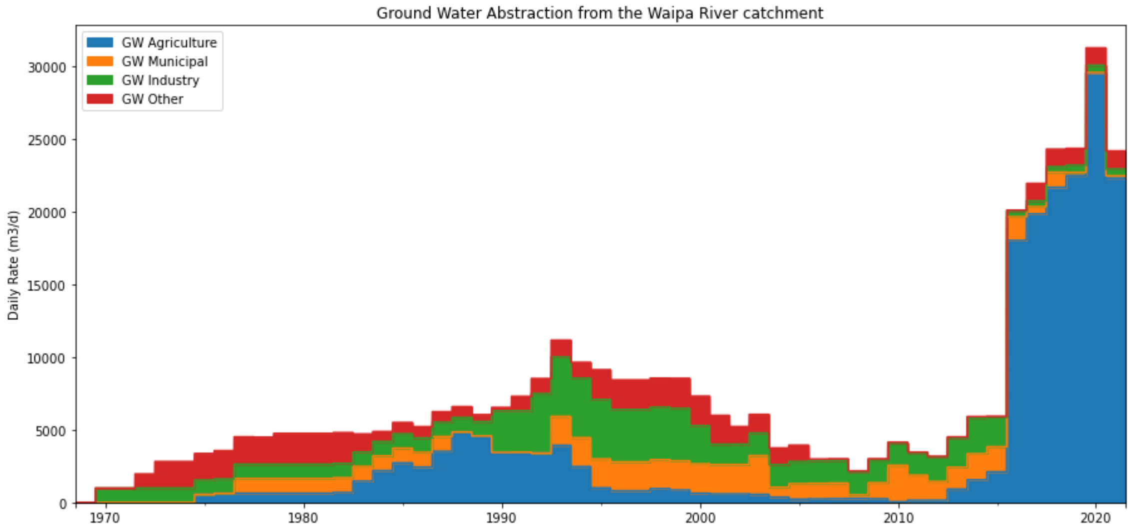


Figure 61. Estimated Groundwater use history in Waipa River catchment 1968-2021.

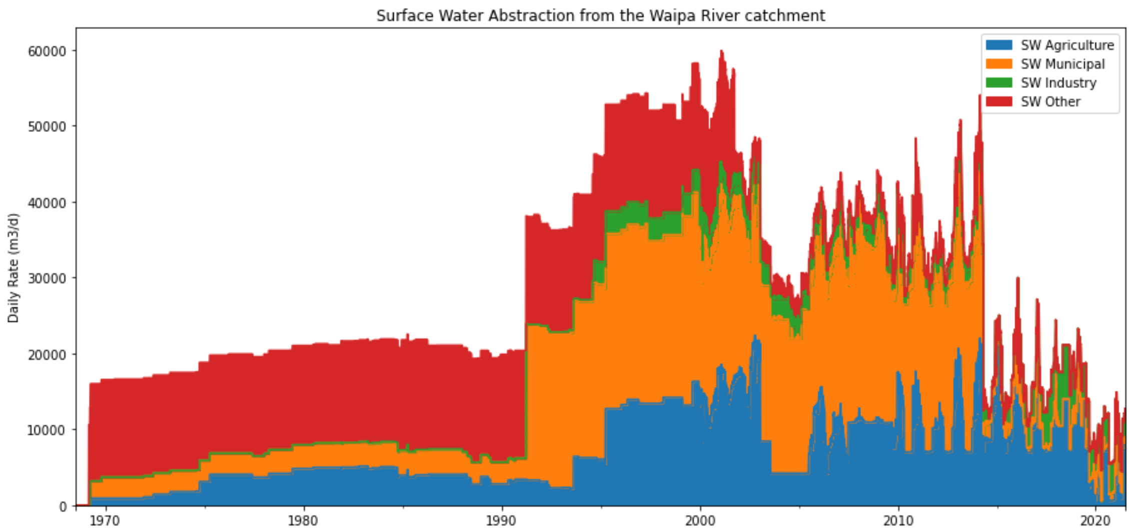


Figure 62. Estimated Surface water use history in Waipa River catchment 1968-2021.

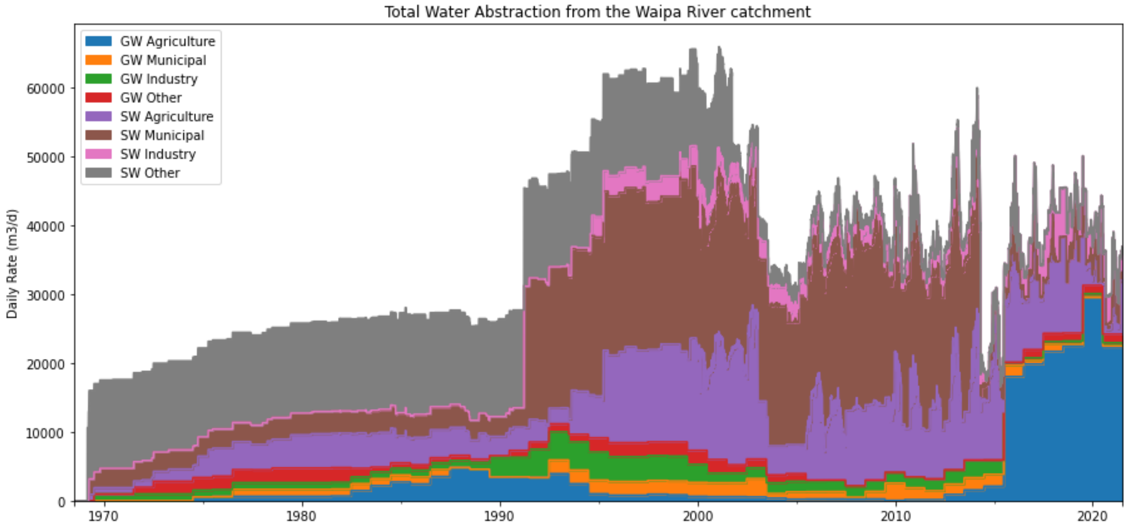


Figure 63. Estimated Total water use history in Waipa River catchment 1968-2021.

4.2.5.2 Trend in Annual Low Flow (ALF)

Waipa River at Honikiwi (1191_13; Figure 64) is also referred to as the Waipa River at Otorohanga SH31 bridge. The two red LOWESS curves of the modified and natural ALFs both peaked in 1994 before declining. A step change in fluctuation range occurred in 2008, with the lower bound of the ALFs dropping from around 4 m^3/s to values as low as 3 m^3/s following a drought. The water take correction was not substantial enough to explain this change and its cause remains to be investigated. Over the period of 1990-2020, the rate of reduction in modified ALF was 1.3 m^3/s (-8% per decade), and over the period of 2010-2020, it was 0.5 m^3/s (-11% per decade). The rate of change accelerated in the recent decade. Climate change contributed 93% of this reduction, while water take accounted for the remaining 7%.

Located downstream of Honikiwi, the Waipa River at Whatawhata (1191_11; Figure 64) displayed a typical regional pattern, with the ALF peaking in 1990 before declining. From 2005, the rate of ALF decline slowed down. In 2020, the lowest ever mod ALF was recorded since the flow station's inception in 1973. Over the period of 1990-2020, the rate of reduction of ALF was 6.1 m^3/s (-10% per decade), and over the period of 2010-2022, it was 1.6 m^3/s (-10% per decade). Climate change contributed 85% to the reduction, while water take contributed 15%.

The Waipa River at Otewa (1191_7; Figure 64) station became operational in 1986, and its ALF has been declining since then. Similar to the Waipa River at Honikiwi and Whatawhata, a sudden drop in the lower bound of the ALF occurred in 2008, leading to an overall downward trend. Over the period of 1990-2020, a decline of 0.9 m^3/s in mod ALF was observed (-12% per decade), and over the period of 2010-2020, it was 0.3 m3/s (-16% per decade). Climate change contributed 99% to the reduction since there were only a few water takes in this catchment, with only 1% of the ALF decline attributed to water takes.

At the Mangaokewa Stream Te Kuiti Pump Station (414_13; Figure 64), the ALF followed the typical regional pattern of increasing until 1995 before declining. Over the period of 1990-2020, the mod ALF declined by 0.2 m^3/s (-6% per decade), and over the period of 2010-2020, it declined by 0.07 m^3/s (-9% per decade). Interestingly, the water take rate in this catchment decreased since 1990, and the contribution from climate change was greater than the observed reduction in ALF of 18% over the past 30 years. Thus, climate change was considered responsible for 100% of the observed reduction.

The Puniu River at Pokuru Bridge (818_2; Figure 64) also displayed the typical regional pattern, but the scale of the change was not as pronounced as other sites. The maximum ALF occurred in 1996 and has since declined. Over the period of 1990-2020, the rate of decline was 0.4 m^3/s (-3% per decade), and over the period of 2010-2020, it was 0.12 m^3/s (-3% per decade). The relative contribution of climate change was 90%, while water take contributed 10% to the decline.

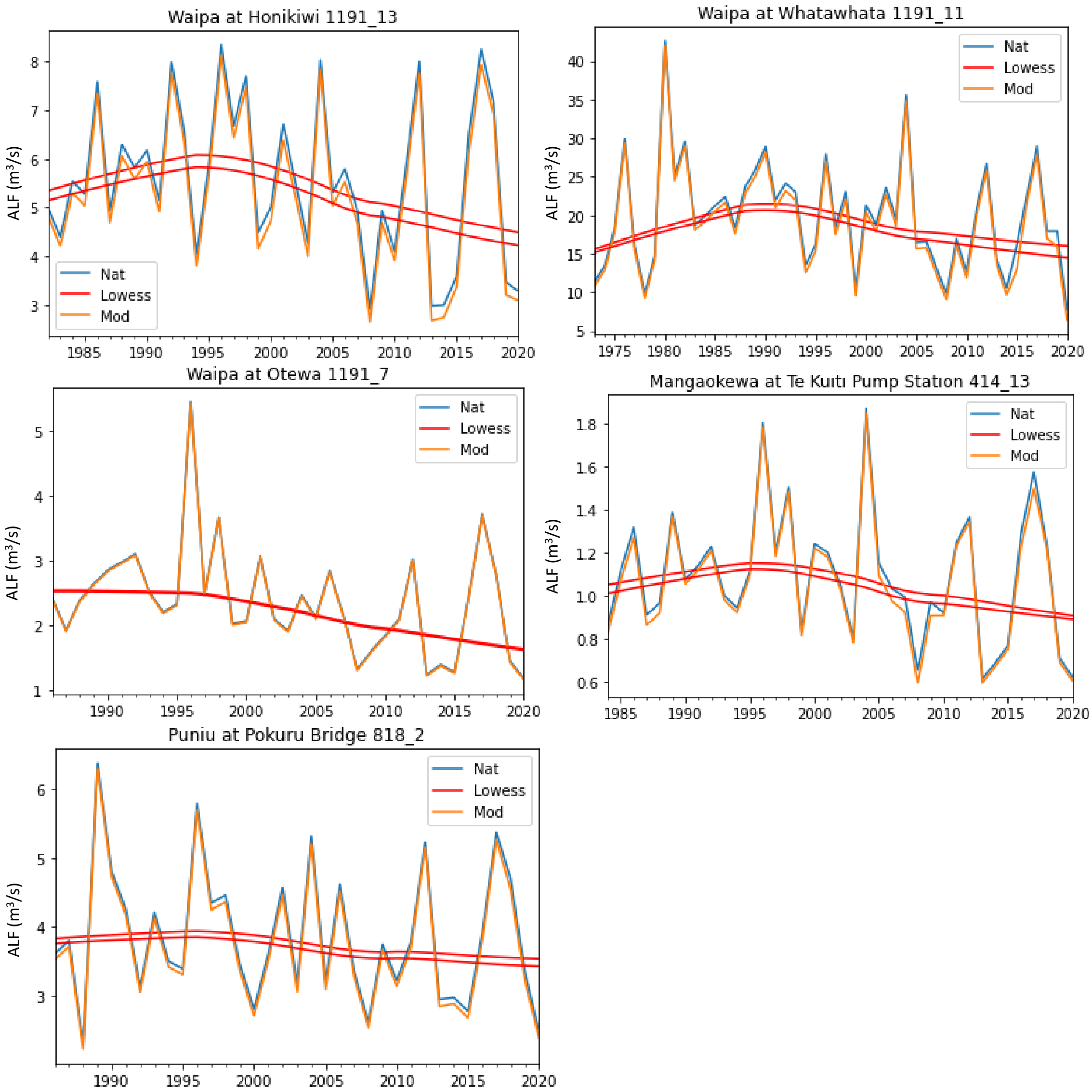


Figure 64. Relative contributions towards Annual Low Flow Trend in Waipa.

Overall, the subregion experienced a decrease in modified ALF at an average rate of 3% up to 10% per decade in the latest decade (Table 14). Typical climate change contribution percentages were smaller than in upper Waikato subregion and were in the range of 85% up to 100%. Correspondingly, the water use contribution to modified ALF were smaller.

Overall, the subregion experienced a decrease in modified ALF at a rate of 3% up to 10% per decade in the latest decade (Table 14). The typical contribution percentages from climate change were smaller compared to the upper Waikato subregion and ranged from 85% to 100%. As a result, the contribution percentage of water use to modified ALF was also smaller.

Table 14. Summary of change in mod ALF of Waipa catchments over the past decade.

WAC ID	Catchment Name	Mod ALF 2010 (m^3/s)	Mod ALF 2020 (m^3/s)	Change in mod ALF in 2010-2020 decade	Climate change contribution %	Water use contribution %
149	Waipa River at Honikiwi	4.76	4.22	-11%	93%	7%
138	Waipa River at Whatawhata	16.14	14.48	-10%	85%	15%
156	Waipa River at Otewa	1.94	1.62	-17%	99%	1%
159	Mangaokewa Stream at Te Kuiti Pump Station	0.96	0.89	-7%	100%	0%
143	Puniu River at Pokuru Br	3.54	3.42	-3%	90%	10%

4.2.6 Central Waikato

The Central Waikato area is defined as the tributary areas to the Waikato mainstem between the outlet of the Karapiro Dam and the Taupiri Gorge, except for the Waipa River and Mangawara Stream catchments.

4.2.6.1 Trend in water use

Agriculture and industry were the primary users of groundwater in the Central Waikato area (Figure 65). Groundwater use was higher in the early decades between 1980 and 2000 but declined drastically thereafter. Municipal groundwater use occurred briefly in the 1970s and 1980s but was phased out after a few years of use.

The records of surface water takes demonstrate the transitional period to the water metering era, starting in 2000. Seasonal fluctuations have been observed from the beginning of the adoption (Figure 66). From 2000 to 2020, surface water use for industry and agriculture has been steady, with seasonal fluctuations visible for both categories. Contrary to the belief that industrial usage would remain steady throughout the year, industrial use in this catchment showed seasonal fluctuations as well. Agricultural use exhibited the expected seasonal fluctuations. The data suggests that this region experienced a spike in surface water use in 2021, primarily attributed to the agricultural sector (Figure 66). The reason for this increase was not investigated in this report, but it would be worthwhile to investigate the underlying cause.

During the earlier period of 1970-2000, the average rates of surface and groundwater takes were similar (Figure 67). However, groundwater takes declined in 2000, while surface water takes increased as if to compensate for the reduction in groundwater use. Since 2000, the total water use level has remained steady, with an average peak rate of up to 40,000 m^3/d.

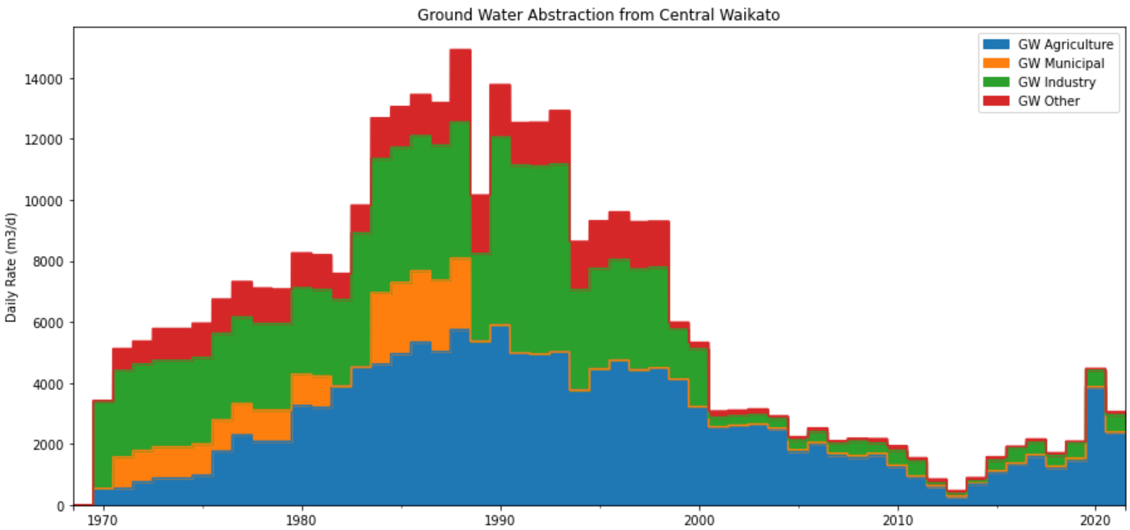


Figure 65. Estimated Groundwater use history in Central Waikato 1968-2021.

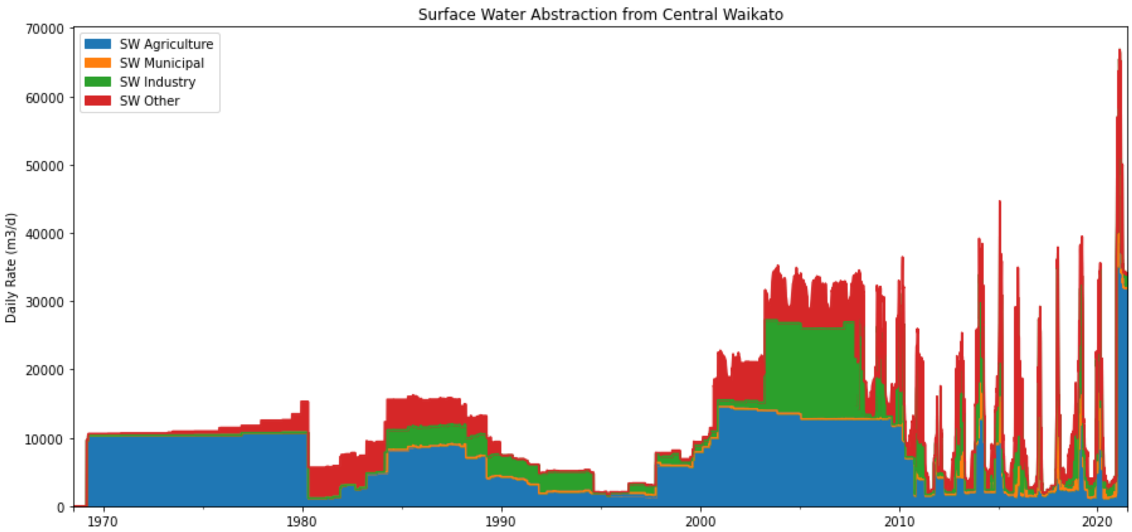


Figure 66. Estimated Surface water use history in Central Waikato 1968-2021.

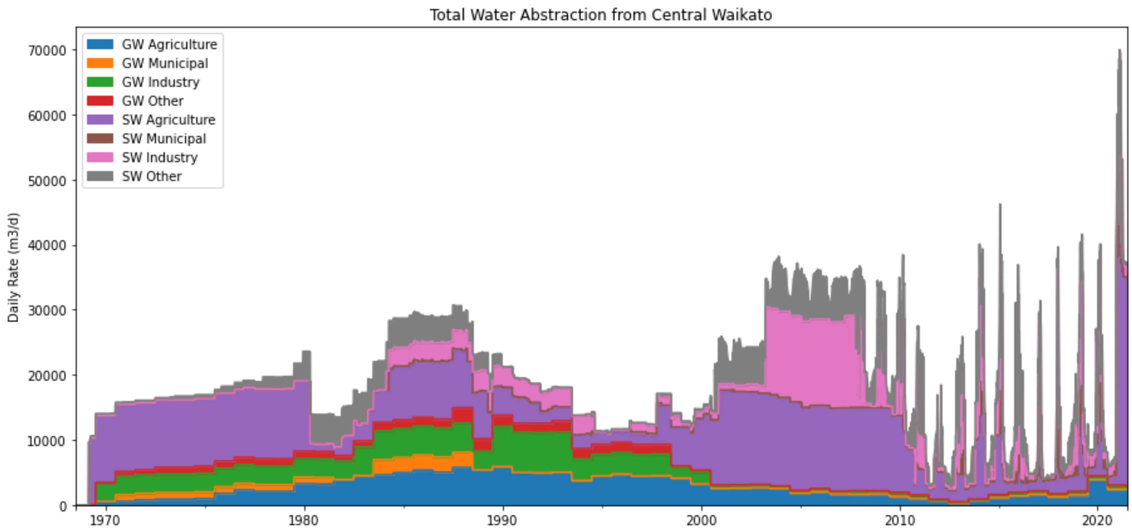


Figure 67. Estimated Total water use history in Central Waikato 1968-2021.

4.2.6.2 Trend in Annual Low Flow (ALF)

The Mangaonua Stream was the only tributary in the Central Waikato area with an operational flow recorder. Due to the influence of hydrodam operations on the Waikato mainstem flow recorders, an analysis of water take contributions to the low flow trend was not conducted on those sites. At the Mangaonua Stream's Dreadnought site (421_4; Figure 68), the ALF increased over the observation period, contrary to the general pattern of the region. The peak water take in this catchment has been decreasing, as indicated by the closing gap between the two red LOWESS curves. The reduction in water takes over the observation period has had a positive influence on increasing the ALF. As the location exhibited a trend behaviour that differed from other locations in the region, further investigation is required to determine its underlying cause.

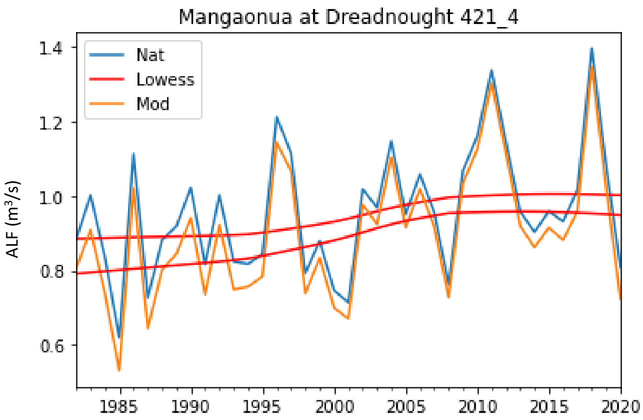


Figure 68. Relative contributions towards Annual Low Flow Trend in a tributary in Central Waikato.

4.2.7 Lower Waikato

Lower Waikato Zone consist of the area downstream of the Taupiri gorge and the Mangawara stream catchment. Mangawara stream is a tributary of the Waikato River just upstream of the Taupiri gorge and this stream was included in this catchment analysis.

4.2.7.1 Trend in water use

The Lower Waikato area has large surface water takes that export freshwater to Auckland. As the rate of export far exceeds local water use in the area, a separate section (2.2.2) is devoted to analysing the Auckland export. This subsection focuses solely on the trend in local water use.

Agricultural groundwater usage began in the 1980s, increased, plateaued in the 1990s, and has experienced a slight decline since 2005 (Figure 69). Industrial groundwater use began in the mid-1980s and underwent a step change in 2004, reaching 20,000 m^3/d. Municipal groundwater use remained small. Before 2004, the agricultural sector was the dominant groundwater user, but it was overtaken by the industrial sector.

Consented agricultural surface water use began in 1968 at a rate of approximately 40,000 m^3/d and remained steady until 2010 (Figure 70). A step growth in agricultural surface water use occurred in 2010, shown as an increase in seasonal peaks. Agriculture was the largest user of surface water, while industrial surface water use began to become larger in the late 1990s. Municipal use remained small, and the Te Kauwhata rural water supply scheme was counted as an agricultural take.

Overall, recent surface water use was four times higher than groundwater use in the latest decade (Figure 71). The peak total water take in this area was around 150,000 m^3/d, equivalent to 1.7 m^3/s, which accounted for approximately 10% of the total allocation for the entire Waikato River catchment, currently at 16.8 m^3/s as of 2022. Total water use remained steady from 1970 to 2010, with a step growth occurring in 2010, primarily due to an increase in agricultural surface water use.

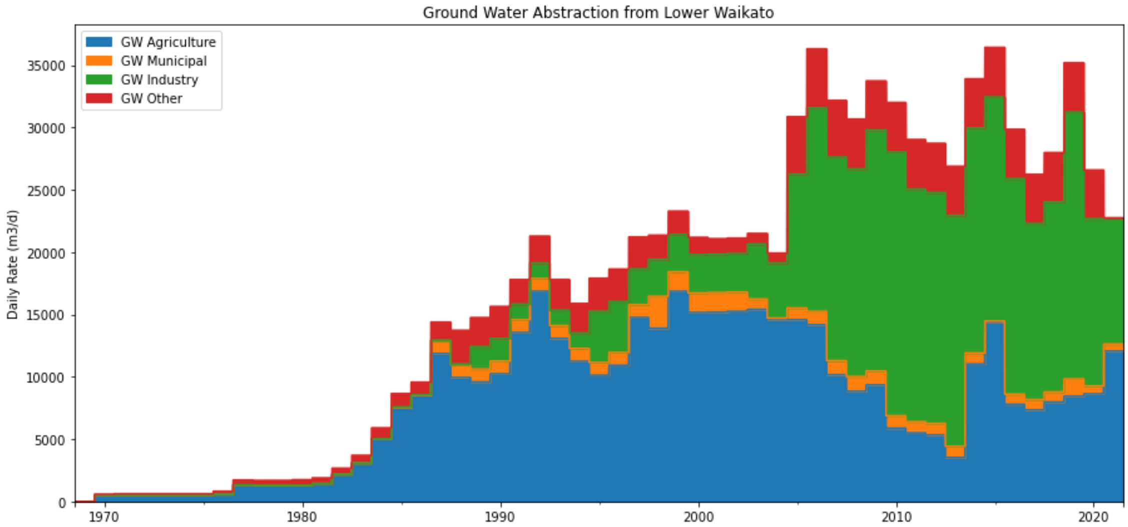


Figure 69. Estimated Groundwater use history in Lower Waikato 1968-2021.

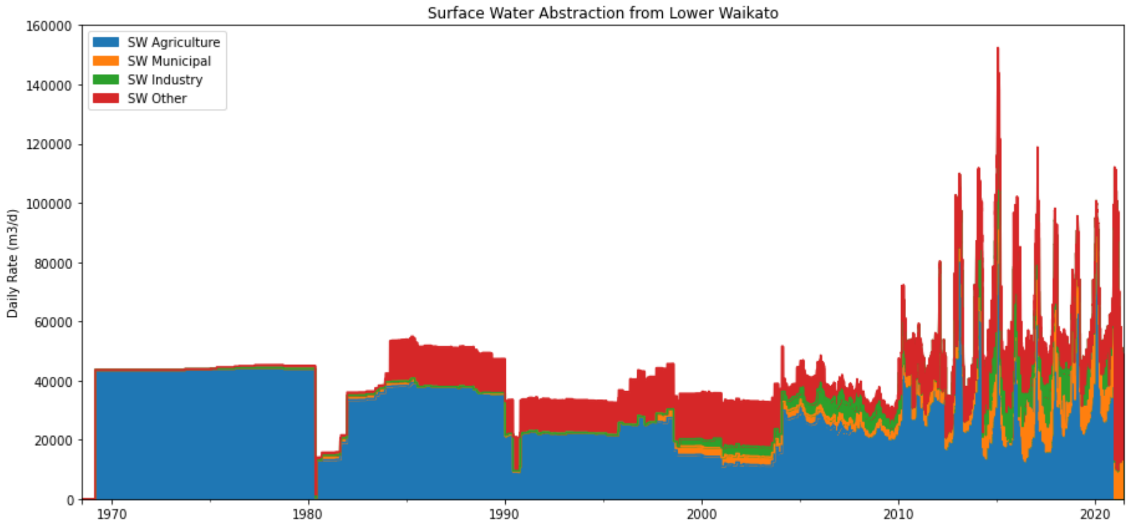


Figure 70. Estimated Surface water use history in Lower Waikato 1968-2021.

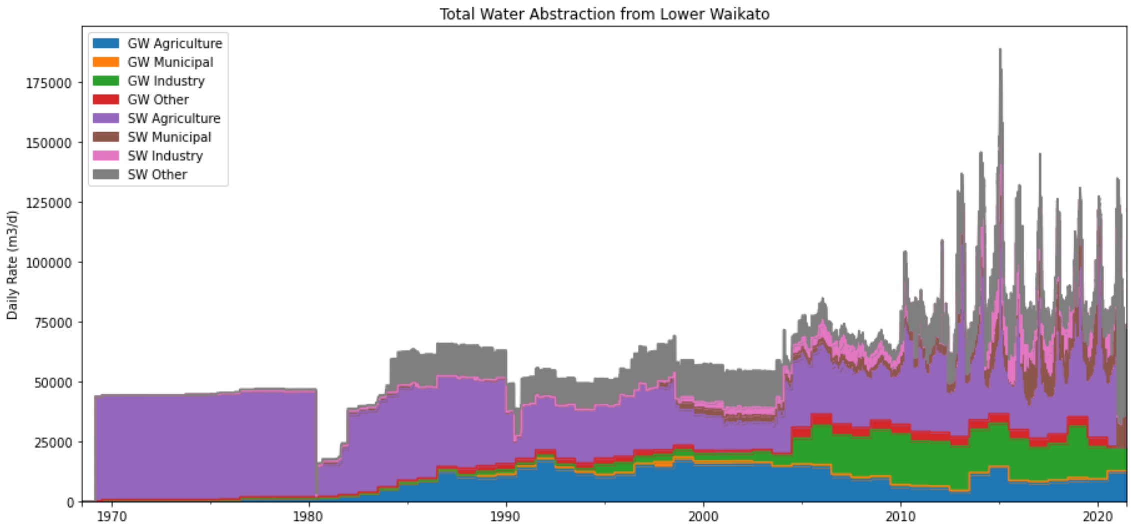


Figure 71. Estimated Total water use history in Lower Waikato 1968-2021.

4.2.7.2 Trend in Annual Low Flow (ALF)

The lower Waikato area has numerous flood management assets, but only the Mangawara Stream at Jefferis (481_2; Figure 72) catchment had a flow recorder that was not affected by such assets. The Mangawara Stream has experienced a consistent decline in ALF since the record began in 1975, with exceptional years of higher ALFs in the 1980s. Between 1985 and 2005, the

ALF fluctuated within a stable range of 0.2 m^3/s to 0.45 m^3/s before undergoing a step change in 2013 and beyond. In 2020, the ALF reached a historic low. The mod ALF has drastically fallen by 0.15 m^3/s over 1990-2020 (-16% per decade) and by 0.09 m^3/s over 2010-2020 (-32% per decade). The primary contributor to this decline was climate change, which accounted for approximately 100% of the change. The water take rate reduced over the analysis period, and the reduction likely contributed to an increase in low flow.

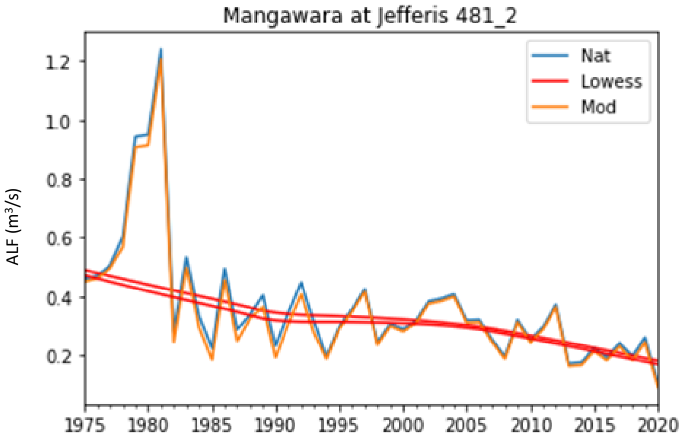


Figure 72. Relative contributions towards Annual Low Flow Trend in a tributary in Lower Waikato.

4.2.8 West coast

4.2.8.1 Trend in water use

Consented groundwater takes began in the late 1970s (Figure 73). It is likely that the "Other" water uses are municipal water, as a similar level of groundwater use was classified for municipal purposes in the period of 2002-2014. The municipal groundwater use remained steady since 1980. The step change in agricultural groundwater use resulted from the registration of dairy shed uses in 2015. Agricultural groundwater use became the primary type of water use thereafter, with peak groundwater usage reaching up to 2,700 m^3/d towards the end of the analysis period.

In general, the level of surface water use has been declining over the years according to the graph (Figure 74). However, it is likely that the apparent reduction is due to more accurate measurement of water take from water metering. Even after the drop in apparent water use due to water metering adoption, estimated surface water use has continued to decrease since 2000. The combined surface water uses in this subregion became less than 500 m^3/d in recent years. Given the number of residents in the area, it is likely that domestic water demands are being met by rainwater harvesting and takes through permitted activity[39]. Considering the number of farms and houses in this subregion, water take occurring under permitted activity can be substantial. The water allocation calculator estimates that permitted activity may be up to 10,000 m^3/d in the Mokau River catchment. Refinement in the water takes, including estimated permitted activity rates, will be included in future investigations, but not in this one.

Surface water used to be the main source of freshwater, but groundwater take has become the primary water supply source in recent decades (Figure 75). Overall, there has not been significant growth in water use since the early days of the water use record. The total average peak water use in this subregion was up to 3000 m^3/d. These water use statistics exclude process water used for iron sand mining operations or quarry dewatering in the West Coast area.

[39] Permitted activity allows a household to abstract up to 15 m^3/d without consents, no notification to the council is needed.

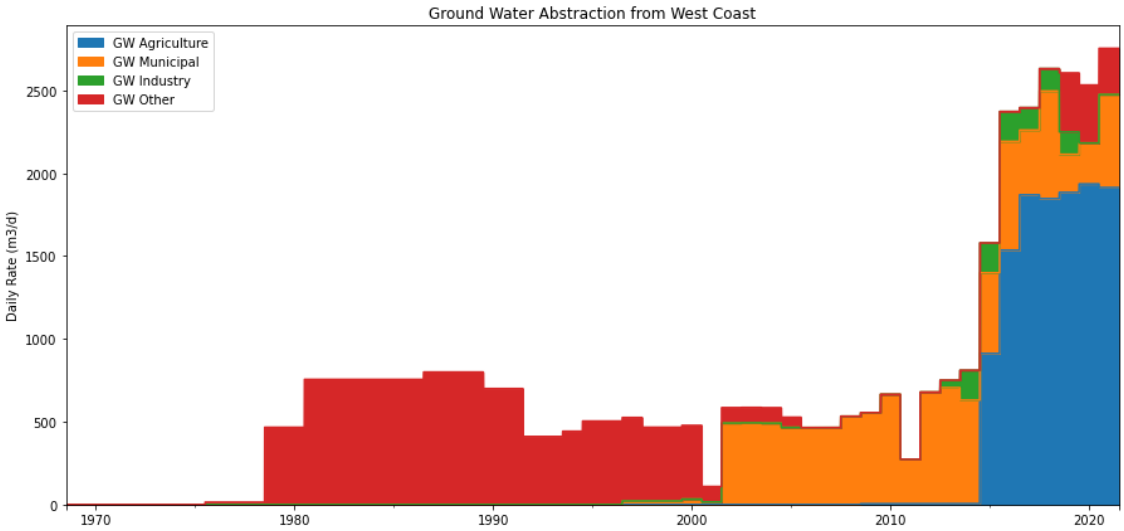


Figure 73. Estimated Groundwater use history in Westcoast 1968-2021.

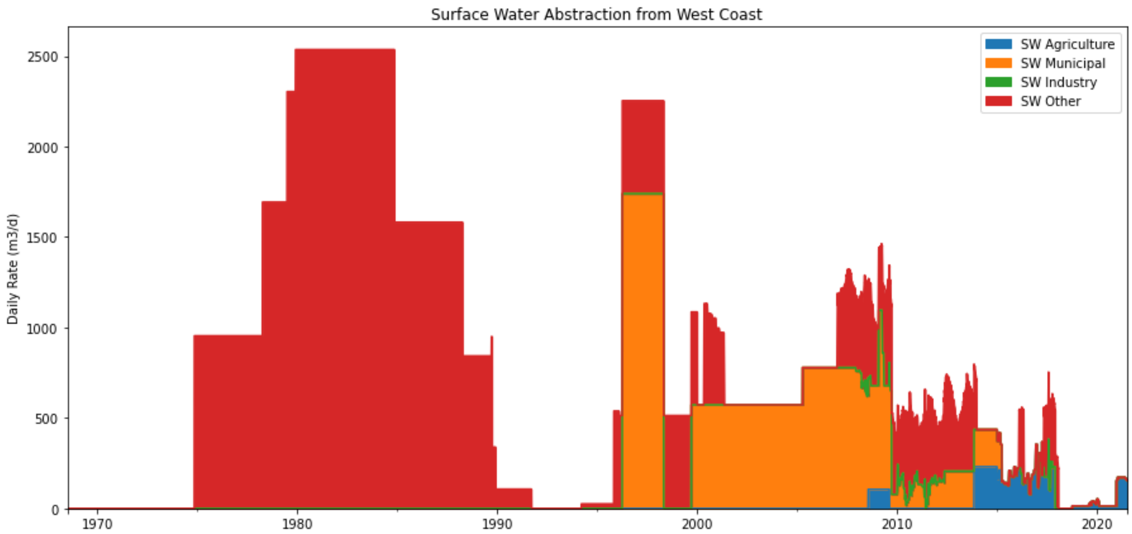


Figure 74. Estimated Surface water use history in Westcoast 1968-2021.

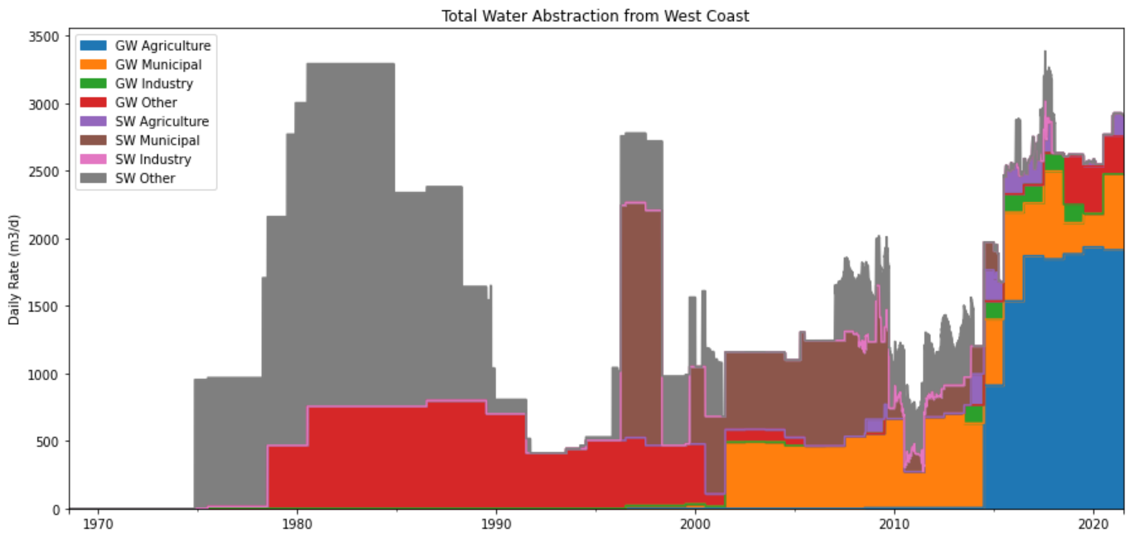


Figure 75. Estimated Total water use history in Westcoast 1968-2021.

4.2.8.2 Trend in Annual Low Flow (ALF)

The Marokopa River at Falls (513_7; Figure 76) followed the typical regional trend of having an increasing ALF until 1994, followed by a decline. The year 2020 saw the driest ALF recorded in the history of the flow record at this location. The mod ALF has weakly declined by 0.2 m^3/s over

1994-2020 (-5% per decade) and by 0.09 m³/s over 2010-2020 (-6% per decade). Climate change was responsible for 94% of the decline, with only 6% attributable to growth in water takes.

The Mokau River at Totoro Bridge (556_9; Figure 76) also followed the typical regional pattern of an increasing ALF until 1995, after which a severe decline was observed. This site experienced record-breaking low flows in 2008, 2013, and approached the historic low in 2020. The rate of decline was 1.9 m³/s over 1995-2020 (-13% per decade) and 0.75 m³/s over 2010-2020 (-16% per decade). Climate change was the primary contributor to this change, accounting for 99% of the decline. Only 1% could be attributed to the growth of water take, as the summer water take did not increase in this catchment, as indicated by parallel LOWESS curves.

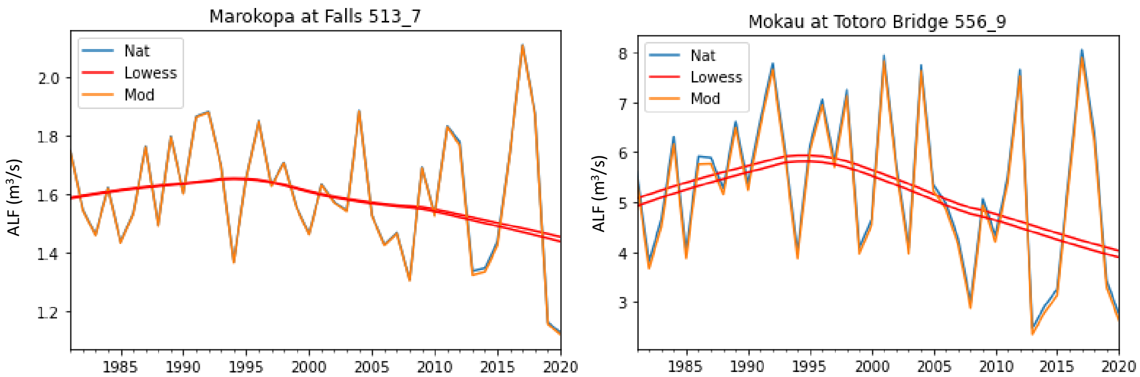


Figure 76. Relative contributions towards Annual Low Flow Trend in Westcoast.

4.2.9 Ohinemuri – Waihi Basin

4.2.9.1 Trend in water use

Groundwater takes in the Waihi basin were not established until the mid-1980s, which is relatively late compared to other subregions (Figure 77). The industrial sector is the major user of groundwater in this catchment, and the rate has remained stable since the inception of industrial groundwater takes. Key industries found in this catchment include quarrying and mining. Surface water takes have been the dominant source of freshwater, with peak take rates almost three times greater than peak groundwater take rates (Figure 78 and Figure 79). Overall, take rates have fluctuated in steps, with step changes occurring at the beginning of each decade (1990, 2000, and 2010). This indicates that the introduction and decommissioning of large water takes have dominated catchment-wide total water take patterns, rather than the gradual introduction of many small-scale uses.

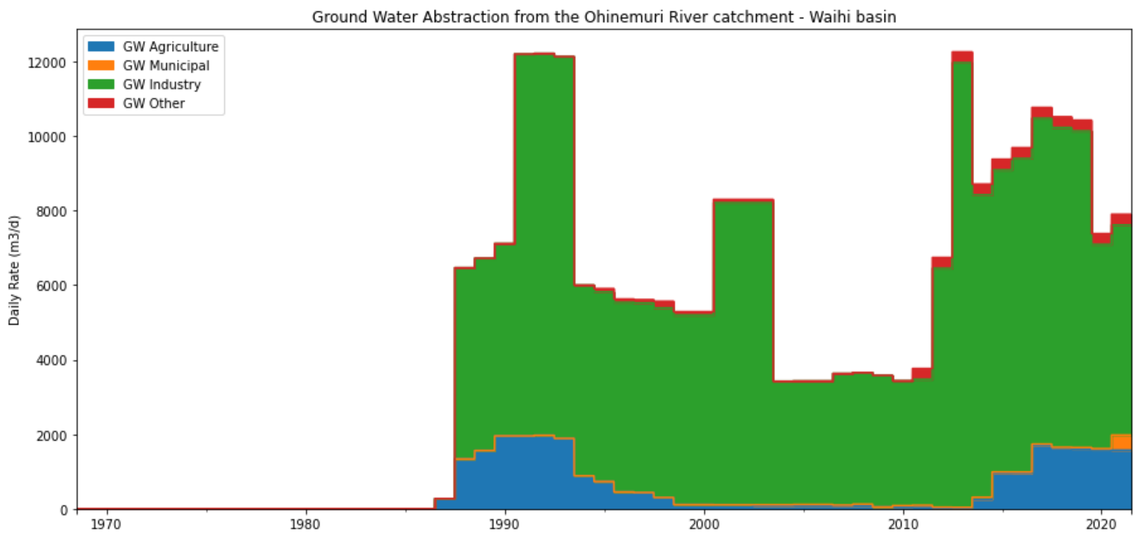


Figure 77. Estimated Groundwater use history in Waihi Basin 1968-2021.

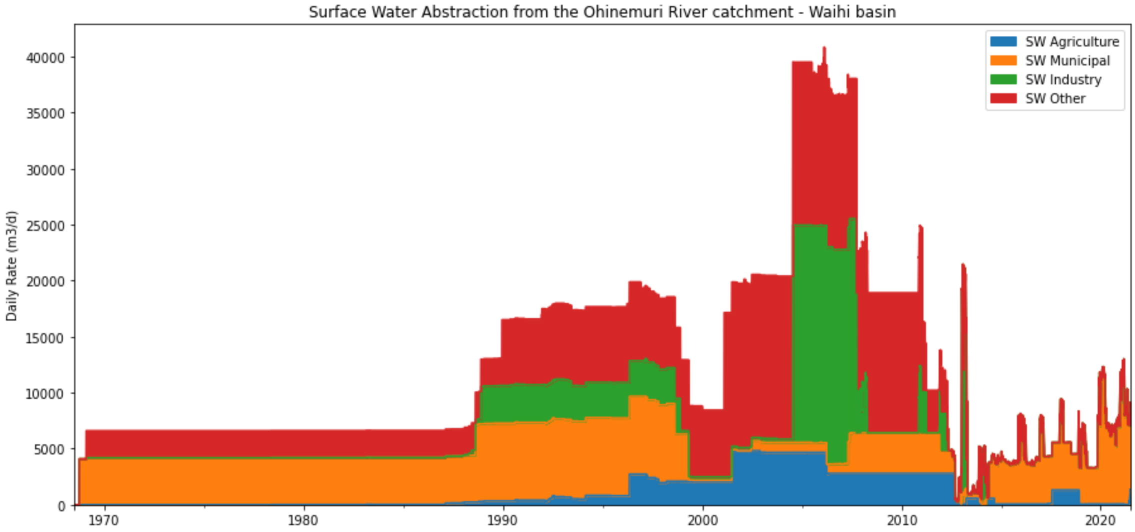


Figure 78. Estimated Surface water use history in Waihi Basin 1968-2021.

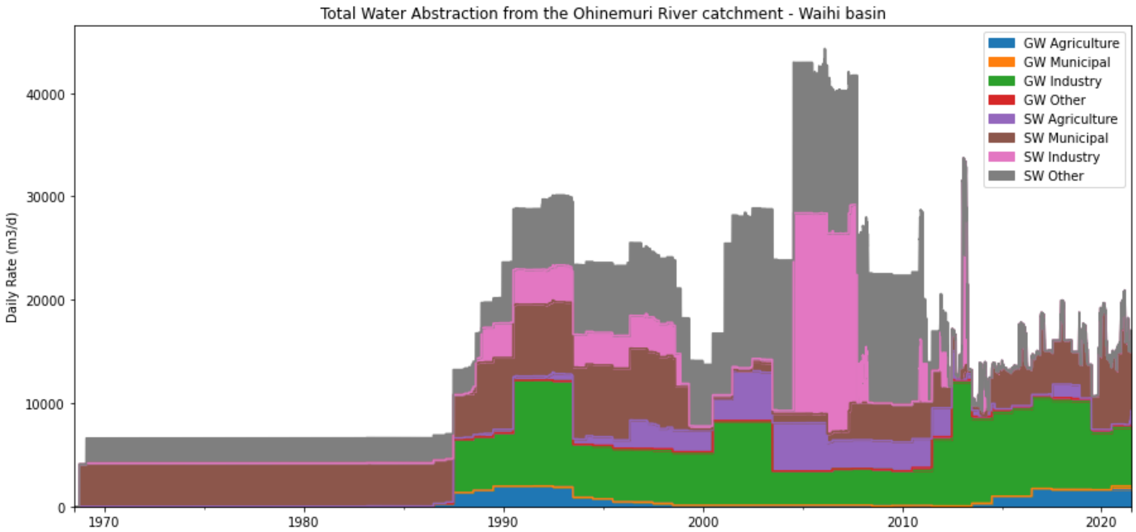


Figure 79. Estimated Total water use history in Waihi Basin 1968-2021.

4.2.9.2 Trend in Annual Low Flow (ALF)

Ohinemuri River at Karangahake (619_16; Figure 80) serves as the outlet of the Waihi basin. This location displayed the typical regional pattern of having the ALF increase until 1990, followed by a decline. The modified ALF underwent a decline of 0.5 m^3/s over 1990-2020 (-8% per decade), while the decline from 2010-2020 was 0.23 m^3/s (-14% per decade). The rate of change increased in the more recent decade. The reduction in ALF over the 30-year period was mainly attributed to climate change drivers, which contributed 58%, while water usage contributed 42%.

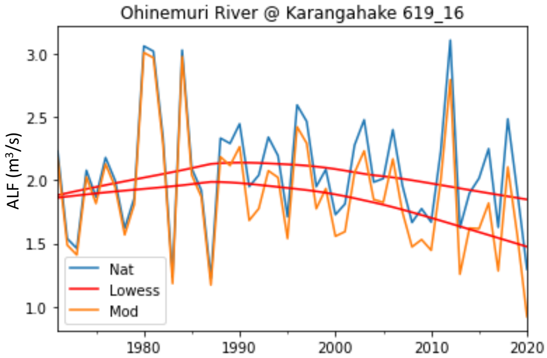


Figure 80. Relative contributions towards Annual Low Flow Trend at the key node in Waihi Basin.

4.2.10 Coromandel

4.2.10.1 Trend in water use

The municipal sectors were the primary users of groundwater in this subregion (Figure 81). The apparent sudden drop in groundwater take in 2003 may have been affected by the introduction of water metering. A temporary industry groundwater take associated with exploration of mines was observed from 2010 to 2013. In the latest decade, the typical peak groundwater take rate was up to 4,000 m^3/d. Most municipal groundwater takes occurred in the coastal towns of Coromandel.

Interestingly, there was a consistent decline in municipal and agricultural surface water take, with an unknown reason (Figure 82). The surface water take was highly seasonal for both municipal and agricultural purposes, which makes sense since many houses in the peninsula are used as summer holiday homes. Overall, the surface water take was the major source of water in this subregion (Figure 83).

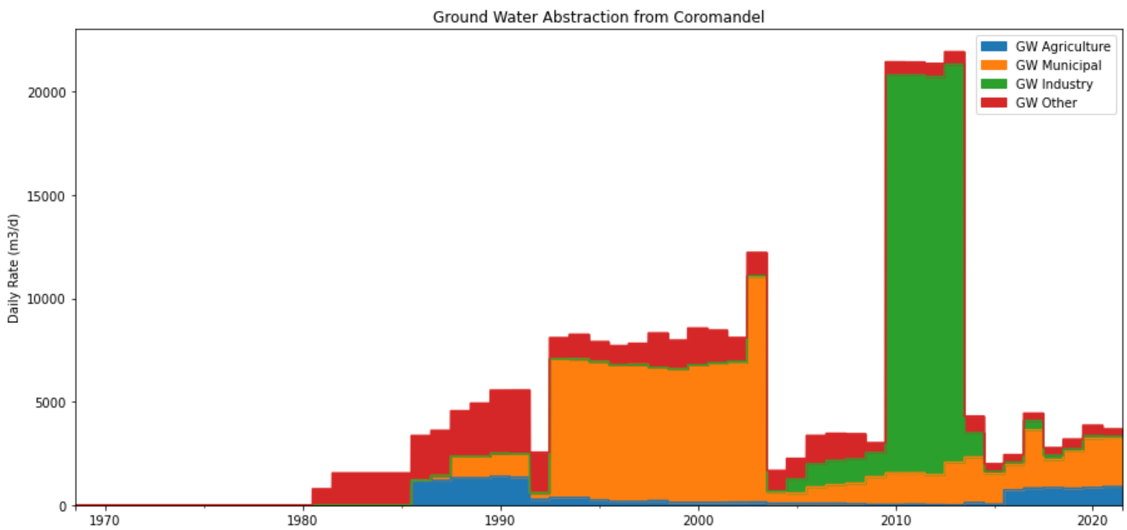


Figure 81. Estimated Groundwater use history in Coromandel Peninsula 1968-2021.

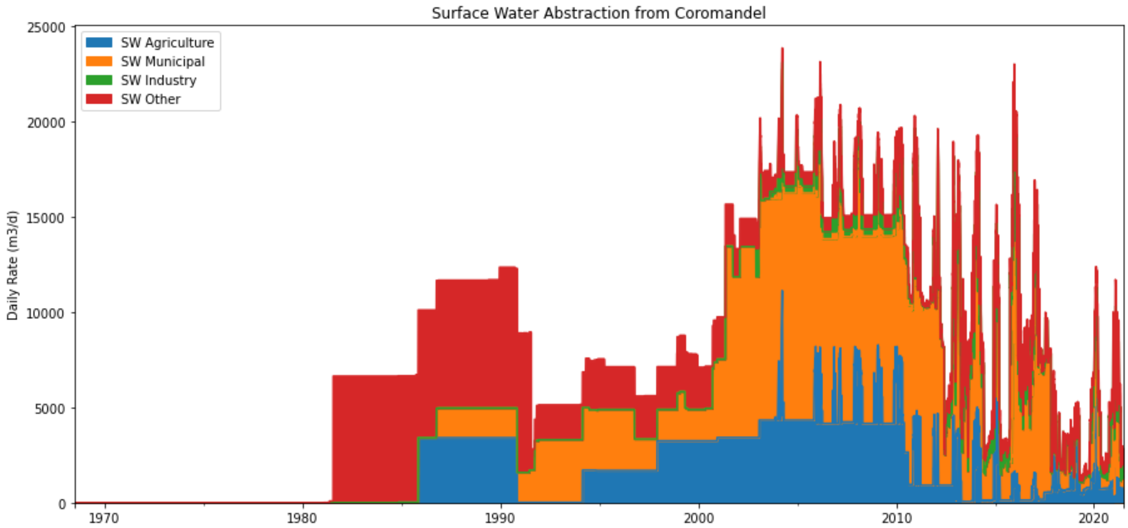


Figure 82. Estimated Surface water use history in Coromandel Peninsula 1968-2021.

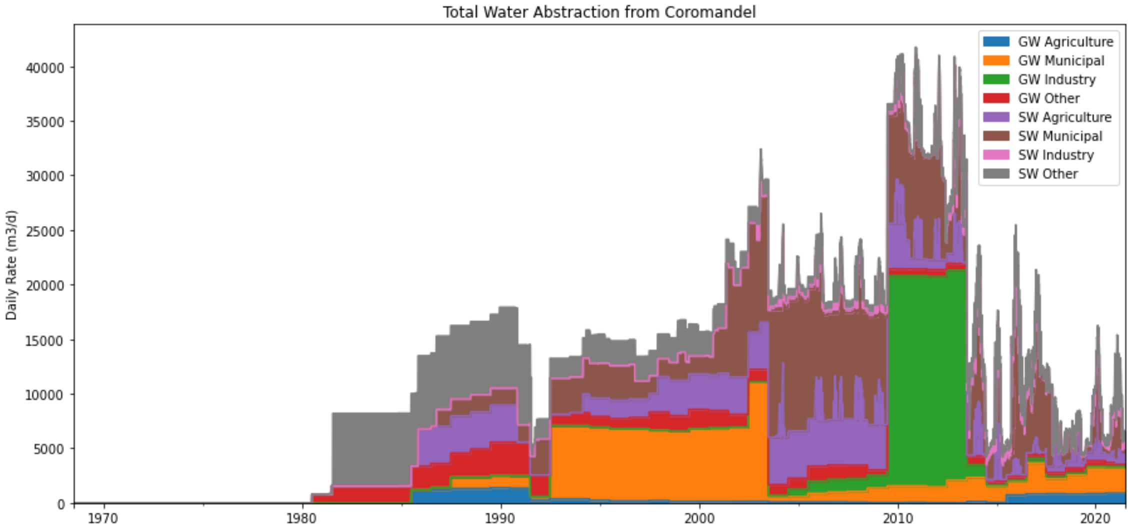


Figure 83. Estimated Total water use history in Coromandel Peninsula 1968-2021.

4.2.10.2 Trend in Annual Low Flow (ALF)

The Kauaeranga River at Smith (234_11; Figure 84) experienced the common trend of increasing ALF until 1993, followed by a decline. The rate of decline was 0.2 m^3/s over 1993-2020 (-11% per decade) and 0.1 m^3/s over 2010-2020 (-17% per decade). Actual water use has decreased in this catchment, as indicated by the closing gap between the two red LOWESS curves. The decrease in water use would have contributed towards an increase in ALF over the years. Thus, climate factor is considered responsible for almost 100% of the decline.

Similarly, the Tapu River at Tapu-Coroglen Rd (954_5; Figure 84) showed a slight increase in ALF until 2005, followed by a sharp decline. The rate of decline was 0.06 m^3/s over 2005-2020 (-25% per decade) and 0.05 m^3/s over 2010-2020 (-30% per decade). Magnitude of actual water use was very small compared to the stream flow and climate factor was the only contributor to this change, accounting for almost 100% of the decline. The rate of decline of ALF was significant at this monitoring location.

The Tairua River at Broken Hills (940_2; Figure 84) showed a consistent, mild declining trend in ALF since its establishment in 1977. The rate of decline was 0.2 m^3/s over 1990-2020 (-8% per decade) and 0.1 m^3/s over 2010-2020 (-13% per decade). Magnitude of actual water use was very small compared to the stream flow and change in climate was the only contributor to this change, accounting for almost 100% of the decline.

The Warekawa River at Adams Farm Br (1312_1; Figure 84) did not show either a growing or declining trend in ALF since its establishment in 1992. The year 2020 was exceptionally dry in this catchment, resulting in the lowest flow ever recorded. The magnitude of water take rate was insignificant compared to the stream flow. The exceptionally low flow achieved in 2020 was not due to over-pumping, but rather the dryness of the catchment.

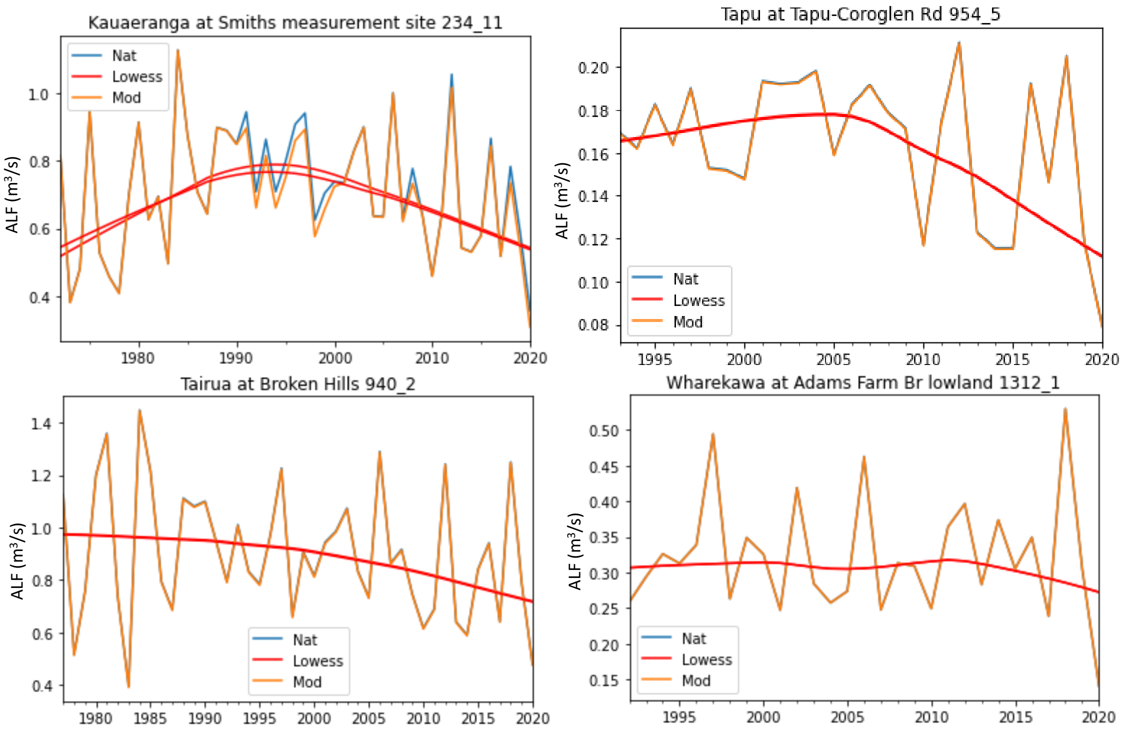


Figure 84. Relative contributions towards Annual Low Flow Trend at key nodes in Coromandel Peninsula.

5 Discussion

5.1 Limitations and reliability

Although this report identified many useful findings from trends in hydrological variables, limitations were identified that could be improved in future works, particularly in two areas: data source reliability and causality establishment. This report relied solely on existing data and did not collect any additional data for analysis.

5.1.1 Data Quality

This work used four groups of data, as categorised and described in section 3.1. The actual water use data had the poorest data quality. They were submitted via telemetry or email by consent holders, who are required to record and report their usage to the council. The quality of the submitted is outside of control of the council at present day. Although resource consent officers revise and control the quality of recently submitted data for compliance, many old water use data suffered from gaps and spikes. Consequently, considerable time and effort were dedicated to dealing with these data issues during this work. Water metering began in 2000, and various assumptions were used to extrapolate water use and construct a long-term history of water use. Therefore, conclusions drawn regarding trends in water use should be used with caution, particularly for the time period before 2000. Although some insight has been gathered in cleaning the water use data, more dedicated resource needs to be allocated in cleaning and maintaining the quality of the water use data.

Although the groundwater level data had fewer gaps and spikes than water use records, the limited spatial coverage of the monitoring sites required review. Mixed trends were identified in the groundwater level, but it remains unclear whether the current spatial distribution of long-term groundwater level monitoring sites with adequate frequency represents the regional trend. Bores with adequate frequency of measurement were clustered at locations where major groundwater production centres are. Although the long-term monitoring stations that had more than 15 years of data appeared to be spread across the region (red circles in Figure 14), data content at bores in remote locations was found to be lacking in frequency (with measurements made only once every 2-3 years) or not visited anymore. The bores reported at the end with trend (Figure 37) and groundwater bores with greater than 15 year data (Figure 14) highlights the need for a review of the regional groundwater level monitoring network to better represent the regional trend in future reporting. The groundwater level monitoring network is currently under review.

VCSN data was utilised to analyse rainfall and evapotranspiration due to its consistent spatial coverage across the region, including remote areas. However, concerns have been raised regarding the accuracy of the interpolation, particularly in high elevation areas (see for example, Tait et al., 2012). Nevertheless, it was deemed adequate for identifying trends in relative changes. Similarly, VCSN selected PET to represent evapotranspiration and it was considered suitable for identifying trend directions. It should be noted that readers should focus on general trend directions in relative change rather than using absolute values presented in the SOE report. Caution should be exercised in using the absolute values.

5.1.2 Analysis

There is room for improvement in establishing causality among the hydrological variables. The primary objective of this report was to provide commentary on the available data, with a focus on identifying trends in the hydrological data. Although efforts were made to provide commentary on causality relationships at a conceptual level, there is still much to be done. For instance, the rainfall-flow correlation was examined at a regional level in section 4.1.4.2, but the mixed trend direction of groundwater levels and the downward trend of all other variables across the region in the latest three decades is still not fully understood. To shed light on this, targeted analysis can be conducted by examining correlations among the variables, as well as the physical characteristics of the recharge process and lag time.

Flow naturalisation is a process that removes human influence from flow data, enabling an assessment of the proportional contribution of climate change and water use to trends in stream and river flow (section 4.2). However, naturalisation was not conducted in several catchments that have dams and weirs, including the Piako catchment with Morrinsville water supply dam, the Whangamarino catchment with a weir and flood assets, and the Waikato mainstem with a series of hydrodams. As these catchments are high interest catchment with high allocation pressures, it is desirable to understand their impact for developing effective water resource management strategies in these catchments. In future iterations of this work, flow naturalisation will include the effect of dams and weirs.

Figure 32 presents the allocation history of the region, which is calculated as the sum of daily maximum consented rates. While this history reflects the overall trend of growth in water allocation in the region and roughly reflects the allocation level of today, the exact value is slightly different from the allocation footprint values calculated by the official Water Allocation Calculator (WAC). The WAC incorporates various business logic, such as GW-SW interaction factors and the agreed-upon way of accounting for grand-parented dairy-shed wash down takes, which are not considered in the history of the consented takes. Therefore, it is important to exercise caution when comparing the latest value estimated by this history to the current allocation pressure since the allocation history used a simplified summation procedure. The values given by the official water allocation calculator provide a more accurate depiction of the allocation status, while the history values reported in Figure 32 provide an understanding of the trend direction.

5.2 Interpretation of Results in a Wider Context

The analysis in this study revealed that the overall downward trend in river flows and water availability in the Waikato region is mainly driven by a decrease in precipitation and an increase in PET (potential evapotranspiration), and to a lesser extent by an increase in water usage. However, due to the inherent uncertainty surrounding the estimated water usage, it is recommended to conduct a more comprehensive study on the estimation of water usage before drawing definitive conclusions for critical policy-making purposes. The uncertainty related to water usage is discussed later in section 5.1.1.

The interaction between atmospheric circulation and the country's orography affects rainfall in New Zealand. The variation of rainfall in New Zealand is influenced by wider climate cycles. For example, Ummernhofer and England (2007) found evidence of recent changes in rainfall patterns due to changes in the hydrological cycle, which coincide with changes to Southern Hemisphere climate modes. Variations in climate parameters such as rainfall in New Zealand have been correlated with El Niño – Southern Oscillation (ENSO), Interdecadal Pacific Oscillation (IPO), Southern Annual Mode (SAM), and climate change. Ummernhofer et al. (2009) found that "increasingly drier conditions across much of New Zealand during austral summer since 1979 are, in large part, consistent with recent trends in ENSO and SAM."

This study suggests that the recent trend towards a reduction in water availability has been ongoing since the mid-1990s, with an acceleration in the rate of change in the most recent decade of 2010-2020. Given that cyclic climate patterns influencing New Zealand have shorter periods, the persistent 30-year-long trend is likely not solely a result of the cyclic climate oscillations.

Examining longer-term flow records provides additional insight into regional climate trends. This report focused on the recent 50 years of climate and flow because the majority of currently active weather stations and flow records began 50 years ago. However, inspecting long-term records extending beyond 50 years may unlock useful insights. For example, the Kauaeranga River at Smith (234_11) has one of the longest continuous flow records in the region and is considered a representative flow recorder of the Coromandel Peninsula. The plot for site 234_11 in Figure 84 shows the regional pattern of increase and decline in modified ALF for the shorter investigation period. However, exploring longer-term time-series reveals that ALF was much higher in earlier decades, specifically in the 1960s and early 1970s. A step reduction in ALF occurred in the mid-1970s, which was responsible for the apparent increase in ALF until the mid-1990s. In a longer-term view, there is a consistent declining trend in low flow in the Coromandel Peninsula. Examining the trend direction with a long-term view may open an alternative avenue for interpreting the current climate conditions, because different investigation period may give different perspective in the trend and cyclical nature of the climate variables.

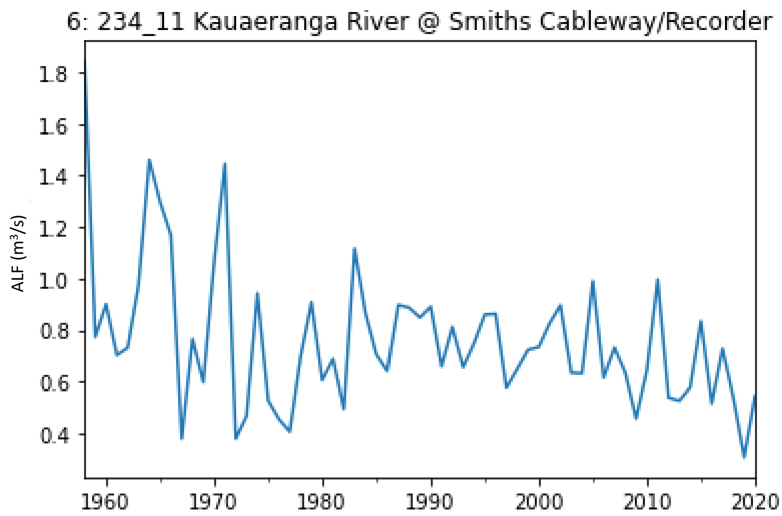


Figure 85. Longer term flow record Annual Low Flow in Kauaeranga River. The plotted timeseries is modified ALF.

The data implies a linkage between climate variables and stream flows, which is consistent with the conceptual understanding of the water cycle. The reduction in rainfall and increase in PET resulted in a reduction in stream flows, and many continuous flow recorders responded to changes in these climate variables. The year 1992 represents a pivot point in the trend reversal patterns of dry spell rainfall and PET. Stream flow monitoring stations showed a delayed response following the changes in these climate drivers, ranging from a few years to several years depending on the location. This delay is likely attributed to changes in storage within the shallow groundwater system before impacting stream flow responses. Exploring the linkage between groundwater levels and the hydrologic response of surface water flow would be a valuable topic for future research. The pivot point of the trend reversal patterns found in stream flows occurred around the mid-1990s or early 2000s, depending on the location. The delay in response demonstrated in the data is consistent with the conceptual understanding.

However, long-term monitoring of groundwater levels has shown mixed trend directions across the region. The groundwater system is considered an intermediary system that provides a buffer and delay in response to stream flow, as suggested in the previous paragraph. It was surprising to find that the bore water levels were not highly correlated with other climate variables. While some bores showed an increasing trend, others showed a decreasing trend. Even in areas with an increasing groundwater trend, stream flows reduced over the period. One potential explanation for this disparity is that the majority of the long-term monitoring bores were screened to deep aquifers, which take longer to respond to changes in recharge. Another aspect is that long-term monitoring bores may have been influenced by major water production bores, as some long-term monitoring data was provided by consent holders. These potential explanations are speculative, and it would be beneficial to have a dedicated study to explain the mixed trends found in groundwater levels and how this behaviour relates to the trend directions shown in other hydrological variables.

The rapid urbanisation in Auckland is contributing to the growth in Northern Waikato, which has been experiencing the fastest growth. Interestingly, the three districts with the fastest growth (as discussed in section 2.1.1) are within the Waikato River catchment, which is currently at 89% allocation pressure at CMA[40], as shown in Table 10. There is limited room for further allocation, and it is uncertain whether the long-term increase in population and growth in industry can be accommodated within the existing water allocation limits. The region is entering a new era of water allocation, where water availability is a limiting factor in growth and demand. Issues of competition between different demands and between instream and out-of-stream use values will become increasingly important. The perception of water availability must change, and

[40] CMA stands for Coastal Management Area, and this location effectively serves as the mouth of the river when accounting for allocation pressure.

discussions on how to allocate water for different purposes must take place within the community. The slowing down of regional water allocation growth is shown in Figure 32, which may be partly influenced by the allocation level nearing the limit. Some major catchments, such as the Piako and Whangamarino River catchments, have already exceeded the allocation limit defined by allocable flows. In fact, allocation levels in these catchments need to be reduced below the limits.

5.3 Implications

5.3.1 Implications to instream values

The reduction in dry spell low flows (section 4.1.4.1) has negative impacts on water quality and ecology. During low flows, streams and rivers have less water volume, resulting in higher concentrations of pollutants and nutrients that increase the risk of harmful algal blooms. Lower flows mean reduced re-aeration potential, causing oxygen levels to drop to harmful or even lethal levels for fish and other aquatic organisms. Additionally, declining low flows can cause changes in the physical characteristics of stream and river habitats, such as changes in water depth, flow velocity, and channel morphology, which can negatively impact the distribution and abundance of aquatic plants and animals. This, in turn, affects the quality and availability of habitat, reproductive success, migration patterns, and overall health of aquatic species, including fish, insects, and other invertebrates.

The reduction in water volume can have a negative impact on water temperature, which in turn can negatively affect water quality and ecology. Elevated water temperatures can lead to reduced dissolved oxygen levels, which can harm aquatic plants and animals, and increase the growth of algae and other organisms, leading to eutrophication and potentially harmful algal blooms. Warmer water can also cause stress or even death to cold-water fish species that are adapted to colder water temperatures. Moreover, high temperatures can increase the rate of chemical reactions, potentially leading to toxic conditions for aquatic life.

Considering the impacts discussed, conducting ecology investigations for setting minimum flows would be useful, especially in catchments that have experienced a rapid decline in low flows as identified in Table 11.

The reduction in rainfall, increased potential evapotranspiration, and longer and more severe dry spells have significant impacts on wetland values. Wetlands rely on a regular and consistent water supply to maintain their ecological function and biodiversity, and reduced water availability can lead to a decline in their extent and health. These changes can have cascading impacts on the wider ecosystem. In the Waikato context, it is worth noting that large wetlands are peat wetlands. When these wetlands are exposed to longer and more severe dry conditions, the peat content in the soil oxidises at a faster rate, known as peat burning. This process leads to the loss of peat and the release of stored carbon into the atmosphere in the form of carbon dioxide, contributing to greenhouse gas emissions. The loss of peat also contributes to sedimentation in nearby waterways.

5.3.2 Implications to water management policies

A significant implication of the declining trend in low flow is that water take restrictions in the Waikato region are becoming more frequent and lasting longer. The minimum flows and allocable flows in the region are defined as percentages of Q_5 rather than specific flow rates. This flexible approach allows for the allocation limits to be adjusted to changing low flow conditions, as updates are regularly made to Q_{5nat} to adapt to the impacts of climate change. However, the more frequent and severe extreme events expected in the future may still put stress on water users by exacerbating restrictions, even with the flexible allocation system in place with the adaptation element.

It would be beneficial to gain a better understanding of how groundwater abstraction affects surface water flow, in particular, how seasonal groundwater production translates to depletion of surface water flow while accounting for the delayed and spread-out response. This study will be related to the groundwater study suggested in section 5.1, which was aimed to examine the role of groundwater storage in providing a delayed response to changes in climate variables that affect low flows of rivers and streams.

The flexible allocation system, which updates the Q_5, has a follow-on consequence that the allocable flow limit of a given catchment will change over time due to changes in low flow conditions. With trend direction of low flow is downward, catchments that were previously under the allocable flow limit may become over-allocated due to the reduction in the limit. This is a concerning issue, particularly given that several major catchments have experienced a reduction in low flow at a rate greater than 20% per decade (Table 11). In preparation for the need to bring over-allocated catchments back below the limit more smoothly, readiness of policy directions could be assessed.

As mentioned in section 5.1, the Waikato River catchment covers almost 59% of the region's land area and has entered close to full allocation status. In response, the catchment's water resource management policy needs to be reviewed if it is ready to deal with the tensions arising from competitive demand and priority. Strategic discussions are being held around viability of water permit trading scheme and more refined ways of allocating water takes, including learning from the experiences of other regions and countries that manage water resources under pressure and at or near full allocation.

6 Conclusion and Future Research

The purpose of this SOE report was to disseminate the data held in the council's database and provide interpretations of the data. This report presents and interprets interesting patterns found in the data relating to hydrology (water quantity). To this end, the following objectives were setup as research questions (section 1.1):

1. What are the key components of the hydrological cycle in the Waikato region, including natural pathways of water and human influences on water movement?
2. What datasets are available to detect changes in the hydrological cycle in the region?
3. Are there any significant patterns in the hydrological variables that the community should be aware of, and if so, what is the explanation for these patterns?
4. Are there any explainable causal relationships among the hydrological variables?
5. What is the uncertainty and reliability of the data used, and what are the limitations of the interpretations presented in this report? Can the findings suggest future research directions?

The key data that were analysed in the report were:

- VCSN data on rainfall and PET - this product is a national interpolation product derived from regional measurements of rainfall and weather variables that impact PET.
- Continuous flow records from regional flow sites.
- Water allocation historic consent data.
- Submitted metered water use records.
- Estimates of water usage are used whenever metered values are not available.
- Submitted and measured bore water levels.

The environmental datasets used in this study varied in terms of their accuracy. Physical data such as flow and rainfall were generally more accurate, as regular quality control and revisions were conducted. However, submitted water use and historic records were less accurate, and further work is required to fill data gaps. Despite varying levels of data quality, interesting patterns can be interpreted by integrating these datasets with environmental data.

From 1961 to 2020, there has been an overall declining trend in annual rainfall across the Waikato region, with each decade generally drier than the preceding one. The last decade was the driest, with the Coromandel, Lower Waikato, and Hauraki subregions experiencing the largest declines in annual rainfall over the same period. There has been a corresponding increase in potential evapotranspiration (PET) from the 1990s through 2020. The combination of less rain and more evaporation has reduced mean river flows at sites monitored by Waikato Regional Council. In 2020, the region recorded its lowest regional rainfall and lowest mean river flows. There is less water flowing in the streams during summer, leading to a reduction in allocable flow over this period. The majority of continuously monitored flow sites showed a declining trend in annual low flow since the 1990s, with some sites displaying a 50% reduction in summer flow over that 30-year period.

The change in climate drivers has not consistently affected the groundwater resources at the regional level, as evidenced by a similar number of bores experiencing both increased and decreased levels over the 30-year period between 1991-2020. This finding was surprising, as one would expect groundwater levels to respond to the region-wide trend of declining water availability, resulting in a decline over the same period. The reason for this behaviour was not investigated but remains a subject for future study. However, the confidence in the declining trends is higher than the increasing trends. Additionally, bore depths were not considered in the trend analysis.

Between 1968 and 2021, water usage has increased in most catchments. Dry spells have become more severe in all catchments since 1990, with less rainfall and increasing potential evapotranspiration (PET). The decline in annual low flow at most sites reflects a combination of climate change and increased water usage. Agricultural water usage, including irrigation, has consistently been the largest source of water usage since the beginning of the record. Additionally, municipal and industrial usage are also significant, supplying towns and cities in the Waikato Region, as well as exporting water to Auckland City from several catchments, including the main stem of the Waikato.

The Tongariro Power Scheme imports water from the Wanganui River, located outside of the Waikato Region. The cross-regional import has had a mean flow of 26.3 m^3/s, which has increased the mean flow of the Waikato River. This increase in annual low flows has been more significant, with modified Q_5 for the Waikato River at the Lake Taupō outlet increasing by approximately 40 m^3/s. This reflects the combined effect of water imports and storage control operations.

The report discusses the implications of observed trends in climate variables, water usage, and allocation pressures, including increased risks to water quality, instream values, and wetland values (section 5.3.1). The rise in allocation pressure also has policy implications, as the region is managing water in catchments that are nearly fully or over-allocated, where competing water uses and prioritisation have become critical management issues (section 5.3.2). The report emphasises the increasing pressure on the water resource system that the region must manage, as water availability decreases while the demand for water increases due to population and industrial growth.

6.1 Future Research

6.1.1 Regional Council database quality assurance

As a part of the data cleaning process, it is recommended to review the database entries for older consents. It was discovered that numerous old consent data entries contain gaps, including the water use purpose classification. Consequently, these entries had to be classified as "Others," despite some potentially belonging to major water use sectors such as Agriculture, Municipal, or Industry. A thorough review of the older consent data entries in the database, coupled with the completion of the data gaps, will prove to be a valuable exercise. This is especially true when conducting long-term trend assessments to track regional changes in the future. having a readily available and clean dataset can attract external researchers, making it a worthwhile investment.

6.1.2 Estimation of water usage

The water use history estimation method has significant potential for improvement. Due to partial water meter coverage, the available water meter data had to be extrapolated into history and consents without water meter data. The extrapolation method used in this report is one way of doing it, but there may be more robust methods for extrapolating water meter data. Another useful exercise would be to track the adoption rate of water metering practices by monitoring the proportion of water takes that were metered and recorded. An indicative assessment of adoption rate growth was conducted based on the count of consents that had water meter records (Figure 13). However, a similar analysis based on consented volume would provide a better understanding of adoption rate growth over the years. Studying the adoption rate growth is crucial, as it provides critical information about the uncertainty in historic actual water use estimates.

Estimating historic actual water use faces another challenge concerning the quality of water meter records, particularly the older ones. Many data spikes and gaps needed to be filled with quick assumptions. A systematic data review of this base water use records is essential to create a clean and robust data source, which will significantly improve the reliability of the historic water use estimates.

To enhance the accuracy of the estimated historic water use, it would be beneficial to investigate how human behaviour in water use changes in response to dry weather conditions. Currently, the method used to construct the history overlooks the varying dryness of irrigation seasons, assuming the maximum amount being used every year based on the ratio between the average actual water use and the maximum consented per industry category. However, actual water use varies from year to year, depending on rainfall patterns. By integrating the pattern of actual water use in response to timing and wetness, a more precise estimation of the history can be achieved.

6.1.3 Focus areas

Of these, the study on the role of groundwater levels and storage as intermediaries between atmospheric hydrology and stream hydrology is highly important. Stream flow monitoring stations have demonstrated a delayed response to changes in these climate drivers, with the duration varying from a few years to several years depending on the location. This delay is likely attributed to changes in storage within the shallow groundwater system before impacting stream flow responses. Exploring the linkage between groundwater levels and the hydrologic response of surface water flow would be a valuable subject for future research.

The Hauraki plain catchments and Upper Waikato regions have been identified as hotspots where there has been a more rapid decrease in rainfall and increase in PET compared to other parts of the region. Targeted instream value assessments will be beneficial in these areas to review and confirm minimum flow targets. These assessments will need to include a comprehensive review of various instream values, such as water quality targets and ecological requirements. It is worth noting that these catchments are heavily utilised for productive pasture lands, specifically for dairy production.

Several locations have been identified with a high level of allocation pressures, with three major catchments[41] displaying an over-secondary allocable flow pressure status. To address this issue, it is necessary to reduce the allocation level below the secondary allocable flow in these catchments.

Waikato's regional policy statement aims to bring down all over-secondary allocable flow catchments by 2031. One approach to achieve this goal, which is being partly used now, is to implement a strategy of not issuing any further water take consents, including renewals, in these catchments. While allowing consents to expire without renewal may eventually reduce the allocation pressures, concerns remain about whether this strategy will be fast enough to meet the 2031 goal. If not, community-wide discussions need to be held to determine additional measures necessary to reach the desired outcome within the available timeframe.

6.1.4 Unexplained patterns

As outlined in the previous section (5.1.2), explaining the underlying reasons for the observed trends and changes was not within the scope of this report and will be left for future study. This report focused on exploring data and providing descriptive commentary on the patterns found in the data. Despite the authors' efforts to explain the observed changes based on their understanding of the hydrological systems, some unexpected patterns that are not readily explainable require further research. These unexpected patterns include:

- Anomalous trends in some flow recorders such as Mangaonua at Dreadnought (Figure 68) and Waihou at Tirohia (Figure 52), which experienced an increase in ALF over the recent 30-year period, while climate drivers and ALFs at all other flow stations experienced a decrease.
- Step changes in observed flows in some flow recorders, such as Mangawara at Jefferies (Figure 72) and Waihou at Tirohia (Figure 52), which had much higher ALF in the early 1980s but quickly dropped in the mid-1980s. Waipa at Honokiwi and Otewa (Figure 64) experienced a step change in the pattern in ALF since 2008.
- The groundwater aquifer, which acts as an intermediary system linking rainfall surplus over PET and river flow, did not show a consistent decline in quantity as other hydrological components, despite the decline in rainfall surplus and river flow at all locations in the region over the recent 3 decades. The lack of a consistent spatial pattern in groundwater levels is unexpected when considering the aquifer as the hydrological component in the middle of the two.
- Some subregions showed step changes in estimated actual water use, and linking these changes to specific events will be beneficial to develop a regional perspective on water use.

[41] the Whangamarino River, Piako River, and Pokaiwhenua River catchments

7 Glossary

7-day Mean Annual Low Flow (MALF): The lowest flow (ALF) for each year is averaged across recorded years to estimate the mean annual low flow. To avoid splitting a single low flow or dry event across years, we use a water year (July-June), instead of a calendar year (January-December).

7-day Annual Low Flow (ALF): The lowest flow for each year from a seven-day moving average. To avoid splitting a single low flow or dry event across years, we use a water year (July-June), instead of a calendar year (January-December).

Climate normal: A climate normal is the average condition computed for a 30-year period (World Meteorological Organization 2017).

Hydrological year (also known as water year): The year starting 1 July and ending 30 June. The use of hydrological year places the summers in the middle of the hydrologic accounting period.

GW: Acronym used in place of “ground water”.

One in Five Year 7-day Low Flow (Q_5): The stream flow at any point that has a 20 percent chance of occurring in any one year (or a likelihood of occurrence of once in every five years, also termed a ‘5-year return period’). The Q_5 is calculated from the lowest seven consecutive days of flow in each year. To avoid splitting a single low flow or dry event across years, we use a water year (July-June), instead of a calendar year (January-December).

Q_{5mod}: Modified Q_5. This is Q_5 derived from observed flow data.

Q_{5nat}: Naturalised Q_5. This is Q_5 derived from the naturalised flow data, which is sum of the observed flow and water use data.

PET: Acronym used in place of “Potential Evapotranspiration”.

Primary and Secondary Allocable Flows: These are limits set on catchments to manage water resources. As allocated volume grows past these limits, more stringent rules are applied to consented water takes.

Primary, Secondary, Tertiary Water Use Purpose: Two categories of water use purposes have been defined and are expressed in the database, enabling the preparation of regional statistics according to these categories. For each consented water take, primary and secondary purposes must be specified. In cases where the consented water take has a dual purpose use, a tertiary purpose must also be specified. A list of the categories is provided in Table 15.

Table 15. Primary, Secondary and Tertiary Water Use Purpose.

Primary Purpose	Secondary/Tertiary Purpose
Agriculture	Bottling
Aquaculture (fresh and saline)	Construction
Domestic & Municipal Water Supply	Cooling
Ecological	Dewatering/water level control
Flood control	Drilling and testing (geothermal)
Horticulture/market gardening	Drilling and testing (non-geothermal)
Industry (Construction/roading)	Drinking water supply - Domestic, rural or urban
Industry (Electricity generation)	Drinking water supply - Emergency supply
Industry (Food processing)	Drinking water supply - Hotel/Motel/Camp
Industry (Others)	Drinking water supply - Industry
Industry (Quarry/mining)	Dust suppression
Industry (Timber/paper)	Factory/industry processing
Recreation	Firefighting
Rehabilitation	Fish farming
	Fish pass
	Flood control
	Frost protection
	Heating (geothermal)
	Hydro turbine operation
	Irrigation
	Maintenance
	Pit/lake filling
	Pools/bathing (geothermal)
	Pools/bathing (non-geothermal)
	Power generation - Geothermal
	Power generation - Hydro
	Recreation (non-geothermal)
	Shed wash
	Stock water
	Stock water and shed wash
	Transporting/loading slurry
	Washing

Resource Management Act (RMA): Resource Management Act (1991) and amendments.

Waikato Region: In relation to a regional council, the region of the regional council as determined in accordance with the Local Government Act 1974.

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