Northland Drought Assessment 2018-2020

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Abbreviation

NRC	Northland Regional Council
SOE	State of Environment
WDC	Whangārei District Council
DEWS	Drought Early Warning System
DM	Drought Monitoring
DA	Drought Vulnerability Assessment
DP	Drought Prediction
SPI	Standardised Precipitation Index
SDI	Standardised Discharge Index
SWI	Standardised Water Level Index
WMO	World Meteorological Organization
SPEI	Standardised Precipitation and Evapotranspiration Index
DMF	Design Minimum Flow
NDEWS	Northland Drought Early Warning System
DMPS	Drought Monitoring and Prediction System
NIWA	National Institute of Water & Atmospheric Research Ltd
SW	Surface Water
WS	Water Storage
FSL	Full Supply Level
MOL	Minimum Operating Level
PWCC	Periphyton Weighted Composite Cover
WCC	Weighted Composite Cover
NPS-FM	National Policy Statement for Freshwater Management
DO	Dissolved Oxygen
DEMP	Drought Ecological Monitoring Plan

Executive Summary

In February 2020 the Northland drought was declared a "Medium Scale Adverse Event" by the NZ government and was upgraded in March 2020 to a "Large Scale Adverse Event" that covered the whole of the North Island and some parts of the South Island. This report aims to build an understanding of this drought event, including how significant the event was, how it compares to historical drought events in Northland, the impact of the drought regarding water resources, water quality and ecology, what may be the likelihood of such events occurring and assessing whether there are any changes over time in the frequency of these drought events.

This information is critical to our understanding of drought in Northland and can be used for future planning and policy measures as well as feed into drought preparation measures (such as council's Drought Management Plan). Furthermore, the methodology used and developed in this report can increase our ability to detect droughts and assess their severity in the future. Notably, Northland Regional Council (NRC) were using some of the drought detection methods described below to assess drought conditions well before drought was officially recognised in February 2020.

The methods used to assess and describe the 2018-2020 drought included the use of a Standardised Precipitation Index (SPI) for rainfall, Standardised Discharge Index (SDI) for river flow, Standardized Water level Index (SWI) for water storage, long term groundwater plots, frequency analysis for return periods of rainfall and low river flows and the frequency of drought occurrence over time. Finally, the results of an extensive ecology and water quality survey are presented. The survey was conducted at 107 river sites with results assessed against known exceedance criteria and compared to flow, wetted width and habitat type to identify any relationships.

The methods above have shown that the drought was prolonged, with drought conditions beginning in July 2018 and ending with a severe flood event in July 2020. In regard to rainfall deficiency, this drought can be considered the second most severe on record, second only to the 1914-1915 drought. Although "Severe Drought" conditions were experienced throughout the region, the Kaitaia area was most affected throughout this event, spending more time in "Severe Drought" conditions than most areas. Frequency analysis of extreme low 6-month rainfall here suggests a return period of >100 years. River flows at all long-term stations reached low levels that have not been recorded previously, with one week mean low flow return periods for the Awanui of >100 years, 50-100 years for the Kaihu and Mangakahia, and 30-50 years in the Maungaparerua, Ngunguru and Waihoihoi Rivers. Similarly, dam water level is lowest since being operated. Northland's shallow unconfined coastal aquifers were similarly affected with the Russell and Ruawai aquifers becoming particularly depleted. A timeline of events is provided below (Figure 1).

The results of ecological field assessments show that for the attributes measured compared to the assigned exceedance criteria, sites had a pass rate of more than 80% except for macrophyte cover in which 72% of sites passed. Dissolved oxygen, water temperature, conductivity and pH tended to decrease with decreasing flow rates and there was a tendency for an increase in periphyton growth (periphyton weighted composite cover) when flows fall within the "Standardised Discharge Index" hydrological drought classification.

An assessment of drought frequency over time suggests that there may be some increase in the frequency of droughts categorised as "Severe Drought" or worse, since 1980, although this observation is not statistically significant and would need further investigation. Cumulative SPI figures are used to examine long term trends in rainfall deficiency and suggest a trend of increasing wetness towards 1980 then a reverse in trend with increasing dryness post 1980.

Recommendations for further work include:

1. furthering our understanding of changes in drought frequency and severity over time and using this to refine predictions for climate change;
2. some alteration of drought indices for better drought detection;
3. use of the long-term State of Environment (SOE) data needs to be used to investigate the impacts of drought at a regional scale.

During the development of this report, NRC has developed some automated methods of drought reporting that will increase our ability to rapidly report on drought conditions and standardise the way droughts are compared.

Date	July 2018	Aug 18	Sep 18	Oct 18	Sep 18	Oct 18	Nov 18	Dec 18	Jan 19	Feb 19	Mar 19	Apr 19	May 19	Jun 19	Jul 19	Aug 19	Sep 19	Oct 19	Nov 19	Dec 19	Jan 20	Feb 20	Mar 20	Apr 20
Impact	Rainfall deficit in most areas		Flow deficit					Rain in some areas	Extremely Dry				Extremely Dry								Extremely Dry	Extremely Dry • Dam level below normal • SM on recession at lowest	• 80% of rivers below DDF • Lake levels continues to decline • GW remains low but signals to recovery	60% of rivers below DDF
Indicator	SPI < 0 SAM (+) phase		SDI < 0				SPI breaking (SPI ≈ 0)		SPI returns (-)	(-) SAM	Global warmest SAM returns (+)				(-) SAM		SAM returns (+)	(-) SAM	SDI < -1.5	SDI <-2.0	**Drought is declared** SAM returns (+)		SPI breaking (SPI ≈ 0)	

Figure 1 Timeline of events

Introduction

Drought is generally defined as a severe moisture deficit below expected levels that restricts some type of activity (Wilhite et al., 2006). It is a normal feature of the climate in nearly all areas but remains challenging to define, particularly in regards to drought beginning, duration and end. Furthermore, droughts differ from other natural hazards in that the impacts can accumulate gradually over a period of time and do not necessarily have an immediate physical impact, unlike other natural hazards. For this reason, it is often referred to as a creeping phenomenon (Tannehill, 1947). In order to make some sense of a drought situation, researchers can quantify a drought based on environmental indicators in the meteorological field (such as the Standardised Precipitation Index), the hydrological field (such as the Standardised Discharge Index) or the agronomic field (such as Soil Moisture Deficit). Additionally, drought can be defined based on its impacts on agriculture/horticulture, drinking water supplies and/or financial impacts. The definition of drought is more complex than explained here, however, the council used some relatively simple yet robust methods to characterise the 2018-2020 event which are outlined in the sections below. This is parts of drought monitoring, a core component of an early drought warning system, the council developed for Northland.

Northland drought early warning system (DEWS)

Drought early warning systems (DEWS) play an important role in the coordination and timely implementation of drought impact mitigation measures. DEWS have been operative in many countries as a shift towards a risk-based drought management approach which offers opportunities to better rationalise expensive relief actions. The development and implementation of a DEWS allows for responsiveness to particular geographic and hydrologic circumstances, as well as value-added information specific to stakeholders in the respective areas (Wilhite & Glantz, 1985).

DEWS require drought monitoring using suitable indicators (DM), drought vulnerability assessment (DA), seasonal drought forecast or prediction (DP), user friendly early warning, training and public awareness, and improved data sharing. **Error! Reference source not found.** below illustrates the DEWS stages in correspondence to drought propagation, i.e. the issuing of a drought warning is required before the effects of drought manifest themselves.

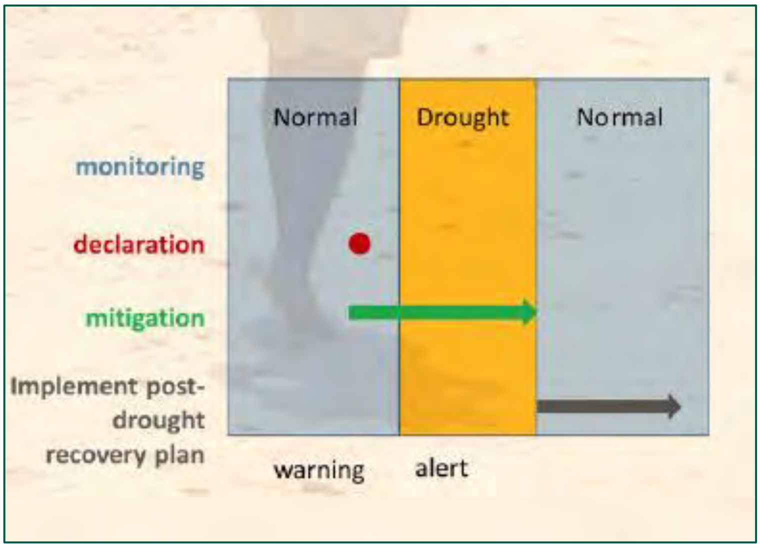

Figure 2: Concept of DEWS (Wilhite & Glantz, 1985).

Northland drought is a complex hazard to define and detect, and its impacts vary from one area to the other. Council has developed its regional drought monitoring and prediction system (DMPS) combining two core constituents of the DEWS together: Drought Monitoring (DM) and Drought Prediction (DP). Outlined in Figure 3 is the DMPS for Northland which currently focuses on the monitoring of meteorological and hydrological droughts with their associated meteorological (SPI), and hydrological (SDI) drought indices derived from rainfall and flow observations as well as climate forecasts.

Other components and associated processes are not yet used but will incorporated when data become available. The remaining components are agricultural and socio-economic droughts which require not only observations but also remotely sensed products and land surface simulations to achieve comprehensive drought monitoring and prediction.

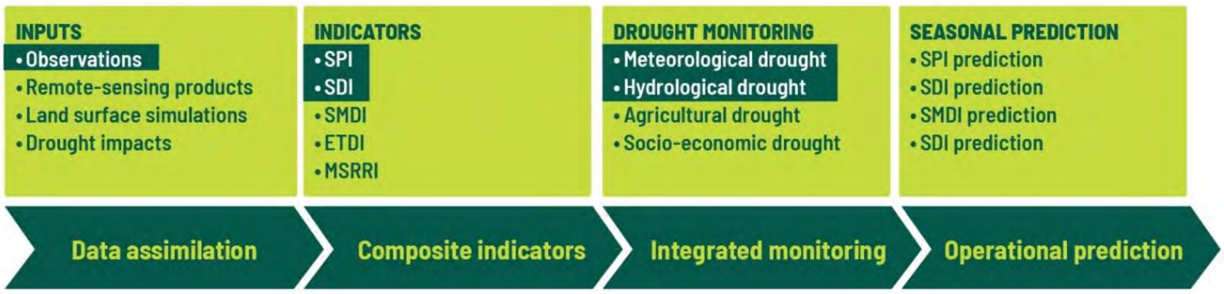

Figure 3: Framework of Northland DMPS: the highlighted components of the DMPS system are what we are currently operating while the remaining components are in progress.

Northland drought monitoring methods

The existing drought monitoring undertaken by council can be used to specify the beginning/end and degree of severity of meteorological and hydrological droughts by their indicators. Drought indicators including Standardised Precipitation Index (SPI), Standardised Discharge Index (SDI) and Standardised Water level Index (SWI) have been applied as they provide better temporal and spatial resolutions than other existing indicators.

The combined use of meteorological (SPI) and hydrological (SDI, SWI) drought indicators allows council to monitor both drought types separately and assess droughts in terms of their intensity, duration and spatial distribution. Furthermore, level of impact of meteorological drought on hydrological drought can be assessed (i.e. impact of meteorological drought on streamflow, for different time scales). The selection of SPI, SDI and SWI and the computation tools follows the World Meteorological Organization recommendation (WMO, 2016).

In addition to SPI and SDI analysis, monthly/seasonal rainfall and flow data are also routinely used as an indication of arrival of the drought before the SPI and SDI modelling takes place. Satellite images are also used to examine the response of soil to the dryness on a monthly basis. We expect remote sensing from satellite imagery to play a larger part in drought determination in the future. Further, work currently being undertaken to develop soil moisture and evapotranspiration monitoring programmes will provide more insight.

Meteorological drought

Meteorological drought intensity is categorised based on the degree of rainfall deficit relative to normal rainfall for a given period (Table 1). In general, a meteorological drought begins when SPI value is less than -0.99 and ends when SPI value is greater than or equal to 0.0. Severity of a meteorological drought ranges between the categories “moderate” to “extreme” and SPI value tends to gravitate toward zero unless there are significant dry or wet spells. SPI can be computed over different precipitation accumulation periods. The resulting SPI indicators for various periods allow for estimating different potential impacts of a meteorological drought (McKee, Doesken, & Kleist, 1993):

- SPI-1 to SPI-3 for shorter accumulation periods (1 to 3 months) can be used as an indicator for estimating immediate impacts such as reduced soil moisture and flow in smaller creeks.
- SPI-3 to SPI-12 for medium accumulation periods (3 to 12 months) can be used as an indicator for reduced streamflow and reservoir storage.
- SPI-12 to SPI-48 for longer accumulation periods (12 to 48 months) can be used as an indicator for reduced reservoir recharge.

SPI has been tested for historic drought events which was a proven powerful tool for monitoring Northland meteorological drought (Pham & Donaghy, 2017). Currently, SPI maps and tabular reports are routinely produced using rainfall data at 32 automatic rain gauges which are extended using additional manually recorded data. This provides information on the state and spatial distribution of dryness. The spatial distribution of dryness may vary depending on the dataset used, i.e. if only automatic rain gauges are used or if all automatic and manual rain gauges are used.

Note: SPI can also be used for quantifying wet conditions over time and space based on precipitation similar for drought. However, SPI should not be used for climate change impact prediction or assessment because it does not include temperature or evapotranspiration.

Table 1: Meteorological drought categories.

SPI	Category	Severity of event (number of times in 100 years)
[±] 2.00 and above/below	Extremely [wet, dry]	1 in 50 years (2.5)
[±] 1.50 to 1.99	Severely [wet, dry]	1 in 20 years (5)
[±] 1.00 to 1.49	Moderately [wet, dry]	1 in 10 years (10)
[±] 0.00 to 0.99	Near normal	1 in 3 years (33)

Hydrological drought

The calculation of Standardised Discharge Index (SDI) as an indication of hydrological drought is undertaken in similar fashion to SPI analysis but using mean monthly flow data at a selection of suitable river flow stations. Hydrological drought refers to persistently low water volumes in streams, rivers, reservoirs and aquifers which starts when SDI is less than -0.99 and ends when SDI is greater than or equal to 0.0. This report focuses mainly on SDI from streams and rivers.

The commencement of hydrological drought coincides with that of meteorological drought in several areas in Northland. In addition, SDI-1 and -3, is a useful complement to the SPI for depicting hydrological aspects of drought on monthly to seasonal time scales (Pham & Perquin, 2019).

At present, SDI maps and tabular reports are routinely produced using data from 20 flow gauges with sufficiently long-term record that are located at the lower reaches of 20 catchments.

Hydrological drought is also examined via Standardized Water Level Index (SWI) using mean water level data of Wilson dam. The relationship of this hydrological drought and meteorological drought is established at longer time scales, 6 months or more.

The degree of severity of hydrological drought is ranked from mild to extreme level (Table 2).

Table 2: Hydrological drought classification.

SDI, SWI	Category
SDI ≥ 0.0	Near normal
-1.0 ≤ SDI < 0.0	Mild drought
-1.5 ≤ SDI < 1.0	Moderate drought
-2.0 ≤ SDI ≤ 1.5	Severe drought
SDI < -2.0	Extreme drought

Rainfall and flow monitoring sites used for the assessment are listed in Appendix 1 andAppendix 2.

Characteristics of 2018-2020 drought

In general, Northland droughts are complex and difficult to characterise. The 2018-2020 drought is even more challenging to characterise particularly due to its longevity, i.e., it started slowly and lasted for a prolonged period (24 months up to July 2020). This long duration of drought occurred despite localised heavy rainfall during the same period. The following sections outline the drought event from the climate and hydrological perspectives by presenting rainfall, river flow, dam water level and groundwater level then comparing these aspects to the most severe recorded droughts by using different drought indicators.

Meteorological Drought

This section describes key characteristics of the 2018-2020 meteorological drought by exploring rainfall deficits as well as SPI indicators for different time scales. This drought is also compared to the historical droughts with intensity and duration using these indicators. SPI-1 and SPI-12 (for one, three twelve consecutive months respectively) are used to display the variation of monthly and annual dry condition as well as of wet condition when appropriate.

Rainfall deficiency

Short duration and geographically isolated rainfall deficits are common in New Zealand, however, rainfall deficits over extended durations greater than one or two months are less common and often manifest as 'agricultural droughts' (NIWA, 2011). Rainfall deficit recorded over some arbitrary duration is sometimes used as a physical indicator of drought, but instead has been used in this report to demonstrate that deficits are an easily calculated metric that can be used as an early indicator of dry conditions.

The total rainfall deficit at selected sites during two of the most significant Northland droughts (1914 to 1915 drought and 2009 to 2010 drought) as well as during the 2018 to 2020 drought is shown in Figure 4. Note that previous reports suggest that the 2009-10 drought was the second worst event after the 1914-15 event, based on the combination of both intensity and duration (NIWA, 2011; Pham & Donaghy, 2017). Rainfall deficit here is monthly rainfall recorded vs long-term median rainfall for each month. It can be clearly seen that rain totals at several sites within the region start falling below long-term monthly averages around July for each of these regionally significant droughts, suggesting an early stage of development of dryness in these areas during winter (Figure 4). The duration of these deficits as well as the duration of SPI < -1 in the next section, give an indication of drought duration.

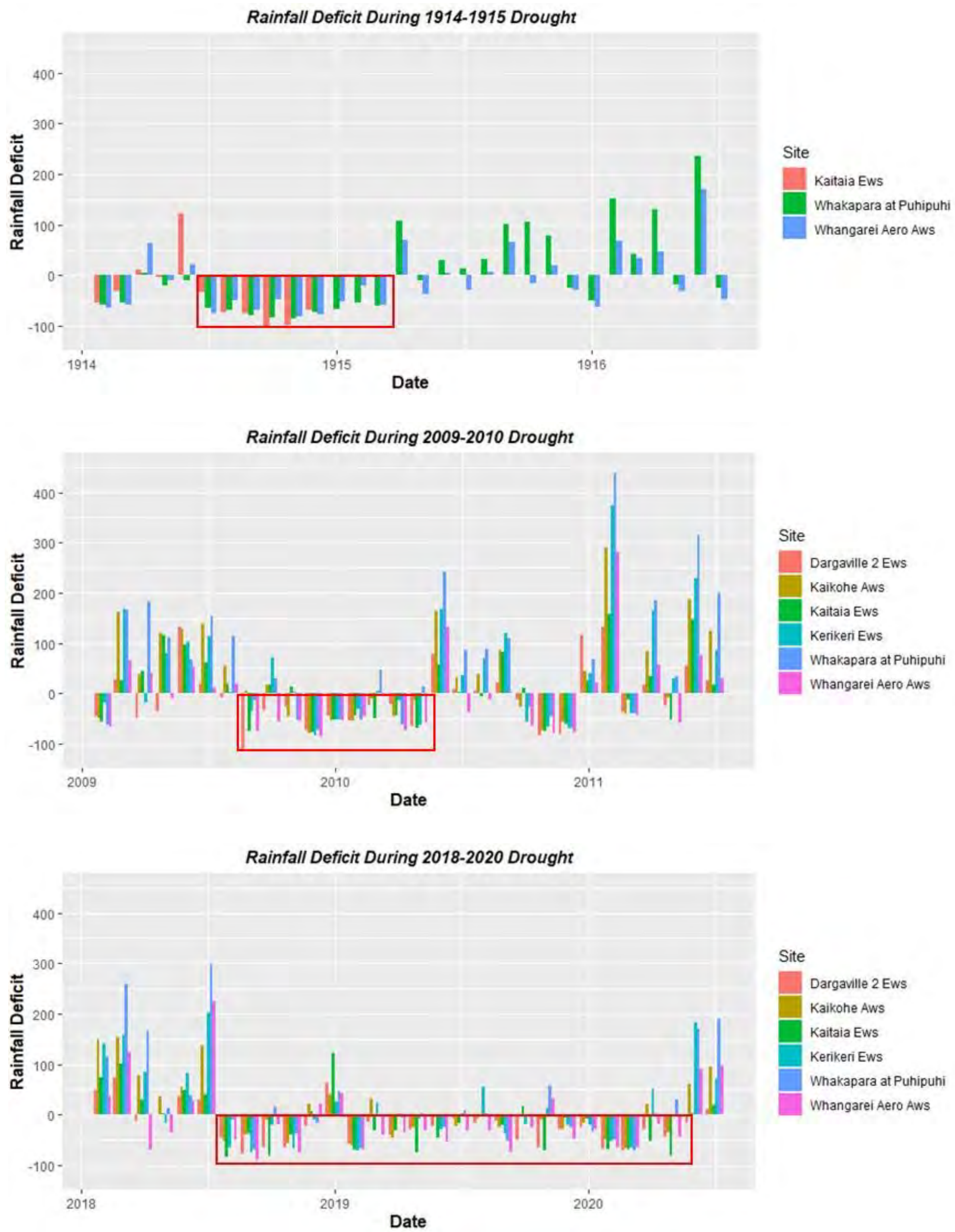

Figure 4: Monthly rainfall deficits (mm) across three significant Northland droughts, including the 2018 to 2020 drought, which is characterised by its long duration. Note that in some cases rainfall record has been extended using record from nearby rain gauges.

Return period analysis of rainfall

Rainfall return periods have been estimated here using 6-month and 12-month rainfall totals. Methodology used here is similar to that used by NIWA (2010) to assess the 2009-2010 Northland drought. Data has been fitted to a normal distribution and minimum rainfall accumulation for the given period is compared to the 0.05 AEP, or 20-year return period rainfall. An indication of return period is also given in the tables below (Table 3 and Table 4). Fitted curves and return period data tables are displayed in Appendix 3.

The frequency analysis used was back-tested against NIWA (2010) results to ensure consistency in method and a good agreeance was found. Return period results over the 6-month period indicated record dryness in Kaitaia (>100 year return period) and significant dryness in Dargaville and Whangārei (30-50 year return period) (Table 3). For the 12-month period, a return period of around 20 years was consistently estimated at all of these long-term stations (Table 4).

Table 3: Return periods of extreme low 6-month rainfall

Rain gauge	Minimum 6-month rainfall accumulation for 2018-2020 event (mm)	6-month rainfall with 20-year return period (mm)	2018-2020 rain as a percentage of 20-year return period rain (%)	Indicative return period for 2018-2020 low rainfall event
Cape Reinga	206	143	144%	5-10y
Kaitaia	149	256	58%	>100y
Kerikeri	329	264	125%	5-10y
Kaikohe	305	282	108%	10-30y
Dargaville	210	238	88%	30-50y
Puhipuhi	392	279	140%	5-10y
Whangārei	200	235	85%	30-50y

Table 4: Return periods of extreme low 12-month rainfall

Rain gauge	Minimum 12-month rainfall accumulation for 2018-2020 event (mm)	12-month rainfall with 20-year return period (mm)	2018-2020 rain as a percentage of 20-year return period rain (%)	Indicative return period for 2018-2020 low rainfall event
Cape Reinga	517	513	100%	10-30y
Kaitaia	838	864	97%	10-30y
Kerikeri	968	1004	96%	10-30y
Kaikohe	1045	977	107%	10-30y
Dargaville	781	762	102%	10-30y
Puhipuhi	1007	971	104%	10-30y
Whangārei	785	760	103%	10-30y

Meteorological drought arrival, intensity and duration

The propagation of the drought is routinely observed at 30 rain gauges across the Northland, but this report focuses on seven key long-term stations. Figure 5 to Figure 9 below show the meteorological drought propagation at these seven key locations over 1-month, 3-month, 6-month and 12-month SPI periods. The meteorological drought generally commenced in July 2018 when SPI value less than -0.99 were recorded and coincided with the beginning of the large monthly rainfall deficits reported in the rainfall deficiency section above.

Records from all rain recorders indicate a persisting meteorological drought between July 2018 until July 2020 (24 months in total). Figure 5 to Figure 9 present the duration and intensity of these drought conditions at the long-term stations. For the shorter 3-month SPI period, drought conditions were temporarily interrupted at Kaitaia, Dargaville and Whangārei in December 2018 and then again in September 2019. The region experienced a number of frontal systems and thunderstorms during November-December 2018 and again in September 2019. Short periods of relief in 3-month SPI suggests some respite in these areas in regards to soil moisture and stream flow, but only very temporarily.

The larger SPI periods tend to obscure ad hoc rain events, as shorter-term variations are buffered by the longer-term analysis. The 6 months and 12-month SPI demonstrate drought persisting from August 2019 beginning in the Far North to July 2020. The Far North experienced drought conditions earlier than areas from Kaikohe south, with the drought extending its reach down the region progressively (Figure 7 and Figure 8 display this clearly). Persistent dry signals for these longer SPI periods are an indicator of stress on groundwater and reservoirs. Indeed, it was from the beginning of 2020 to June 2020 that town drinking water supplies from reservoirs in the Whangārei District and groundwater throughout the region became severely depleted. Record low Whangārei water supply dam levels were recorded in April 2020 and most groundwater stations recorded levels in the "Extremely Low" category (0-5th percentile) for May 2020.

At most locations these meteorological drought conditions were interrupted between May to August 2020 with considerable rainfall during these months, particularly July 2020 when parts of Northland experienced a significant flood event (focused mainly around the Bay of Islands and Whangārei). This event marked the end the regional drought, although Table 5 shows that there are some notable localised exceptions, specifically, Kaitaia and Dargaville for the 6-month SPI and Cape Reinga, Kaitaia, Kerikeri and Dargaville for the 12-month SPI period.

Three-month SPI has been used to determine periods of most intense drought. This SPI period is chosen as shorter period (e.g., 1-month) values tend to be erratic spatially and temporally, while longer periods (6 and 12 months) buffer out the timing of dry periods due to a longer period smoothing effect. Kaikohe, Kerikeri, Dargaville, Puhipuhi and Whangārei were at their driest around February 2020, Kaitaia at its driest around April 2020, and Cape Reinga notably earlier, near the beginning of the drought around August 2018. All areas experienced conditions that are classified as "Extremely Dry" at least once during the drought, but Kaitaia was a standout, experiencing dryness represented with a 3-month SPI of <-3 at its driest (anything lower than -2 is classified as "Extremely Dry" and the driest category) (Figure 6).

Table 5: Periods that can be defined as "drought" periods according to SPI analysis over 3-, 6- and 12-months SPI periods. Note that periods ending in * show drought remaining to the time of writing.

RF Station	SPI-3	SPI-6	SPI-12
Cape Reinga	Jun 2018 to Aug 2019 Jan 2020 to Jun 2020	Jul 2018 to Dec 2019 Feb 2020 to Jul 2020	*Nov 2018 to* *
Kaitāia	Sept 2018 to Dec 2018 Mar 2019 to Sept 2019 Dec 2020 to Jul 2020	*Sept 2018 to* *	*Mar 2019 to* *
Kaikohe	Sept 2018 to Jul 2020	Apr 2019 to Jul 2020	Apr 2019 to Aug 2020
Kerikeri	Sept 2018 to Apr 2020	Dec 2018 to Jun 2020	*Mar 2019 to* *
Dargaville	Sept 2018 to Dec 2018 Mar 2019 to Aug 2019 Dec 2020 to Aug 2020	*Nov 2018 to* *	*Apr 2019 to* *
Puhipuhi	Sept 2018 to May 2020	Dec 2018 to June 2020	May 2019 to July 2020
Whangārei	Sept 2018 to Dec 2018 Mar 2019 to Oct 2019 Jan 2020 to Jun 2020	Jan 2019 to Jul 2020	May 2019 to Aug 2020

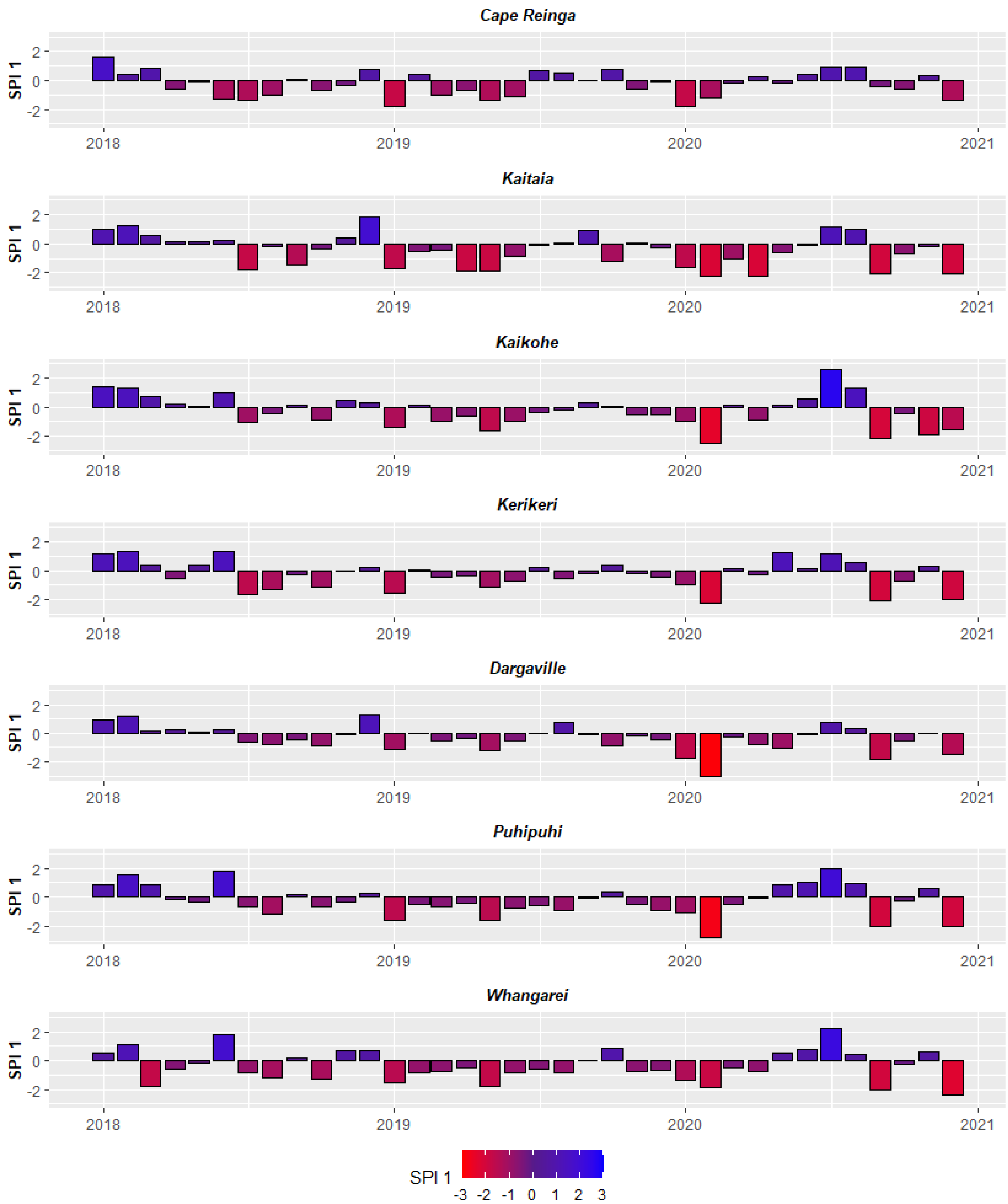

Figure 5: One-month SPI (SPI-1) for the 2018 to 2020 period.

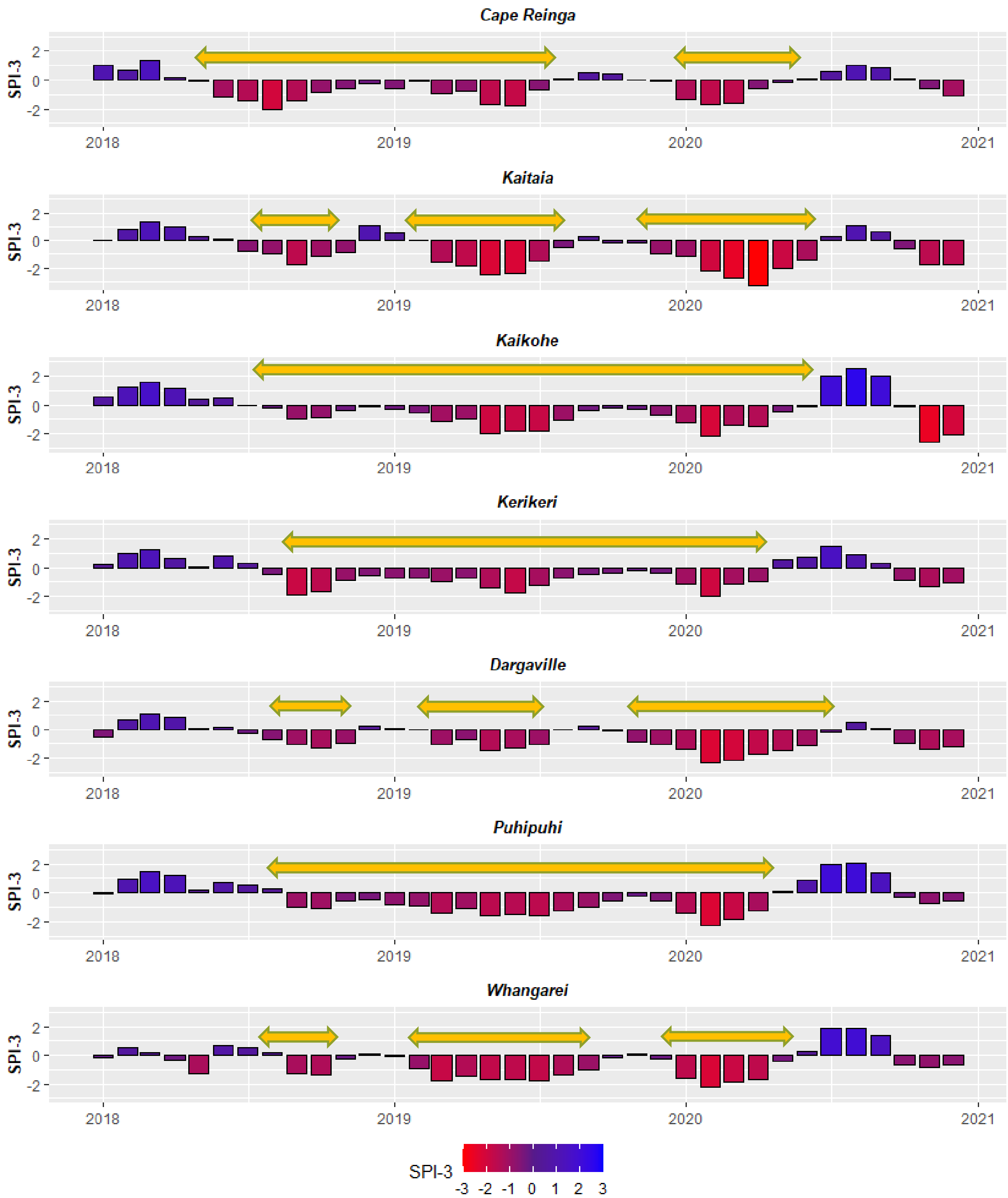

Figure 6: Three-month SPI (SPI-3) for the 2018 to 2020 period. Yellow arrows indicate the extend of periods classified as "drought" for the given SPI period.

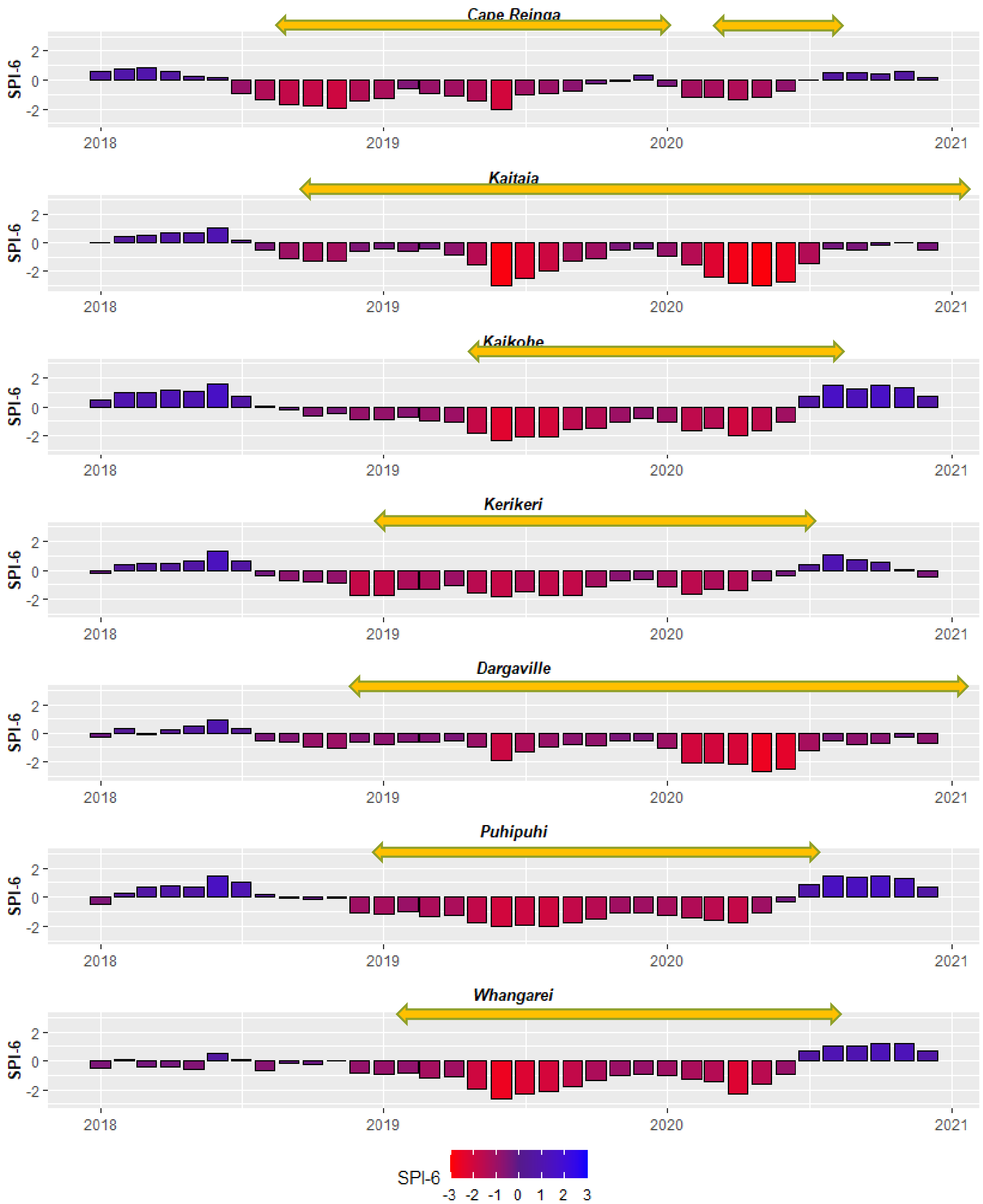

Figure 7: Six-month SPI (SPI-6) for the 2018 to 2020 period. Yellow arrows indicate the extend of periods classified as "drought" for the given SPI period.

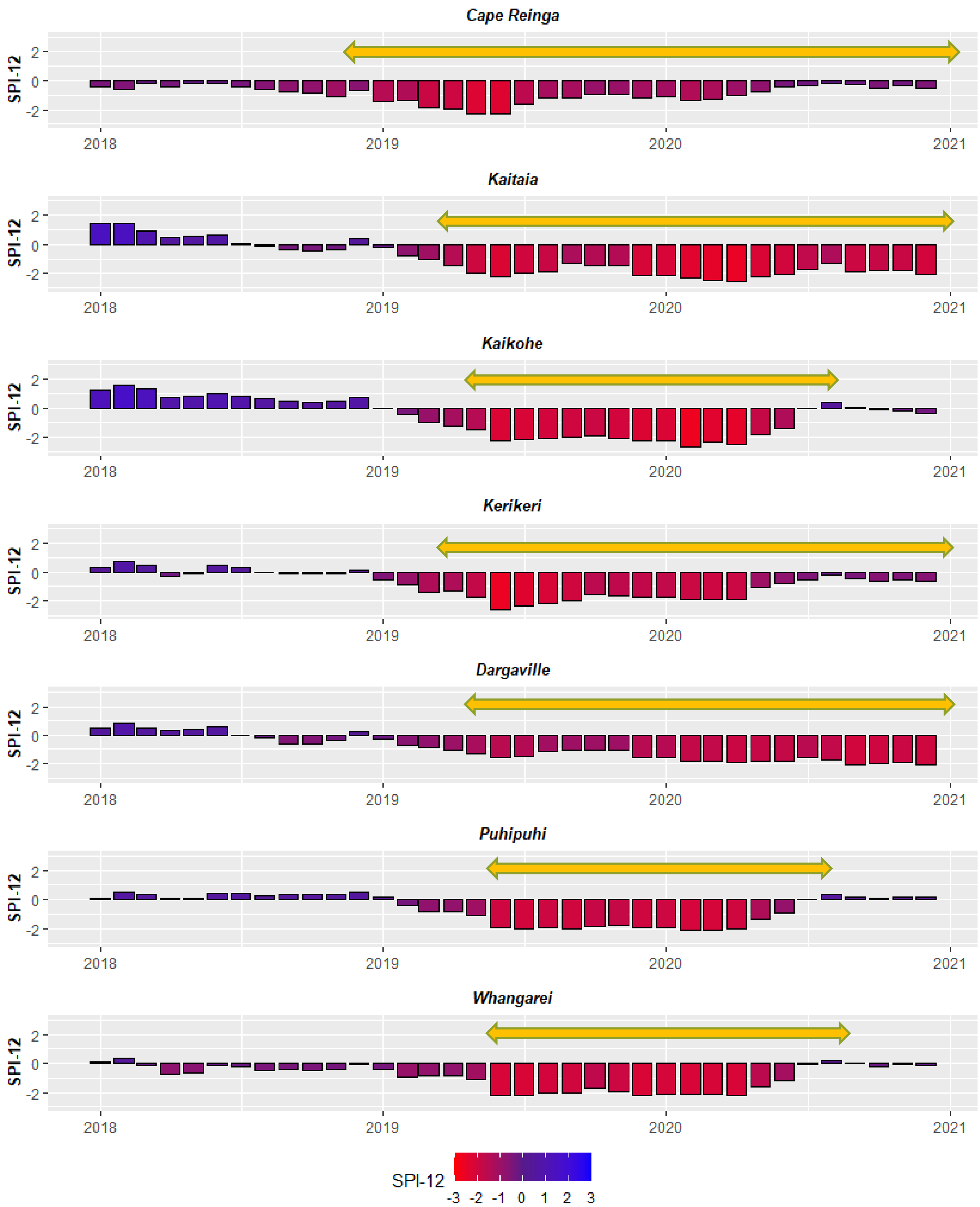

Figure 8: Twelve-month SPI (SPI-12) for the 2018 to 2020 period. Yellow arrows indicate the extend of periods classified as “drought” for the given SPI period.

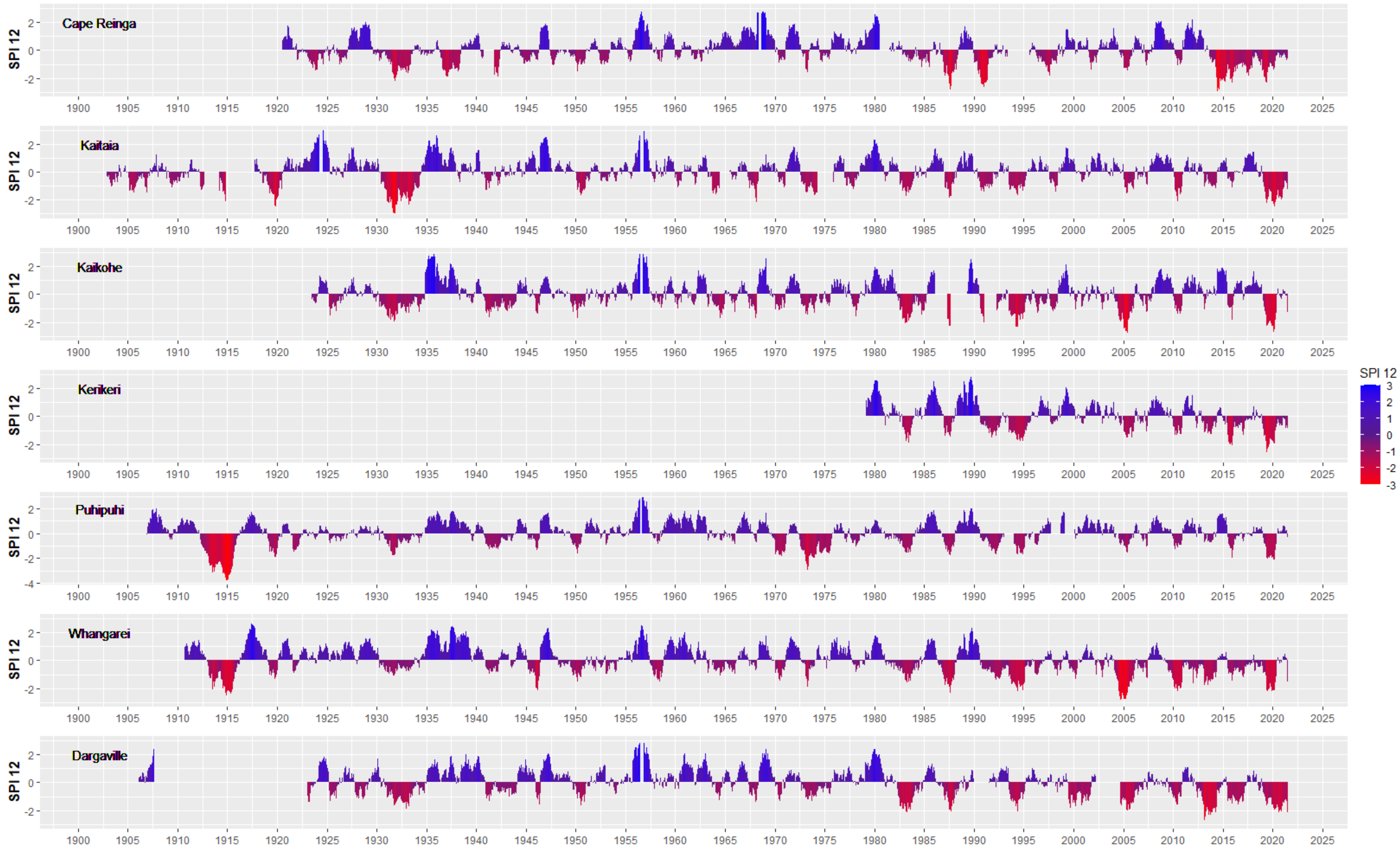

Figure 9: Twelve-month SPI (SPI-12) for the overall recording period.

Localised vs. regional meteorological drought

SPI maps over 1-month (Appendix 4), 3-month (Figure 10), 6-month (

Appendix 5) and 12-month (Appendix 6) SPI periods are used here to represent the spatial variations SPI figures over time, and therefore the evolution of meteorological drought severity and extent from 2018 to 2020. As with the section above, 3-month SPI figures are used here to describe the spatial evolution of the drought, as shorter periods (1 month) tend to be erratic, while longer periods (6 and 12 months) buffer out the timing of changes due to a smoothing effect.

The existence of both localised and regional meteorological drought types during longer drought periods is a common situation for Northland and is consistent with spatial variation of rainfall across the region. This mixture of localised and regional drought conditions was also observed in droughts from 1982-83 and 2013-14 (Figure 10 and Appendix 7). The 2018-2020 drought similarly evolved from a localised drought, with the event focused mainly around Cape Reinga from July to August 2018, then begins to spread with “Severe” drought conditions encompassing the Kaitaia area, Kaeo and parts of the west coast in September-October 2018. Some relief in dry conditions occurs in December 2018 to February 2019 mainly due to rainfall in December 2018, then dry conditions resume, becoming region wide drought until July 2019, particularly in the north and north-east where “Extremely Dry” conditions occur. Some relief from dry conditions occurred once again from September to December 2019 then regional drought resumes with “Extremely Dry” conditions across virtually the whole region in February 2020. These dry conditions persisted until May and June 2020 when some rain was delivered to the east coast, then the rainfall event in July 2020 saturated parts of the east coast and alleviated dryness throughout most of the region.

This drought evolved to become a “Regional Drought” as described above, but it is notable that some areas appeared to be more prone to drought during this event than others. The Kaitaia area in particular spent more time in “Extreme Drought” conditions than most locations.

SPI-12 maps for year 2018, 2019 and 2020 (Appendix 6) also show that the cumulative effect of meteorological drought over 12-month periods is significant. In principle, the longer the drought duration, the more severe the meteorological drought and the more locations likely to experience these drought conditions. SPI-12 maps show that there was a wide regional spread in locations experiencing drought conditions and a prolonged period of “Extremely Dry” drought conditions experienced when examined on this time scale. This represents persistent rainfall deficit across the region and in foresight was used as an early flag of risk, particularly in regard to groundwater levels and in hindsight can be used as an indication of the duration and spatial extent of these “Extremely Dry” conditions.

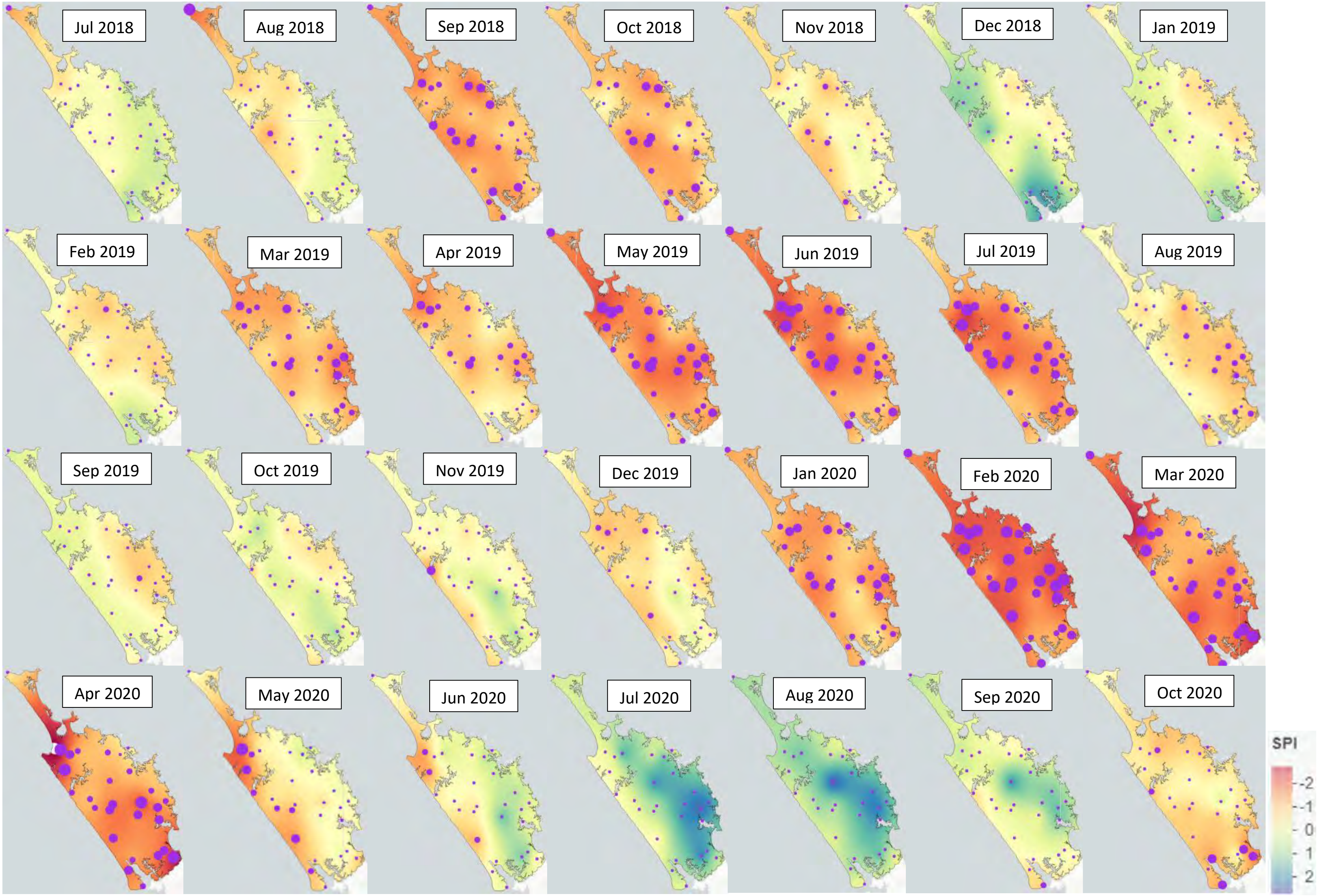

Figure 10: SPI-3 distribution for July 2018 to July 2020. The severity of meteorological drought is highlighted in orange and red colours for severe and extreme dryness, respectively.

Severity of meteorological drought

The intensity of 2018-2020 meteorological drought over its entire duration has been compared to a selection of the most anomalous events (1914-1915, 1945-1946, 1982-1983, 1990-1994, 2009-10 and 2012-2013). The 2009-10 drought has previously been considered to be the second worst since 1914 and the worst over past three decades of the droughts declared by the government (NIWA, 2010, Pham, 2017). Although the 1990-1994 event is not recorded as the top five most severe droughts, it is considered an abnormal event with lengthy duration, so used as a comparison here. Drought comparisons in this report have been made by: 1) summarising data on a regional scale for comparison of "Regional Drought", and 2) summarising data at seven long-term stations individually, for a comparison of "Local Drought".

For a "Regional Drought" comparison (Table 6), SPI values were firstly subset for each of the drought periods identified above, then SPI values for all sites have been averaged to give a series of monthly average SPI values. Finally, the minimum of these average values is isolated to represent the worst condition observed for each SPI interval (3, 6, 12 and 24 months) over the subset drought period. The subset drought data are then compared and represented in Figure 11 below. The 1914-1915 drought is a standout here being "Extremely Drought" over short and long SPI periods indicating this was an extremely severe drought that continued for a very long time. This is consistent with previous studies which also identified this to be Northlands worst recorded drought (Keyte, 1993; NIWA, 2010; Pham, 2017). Both the 1945-1946 and the 2012-2013 droughts were classified as "Extreme" over shorter periods, but did not experience the long duration of dryness. The 2018-2020 drought can certainly be categorised as "Extreme Drought" over a prolonged timescale. For example, during the 2009-2010 drought "Extreme Drought" conditions were experienced buy only over the 3 and 6 month timescales at a regional level. Considering this information, the 2018-2020 drought should be considered more severe than 2009-2010 and second only to the 1914-1915 drought.

A notable limitation of the analysis, particularly for early droughts, is the scarcity in data available at the time. For example, data is only available from three locations during the 1914-1915 drought (Kaitaia, Puhipuhi and Whangārei). As time progresses, more data becomes available to better represent regional coverage of drought.

Local scale drought has been compared by subsetting drought periods, then calculating the minimum SPI value recorded for the site during the subset period. This is an indication of the driest conditions experienced during each drought by site. At this local scale the 2018-2020 drought ranks as the second most severe meteorological drought at Cape Reinga, with drier conditions occurring in 1990-1994 (Appendix 8A). Dry conditions also occurred here in 1945-1946 but only over a shorter timescale. For Kaitaia, 1914-1915 was the most severe drought, but drought conditions in 2018-2020 were the most severe on record over longer time periods (12 and 24 months) (Appendix 8B). In Kaikohe, the 2018-2020 ranks as the most severe drought, with 2009-2010 being the second most severe, due to the duration of dryness being shorter as represented by lower severity over longer SPI scales (Appendix 8C). Similarly, in Kerikeri, the 2018-2020 drought ranks as the most severe over these longer 12 and 24-month timescales (Appendix 8D). For Puhipuhi, the 1914 to 1915 drought dwarfs all others and during most drought events "Extreme Drought" conditions were experienced over shorter timescales. However, the 2018-2020 drought is the only drought bar 1914-1915 to experience "Extreme Drought" conditions over the longer 12-month period (Appendix 8E). The 2018-2020 drought in Whangārei was less severe than 1914-1915 and quite comparable to most of the other drought events (Appendix 8F). Finally, conditions in Dargaville during 2018-2020 were not as severe as 2012-2013, but could be considered the second most severe drought (Appendix 8G).

It should be noted here that the meteorological drought details above do not take into account temperature changes through time. Evapotranspiration increases with increasing temperature and thus, water availability decreases. Therefore, with increasing temperatures occurring through time as climate changes (Figure 12) the impact of meteorologically dry conditions increases. This results in dry conditions observed today having a similar impact on the ground as even drier conditions observed 100 years ago.

Table 6: Drought ranking of observed drought events. The level of drought severity is based on their severity over their entire duration with 1 being the most severe and 6 the least.

Severity level	Keyte (1993)	NIWA (2010)	Pham (2017)	Current Report
1	1914-15	1914-15	1914-15	1914-15
2	1945-46	2009-10	2009-10	2018-20
3	1982-83	1945-46	1945-46	2009-10
4		1982-83	2012-13	1945-46
5			1982-83	2012-13
6				1982-83

(Refer to Appendix 13 for a matrix of drought characteristics by intensity and duration)

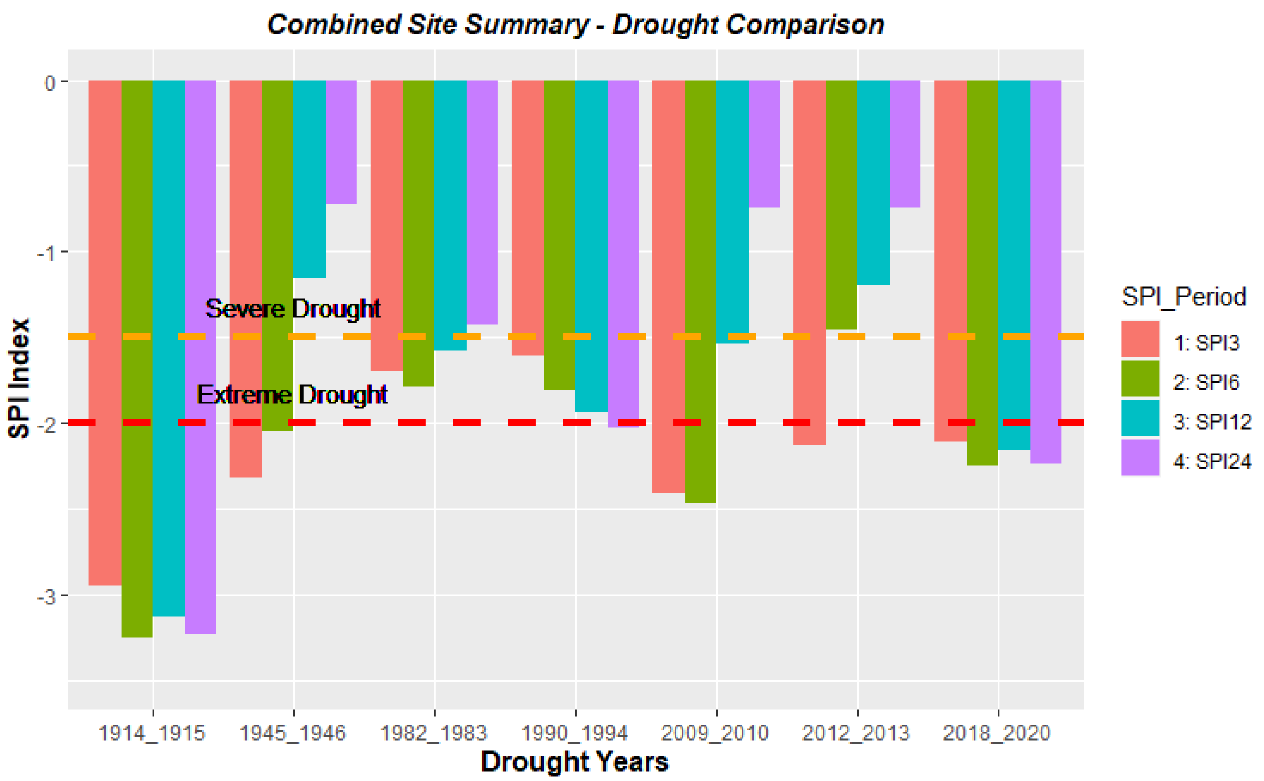

Figure 11: Regional drought comparison over significant drought years

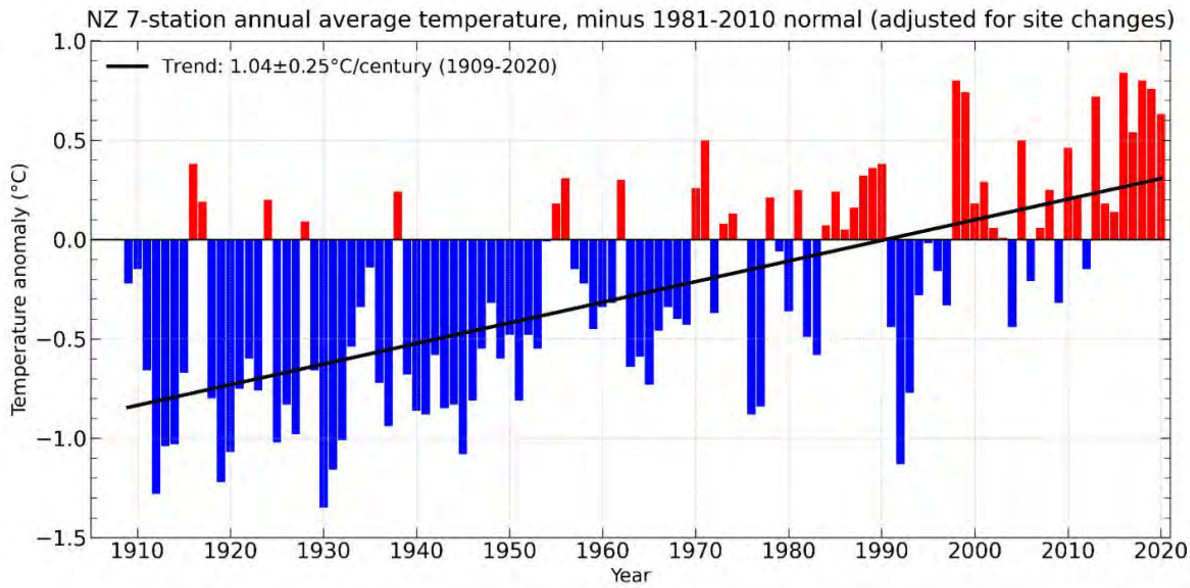

Figure 12: Historical nation-wide annual temperature anomalies (degrees above or below the 1981-2010 normal) from NIWA's seven-station temperature series which begins in 1909. Six of the past eight years have been among New Zealand's warmest on record. Sourced from NIWA Annual Climate Summary (2020).

Trend in meteorological drought

Trend in meteorological drought is examined in two ways here. Firstly, the frequency of drought months is examined by counting the months in each year that recorded SPI values fell below -1.0 SPI, -1.5 SPI, and -2.0 SPI, indicating the frequency of moderate, severe and extreme drought months respectively. Secondly, the long-term systematic trend in dryness has been examined by generating a rolling sum of SPI-1 values over time. As these SPI values tend to revolve around a mean of zero, increasing trends in the accumulated values indicate increasing wetness, and decreasing trends indicate increasing dryness.

There is no obvious trend over time at any sites in the frequency of drought months categorised as "Moderate Drought" or worse (<-1.0 SPI) (Figure 13). However, there may be some indication that the frequency of droughts categorised as "Severe Drought" or worse (<-1.5 SPI) (Figure 14) and "Extreme Drought" or worse (<-2.0 SPI) (Figure 15), is increasing. There tends to be a higher count of months per year below these thresholds post 1980, although R-squared of regression analysis does not give high confidence in this observation and further investigation is needed here.

There are some notable systematic trends in dryness over time, with quite similar trends observable at Cape Reinga, Kaikohe, Whangārei and Dargaville (Figure 16 andFigure 17). These stations display an increasing trend in wetness towards a peak around 1980. Following this date, the trend tends to be one of increasing dryness over time. The trend in drought frequency mentioned above suggested that the increasing dryness post 1980 may be influenced by an increase in the frequency of months categorised as "Severe Drought" or worse. Speculating further towards the cause of this trend is outside the scope of this report, but some possibilities include changes in the frequency or severity of El Niño events, the influence of other climate cycles such as the Interdecadal Pacific Oscillation, changing climate characteristics with greenhouse gas emissions or a combination of these factors.

Similarly, duration of drought tends to be longer post-1980 with accumulative SPI-3, 6, 12, 24 for 3 months, 6 months, 12 months and 24 months are less than –1 at almost all key rain stations (Figures 6-9 and Appendix 8). It is clear that the 2018-20 drought is the most lengthy event since beginning of record.

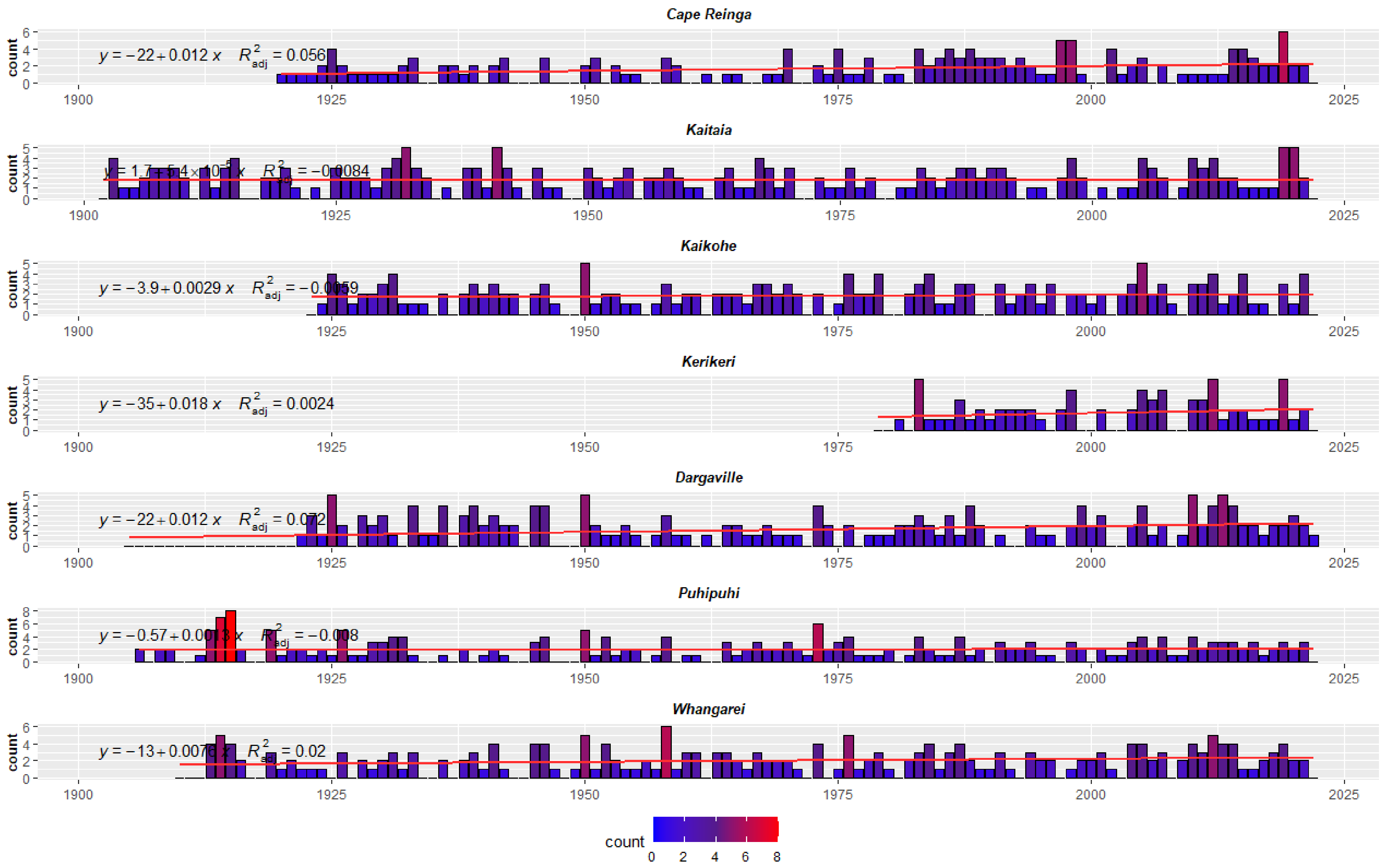

Figure 13: Count of drought months < -1.0 SPI per water year for full record length.

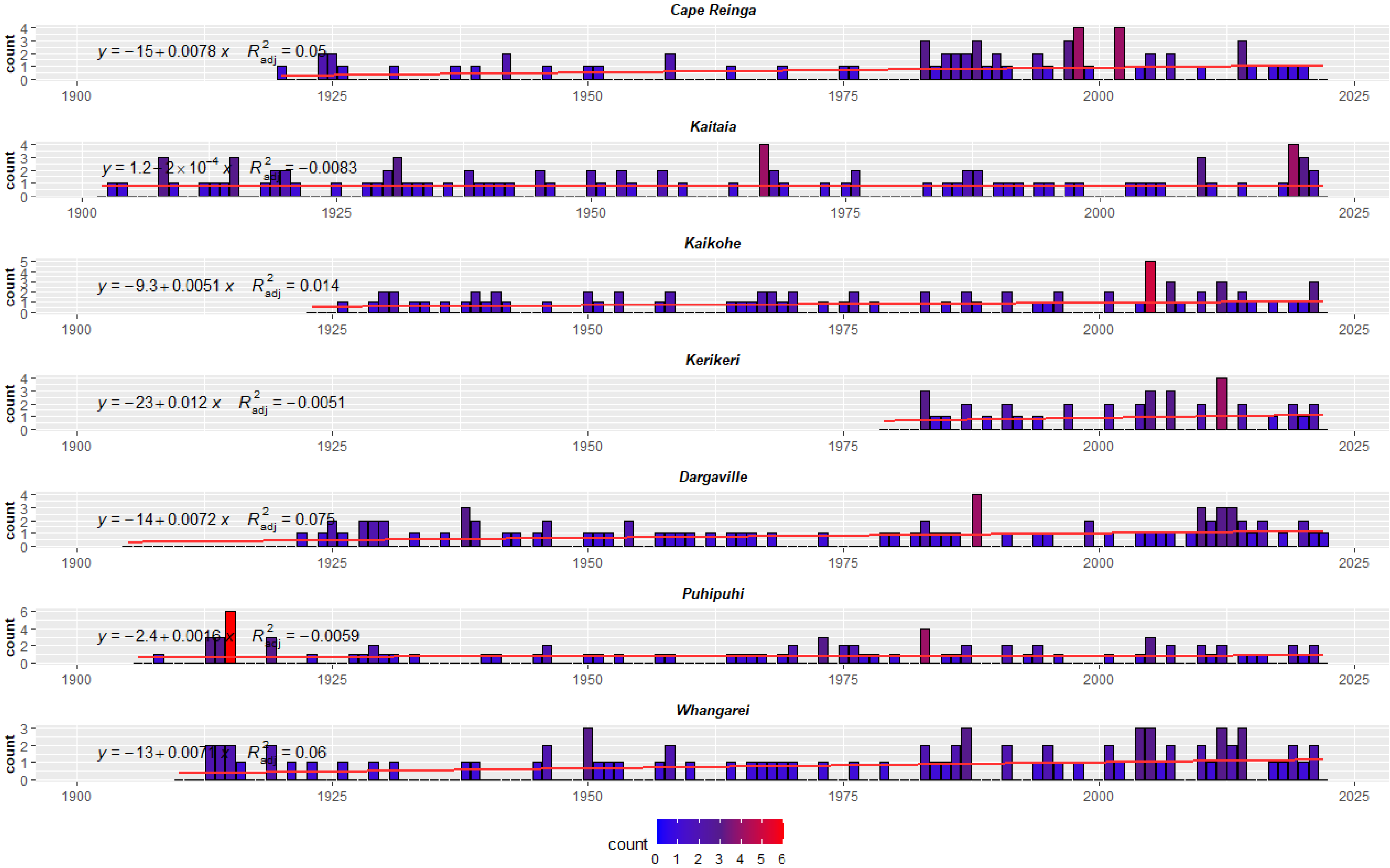

Figure 14: Count of drought months < -1.5 SPI ("Moderate Drought" or above) per water year for full record length.

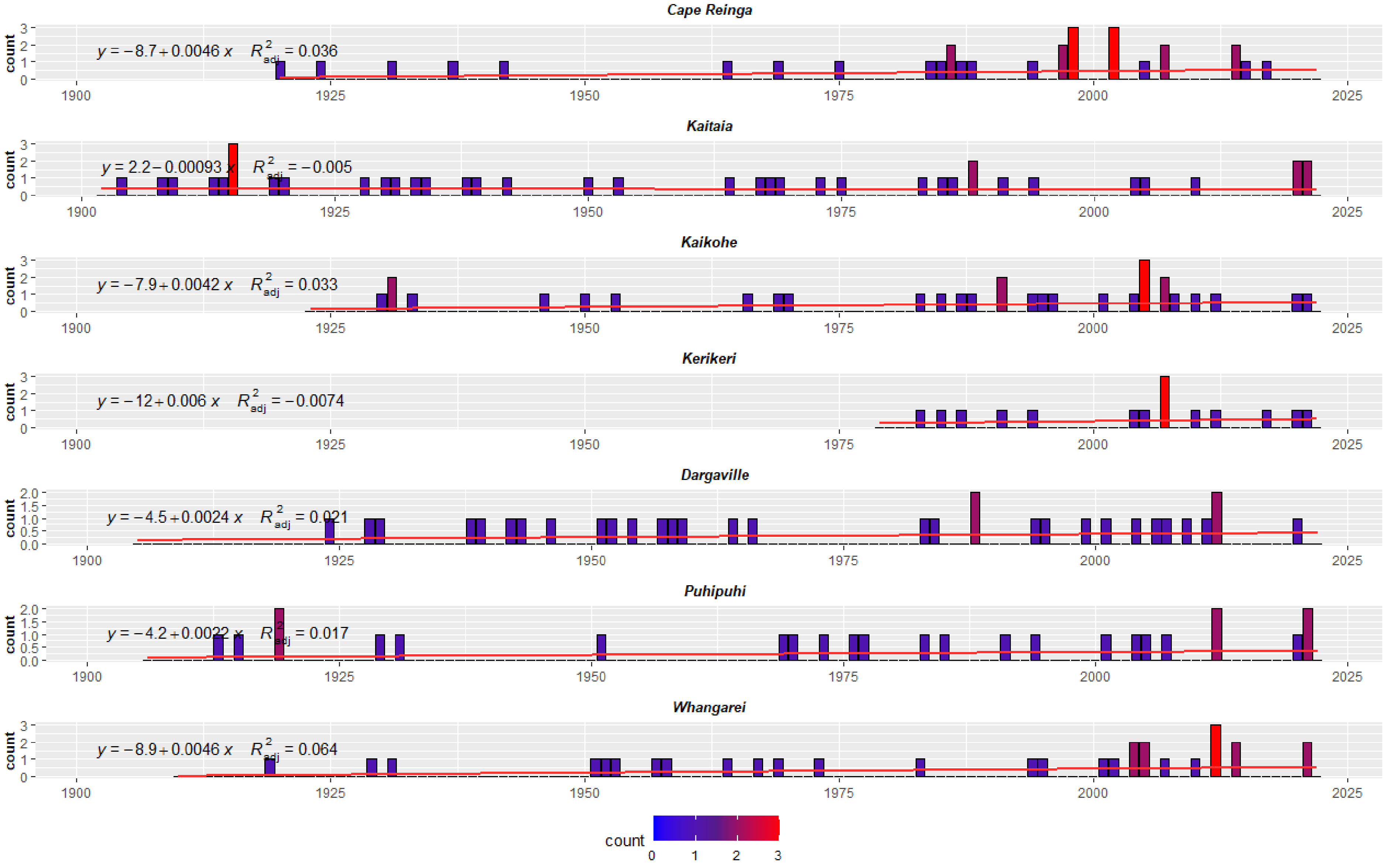

Figure 15: Count of drought months < -2.0 SPI (“Severe Drought” or above) per water year for full record length.

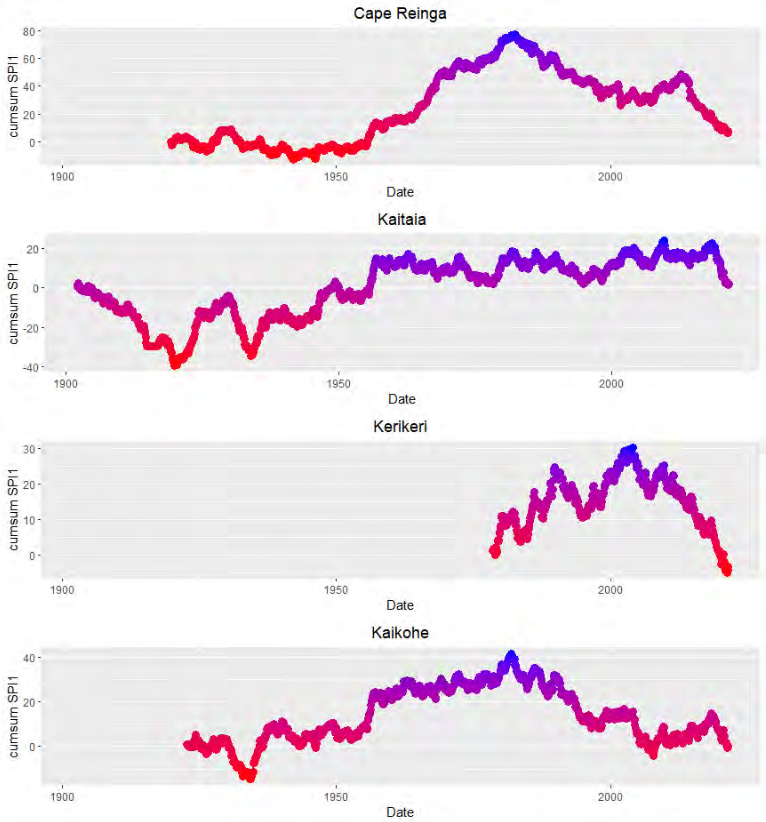

Figure 16: Cumulative SPI-1 though the full length of each record at Cape Reinga, Kaitaia, Kerikeri and Kaikohe, as an indication of systematic changes in dryness through time.

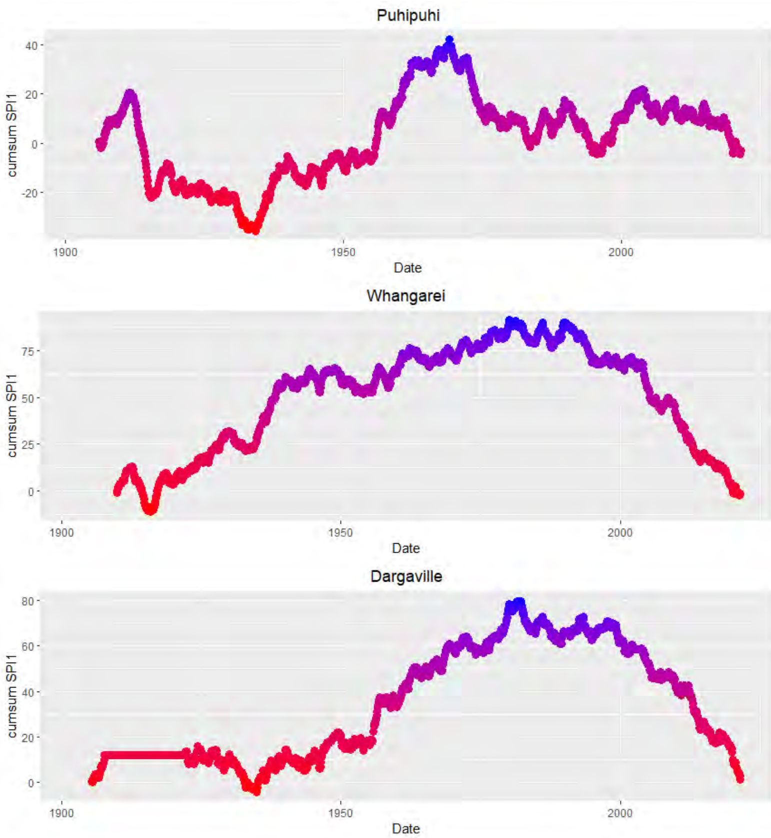

Figure 17: Cumulative SPI-1 though the full length of each record at Puhipuhi, Whangārei and Dargaville, as an indication of systematic changes in dryness through time.

Hydrological Drought

This section describes the characteristics of the 2018-2020 drought in relation to impacts on surface water flows, water storage and groundwater.

Different drought indicators are used to characterise this drought that is also compared to previous drought events using same indicators. The arrival of hydrological drought is examined in relation to that of meteorological drought.

The SDI index for surface water flows is also examined in the context of soil moisture deficit observed at five NIWA climate stations.

Groundwater propagation is then examined in a separate section below.

Hydrological – surface water (SW) drought

The arrival, intensity and duration of this "Hydrological surface water Drought" (hydrological SW drought) is characterised by examining the results of Standardised Discharge Index (SDI) results for four durations in the same manner as meteorological drought analysis (3-month, 6-month, 12-month and 24-month durations).

Conventionally, drought low flow (7 day 1 in 5 years low flow) has been used for drought flow monitoring. The number of drought days at several flow sites has been compared using this approach vs the SDI approach used in this report. This reveals that DMF does not characterise drought severity well and when river flow reaches DMF threshold the hydrological drought could have already occurred and become very intensive (i.e. severely dry). In fact, the hydrological SW drought is likely to occur in the same month as the meteorological drought.

The arrival, intensity and duration of hydrological surface water drought

The propagation of Hydrological SW Drought has been examined here at ten long-term flow stations. Hydrological drought conditions (characterised by SDI values <0.99) arrive abruptly in July 2018 in response to the beginning of meteorological drought (Figure 18). This demonstrates that rainfall deficit quickly results in flow deficit for most Northland catchments. SDI values at these flow stations reveal that hydrological drought persisted between July 2020 to June 2020 (23 months in total) (Figure 18). The trend in SDI intensity mirrors that of meteorological drought SPI displayed in Figure 5, again suggesting a strong relationship in timing and intensity of these drought types. Hydrological drought conditions were temporarily broken at most stations in December 2018 and then again in September 2019 with the frontal systems and thunderstorms during these months. The break in Hydrological SW drought with this rain in December 2018 was only fleeting due to the soil moisture conditions mentioned above. Hydrological SW drought conditions were at their worst in May/June 2019, then again in May 2020 just prior to some rain relief through June and July 2020. SDI values in May 2019 were categorised as "Extreme Drought" flows at four of the ten rivers (Awanui, Kaihu, Mangakahia and Manganui) and below "Severe Drought" flows at all except the Waihoihoi river. During June 2019, SDI values in the Awanui River were approaching -2.5, the lowest 1-month SDI recorded during the drought. Following the brief respite with September 2019 rainfall, SDI values gradually decreased until the end of the drought, with four of the ten stations recording "Severe Drought" flows in May 2020.

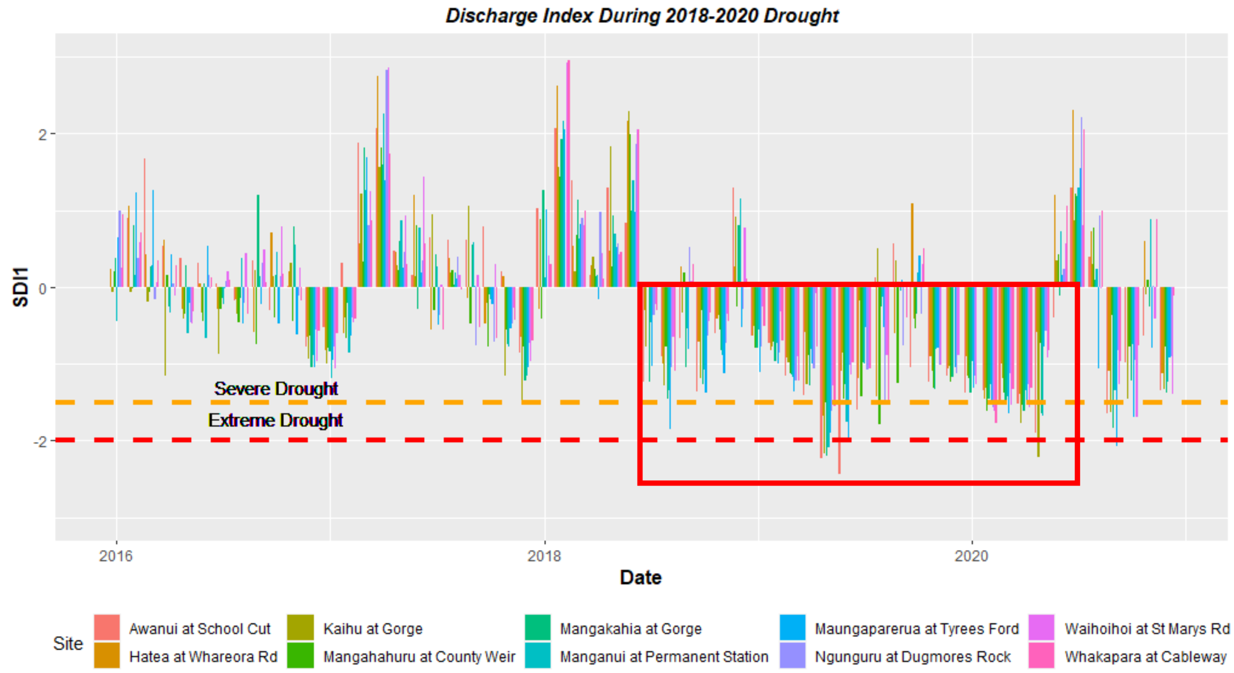

Figure 18: One-month SDI values (SDI-1) during the 2018-2020 drought.

Severity of hydrological surface water drought

Hydrological SW drought during 2018-2020 has been compared here to know historical drought events where flow record is available. Sufficient flow record exists to compare the 1982-1983, 1990-1994, 2009-2010 and 2012-2013 droughts with the 2018-2020 drought. Firstly, for a region wide comparison, SDI values were firstly subset for each of the drought periods identified above, then SDI values for all sites have been averaged to give a series of monthly average SDI values. Finally, the minimum of these average values is isolated to represent the worst condition observed for each SDI interval (3, 6, 12 and 24 months) over the subset drought period. The subset drought data are then compared and represented in Figure 19 below. Secondly flow frequency analysis has been carried out on the lowest one day mean flow during the full record for each station (Table 7).

Hydrological SW Drought conditions experienced region wide during the 2018-2020 drought were the worst on record across the board, since sufficient record began (Figure 19). Hydrological SW drought during 2018-2020 was considerably more severe than the next most severe droughts in 1982-1983 and 1990-1994 (

Appendix 9-

Appendix 12). Frequency analysis on the lowest daily mean flow recorded during the 2018-2020 event suggest that these lowest recorded flows could have return periods of >100 years for the Awanui, 50-100 years in the Maungapererua, Kaihu and Mangakahia and 30-50 years in the, Ngunguru, and Waihoihoi rivers. Frequency analysis on the lowest one week mean flow recorded during the 2018-2020 event suggest that these lowest recorded flows could have return periods of >100 years for the Awanui, 50-100 years in the Kaihu and Mangakahia and 30-50 years in the Maungaparerua, Ngunguru, and Waihoihoi rivers (Table 7).

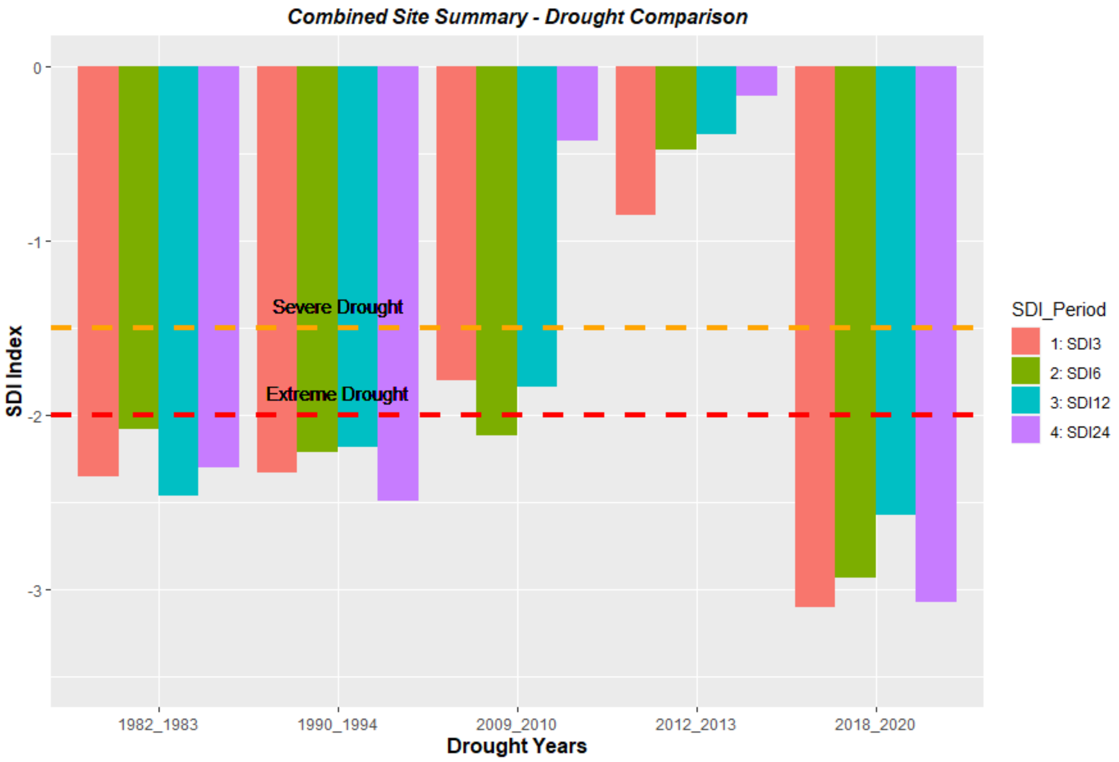

Figure 19: Hydrological SW Drought at a regional scale compared over significant drought years.

Table 7: Frequency analysis of 1 day and 1 week mean lowest flows during the 2018-2020 drought. Flow data has been fitted to either Gumbel or GEV distributions.

Flow gauge	Year record begins	Return period for one day mean flow	Return period for one week mean flow
Awanui	1958	>100y *(rank = lowest)*	>100y *(rank = lowest)*
Maungaparerua	1967	50-100y *(rank = lowest)*	30-50y *(rank = lowest)*
Kaihu	1970	50-100y *(rank = lowest)*	50-100y *(rank = lowest)*
Ngunguru	1969	30-50y *(rank = lowest)*	30-50y *(rank = lowest)*
Mangakahia	1960	50- >100y *(rank = lowest)*	50- >100y *(rank = lowest)*
Waihoihoi	1984	30-50y *(rank = lowest)*	30-50y *(rank = lowest)*

Trend in hydrological surface water drought intensity

Trend in Hydrological SW Drought is examined here using the same methodology as Meteorological Drought trend discussed in a previous section of this report. Firstly, any changes in the frequency of drought months over time is examined by counting months in each year that recorded SDI values <-1.0, i.e. counting months per year that are categorised as “Moderate Drought” or drier. Secondly, the long-term systematic trend in dryness has been examined by generating a rolling sum of SDI-1 values over time.

Figure 20 andFigure 21 clearly display the large number of months that are categorised as drought months during the 2018-2020 drought. Aside from this observation, it is difficult to distinguish any significant increasing or decreasing trend in the frequency of drought months at these flow stations.

However, cumulative SDI-1 plots tell an interesting story (Figure 22 andFigure 23). The more western rivers (Mangakahia, Kaihu and Manganui) display a pattern of increasing SDI towards a peak around 1980/1990, then a decreasing trend beyond this peak to current. This is quite consistent with the systematic SPI (rainfall) trend in many locations including Dargaville (Figure 23). The cumulative SDI trends for the eastern rivers; Whakapara, Mangahahuru, Ngunguru and Waihoihoi are quite different. These show a steep decline in SDI during the prolonged dryness of the 1990-1994 drought followed by a gradual increasing trend, suggesting the impacts of this prolonged dryness was profound on these catchments (Figure 17). For all rivers examined there is a clear relationship between river flow and drought periods, and many display a similar trend to cumulative SPI (rainfall). As previously mentioned, speculating further towards the cause of these trends is outside the scope of this report.

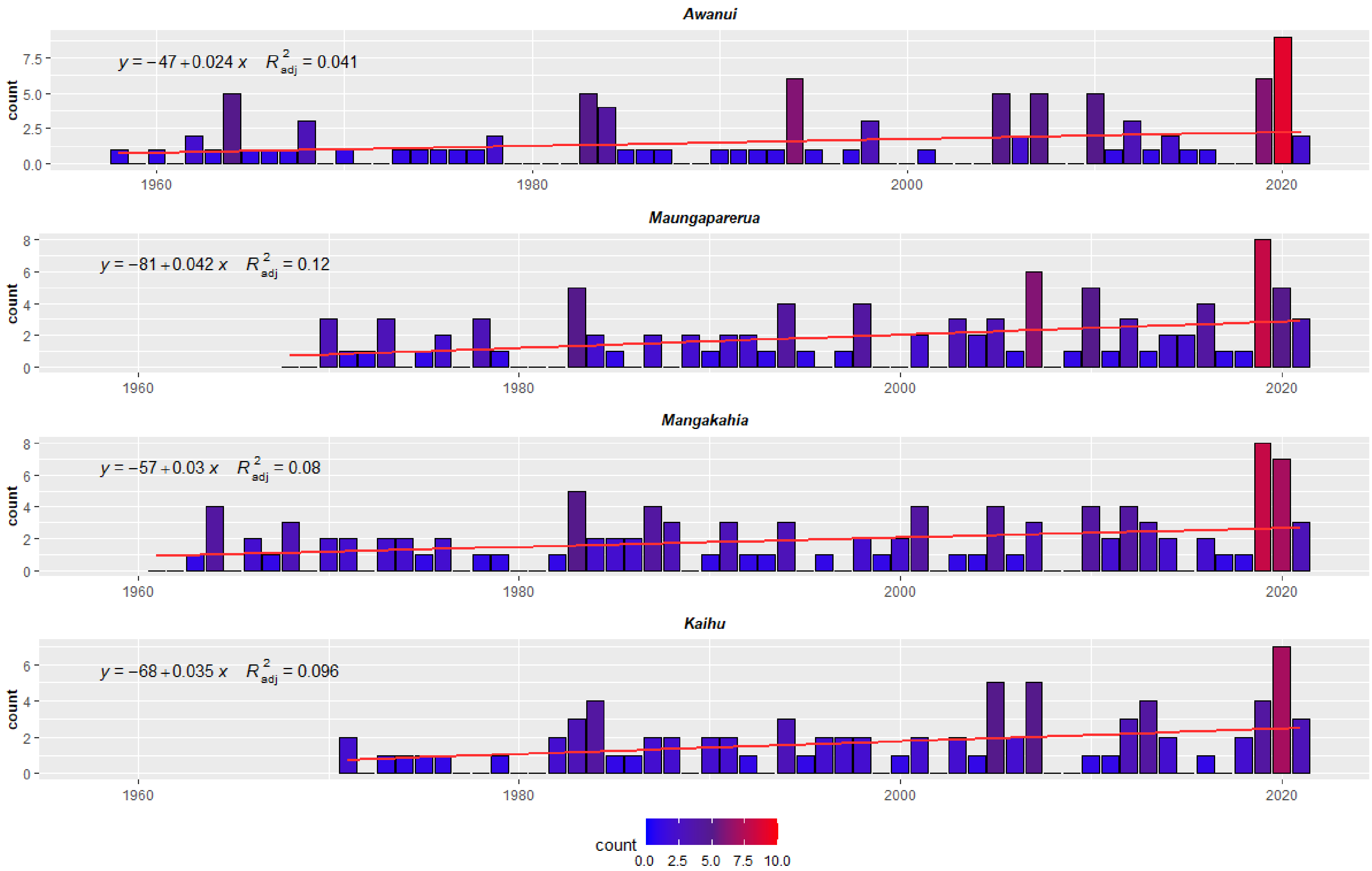

Figure 20: Count of months per year below SDI of -1.0, as an indication of frequency of drought months classified as “Moderate Drought” or drier, at the Awanui, Maungaparerua, Mangakahia and Kaihu rivers.

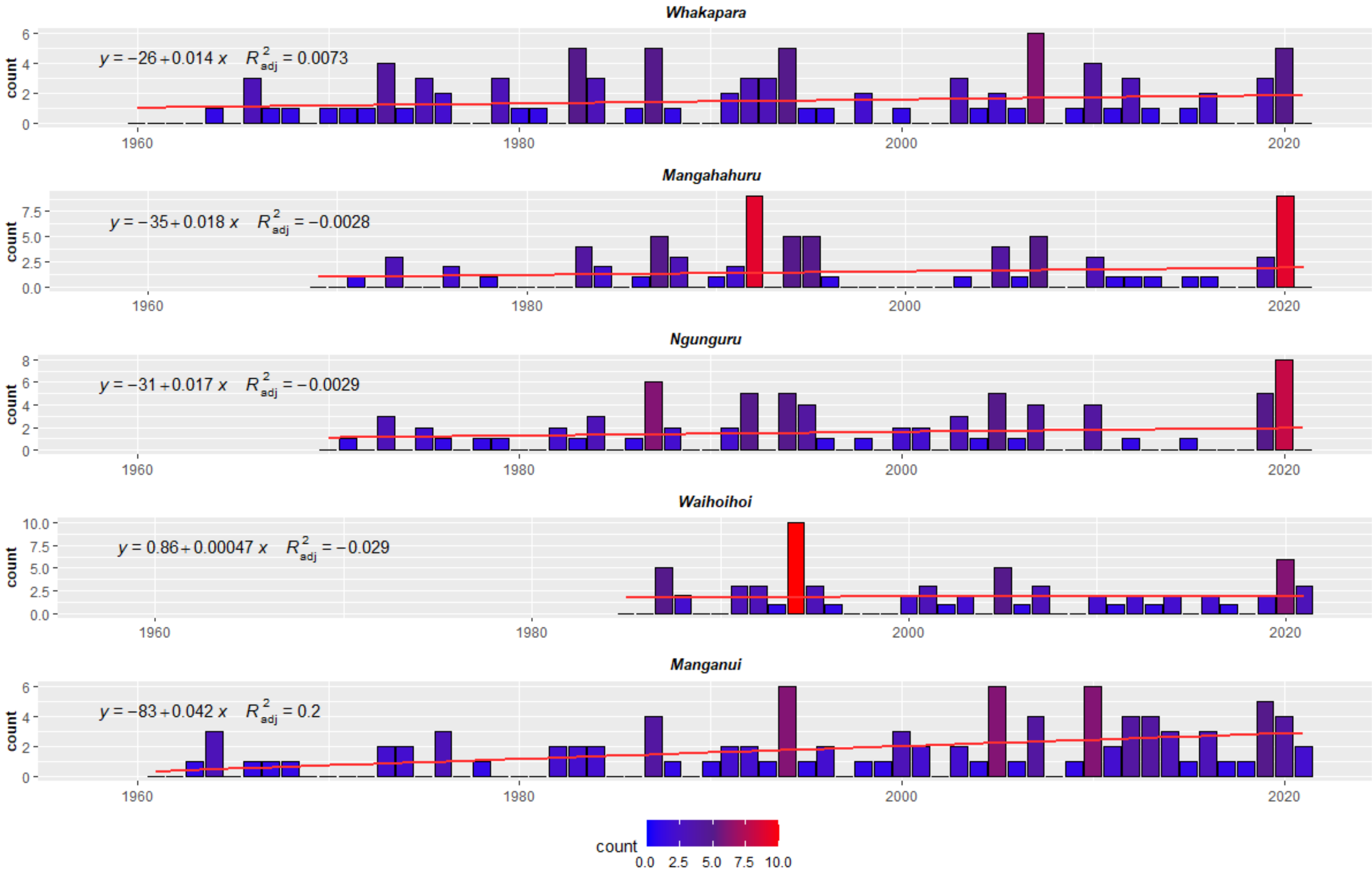

Figure 21: Count of months per year below SDI of -1.0, as an indication of frequency of drought months classified as “Moderate Drought” or drier, at the Whakapara, Mangahahuru, Ngunguru, Waihoihoi and Managanui rivers.

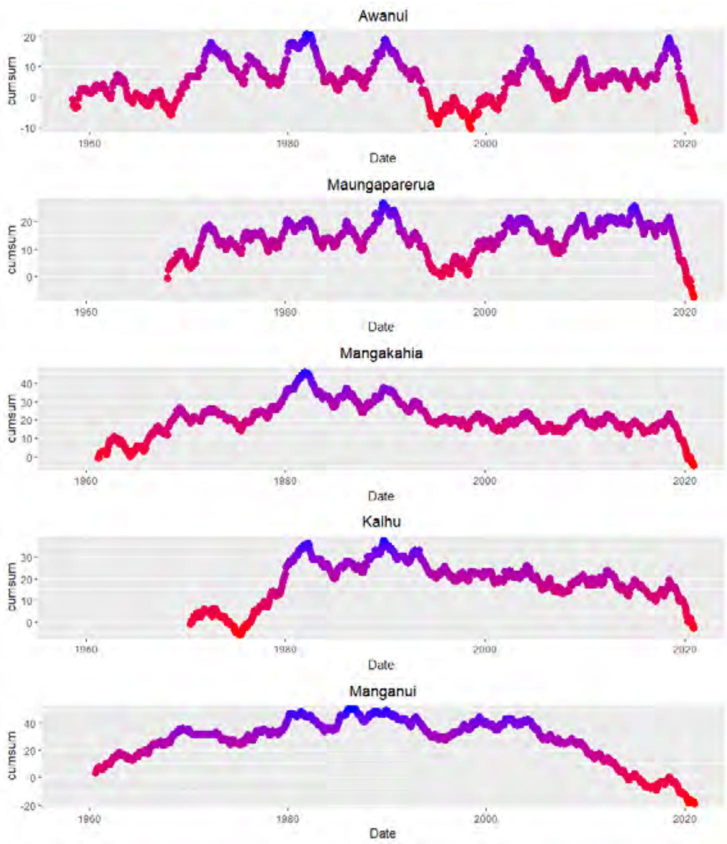

Figure 22: Cumulative SDI-1 through the full record for the long-term flow stations; Awanui, Maungaparerua, Mangakahia, Kaihu and Manganui. This is an indication of systematic changes in flow conditions over time.

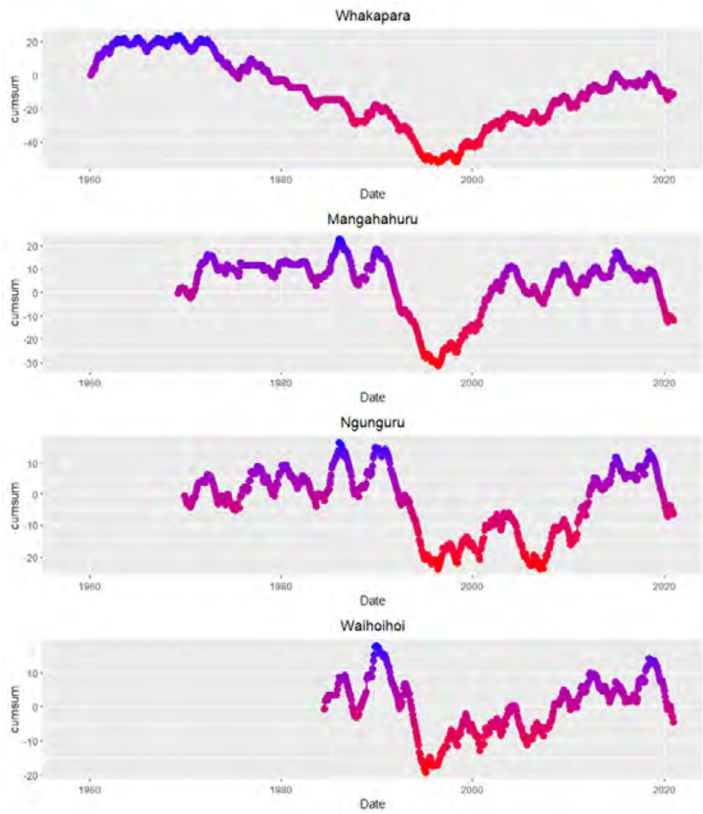

Figure 23: Cumulative SDI-1 through the full record for the long-term flow stations; Whakapara, Mangahahuru, Ngunguru and Waihoihoi. This is an indication of systematic changes in flow conditions over time.

Hydrological – water storage (WS) drought

One of the objectives of NDEWS is to inform the stakeholders about the potential impacts of drought on the usable water resources, especially on reservoir storage as a key focus. Hence, it is essential to investigate the time period from the start of meteorological drought to when the reservoir water level is likely to be at the restriction level.

Hydrological drought in relation to impact of reservoir water level anomalies, hydrological storage drought or hydrological water storage drought, is examined. Drought index, Standardized Water level Index (SWI), is computed based on monthly reservoir water level similar to what SPI is computed.

Due to Whangārei District Council (WDC) limited data, the assessment is carried out for Wilson dam only up to December 2019. The trend of the hydrological storage drought is not detected for the same reason.

Figure 24 illustrates the catchment boundary, the dam site, and the rain gauge location. The dam site is located at the mouth of the Waiwarawara Valley where it just passes out from the hill section of the Hinterland to the broad plain of the Ruakaka Valley. The dam retains the water resources that the catchment collects. The catchment area is 3.85 km^2 and the maximum elevation is 262 m at the Kukunui Hill.

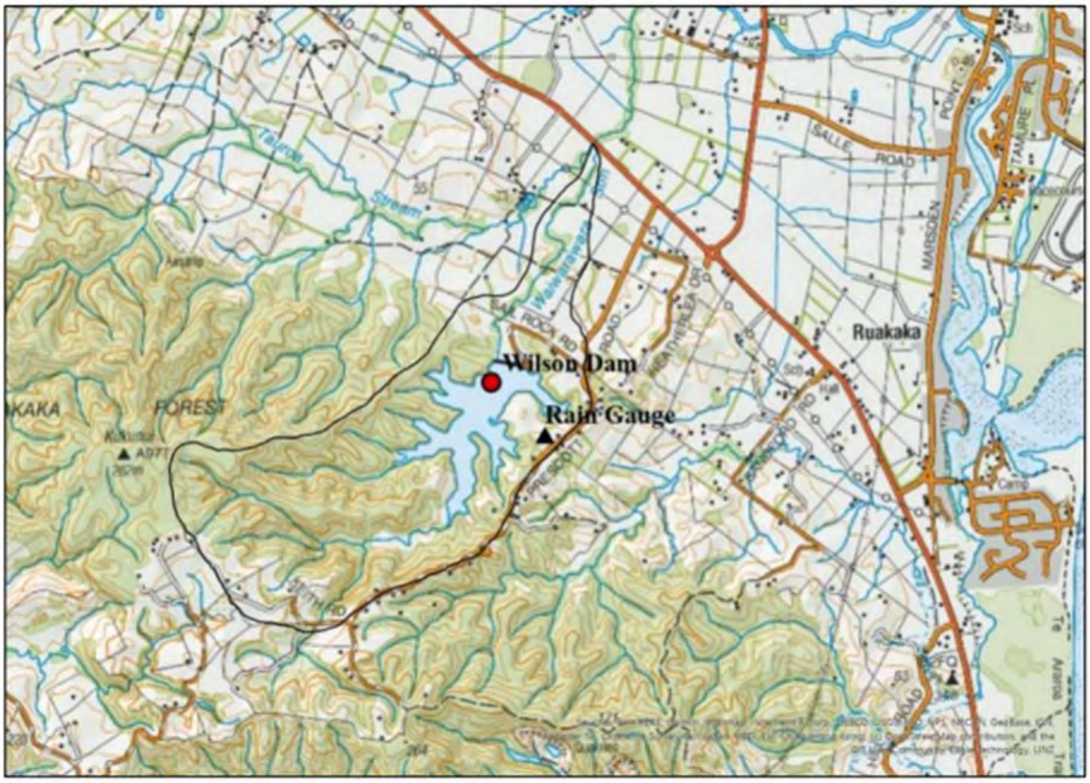

Figure 24: The Wilson Dam site (red spot), the rain gauge (black triangle) location, and the Waiwarawara Stream Catchment boundary (enclosed area by the solid black line).

Wilson reservoir water level

Based on the daily records, the mean monthly reservoir water level is 33.76 m. The frequency of daily reservoir water level is illustrated in Figure 25. Around 74% of time the reservoir water level is between the full supply level (FSL) with dam crest level of RL 33.8 m and the 1000- year flood water level (RL 35.2 m). Likewise, around 25.6% of time the reservoir water level is below the FSL (RL 33.8 m). Note, the Minimum Operating Level (MOL) is at RL 26.5 m (WDC, 2000).

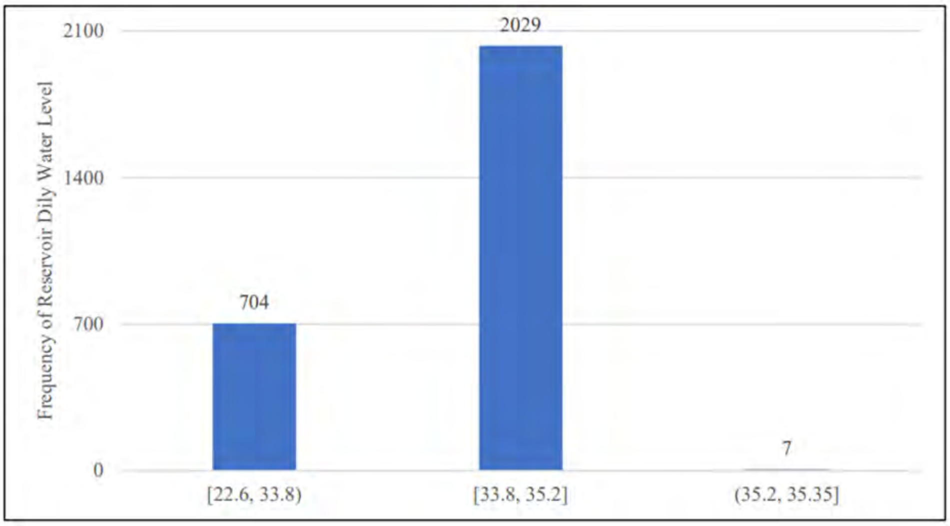

Figure 25: Histogram of daily reservoir water level frequency.

The reservoir generally runs above the FSL (RL 33.8m) from August to January, and the water level drops from around 34.5 m to 33.1 m between October to June and rises back to 34.5m from June to October. It appears that the water stored in the reservoir during the winter months is used for the water consumption from November to May as rainfall total amounts in these months are relatively lower. It is expected that the accumulated rainfall amounts during June to September are able to bring the water level back to above the FSL (RL 33.8m). Thus, the rainfall amounts that accumulated in these months are crucial for the water supply from January to June as demonstrated in Figure 26 below.

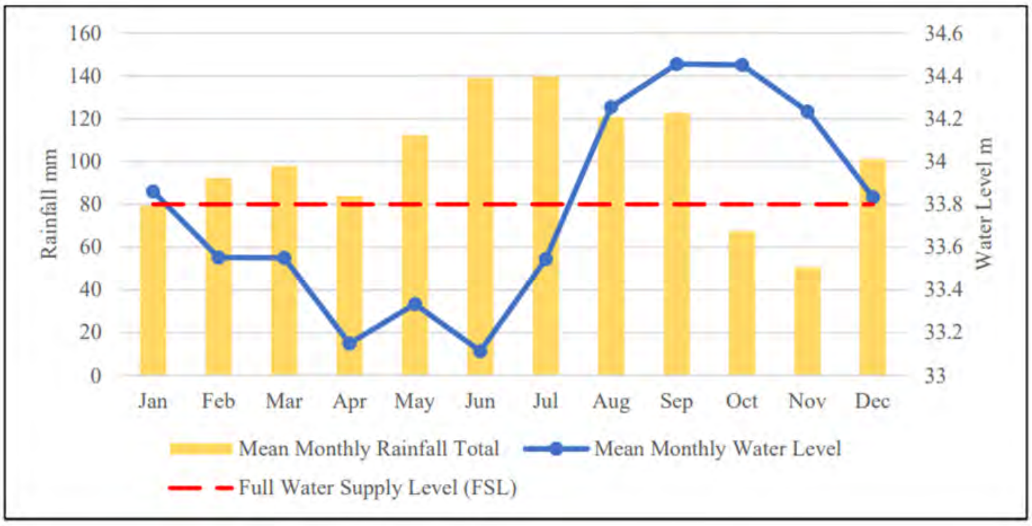

Figure 26: Mean monthly rainfall amounts and reservoir water level.

Accordingly, the precipitation deficits during the winter months might put the reservoir at a risky water level in the following months and the extended precipitation deficits might make the situation worse. Accumulated precipitation deficits over the longer timescales are more likely to trigger a drought in reservoir storage to develop, while a drought in streamflow is more likely to be caused by the precipitation deficiency over shorter timescales. it was found that accumulated precipitation over timescales of six to twelve months is related to the monthly reservoir water level anomalies. Figure 27 shows water level anomalies during the drought events compared to the long-term changes.

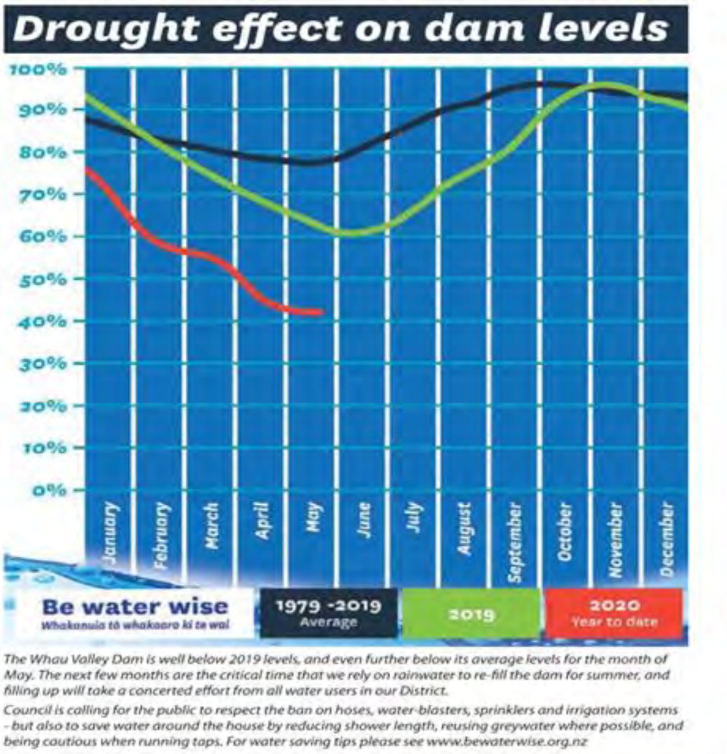

Figure 27: Whau Valley Dam level during the 2018 – 2020 drought in comparison to other periods (WDC, 2020). Wilson dam is at 59% of capacity at the same time of observation.

Dam water level thresholds of hydrological surface water drought

Based on the frequency of the daily water level records shown in Figure 19, the threshold should be greater than 33.8 m (the FSL water level) and lower than 35.2m (the 1000-year flood water level). This is because the reservoir is managed in this range over 74% of the time. If threshold value were set lower than 33.8 or greater than 35.2 m, then it would not be possible to identify historical hydrological droughts reasonably. For instance, if the threshold value is set less than 33.8 m it will result in at least 74% of positive anomalies, resulting in few drought events with short durations. On the other hand, the setting of the threshold value greater than 35.2 m will make almost all anomalies be negative, and only few long-lasting drought events would be detected. Moreover, a fixed threshold is considered in this report since most of the reservoir statistics related to operational water levels are with fixed values (e.g., FSL and MOL).

Table 8 shows several threshold values together with the corresponding number of identified historical hydrological water storage drought events between December 2012 and December 2019. In this regard, the 34.5 m threshold value is selected for the SWI computation because the maximum number of hydrological water storage drought events can be identified at this level and it is also in the range between 33.8 m to 35.2 m.

Table 8: Number of identified hydrological SW droughts based on different threshold levels.

Reservoir Water Level Thresholds (m)	Number of Hydrological Drought Event
33.8	3
34	4
34.25	6
34.5	8
34.75	5
35	4

The characteristics of hydrological water storage drought

To characterise hydrological storage drought and its relation to the meteorological drought, SPI for 1-month to the 24-month timescales while SWI on a monthly time basis are used. In this report, the computation of these two indices is based on the threshold-based index method because this method allows the investigation of how meteorological drought is transferred to hydrological drought through the terrestrial hydrological cycle.

In general, the monthly reservoir water level anomaly (SWI) is related to SPI over the timescales from 6 to 12 months (SPI6 to SPI12), especially at the 7-month timescale (SPI7). This suggests the hydrological SW occurs 6 months later of the meteorological drought, exceptionally for this drought event (Figure 28). Severe hydrological SW drought occurred from December 2018 to December 2019, with its intensity is less than –1.00, appx. 5 months after the meteorological drought starts. Between April and July 2019, the hydrological water storage drought is at extreme level with SWI values ranges between -2.99 to -5.07. After 2-month remaining at severe level, the hydrological water storage drought becomes worst in December 2019. However, the data after this month is unavailable for assessment.

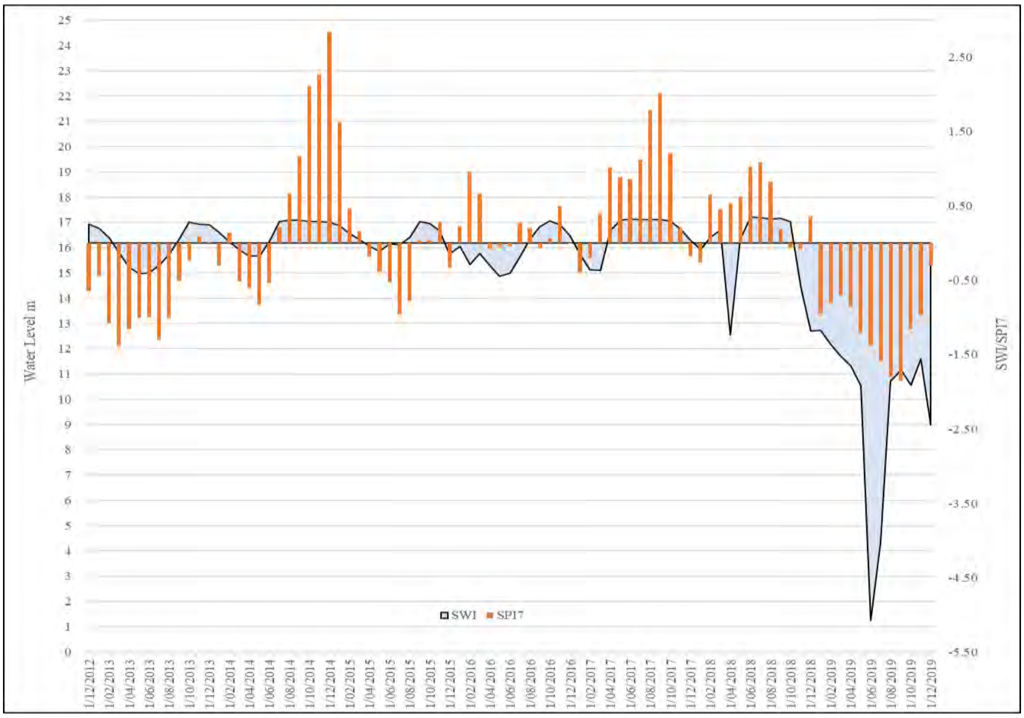

Figure 28: Dam water level vs one-month SWI and 7-month SPI.

Table 9 compares the severity of identified hydrological water storage droughts. Since 2013 when the dam water level is first recorded, this drought is ranked as the worst and lengthiest even though the data provided by WDC does not cover the entire drought event. It is clear that the long-lasting dry climate conditions (here is a prolonged meteorological drought) is likely to lead to a severe hydrological SW drought. However, more historical data is needed to validate this hypothesis.

The relation between the hydrological drought duration and magnitude is non-linear due to the combined effects of climate variability and catchment properties. This means that the relationship between the intensity and the duration of the hydrological SW drought is controlled by local environment such as, localised rainfall, instream flow, surface water abstraction, etc.

Table 9: Identified hydrological events between December 2012 to December 2019 and their characteristics.

No. of Events	Start	End	Hydrological drought duration	Hydrological drought magnitude	Hydrological drought intensity
1	Mar 2013	Aug 2013	6	-1.713	-0.286
2	Mar 2014	May 2014	3	-0.432	-1.144
3	Apr 2015	Jul 2015	4	-0.180	-0.045
4	Dec 2015	Jul 2016	8	-1.921	-0.240
5	Jan 2017	Mar 2017	3	-0.865	-0.288
6	Jan 2018	Jan 2018	1	-0.889	-0.889
7	Apr 2018	Apr 2018	1	-1.238	-1.238
8	Nov 2018	Dec 2019	14	-27.959	-1.997

Groundwater drought propagation

A ‘groundwater drought’ typically refers to a period of lowered groundwater levels which may result in water availability related problems. The amount of groundwater decline that would be considered a ‘drought’ varies regionally and locally due to differences in groundwater conditions and groundwater needs for humans and the environment. The lowered water level could lead to a reduction in baseflow to streams, wetlands and impact on irrigation schedules in agriculture. Reducing the demand on vulnerable aquifers will allow natural recovery of the resource.

Northland’s aquifers can be grouped into four different geological units namely Jurassic greywacke, Cretaceous sandstone, Cenozoic basalt and Quarternary sand, shell and gravel. (Figure 29) There is an estimated 28 small, shallow, sand, gravel coastal aquifers and less productive greywacke aquifers throughout the region. These types of aquifers are normally unconfined and directly relate to meteorological conditions, and therefore, recharge-dependent on current rainfall regimes.

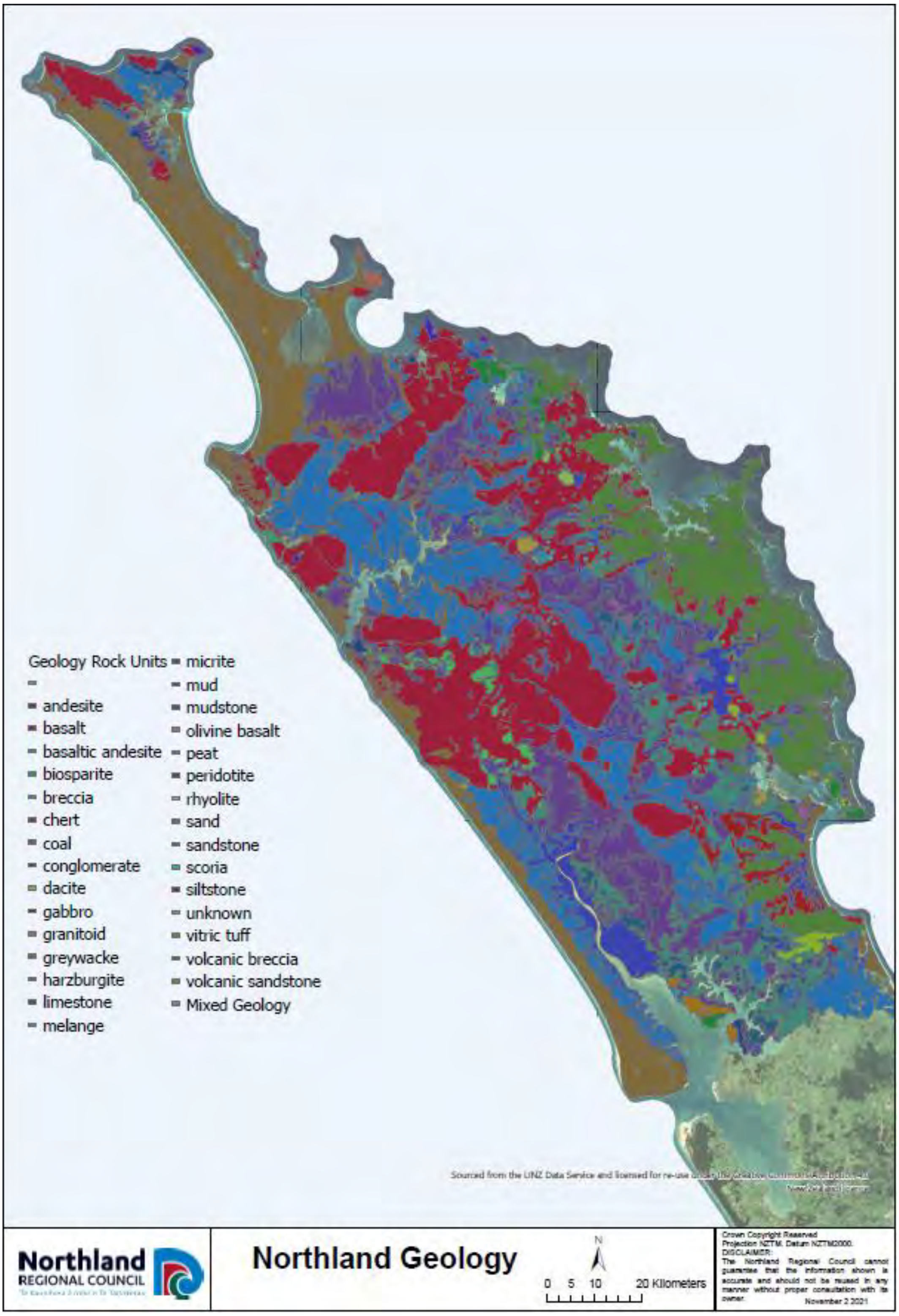

Figure 29: Northland Regional Geology.

- Confined aquifer: An aquifer whose upper and lower boundaries are defined by impermeable layers (Figure 30).
- Unconfined aquifer: An aquifer in which the water table forms the upper boundary (Figure 30).

- Semi-Confined aquifer: An aquifer whose upper layer or lower layer is semi-pervious and the other layer is impermeable (Figure 30).

The semi-confined to confined basalt aquifers normally do not show the impact of the drought due to recharge rates in these aquifers. The impact of drought is usually negligible in these types of aquifers. Based on isotope analysis the retention time for the rainfall/recharge to reach the groundwater system takes 30+ years.

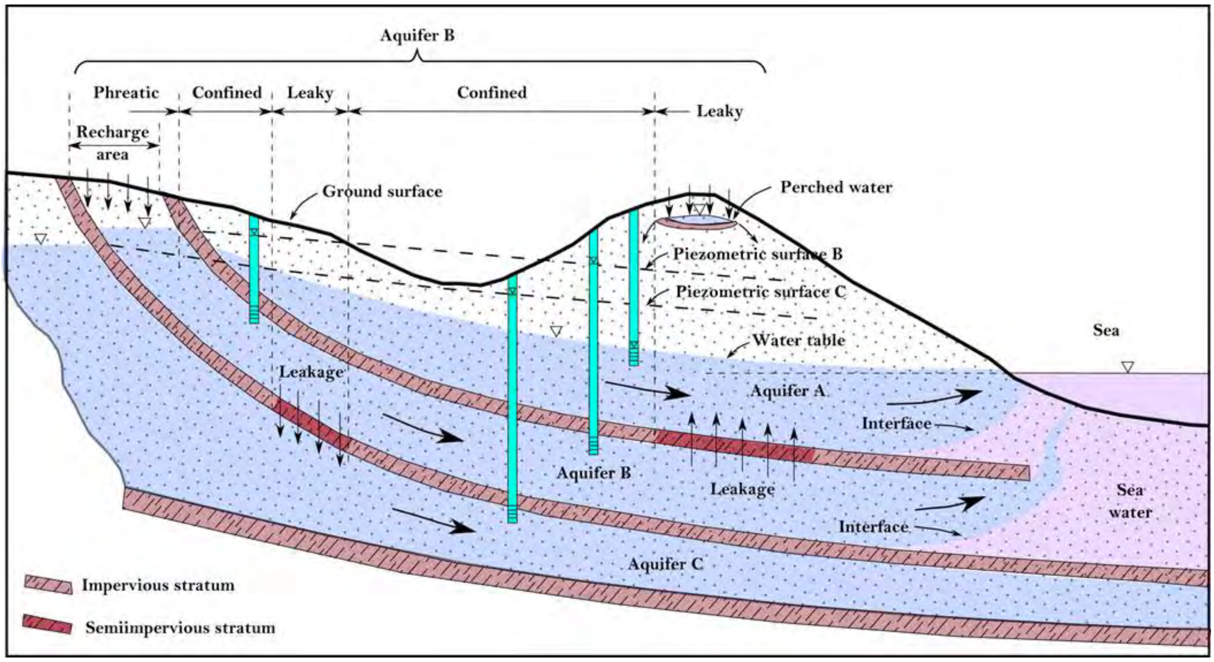

Figure 30: Illustration of the different aquifer types. Aquifer A) Unconfined aquifer, Aquifer B) Semi-confined aquifer and Aquifer C) Confined aquifer.

During the 2018-2020 drought period the aquifers in the Russell and Ruawai area were impacted the most (Figure 31 andFigure 32; **Error! Reference source not found.**). The drought can be seen in the water level dropping during the period of February 2019 through to March 2020. The confined aquifers in Glenbervie showed very little response to the drought (Figure 33; **Error! Reference source not found.**) as recharge periods could be tens to hundreds of years.

Moving forward processes are now in place to look at the state of the aquifers more frequently and identify drought indicators more regularly.

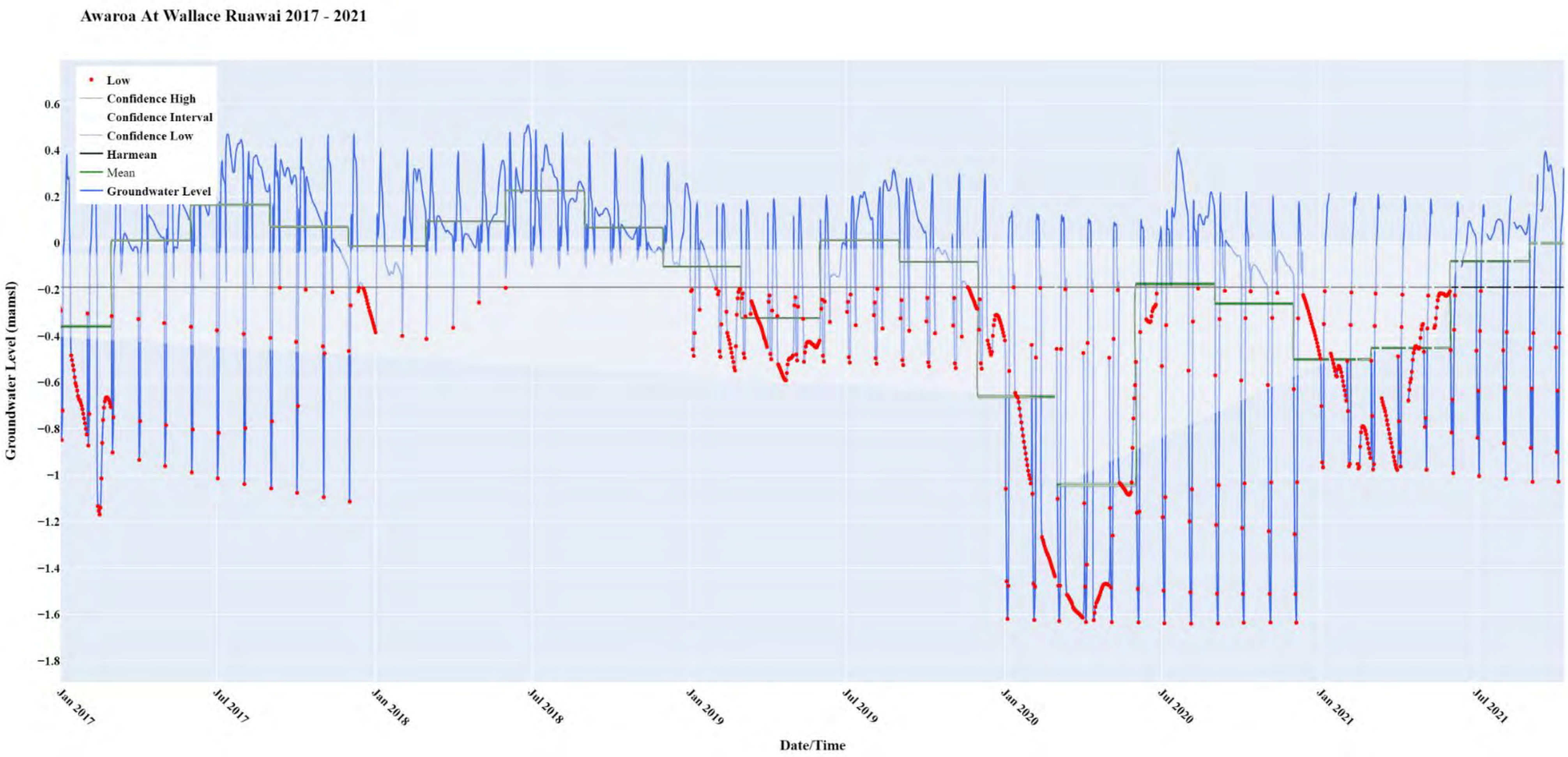

Figure 31: Ruawai, unconfined aquifer, Drought affect during the period of 2019-2020.

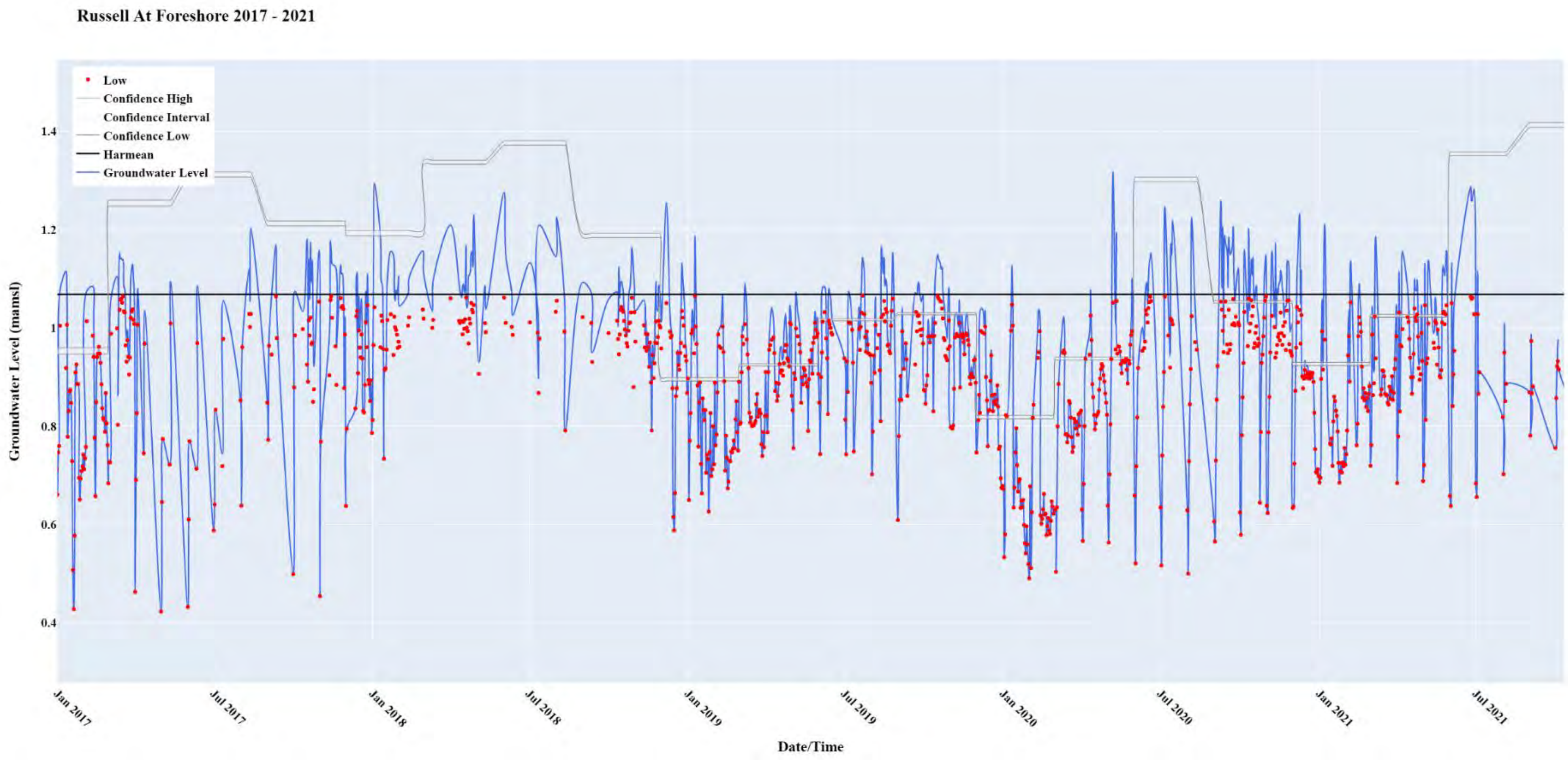

Figure 32: Russell, semi-confined aquifer, Drought affect during the period of 2019-2020.

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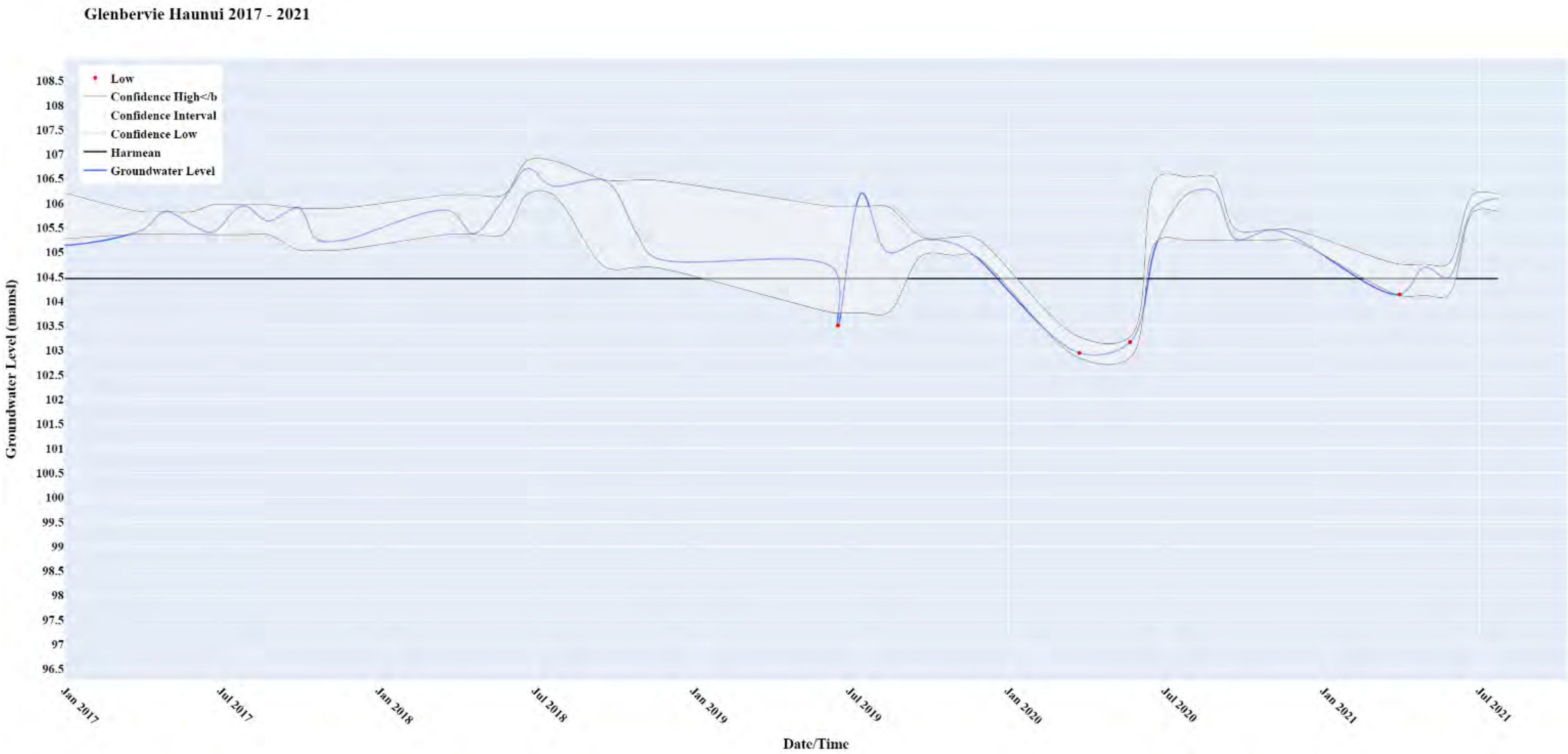


Figure 33: Glenbervie, confined aquifer, Drought affect during the period of 2019-2020.

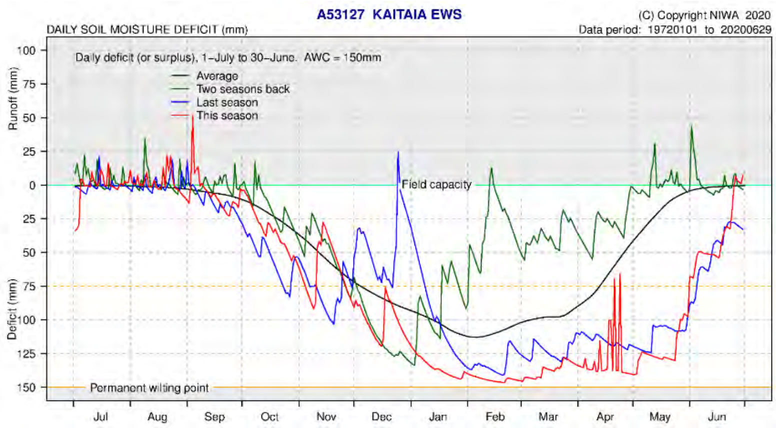
Agricultural drought / Soil moisture drought

Soil moisture is currently used alongside for drought monitoring and characterization. Efforts toward understanding soil moisture drought (agricultural droughts) variability have been largely limited due to data scarcity.

Soil moisture deficit information for this this report has been obtained from soil water balance data at five NIWA climate stations. There is a close association between rainfall and soil moisture, but also between soil moisture and river flows as examined here. Soil moisture levels at all of these stations were predominantly below the long term median for between October and June for 2018/2019 and 2019/2020 (Figure 34 and Figure 35). During these months of the year, it is quite typical for soil moisture levels to be below field capacity, indicating that rainfall will be adsorbed by soils readily with little runoff. However, the long period of time and the magnitude below the long-term median was abnormal during the 2018-2020 drought. At these locations, soil moisture only convincingly broke above the median in December 2018, but only at Kaitaia was the spike in soil moisture large enough to lead to significant runoff to rivers. Runoff from this event would have been supressed by soil absorption in most areas. Overall, these extremely low soil moisture levels throughout the 2018-2020 drought were a symptom of significant rainfall deficit as well as high temperature anomalies, and the impact of these dry soils was that rivers only responded to rainfall in a minor and fleeting manner, as dry soils soaked up the water and impeded runoff.

During the drought years, irrigation and overexploitation of groundwater resources play important roles.

A



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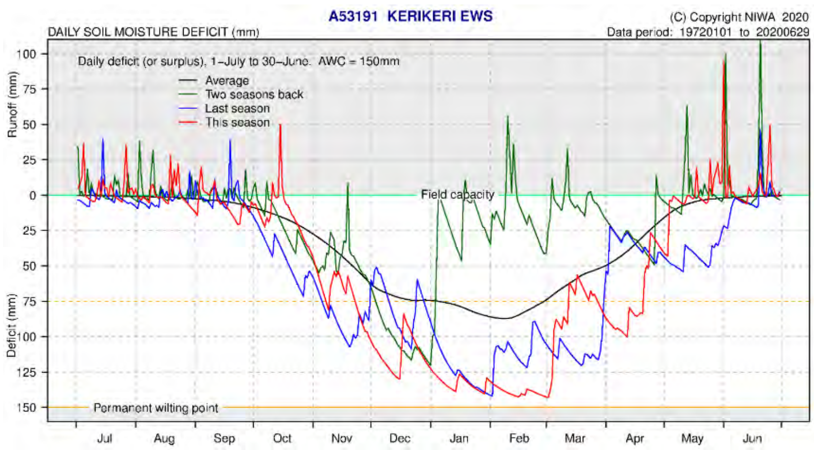


Figure 34: Soil Water Balance at NIWA climate stations indicating soil moisture deficit. A) Kaitaia, and B) Kerikeri. Refer to **Error! Reference source not found.** for NIWA sites.

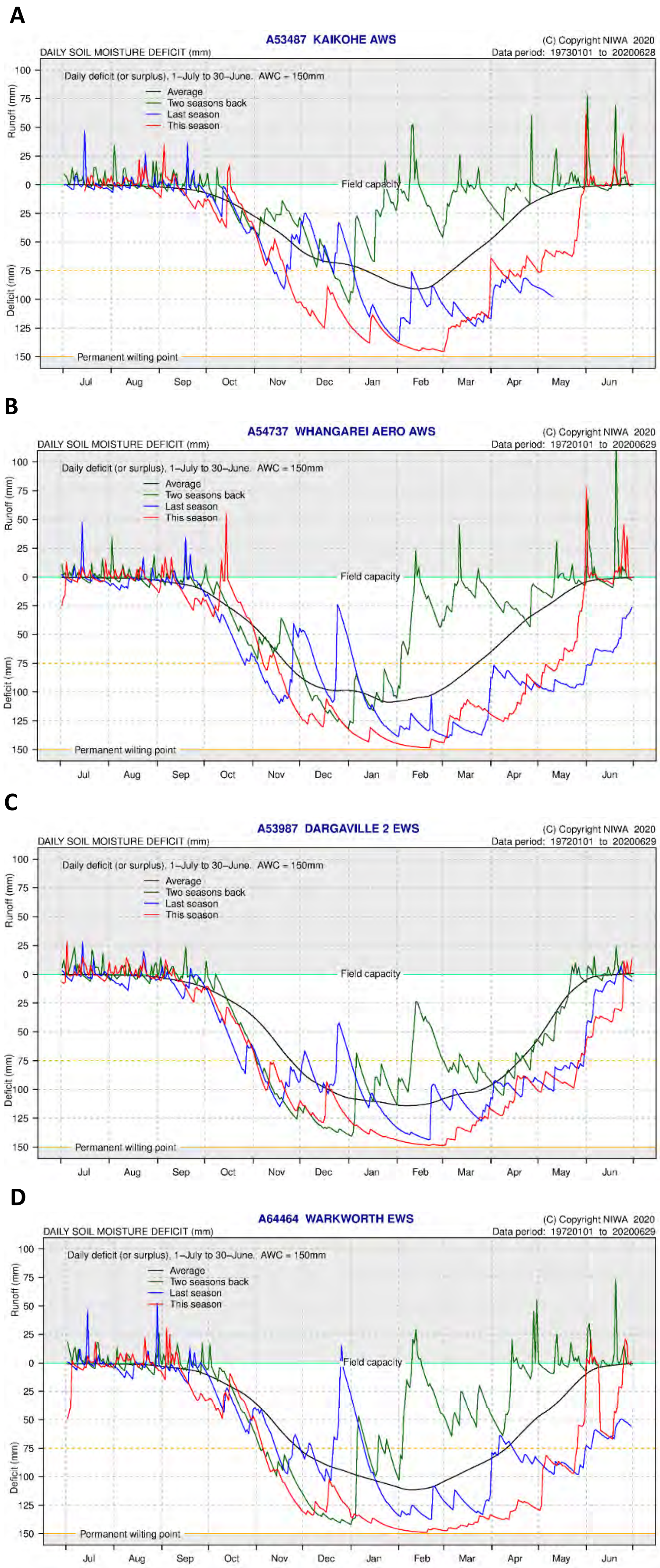


Figure 35: Soil Water Balance at NIWA climate stations indicating soil moisture deficit. A) Kaikohe, and B) Whangārei Aero, C) Dargaville 2, D) Warkworth. Refer to **Error! Reference source not found.** for NIWA sites.

Ecological Drought Assessment February–March 2020

Drought conditions can have detrimental effects on freshwater ecosystems. Reductions in flow rates and water levels can lead to stranding of aquatic flora and fauna as well as decrease connectivity within river systems, restricting the ability of species to move to refuge or complete life cycles (e.g. migratory fish; Bond et al. 2008). Other consequences can include increased water temperatures, decreased dissolved oxygen levels, and increased concentration of contaminants because of longer water residence period under low flow condition, all of which can stress aquatic organisms (Bond et al. 2008; Kovach et al. 2019).

Ecological surveys methodology

In response to the 2018-2020 drought, Northland Regional Council undertook one-off, targeted ecological surveys at 107 sites in February and March 2020 (Figure 36; Appendix 16). A suite of biological, ecological, and physical attributed were sampled or recorded for each site (Table 10). Catchments with high water allocation were given priority during this survey.

Table 10: Measurements and attributes with exceedance criteria recorded during 2020 ecological survey as well as quality bands and exceedance criteria.

Measurement	Attribute	Exceedance Criteria
Water Quality	Temperature (°C)	Pass: Temp < 24°C Fail: Temp ≥ 24°C
	pH	Pass: 6.0 ≤ pH ≤ 9.0 Fail: pH ≤ 6.0 or pH ≥ 9.0
	dissolved oxygen (DO; mg/L)	Pass: DO ≥ 4.0mg/L Fail: DO < 4.0 mg/L
Periphyton	Percent cover of categories • Filamentous, film, sludge, mat, clean	N/A
	Percent cover of Cyanobacteria	Pass: Cyano ≤ 50% Fail: Cyano ≥ 51%
	Periphyton Weighted Composite Cover (PWCC) • $\%\, filamentious + \frac{\%mat}{2}$	Pass: PWCC ≤ 55% Fail: PWCC > 55%
Macrophytes	Percent cover	Pass: Macrophyte < 50% Fail: Macrophyte ≥ 50%

Water quality attributes (Table 10) were recorded using a handheld YSI ProDss Multiparameter Digital Water Quality Meter at each site. Wetted width (width from wetted edge to wetted edge) and bankfull width (width from top of one bank to the other bank) were measured at three transects at each site and later averaged for any analyses. Periphyton cover within the survey reach was estimated visually, and the percentage of each category (modified from Kilroy et al. 2013) was recorded. Cyanobacteria (0%, 1-20%, 21-50%, and 51-100%) and macrophyte (< 50% or ≥ 50%) cover percentage categories within the reach were also estimated. The percentage of run, riffle, and pool habitat at each site was recorded. Flow rate was recorded via different methods/instruments (e.g. Flow Tracker, StreamPro, visual assessment, etc.) depending on the site. Finally, photos were taken at each site to document current state.

For periphyton, the periphyton weighted composite cover (PWCC) was calculated and quality bands assigned according to Matheson et al. (2012) (Table 10). Dissolved oxygen (mg/L) exceedance criteria were set based on 1-day minimum values according to the National Policy Statement for Freshwater Management (NPS-FM, 2020) because each site was only surveyed once. A water temperature bottom line was set based on Olsen et al. (2012) and Davis-Colley et al. (2013) as it sits just below the upper incipient lethal temperature for many freshwater animals. For pH, exceedance values were set according to Davis-Colley et al. (2013). Considering the qualitative method used for both cyanobacteria and macrophyte cover measurements, sites with cover greater than 50% were considered in exceedance.

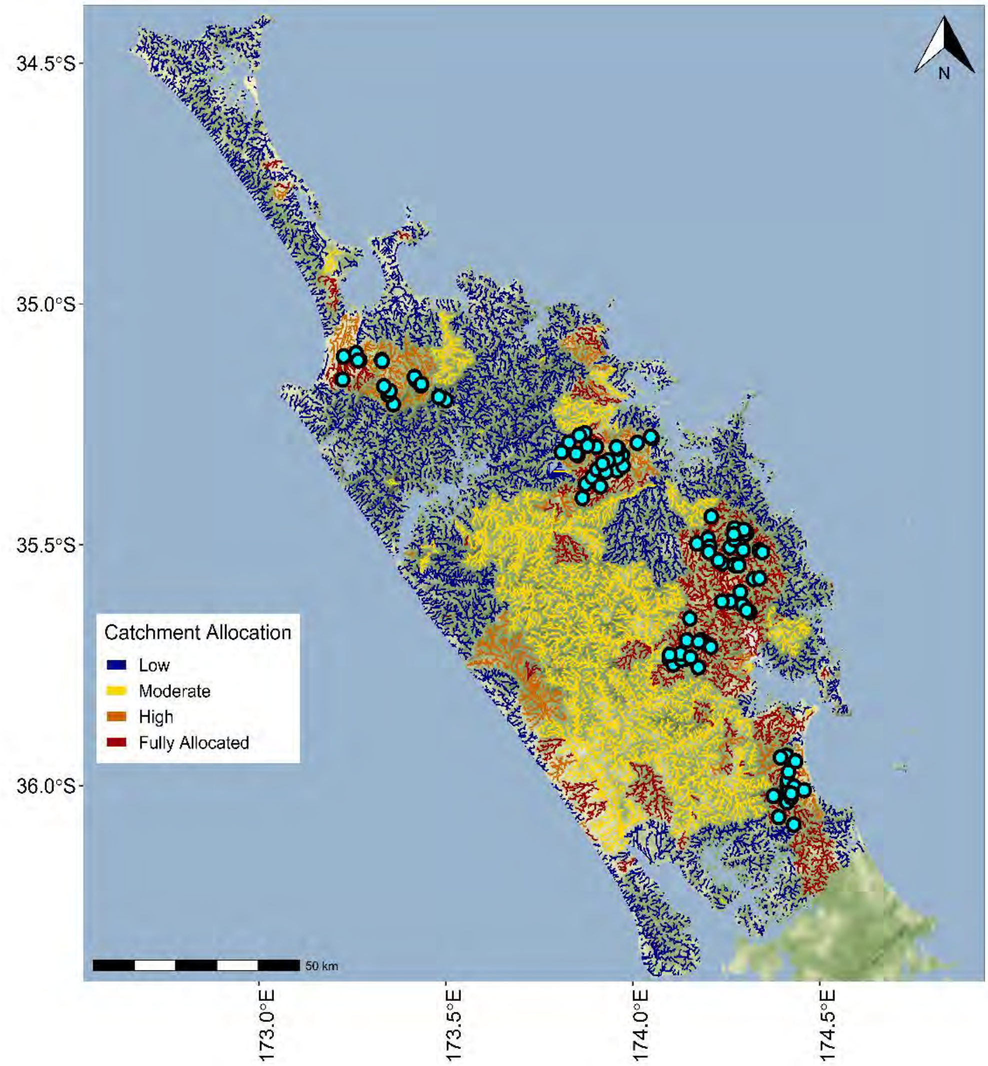


Figure 36:Map of sites surveyed during the Ecological Drought Survey in February and March 2020 and degree of catchment water allocation.

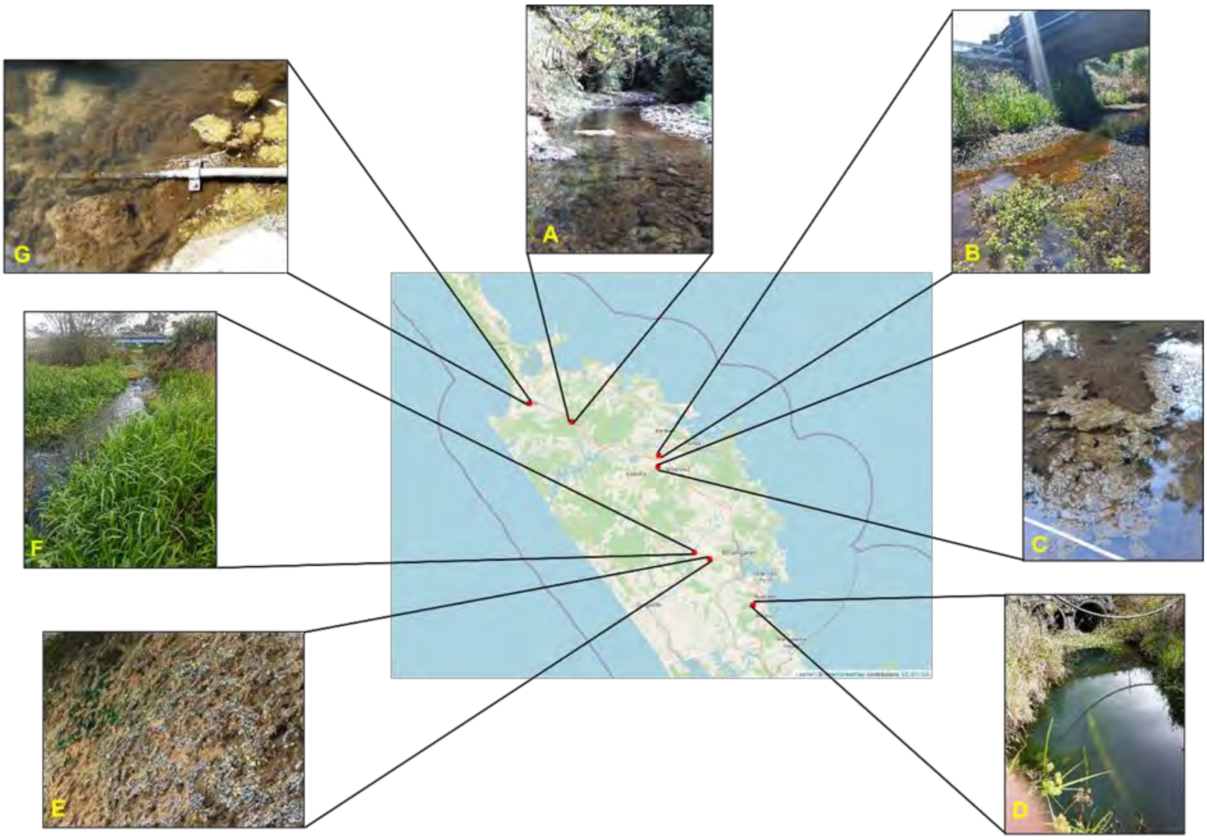


Figure 37: Selection of site photos taken during the 2020 ecological survey: A) Tapapa at SH1, B) Waikaramu at Old Bay Rd, C) Waiaruhe downstream of Mangamutu confluence, D) North Tributary at Mountfield Rd, E) Kauritutahi at SH15, F) Waipao at Kokopu Rd, and G) Tarawhatoroa at Redan Bridge.

Table 11: Number of sites assessed, percent of exceeding or passing sites for each attribute.

Attribute	Bottom Line	Number of Sites Assessed	Percent Exceedance	Percent Passed
Water Temperature (°C)	≥ 24°C	105	3%	97%
Dissolved Oxygen (mg/L)	< 4.0 mg/L	106	15%	85%
Macrophyte Cover (%)	≥ 50%	96	28%	72%
Periphyton Weighted Composite Cover (%)	> 55%	107	16%	84%
Cyanobacteria Cover (%)	≥ 51%	101	3%	97%
pH	< 6.0 or > 9.0	106	7%	93%

Ecological survey findings and implications

Northland Regional Council undertook the ecological survey as part of a response to the 2018-2020 drought event. Survey sites were distributed across high and fully allocated catchments. The survey photos provide some visual documentation of the variation among sites during this drought period; with some showing possible algal and macrophyte growth as well as potential shrinkage of wetted area (Figure 37B-G) while others (i.e. Figure 37A) do not. Surveys were conducted only once per site at the end of the drought period, therefore, the possibility of interpretating the results was limited. Most of the 107 sites surveyed in 2020 did not exceed the assigned bottom line for all attributes

Most exceedances were for dissolved oxygen (DO), macrophyte cover, and periphyton weighted composite cover (PWCC). It is possible that temperature and DO exceedances are not indicative of the state of the streams during this time because they are known to change throughout the day and sites were sampled once at various times throughout the day. Likewise, much of the data collected was semi-quantitative (e.g. periphyton percent cover) or qualitative (e.g. cyanobacteria percent cover), limiting the depth of interpretation. Finally, while fish and invertebrates were not investigated as part of the surveys both can be impacted by drought conditions (Deacon et al. 2019; Lennox et al. 2019). However, following the 2020 drought, council commissioned a report, Death et al. (2020), to investigate the impact of drought on macroinvertebrate communities. Using data from SOE sites plus 10 outside the network the report concluded that there is likely an impact on invertebrate communities during more severe droughts.

Key drawbacks of the survey were one-off sampling events and the limited use of sites within the State of Environment monitoring network. As part of an additional exercise, three sites: Victoria at Victoria Valley, Waipao at Draffin Bay Rd, and Waitangi at Waimate North Rd, that were part of the drought survey as well as monthly SOE periphyton monitoring, were selected for further data analysis over several years. All three sites have associated flow gauges, so PWCC and 1-month standardised discharge index (SDI-1) were calculated monthly from 2014 through to 2020. Negative SDI-1 values are indicative of the occurrence and degree of drought conditions (Table 2). Qualitatively, PWCC is highest when SDI-1 indicates drought conditions (Figure 37 and 38). This indicates the importance of utilising multi-year data to understand the impacts of these conditions.

The ecological survey in 2020 does not allow to comment on the impact of drought, beyond current state at the time of sampling, on Northland rivers due to the limited scope of data collection. However, these efforts have highlighted the need for and development of a Drought Ecological Monitoring Plan (DEMP). Northland Regional Council's draft (DEMP), developed since the original survey, focuses on using SOE sites with long-term ecological, biological, and hydrological data to monitor the impacts of drought in the region. Further, the plan makes provisions for responsive monitoring in catchments not adequately covered by the existing SOE network and ensuring they are sampled at regular intervals throughout the drought period.

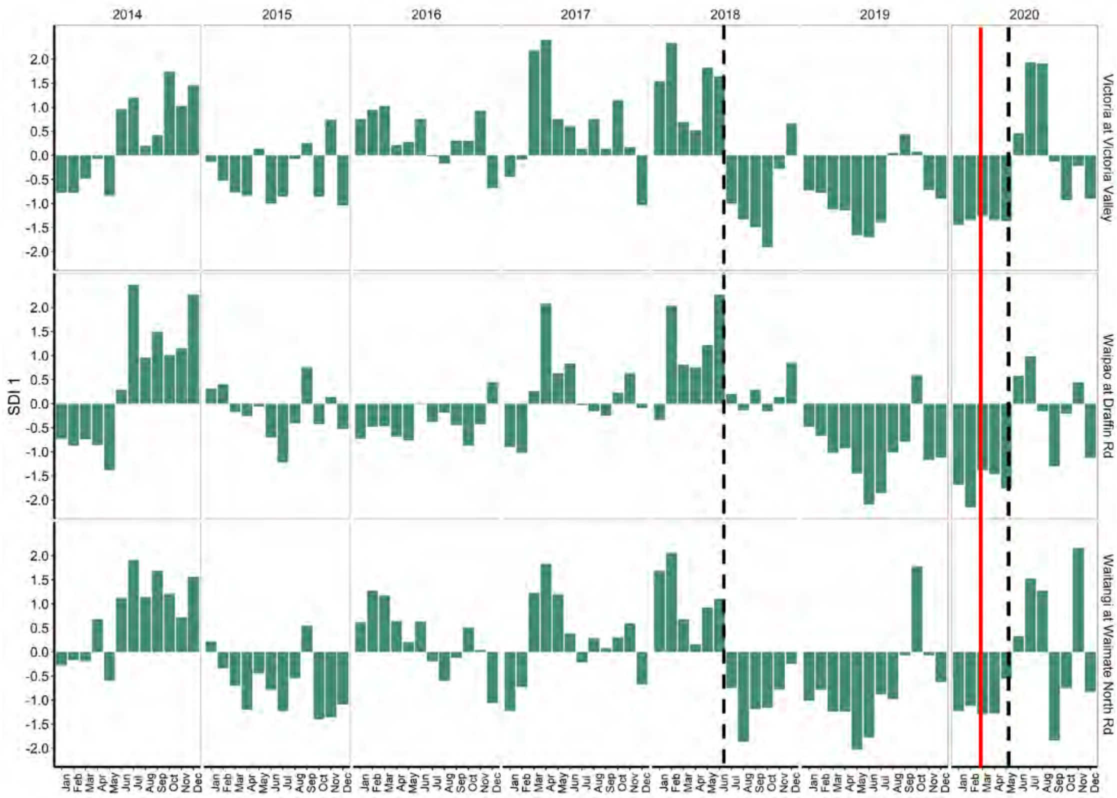


Figure 38: One-month stream flow drought index (SDI 1) for each month from 2014-2020. Black dashed vertical lines indicate duration of the 2018-2020 drought in Northland and the red vertical line marks the start of ecological surveys.

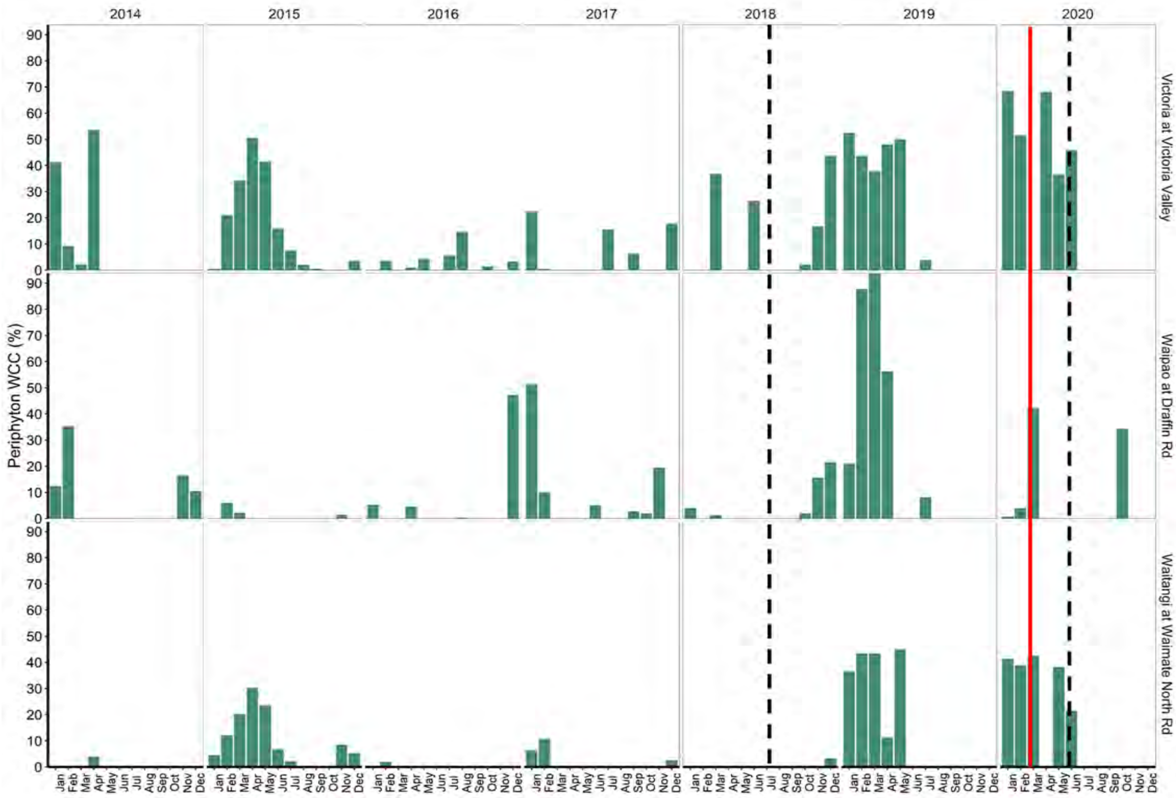


Figure 39: Monthly periphyton weighted composite cover (WCC) from 2014-2020 and three state of environment monitoring sites. Black dashed vertical lines indicate duration of the 2018-2020 drought in Northland and the red vertical line marks the start of ecological surveys.

Conclusions

The July 2018 to July 2020 drought was significant for Northland and is characterised by a long duration drought (two years) which, similar to many other significant droughts in Northland, began over a winter period, well before the typically dry summer months. Dryness began in the northern half of the region and extended downwards through the rest of the region from December 2018.

This drought can be considered the second most severe meteorological drought region wide, since rainfall records began in the early 1900's and second only the 1914-1915 drought. The Kaitaia area became particularly dry with a longer period in "Extreme Drought" conditions compared to other areas. Furthermore, the extreme low 6-month rainfall for Kaitaia during the 2018-2020 drought indicated a return period of >100y, while Dargaville and Whangārei figures indicated a return period of 30-50y.

The impacts of this rainfall drought on river flows in particular were significant with flows characterised as "drought flows" persisting between July 2018 and June 2020 (similar to meteorological drought) and the most severe hydrological surface water drought conditions occurring in May/June 2019 and May 2020. The Awanui River recorded the most severe hydrological SW drought conditions for the rivers monitored throughout the region, with an SDI value approaching -2.5 (Extreme drought begins at SDI <-2).

Hydrological surface water drought conditions across the region were the worst since records began, with lowest one week mean flow return periods for the Awanui of >100 years, 50-100 years for the Kaihu and Mangakahia, and 30-50 years in the Maungaparerua, Ngunguru and Waihoihoi Riovers.

Hydrological water storage drought is also identified as the most severe and the most prolonged in the record for Wilson water supply dam even though the data does not cover the entire drought.

Groundwater levels dropped in most Northland aquifers, as these are typically shallow, coastal, unconfined aquifers which respond quickly to meteorological conditions. The Russell and Ruawai aquifers were particularly impacted between February 2019 and March 2020.

A survey of water quality and ecological conditions was conducted at the end of the drought period and results were compared to defined exceedance criteria as an indication of possible impact. At most sites assessed, these bottom lines were not exceeded. However, dissolved oxygen, macrophyte cover, and periphyton weighted composite cover (PWCC) had the highest proportion of sites that failed the defined criteria. It is possible these could be attributed to decreased flow rates, but no directed measurements were taken to show a relationship between flow and these variables. A comparison of Standardised Discharge Index (SDI) and PWCC showed that under drought conditions PWCC demonstrated the importance of using long-term datasets to assess the impact of drought on freshwater ecosystems. Northland Regional Council has subsequently developed a Drought Ecological Monitoring Plan.

Drought in Northland has increased in both intensity and duration post-1980 and noticeably since 2009. Drought intensities and durations are envisaged to continue on this trend as an impact of climate change. By 2090, Northland could expect time spent in drought conditions to double according to NIWA's New Zealand climate change scenarios (NIWA 2011, 2016).

Recommendations

- Since there is no single drought index meeting requirement of all applications, the combination of different indices is essential.
- The inclusion of evapotranspiration and by extension, temperature into meteorological drought indexing. This is called SPEI (Standardised Precipitation and Evapotranspiration Index). This is important for quantifying dryness inclusive of temperature changes with climate change.
- Assess individual flow stations for most suitable flow distribution for SDI analysis. This will improve comparison between stations geographically.
- Use gauge corrected radar data to extend our regional scope of dryness. Incorporate this radar data into SPI maps and rain deficit maps.
- Improve access and automation of satellite remote sensing information in regards to soil moisture, evapotranspiration and plant condition.
- Improve our understanding of how these indexes can be used for drought declaration or to predict possible drought declaration
- Build a better understanding of how Northland's climate has changed through time, particularly in relation to drought frequency and severity. A separate study may be needed here.
- The ecological survey conducted in 2020 was an ad hoc exercise and as such was subject to limitations. However, it has allowed us the opportunity to evaluate and improve our methodology for the future. Moving forward, a more nuanced ecological monitoring plan is required to adequately characterise the impact of drought conditions on Northland's rivers and streams. Specifically, the long-term SOE data needs to be used to investigate the impacts of drought at a regional scale. The updated monitoring network will increase the number of SOE sites with associated flow gauges as well as seven sites with continuous DO, conductivity, temperature, and pH, increasing the amount and quality of data available before, during, and after a drought. Responsive monitoring will need to be conducted outside of the SOE network to provide coverage of the most affected catchments. Attributes recorded at these sites will need to be qualitative, i.e. by following nationally accepted protocols, to increase interpretability. Ideally, these sites will be monitored periodically throughout the duration of the drought to provide the best quality data possible. In doing so, we will be able to inform the public on the impacts of drought conditions both locally and regionally. These recommendations will be incorporated into the ecological monitoring plan giving effect to the Drought Management Plan[1].

[1] Document available on request from Northland Regional Council.

References

Bond NR, Lake PS, Arthington AH (2008). The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia*. 600:3-16.

Davies-Colley R, Franklin P, Wilcock B, Clearwater S, Hickey C (2013). National objectives framework – temperature, dissolved oxygen, & pH. *NIWA*.

Deacon C, Samways MJ, Pryke JS (2019). Aquatic insects decline in abundance an occupy low-quality artificial habitats to survive hydrological droughts. *Freshwater Biology*. 64:1643-1654.

Death RG, Nicholson C, Chakraborty M, Pohe S (2020). Ecological health of stream invertebrate communities in Northland. *Northland Regional Council*.

Keyte M. (1993). Droughts in Northland. MSc Thesis. Waikato University. Hamilton. NZ.

Kilroy C, Booker DJ, Drummond L, Wech JA, Snelder TH (2013). Estimating periphyton standing crop in streams: a comparison of chlorophyll *a* sampling and visual assessments. *New Zealand Journal of Marine and Freshwater Research.* 47:208-224.

Kovach RP, Dunham JB, Al-Chokhachy R, Snyder CD, Letcher BH, Young JA, Beever EA, Pederson GT, Lynch AJ, Hitt NP, et al. (2019). An integrated framework for ecological drought across riverscapes of North America. *BioScience*. 69:418-431.

Lennox RJ, Crook DA, Moyle PB, Struthers DP, Cooke SJ (2019). Toward a better understanding of freshwater fish responses to an increasingly drought-stricken world. *Reviews in Fish Biology and Fisheries*. 29:71-92.

Matheson F, Quinn J, Hickey C (2012). Review of the New Zealand instream plant and nutrient guidelines and development of an extended decision making framework: Phases 1 and 2 final report. *NIWA*.

McKee, T. B., Doesken, N. J., & Kleist, J. (1994). Drought Monitoring with Multiple Time Scales. 9th Conference on Applied Climatology. 233-236.

McKee, T. B., Doesken, N. J., & Kleist, J. (1993). *The relationship of drought frequency and duration to time scales.* Paper presented at the 8th Conference on Applied Climatology, Anaheim, California, 7(22), 179-184.

National Institute of Water & Atmospheric Research Ltd (NIWA), (2016). Climate change projections and implications for Northland, report prepared for NRC. Auckland, NZ.

National Institute of Water & Atmospheric Research Ltd (NIWA), (2013). The 2012-13 drought: an assessment and historical perspective, report prepared for Ministry for Primary Industries. Wellington, NZ.

National Institute of Water & Atmospheric Research Ltd (NIWA), (2011). Scenarios of Regional Drought under Climate Change, report prepared for Ministry of Agriculture and Forestry.

National Institute of Water & Atmospheric Research Ltd (NIWA), (2010). The Northland drought of 2009-2010, report prepared for NRC. Christchurch, NZ.

National Institute of Water & Atmospheric Research Ltd (NIWA). (2006). Climate variability - The Southern Annular Mode and New Zealand climate. Water & Atmosphere: 14(2).

NIWA Annual Climate Summary 2020. (2021). Retrieved 10 December 2021, from https://niwa.co.nz/climate/summaries/annual-climate-summary-2020.

Olsen D, Tremblay L, Clapcott J, Holmes R. (2012). Water temperature criteria for native aquatic biota. *Auckland Council Technical Report 2012/036*.

Pham, H. X., & Donaghy, J. (2017). Northland drought assessment using SPI. *NZ Hydrological Society Newsletter, November*(56).

Pham, H. X., & Perquin, J.-C. (2019). Does meteorological drought have immediate effect on low flow in Northland rivers? *NZ Hydrological Society Newsletter, November*(56).

Tannehill, I. R. (1947). Drought: Its Causes and Effects. *Princeton University Press, Princeton, New Jersey*, 64(1), 83.

World Meteorological Organization (WMO) and Global Water Partnership (GWP). (2016). Handbook of drought indicators and indices (M. Svoboda and B. A. Fuchs). Integrated drought management programe (IDMP), integrated drought management tools and guidelines series 2. Geneva, Switzeland.

World Meteorological Organization (WMO). (2012). Standardised Precipitation Index User Guide (M. Svoboda and B. A. Fuchs). (WMO-No. 1090). Geneva, Switzerland.

Whangārei District Council (WDC). (2000). Wilson's Dam Final Design Report.

Wilhite, D. A., & Glantz, M. H. (1985). Understanding: the drought phenomenon: the role of definitions. *Water International, 10*(3), 111-120.

Wilhite, D.A., Svoboda, M.D., Hayes, M.J. (2006). Understanding the complex impacts of drought: a key to enhancing drought mitigation and preparedness. Water Resources Management, 21: 763-774. https://www.researchgate.net/publication/225339430_Understanding_the_Complex_Impacts_of_Drought_A_Key_to_Enhancing_Drought_Mitigation_and_Preparedness

Appendices

Appendix 1: List of rainfall monitoring sites.

IRISID	Common Name	X	Y	Data Owners	Altitude	Start Date
LOC.641010	Awaroa at Wallace Road	1696027	6001447	NRC	2	19/09/2007
LOC.424602.01	Cape Reinga AWS	1570554	6190208	Metservice	216	1/07/1983
LOC.539807	Dargaville 2 EWS	1676892	6023375	NIWA	66	5/01/2004
LOC.641512	Hakaru at Tara (combined with Tara Bore)	1737288	6003024	NRC	103	4/11/2013
LOC.546301	Hatea at Glenbervie Forest HQ	1721808	6053455	NRC	100	1/09/1947
LOC.534403	Hokianga Harbour Omapere	1635506	6068894	NRC	10	25/09/2006
LOC.531717	Kaeo at Bramleys	1672077	6108873	NRC	120	19/09/2003
LOC.534807	Kaikohe AWS	1674191	6080606	Metservice	204	31/10/1985
LOC.643118	Kaipara Harbour at Pouto Point	1706011	5975181	NRC	10	23/11/2006
LOC.530206	Kaitaia Aero EWS	1626195	6119414	Metservice	80	23/02/2000
LOC.531207	Kaitaia EWS	1624039	6112216	Metservice	85	17/12/1998
LOC.531205	Kaitaia Observatory	1624033	6112216	Metservice	85	1/04/1985
LOC.531901	Kerikeri EWS	1684704	6106759	Metservice	79	1/08/1981
LOC.642802	Leigh 2 Ews	1761683	5984601	Metservice	60	1/08/1967
LOC.536816	Mangakahia at Twin Bridges	1676973	6056815	NRC	85	22/04/1999
LOC.546416	Ngunguru at Dugmores Rock	1729694	6059444	NRC	150	28/10/1987
LOC.546216	Okarika at Rowland Rd	1705764	6058401	NRC	106	1/05/1977
LOC.642010	Okoraka at Ngatawhiti Road	1692172	5991172	NRC	130	9/09/2015
LOC.536812	Opouteke at Brookvale	1673647	6051272	NRC	116	2/11/1987
LOC.530511	Oruru at Bowling Club	1644720	6122360	NRC	40	29/10/2010
LOC.641213	Paparoa at Maungaturoto	1721626	6005201	NRC	116	24/09/2003
LOC.641214	Paparoa at Taylor's	1714086	6003157	NRC	90	20/07/2005
LOC.541001	Purerua Aws	1692678	6113569	Metservice	82	6/10/1983
LOC.533302	Rotokakahi at Kohe Road	1628714	6091965	NRC	20	19/11/1998
LOC.531313	Takahue at Te Rore	1633905	6107104	NRC	180	11/12/2003
LOC.531415	Te Puhi at Mangakawakawa Trig	1641523	6110696	NRC	475	31/10/2002
LOC.547340	Waiarohia at Kensington	1718892	6047394	NRC	44	19/11/2006
LOC.547339	Waiarohia at NRC Water Street	1719188	6045712	NRC	40	25/06/2004
LOC.640436	Waihoihoi at Brynderwyn	1727624	6010302	NRC	92	16/02/1981

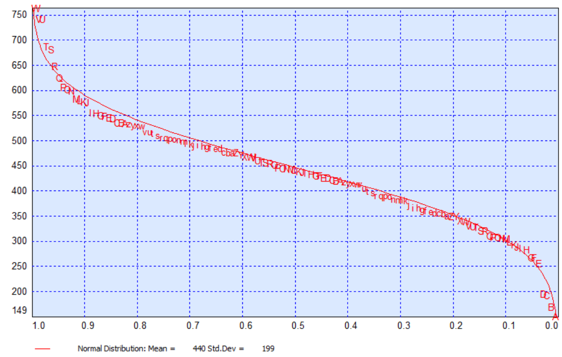
IRISID	Common Name	X	Y	Data Owners	Altitude	Start Date
LOC.536613	Waima at Tutamoe	1658951	6053300	NRC	542	23/10/2003
LOC.535513	Waimamaku at Wekaweka Road	1654076	6062504	NRC	310	9/12/2016
LOC.547119	Waipao at Williams (Draffins Road)	1701951	6045879	NRC	70	25/09/2007
LOC.543010	Waitangi at McDonald Road	1693830	6089839	NRC	91	30/04/1986
LOC.644604	Warkworth Ews	1749567	5966780	Metservice	72	1/11/1999
LOC.545201	Whakapara at Puhipuhi	1715721	6070047	MetService	400	1/10/1999
LOC.547307	Whangārei Aero Aws	1723427	6041032	Metservice	37	3/12/1991

Appendix 2: List of flow monitoring sites.

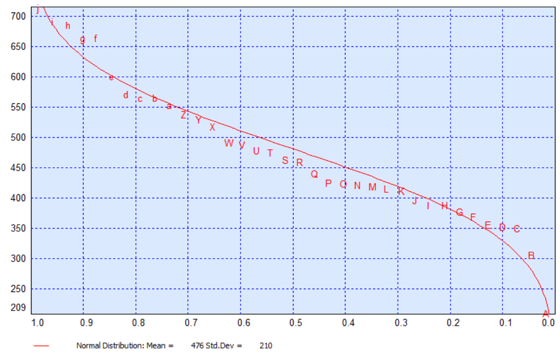
IRISID	CommonName	X	Y	Data Owners	Period
LOC.006018	Ahuroa River at Braigh Flats	1727294	6014955	NRC	1983-
LOC.001316	Awanui at School Cut	1624509	6113973	NRC	1958-
LOC.005538	Hatea at Whareora Road	1720292	6048352	NRC	1986-1995, 2007-
LOC.046625	Hikurangi at Moengawahine	1694224	6054696	NRC	1960-1969, 1987-
LOC.046611	Kaihu at Gorge	1661809	6042221	NRC	1970-
LOC.046674	Mangahahuru at County Weir	1718795	6055188	NRC	1968-
LOC.046618	Mangakahia at Gorge	1677078	6056979	NRC	1960-
LOC.046651	Manganui at Permanent Station	1700424	6019736	NRC	1960-
LOC.003506	Maungaparerua at Tyrees Ford	1680409	6100378	NRC	1967-
LOC.004901	Ngunguru at Dugmores Rock	1729803	6059397	NRC	1969-
LOC.1046651	Opouteke at Suspension Bridge	1678489	6049532	NRC	1984-
LOC.003432	Rangitane at Stirling	1688002	6105135	NRC	2001-
LOC.005901	Ruakaka at Flyger Road	1726748	6029605	NRC	1984-
LOC.003819	Waiharakeke at Willowbank	1692618	6082779	NRC	1967-
LOC.006016	Waihoihoi at Saint Marys Rd	1728960	6014887	NRC	1984-
LOC.046627	Waiotu at S.H. 1 Bridge	1711408	6067208	NRC	1987-
LOC.046641	Waipao at Draffins Rd	1701944	6045872	NRC	1979-
LOC.047804	Waipapa at Forest Ranger	1662574	6096259	NIWA	1978-
LOC.046644	Wairua at Purua	1704288	6053954	NRC	1960-
LOC.003722	Waitangi at Wakelins	1695285	6095810	NIWA	1979-
LOC.046632	Whakapara at Cableway	1715253	6066134	NRC	1959-1977, 1977-

Appendix 3: Six-month low rainfall return period distribution. A) Kaitaia, B) Kaikohe, C) Dargaville, D) Puhipuhi, E) Whangārei, F) Cape Reinga, and G) Kerikeri

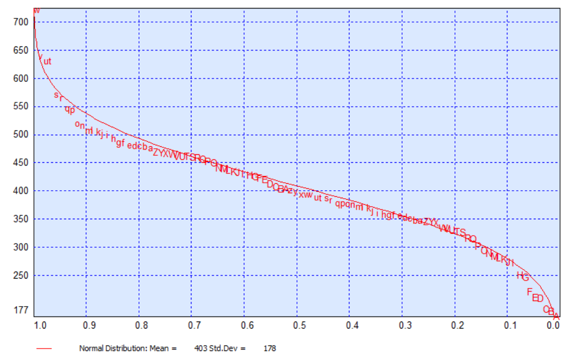
A Kaitaia



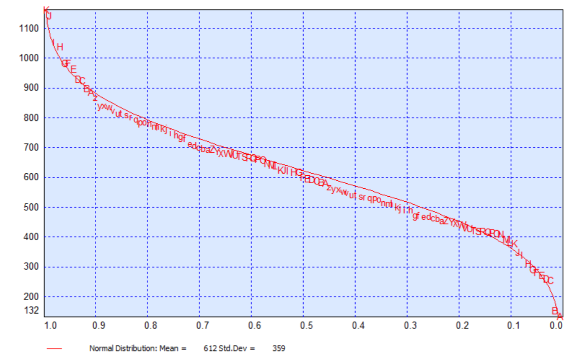
B Kaikohe



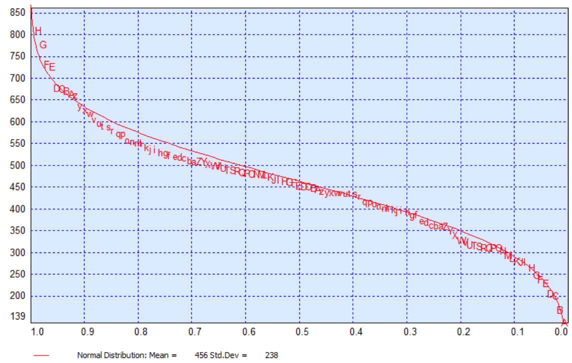
C Dargaville



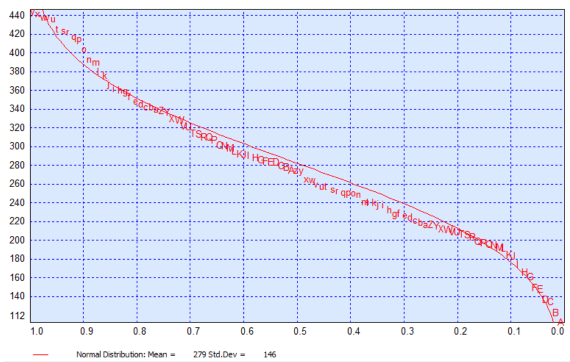
D Puhipuhi



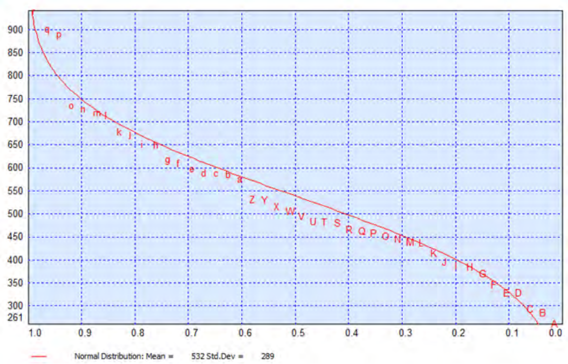
E Whangārei



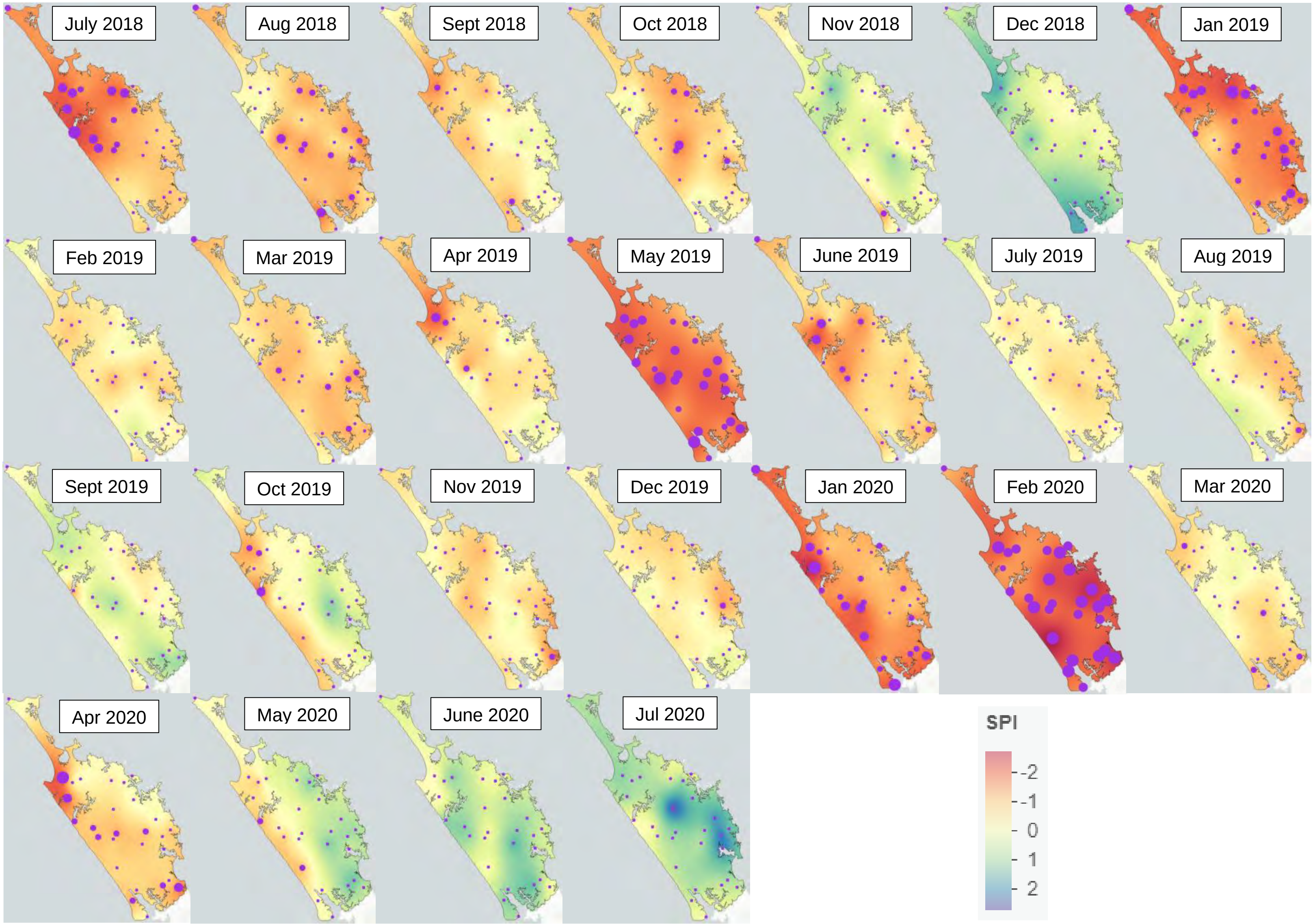
F Cape Reinga



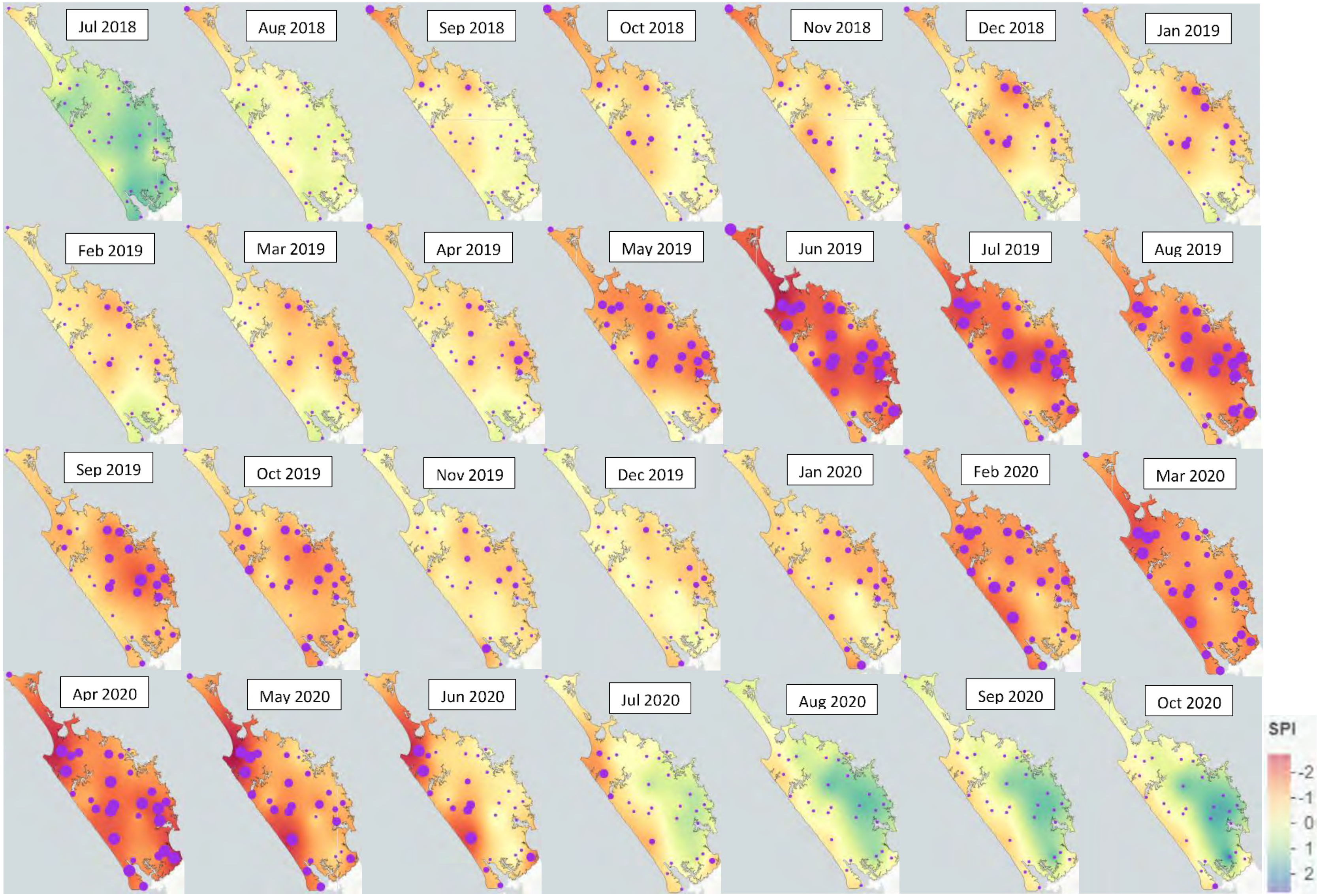
G Kerikeri



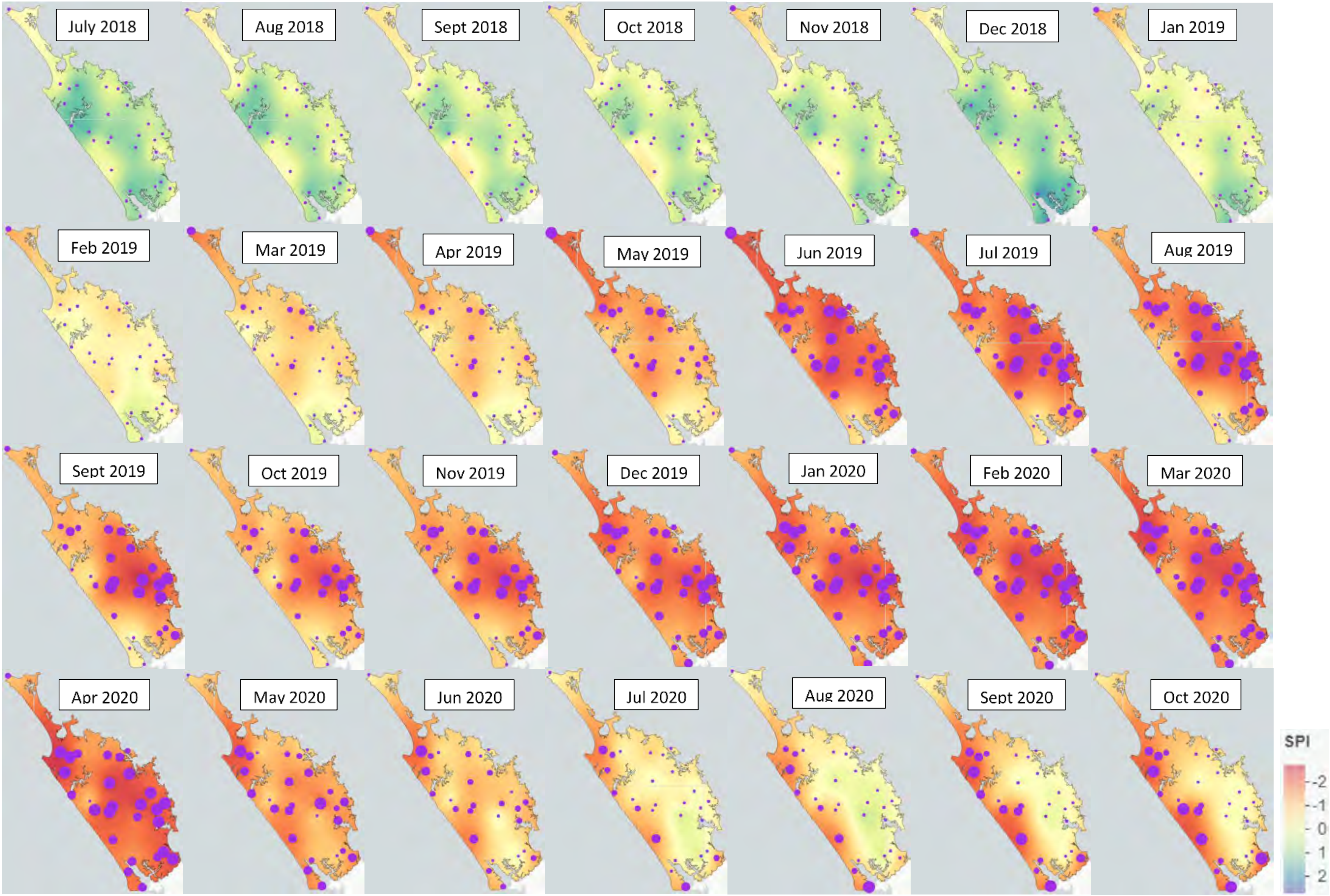
Appendix 4: SPI-1 distribution for July 2018 to July 2020.



Appendix 5: SPI-6 distribution for July 2018 to July 2020.

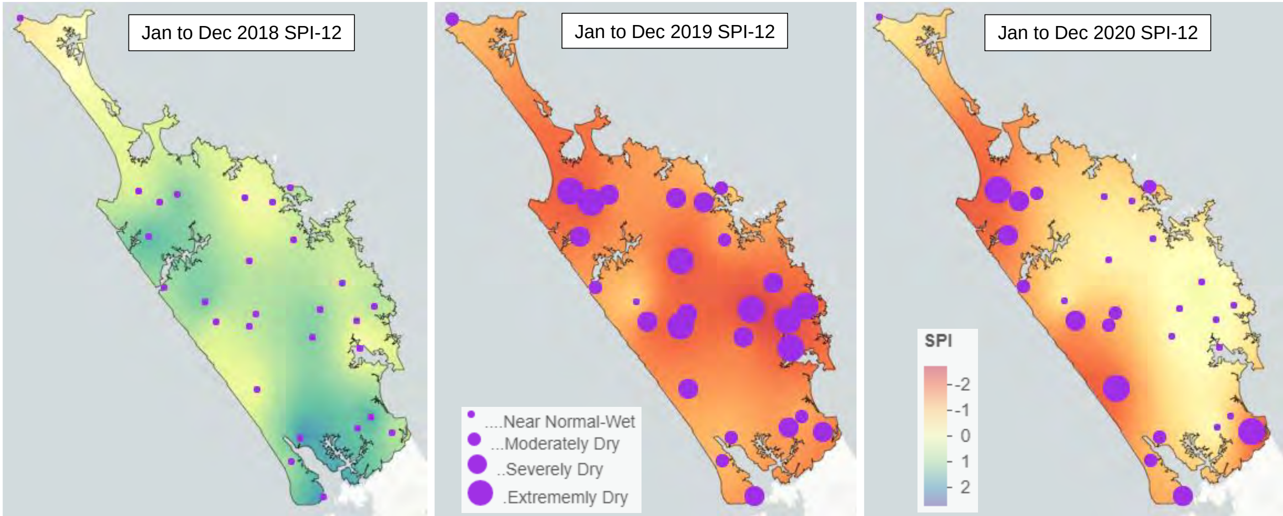


Appendix 6:SPI-12 distribution for July 2018 to July 2020.

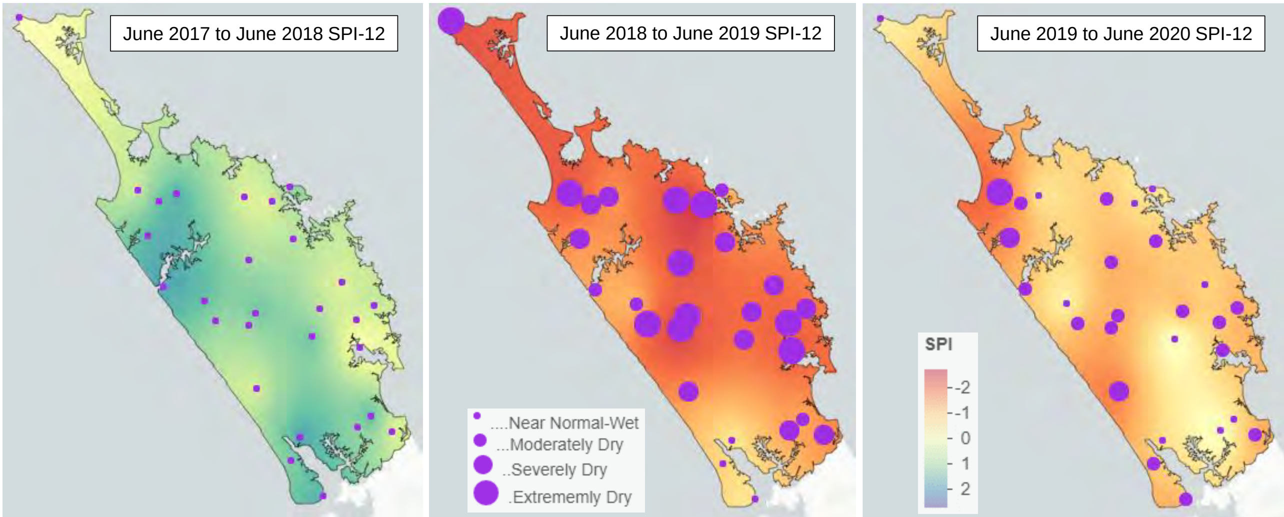


Appendix 7:: A) SPI-12 distribution for calendar years 2018, 2019 and 2020. B) SPI-12 distribution for water years 2018, 2019 and 2020.

A

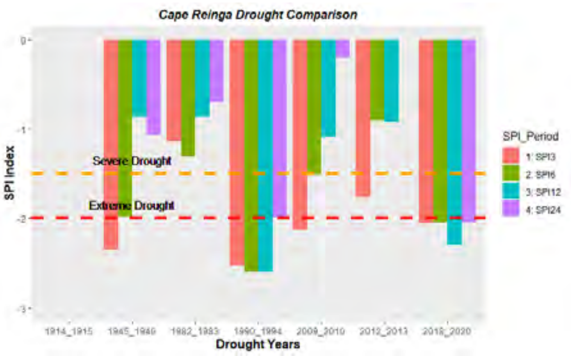


B

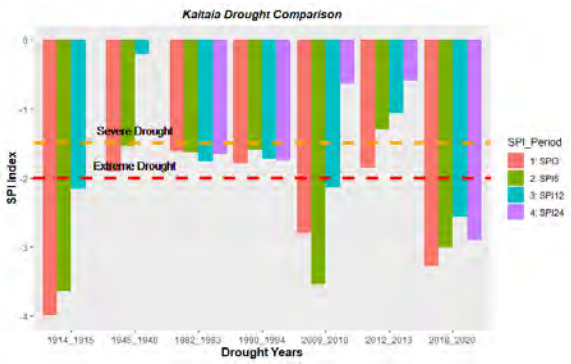


Appendix 8: Drought comparison at Cape Reinga, Kaitaia, Kaikohe, Kerikeri, Puhipuhi, Whangārei, and Dargaville over known significant drought periods.

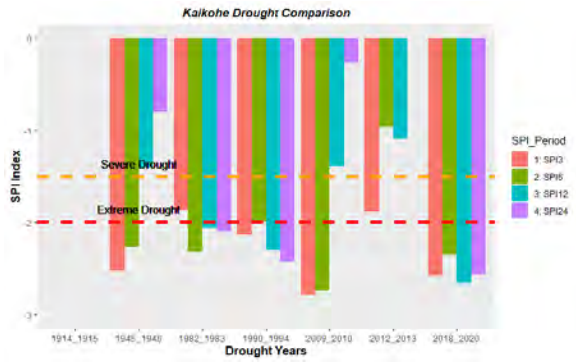
A



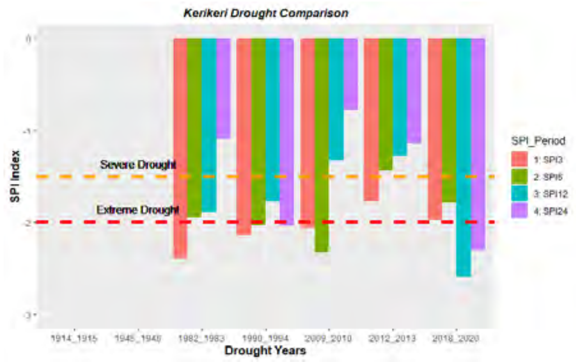
B



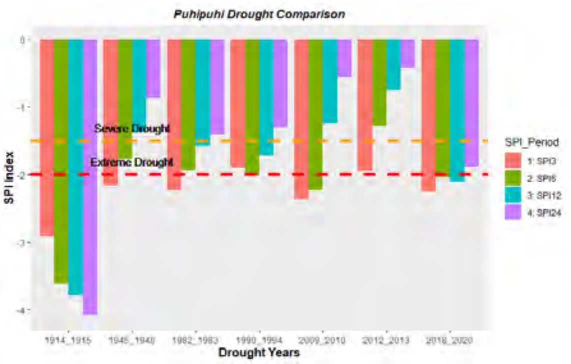
C



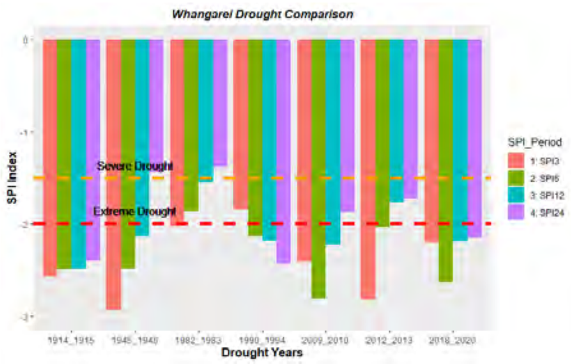
D



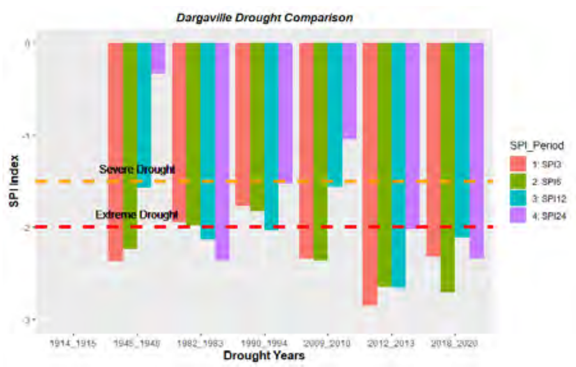
E



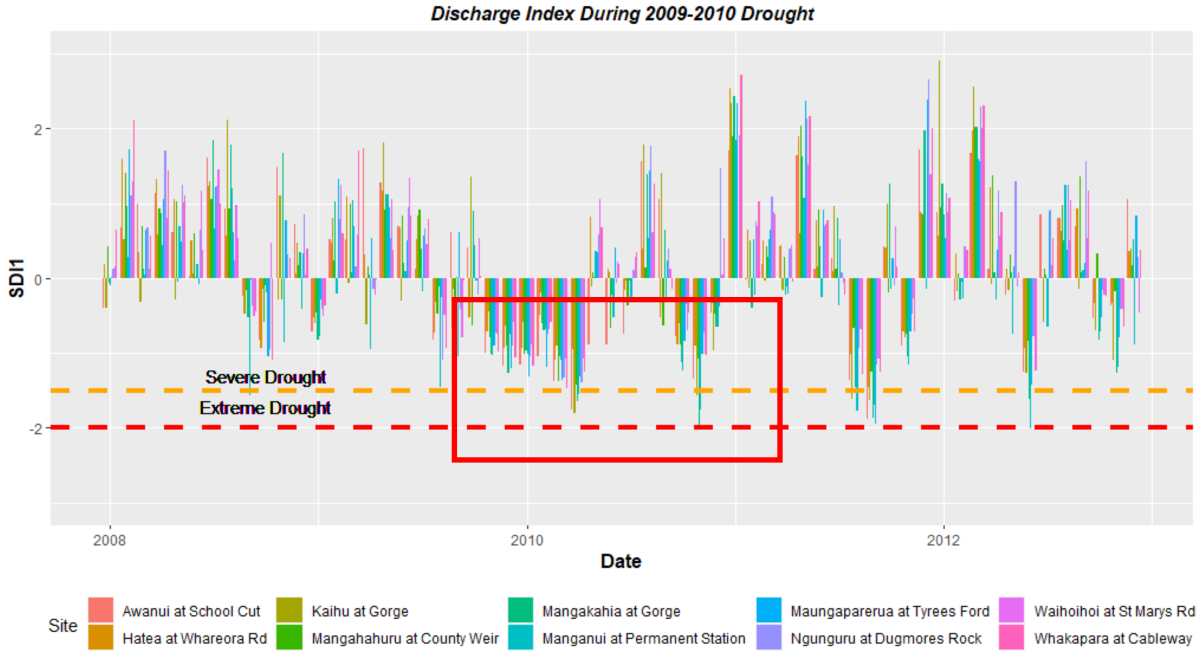
F



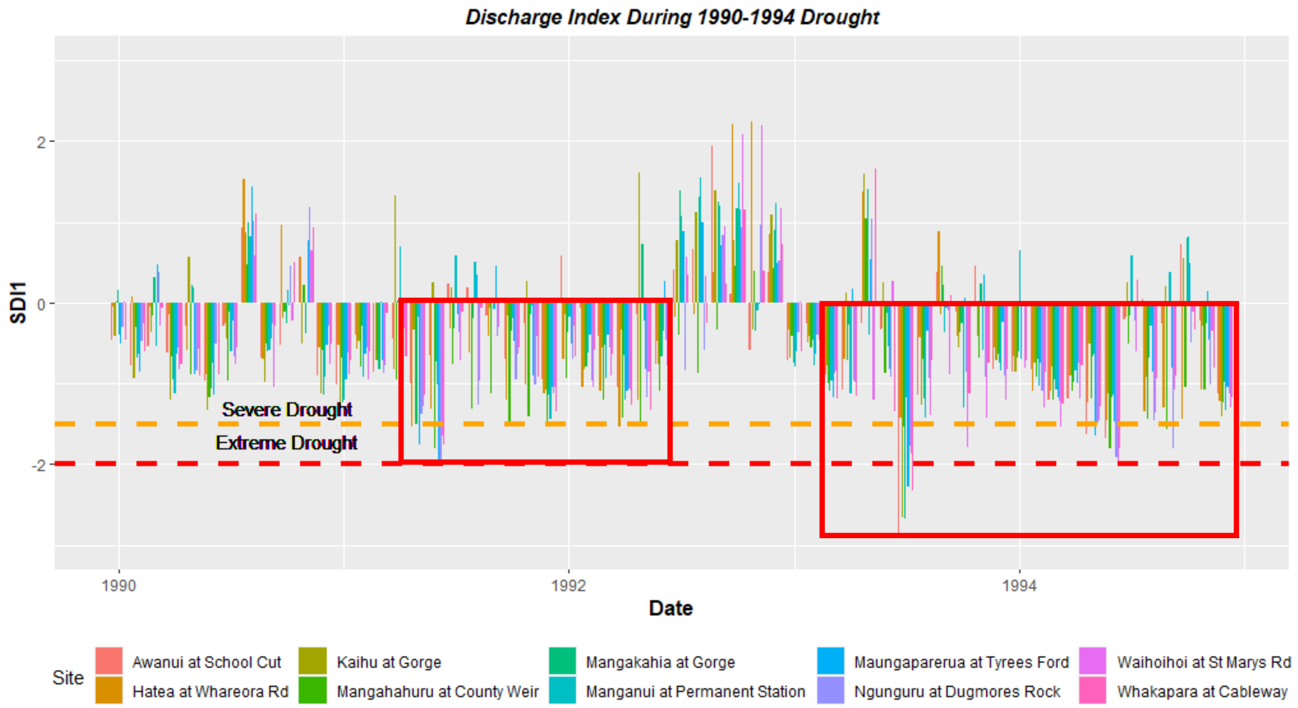
G



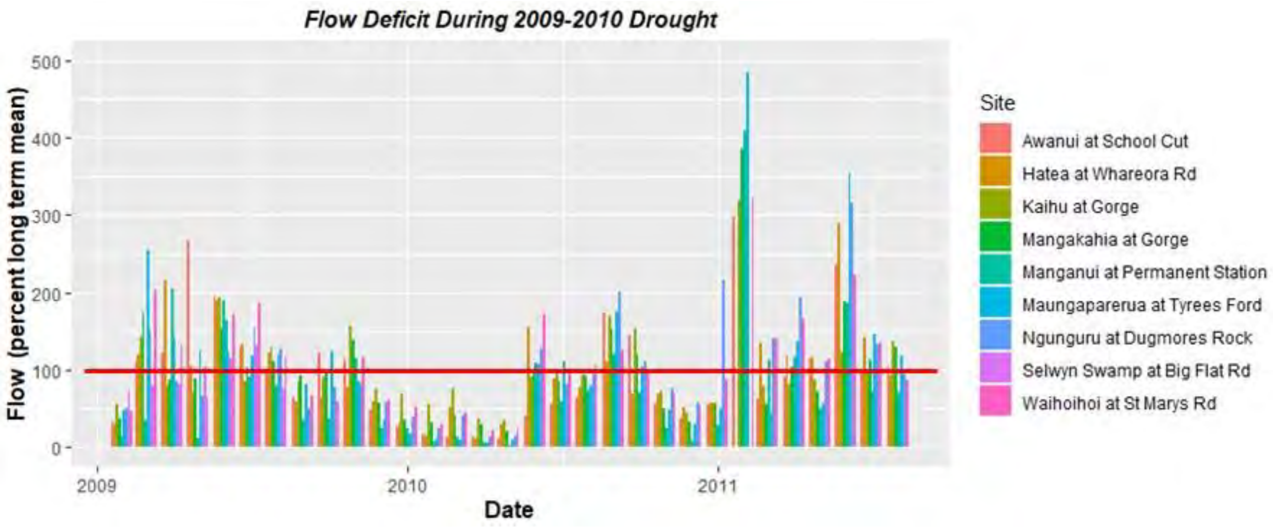
Appendix 9: SDI-1 during 2009-2010 drought.



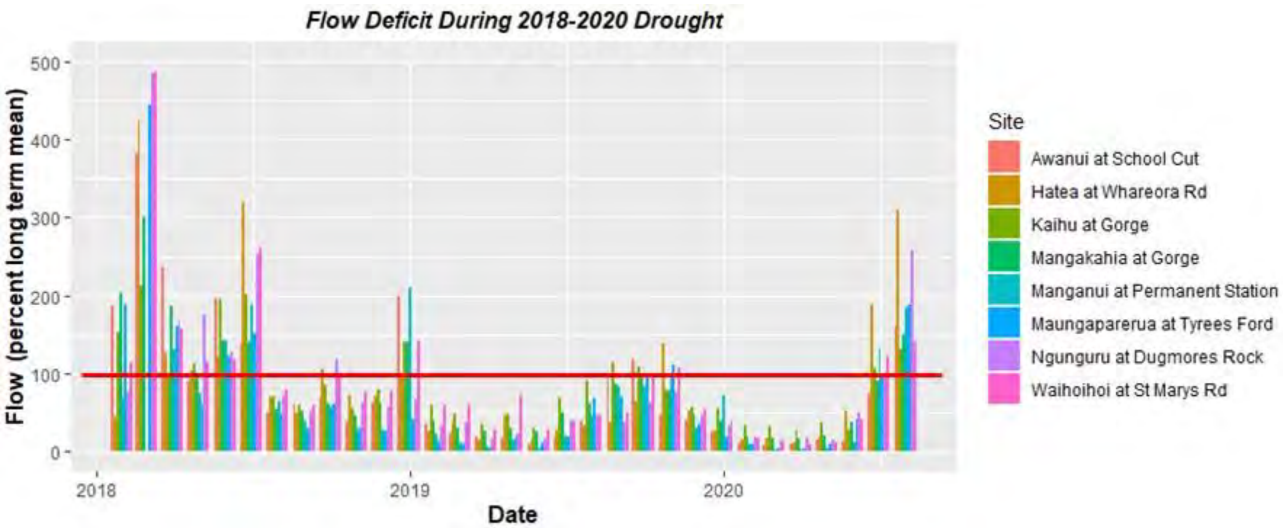
Appendix 10: SDI-1 during 1990-1994 drought.



Appendix 11: Percentage of monthly flow for 2009-2010 drought; based on long-term averages for the corresponding month at Awanui, Kaihu, Manganui, Mangakahia, Maungataperarua, Ngunguru, Hatea and Waihoihoi stations. Flow deficit exists when percentages are below the red line.



Appendix 12: Percentage of monthly flow for 2018-2020 drought; based on long-term averages for the corresponding month at Awanui, Kaihu, Manganui, Mangakahia, Maungataperarua, Ngunguru, Hatea and Waihoihoi stations. Flow deficit exists when percentages are below the red line.



Appendix 13: A matrix of characteristic droughts experienced in New Zealand with associated assumptions about duration (drought length in days or months) and intensity thresholds (percentiles based on historical variability) – (NIWA, 2011).

		Intensity		
		High (<=10th)	**Moderate** (<=25th)	**Low** (<=50th)
Duration	**Short** 1month (>0 days, <31days)	Short duration high intensity **(SH)**	Short duration moderate intensity **(SMo)**	Short duration low intensity **(SLw)**
	Medium 1-3 months (>31 days, <=93 days)	Medium duration high intensity **(MH)**	Medium duration moderate intensity **(MMo)**	Medium duration low intensity **(MLw)**
	Long 6 Months (>93 days)	Long duration high intensity **(LH)**	Long duration moderate intensity **(LMo)**	Long duration low intensity **(LLw)**

Appendix 14: List of Groundwater monitoring sites.

IRIS ID	Common Name	Date Created	Reduced	Data	X	Y
LOC.641010	Awaroa at Wallace Road	12/02/2008	0	NRC	1696028	6001436
LOC.5463005	Glenbervie GW at 279 Ngunguru	27/07/2005	110.78	NRC	1722605	6052066
LOC.5421018	Russell at Foreshore Bore	23/07/2008	3.66	NRC	1702050	6097230

Appendix 15: List of NIWA soil moisture monitoring sites.

Agent_Number	Network_Number	Start_Date	End_Date	Name	Lat	Long
25119	A53987	29/10/2003	18/06/2017	Dargaville 2 Ews	-35.93	173.85
17067	A53127	29/10/1999	18/06/2017	Kaitaia Ews	-35.14	173.26
1056	A53191	27/06/2002	18/06/2017	Kerikeri Ews	-35.18	173.93
40980	A54738	20/08/2015	18/06/2017	Whangārei Ews	-35.74	174.33
17838	A64464	2/11/1999	18/06/2017	Warkworth Ews	-36.43	174.67
1134	A53487	15/11/1985	6/06/2022	Kaikohe Aws	-35.42	173.82

Appendix 16: List of ecology survey sites.

Site Name	Site Number	Creation Date	Edit Date	WQ Site Number	x	y
Waiaruhe at DS of Mangamutu Confluence	LOC.003769	20/02/2020	17/04/2020	LOC.306661	173.9128	-35.3786
Puketotara Stream SH10 Bridge (Soda springs)	LOC.003708	21/02/2020	17/04/2020		173.9574	-35.3458
Ngawha at Above Falls (Gins Weir)	LOC.003711	20/02/2020	17/04/2020	LOC.108354	173.8646	-35.4027
Waiaruhe at SH1 Bridge	LOC.003714	20/02/2020	17/04/2020	LOC.101938	173.9271	-35.3485
Titahi at SH1 bridge	LOC.003702	20/02/2020	17/04/2020		173.9039	-35.3438
Waitangi at Whakataha Road	LOC.003768	25/02/2020	17/04/2020		173.878	-35.294
Kanikau Stream at 84 Waitaheke Road	LOC.003766	20/02/2020	17/04/2020	LOC.324293	173.8736	-35.3735
Waikaramu Stream at Old Bay Road	LOC.003767	20/02/2020	17/04/2020		173.9185	-35.3313
Te Keene Stream at SH10	LOC.003765	21/02/2020	17/04/2020		173.9734	-35.3359
Waiaruheiti at Old Bay Road	LOC.003738	20/02/2020	17/04/2020		173.9334	-35.3246
Pekapeka at Ohaeawai	LOC.003754	20/02/2020	17/04/2020	LOC.306643	173.8907	-35.3592
Waitangi at Waimate North Road	LOC.003725	25/02/2020	17/04/2020	LOC.103178	173.9019	-35.2967
Waiaruhe at Porotu Road	LOC.003723	21/02/2020	17/04/2020		173.9585	-35.3189
Waitangi at Haruru Falls	LOC.003704	20/02/2020	17/04/2020	LOC.101225	174.0508	-35.278
Manaia stream DS of SH10 bridge	LOC.003760	21/02/2020	17/04/2020		173.9716	-35.3138
Waitangi at Lily Pond Lane	LOC.003706	21/02/2020	17/04/2020	LOC.104830	174.0117	-35.2882
Waitangi at Wakelins	LOC.003722	21/02/2020	17/04/2020	LOC.101752	174.0474	-35.2756
Waitangi trib Wehirua Road	LOC.003761	21/02/2020	17/04/2020		173.809	-35.3074
Pateretere at Waiare Rd	LOC.003762	21/02/2020	8/06/2020		173.8282	-35.2877
Whangae at Wiroa Road	LOC.003710	21/02/2020	20/04/2020		173.8563	-35.273
Waipapa Stream at Wiroa Road	LOC.003709	21/02/2020	20/04/2020		173.8716	-35.2684
Waiaruhe at Puketona Junction	LOC.003707	25/02/2020	31/03/2020	LOC.304589	173.9611	-35.3006
Waikuku Stream at Waikuku Road	LOC.003763	21/02/2020	17/04/2020		173.8478	-35.3111
Waitangi at SH10	LOC.003703	25/02/2020	17/04/2020	LOC.304595	173.9562	-35.2974
Kamore Stream at Waikuku Road	LOC.003764	21/02/2020	17/04/2020		173.8523	-35.3138
Mangahahuru at County weir	LOC.046674	9/03/2020	30/03/2020		174.3121	-35.64
Waiotu at Tapuhi Road	LOC.046601	10/03/2020	17/04/2020		174.205	-35.504
Waipao at Draffin Road	LOC.046641	9/03/2020	17/04/2020	LOC.108941	174.127	-35.7259
Whakapara at Cableway	LOC.046632	9/03/2020	17/04/2020	LOC.102249	174.2716	-35.5418
Waiotu at SH1 Br	LOC.046627	10/03/2020	17/04/2020	LOC.102248	174.2285	-35.5321
Waipao at McBeth Road	LOC.1046625	9/03/2020	17/04/2020		174.1536	-35.7338
Mangere at Woods Road	LOC.1046674	9/03/2020	17/04/2020	LOC.102106	174.2084	-35.7124
Mangahahuru at Upstream of Fonterra Take	LOC.1046681	9/03/2020	17/04/2020		174.3038	-35.6365
Kaiikanui at Hodgson Road	LOC.1246644	9/03/2020	17/04/2020		174.2947	-35.5108
Kauritutahi Stream upstream of Waipao Confluence	LOC.1146613	9/03/2020	17/04/2020		174.1542	-35.734
Mangahahuru at Downstream of Fonterra Take	LOC.1046677	9/03/2020	17/04/2020		174.3037	-35.6355
Waiariki at SH1	LOC.046630	10/03/2020	17/04/2020		174.2382	-35.539
Kauritutahi at McBeth Road	LOC.046666	9/03/2020	17/04/2020	LOC.102141	174.1542	-35.7346

Site Name	Site Number	Creation Date	Edit Date	WQ Site Number	x	y
Mangere at Kara Road Bridge	LOC.1246630	9/03/2020	17/04/2020	LOC.102107	174.1939	-35.7035
Kaiikanui at Pigs Head Road	LOC.1246642	9/03/2020	17/04/2020		174.3378	-35.5115
Mangahahuru at SH1 Bridge	LOC.046637	9/03/2020	17/04/2020		174.2932	-35.6253
Waiariki at Mine Road	LOC.1246640	10/03/2020	17/04/2020		174.2595	-35.5056
Mataroa at Bushby Road	LOC.1146684	9/03/2020	17/04/2020		174.3462	-35.5152
Kauritutahi at SH15	LOC.1046623	9/03/2020	17/04/2020		174.1747	-35.7544
Mangere at Kokopu Road	LOC.1246649	9/03/2020	17/04/2020	LOC.102109	174.1817	-35.6978
Ngaruawahine Stream trib at Akarama Road	LOC.1246669	10/03/2020	17/04/2020		174.1709	-35.4972
Kirikiritoki at Ford	LOC.046681	9/03/2020	17/04/2020		174.3224	-35.5714
Waipuakakahau Stream at Tapuhi Road	LOC.1046645	10/03/2020	17/04/2020		174.2026	-35.5149
Waiotu at Morgans Road	LOC.1246671	10/03/2020	17/04/2020	LOC.301213	174.2007	-35.4868
Mangere at Upstream of Anderson take	LOC.1246611	9/03/2020	17/04/2020	LOC.101022	174.1757	-35.7011
Mangere at Knights Road	LOC.046646	9/03/2020	30/03/2020	LOC.101625	174.1437	-35.6983
Mangaharuru at Apotu Road	LOC.1246667	10/03/2020	17/04/2020	LOC.100281	174.2599	-35.6178
Mangaharuru at Rushbrook Road	LOC.1246668	10/03/2020	17/04/2020		174.2377	-35.6177
Poroti Springs at Fig tree	LOC.1046607	10/03/2020	17/04/2020		174.1397	-35.7366
Pukekaikiore Stream at Puhipuhi Road Bridge	LOC.1246605	10/03/2020	17/04/2020	LOC.301211	174.272	-35.4765
Tapahina at SH15 Mangakahia Road	LOC.1246656	10/03/2020	17/04/2020		174.129	-35.738
Okoihu Stream at Wharekohe Road	LOC.1246657	10/03/2020	17/04/2020		174.1076	-35.7485
Wairua at Purua	LOC.046644	11/03/2020	17/04/2020	LOC.101753	174.1521	-35.6529
Kaimamaku at Peach Orchard Road Bridge	LOC.1246664	12/03/2020	17/04/2020		174.301	-35.4771
Waikiore Stream at Rockells Dam outflow downstream	LOC.1146677	10/03/2020	17/04/2020	LOC.105937	174.2695	-35.4779
Okoihu at Whatitiri Road	LOC.1246658	10/03/2020	17/04/2020		174.0969	-35.7369
Mangawhero at behind the Hikurangi Hotel	LOC.046664	10/03/2020	17/04/2020		174.2871	-35.5986
Waipao at Kokopu Road	LOC.1146656	10/03/2020	17/04/2020	LOC.102590	174.098	-35.7283
Taotaoroa Stream at Peach Orchard Road	LOC.1246661	12/03/2020	17/04/2020		174.2967	-35.4691
Pukekaikiore Stream Trib at North Dam	LOC.1246672	10/03/2020	17/04/2020		174.2712	-35.4659
Pukekaikiore Stream at Downstream of dam outlet	LOC.1146683	10/03/2020	17/04/2020	LOC.104612	174.2778	-35.4706
Kirikiritoki at Marua Road	LOC.1246666	11/03/2020	17/04/2020		174.3375	-35.5699
Haumakariri Stream at Russell Road (opposite Matheson Rd)	LOC.1246662	12/03/2020	17/04/2020		174.3039	-35.4751
Kirikiritoki Trib at Marua Bridge	LOC.1246665	11/03/2020	17/04/2020		174.3384	-35.5696
Haumakariri Stream trib at Matheson Road	LOC.1246663	12/03/2020	17/04/2020		174.3042	-35.4754
Waiotu at Nelson Road	LOC.1246670	10/03/2020	17/04/2020		174.2096	-35.4414
Mangawhero trib at Upstream of Hikurangi Hotel	LOC.1246659	10/03/2020	17/04/2020		174.287	-35.5977
Whakapara at Russell Road Bridge	LOC.1246660	12/03/2020	17/04/2020		174.2827	-35.5431
Waiariki at Rockells Ford	LOC.1146672	10/03/2020	17/04/2020	LOC.104640	174.271	-35.4888
Piroa at Quarry	LOC.006024	11/03/2020	17/04/2020		174.4301	-36.0809
Waionehu at McLean Road	LOC.006007	11/03/2020	17/04/2020	LOC.102262	174.4578	-36.0095
Victoria at Raetea Reserve above ford	LOC.001358	11/03/2020	17/04/2020	LOC.104908	173.4337	-35.1691
Ahuroa at Piroa Falls	LOC.006038	11/03/2020	6/05/2020	LOC.317597	174.3897	-36.0653

Site Name	Site Number	Creation Date	Edit Date	WQ Site Number	x	y
Waihoihoi at St Marys Road	LOC.006016	11/03/2020	1/04/2020		174.431	-36.0019
Victoria Trib at SH1 Raetea Reserve	LOC.001357	11/03/2020	17/04/2020		173.4339	-35.1663
Ahuroa at Braigh Flats	LOC.006018	11/03/2020	31/03/2020	LOC.101978	174.4123	-36.0012
Tawai Stream at Upstream of Takahue Confluence	LOC.001363	11/03/2020	17/04/2020		173.3453	-35.1884
Ahuroa at Durham Rd	LOC.006014	11/03/2020	20/04/2020	LOC.101977	174.412	-36.0348
Te Kahikatea Stream at SH1	LOC.001359	11/03/2020	17/04/2020		173.4195	-35.1578
Ahuroa at Finlaysons Brooks Road Bridge	LOC.006022	11/03/2020	17/04/2020		174.3758	-36.0216
Ahuroa at Rowntrees	LOC.006004	11/03/2020	17/04/2020		174.4135	-35.9892
Takahue at Crene Road	LOC.001323	11/03/2020	30/03/2020	LOC.104567	173.3478	-35.1843
Victoria at Victoria Valley Road	LOC.001351	11/03/2020	30/03/2020		173.4155	-35.1515
Waiataraire at Takahue Road Bridge	LOC.001345	11/03/2020	17/04/2020		173.3497	-35.1808
Waikawa Stream at Diggers Valley Road	LOC.001338	11/03/2020	17/04/2020		173.3339	-35.1707
Te Puhi at Clough Road	LOC.001317	11/03/2020	17/04/2020		173.3276	-35.1166
Victoria at Double Crossing	LOC.001319	11/03/2020	30/03/2020		173.3288	-35.1185
Takahue at Takahue Saddle Road	LOC.001364	11/03/2020	17/04/2020		173.359	-35.2081
Pukepoto Stream at Kaitaia-Awaroa Road	LOC.001340	12/03/2020	17/04/2020		173.2233	-35.157
North at Applecross Road	LOC.006015	12/03/2020	21/05/2020	LOC.101979	174.4103	-35.9381
Waihoe Channel at Floodgate	LOC.001346	12/03/2020	17/04/2020	LOC.103327	173.2261	-35.1086
Ahuroa at Brooks Road	LOC.006039	12/03/2020	6/05/2020		174.415	-36.0115
Awanui at School Cut	LOC.001316	12/03/2020	27/03/2020	LOC.100366	173.2692	-35.1168
Awanui at Waikuruki	LOC.001314	12/03/2020	27/03/2020	LOC.100365	173.2593	-35.1022
North Trib at Mountfield Road	LOC.006037	12/03/2020	17/04/2020		174.3946	-35.9414
Millbrook at Millbrook Road	LOC.006003	12/03/2020	17/04/2020		174.416	-35.9714
Waihoihoi at Glenmhor Road	LOC.006023	12/03/2020	17/04/2020		174.4231	-36.0242
Tarawhatoroa at Redan Bridge	LOC.001312	12/03/2020	17/04/2020		173.2646	-35.1173
Waihoihoi at US Drinnan Take	LOC.006034	12/03/2020	17/04/2020		174.4231	-36.0164
Pohuenui at McKay Road	LOC.006002	12/03/2020	17/04/2020		174.4346	-35.9492
Tapapa Stream at SH1 roadside reserve	LOC.048019	12/03/2020	17/04/2020	LOC.313165	173.4804	-35.1929
Mangamuka at Gorge	LOC.048015	12/03/2020	17/04/2020		173.4992	-35.1992

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