CLIMATOLOGICAL VARIABILITY AND LIMITATIONS OF FORECASTING EXTREME RAINFALL STATISTICS

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ABSTRACT

Rainfall frequency analyses play a vital role in water resources engineering for accurate prediction of flood risk, efficient stormwater management and design of flood control and drainage infrastructure. Limited rainfall data at some sites in the Auckland Region leads to difficulties in fitting a probability distribution and estimation of extreme rainfall event statistics. Climate change and phase changes in the Inter-decadal Pacific Oscillation (IPO) affect rainfall patterns and create more issues in estimating extreme rainfall.

Log-Pearson Type III (LPIII) rainfall frequency distribution analyses were carried out for 10 rainfall gauges within the Auckland Region using HYDSTRA software (HYIFD) to generate intensity-frequency-duration tabular data. Rainfall trend analyses were also carried out based on frequency analyses for moving 20-year interval of rainfall data bins at six rainfall gauges within the Auckland Region with rainfall records ranging from 34 to 72 years of data.

Rainfall trend analyses show higher design rainfall depths during the 1978-1999 period and lower design rainfall depths during the 2000-2017 period. These are because of phase changes in the IPO on rainfall trends i.e. higher rainfall in the positive phase (1978 – 1999) of the IPO and lower rainfall in the negative phase (2000 – 2017) of the IPO. It demonstrates that the natural climatological variability of rainfall extremes is much greater than climate change effects.

Rainfall data shows that 80% of the total rainfall record in the Auckland region has been recorded in the past 19 years during the negative IPO phase. So if these data were used in a regional rainfall frequency analysis (HIRDS V4) the extreme event statistics would be skewed by the preponderance of recent data.

During the past 20 years less extreme rainfall occurred in the Auckland Region than in the 20 years previous. LPIII rainfall frequency distribution analyses of four rainfall gauges with 18-19 years of data show very low design rainfall depths compared to TP108, HIRDS V3 and HIRDS V4 design rainfall depths. TP108 and HIRDS V3 frequency analysis did not have the last 20 years of rainfall data, as a result predict higher design rainfall depths.

Climatological variability is increasingly creating severe risks to New Zealand as a result of continuing sea level rise and the increased frequency and intensity of flood damage on our infrastructure. This paper demonstrates the importance of both the climate variability (IPO) and limited rainfall data availability in estimating the extreme rainfall event statistics. This is critical to accurately predict the flood risk and ensure infrastructure is capable of performing now and into the future.

KEYWORDS

Climate, Rainfall Frequency Analysis, HIRDS, Inter-decadal Pacific Oscillation (IPO), El Niño Southern Oscillation (ENSO)

PRESENTER PROFILE

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1 INTRODUCTION

In New Zealand and the South Pacific, annual and seasonal rainfall is highly variable and depends on short-term weather patterns and long-term climate oscillations such as the El Niño Southern Oscillation (ENSO) and Inter-decadal Pacific Oscillation (IPO). The ENSO is a significant source of seasonal and year-to-year climate variability in rainfall pattern. The IPO exerts a long-term influence over the ENSO cycle that operates on decadal time scale. The long-term climate change influenced by increasing greenhouse gases are superimposed on these annual and decadal climate variations resulting in change in wind circulation, temperature and rainfall patterns thereby affecting our water resources and energy needs.

The IPO cyclical climate change pattern lasts for 20 to 30-year period, much longer than ENSO. These cyclical patterns are known as phases of the IPO, the IPO was in a negative phase from 1945-1977 and in positive phase from 1978-99. During the positive phase, El Nino events and westerly winds are more frequent and intense than usual in New Zealand, and rainfall in the west and south of South Island is higher than usual. The opposite applies during the negative phase (NIWA, 2011). Flood frequency analysis for the Lake Te Anau showed very marked changes in the frequency of extreme flows with the phase of the IPO, a high flow with an estimated return period of 50 years during the negative IPO phase (1947–1977) has a return period of approximately 7 years during the positive IPO phase (1978–1994) (McKerchar and Henderson, 2003).

Rainfall is very erratic and varies with time and space which makes difficulties in hydrology to interpret the historical records of rainfall events and estimate reliable and accurate future probable occurrence of extreme rainfall events. Rainfall frequency distribution analyses are usually used to estimate the extreme rainfall event statistics. TP108 (AC, 1999) design rainfall depths for various average recurrence intervals (ARIs) were developed using the at-site Gumbel frequency distribution approach.

Limited rainfall data at the majority of sites in the Auckland Region leads to difficulties in fitting a probability distribution and estimation of extreme rainfall event statistics. Climate change and phase changes in the Inter-decadal Pacific Oscillation (IPO) affect rainfall patterns and create more issues in estimating extreme rainfall.

Considering limited availability of rainfall data HIRDS V4 (NIWA, 2018) used the regional frequency approach to estimate high intensity rainfall for all New Zealand at ungauged locations for a range of return periods and event durations. Regional frequency analyses are used as an alternative to at-site frequency analysis to improve the estimation of rainfall statistics at sites for recurrence intervals significantly larger than the available records and at locations for which no observed records are available.

This paper presents the rainfall frequency distribution analyses for 10 rainfall gauges within the Auckland Region, compared the estimated design rainfall depths with TP108, HIRDS V3 and HIRDS V4 design rainfall depths, and demonstrates the importance of both the climate variability (IPO) and limited rainfall data availability in estimating the extreme rainfall event statistics.

2 BACKGROUND

Auckland Council runs 76 automatic tipping buckets rain gauges spread throughout the Auckland Region. All rain gauges are maintained to the NEMS standards. Similar to elsewhere in New Zealand and internationally the number of automatic rain gauges have increased dramatically in the past two decades.

The longest 5 minute rainfall data record in Auckland is from the Whenuapai rain gauge which has been running for 72 years since 1946. For each year between 1946 and 1963 Auckland collected 1 year of rainfall data, over this period 17 years of rainfall data were collected.

From 1963 until 1974 2 years of rainfall data were collected for every calendar year because two rain gauges were operating. Over these 11 years 22 years of rainfall data were collected. In 2019 we have 76 rain gauges operating providing us with 76 years of rainfall data every year.

Prior to the year 2000 we had collected 300 years of rainfall data from the rain gauge network which was in operation up until that date. Since 2000 with the preponderance of rainfall data which we have collected we now have 1500 years of rainfall data available from the Auckland Region. 80% of the rainfall data available is from the past 19 years. 20% of the rainfall data has a record length of more than 19 years.

Typically hydrological analyses to extrapolate extreme event statistics are deemed valid if the length of rainfall record is greater than 16 years. Some analysis undertaken in New Zealand has used record lengths as short as 12 and 13 years for extreme event estimation.

3 RAINFALL FREQUENCY ANALYSIS

Rainfall frequency analysis is carried out to relate the magnitude of extreme events to their frequency of occurrence using probability distributions. The key assumptions of frequency analysis are that the rainfall data to be analyzed are independent and identically distributed, and the hydrologic system producing them is considered to be stochastic, space-independent and time-independent (Chow et al., 1988). It is vital that the rainfall data to be analyzed are carefully selected so that the assumptions of independence and identical distribution are satisfied.

Log-Pearson Type III (LPIII) rainfall frequency distribution analyses were carried out for 10 rainfall gauges within the Auckland Region using HYDSTRA software (HYIFD) to generate intensity-frequency-duration (IFD) tabular data. LPIII rainfall frequency distribution has been found to fit the rainfall data series and is comparable with other methods. LPIII frequency distribution analyses were carried out for two sets of rainfall records – one used the complete available rainfall records and the other used partial rainfall records up to 1999. Out of 10 rainfall gauges, 6 gauges have rainfall records ranging from 34 to 71 years of data and the remaining 4 gauges have 18-19 years of rainfall records.

Table 1 and 2 show the estimated LPIII 24-hour rainfall depths for 2, 5, 10, 20, 50 and 100-year ARIs at the 6 rainfall gauges with greater than 30 years of rainfall records. The estimated LPIII 24-hour design rainfall depths were compared with TP108, HIRDS V3 and HIRDS V4 design rainfall depths.

Table 1: 24-hour rainfall depths at 3 gauges (39-72 years of rainfall data)

ARI	24-hour Rainfall Depth (mm)					
	Whenuapai @ Airbase (72 years of rainfall data)					
	1946-1999	1946-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	95.5	90.9	91.0	80.0	89.3	77.6
5-year ARI	115.5	110.6	117.7	113.0	115.2	100.0
10-year ARI	130.2	124.9	124.1	133.0	136.4	117.0
20-year ARI	145.6	139.9	151.2	155.0	160.4	134.0
50-year ARI	166.7	160.4	165.6	180.0	197.9	158.0
100-year ARI	183.9	177.1	176.6	200.0	231.6	175.0
	Wairau at Testing Station (44 years of rainfall data)					
	1974-1999	1974-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	89.1	89.3	87.0	80.0	83.6	75.5
5-year ARI	117.9	114.3	116.7	120.0	109.2	98.1
10-year ARI	141.5	133.9	152.1	140.0	130.3	115.0
20-year ARI	168.2	155.2	184.8	169.0	154.5	132.0
50-year ARI	204.8	185.7	191.1	200.0	192.5	156.0
100-year ARI	237.7	211.8		220.0	227.0	175.0
	Hoteo @ Oldfields (39 years of rainfall data)					
	1979-1999	1979-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	97.5	97.4	92.9	98.0	85.5	85.8
5-year ARI	125.6	122.9	136.5	145.0	112.7	112.0
10-year ARI	147.3	141.6	155.1	176.0	135.4	132.0
20-year ARI	170.8	161.1	167.7	206.0	161.3	153.0
50-year ARI	204.3	188.0	181.0	243.0	202.4	181.0
100-year ARI	232.8	210.2		274.0	239.9	203.0

Comparisons of 24-hour design rainfall depth for various ARIs show that in general HIRDS V4 24-hour design rainfall depths are lower compared to HIRDS V3, Gauge LPIII, and TP108 design rainfall depths. This is because HIRDS V4 includes more rainfall data from the negative IPO phase (2000-2017). Similarly, TP108 and HIRDS V3 design rainfall depths are higher compared to Gauge LPIII and HIRDS V4 design rainfall depths as they do not include the recent rainfall data in the negative IPO phase (2000-2017).

The estimated LPIII 24-hour design rainfall depths based on partial rainfall records up to 1999 are higher compared to that based on complete rainfall records and are similar to TP108 or HIRDS V3 design rainfall depths (refer to Table 1 and 2).

Rainfall IFD analysis shows 24-hour 100-year ARI design rainfall depth at Whenuapai rain gauge (72 years data) is similar to the highest observed rainfall depth, similarly at Wairau rain gauge (44 years data) the 50-year ARI design rainfall depth is similar to the highest observed rainfall depth (refer to Table 1).

Table 2: 24-hour rainfall depths at 3 gauges (34-39 years of rainfall data)

ARI	24-hour Rainfall Depth (mm)					
	Rangitopuni @ Walkers (39 years of rainfall data)					
	1979-1999	1979-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	97.3	93.6	92.7	80.0	89.2	84.4
5-year ARI	129.3	118.0	115.3	110.0	114.3	109.0
10-year ARI	156.2	138.7	141.0	130.0	134.7	127.0
20-year ARI	187.1	162.6	167.1	150.0	157.6	146.0
50-year ARI	233.7	198.1	238.5	174.0	193.3	171.0
100-year ARI	275.6	229.8		193.0	225.2	190.0
	Wairoa @ Hunua Nursery/Bowling Club (38 years of rainfall data)					
	1980-1999	1980-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	88.2	88.8	90.5	84.0	79.4	79.6
5-year ARI	109.4	107.0	115.4	120.0	102.6	104.0
10-year ARI	126.9	121.4	146.1	150.0	121.6	123.0
20-year ARI	146.8	137.2	168.6	170.0	143.1	143.0
50-year ARI	175.9	159.5	183.8	200.0	176.7	172.0
100-year ARI	201.4	178.6		220.0	206.9	195.0
	Puhinui @ Botanics (34 years of rainfall data)					
	1984-1999	1984-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	88.5	83.8	83.5	76.0	76.4	71.8
5-year ARI	113.7	103.4	103.4	113.0	98.8	94.0
10-year ARI	133.9	118.5	116.1	139.0	117.1	111.0
20-year ARI	156.5	135.0	145.4	162.0	137.8	129.0
50-year ARI	189.3	158.3	177.6	193.0	170.2	153.0
100-year ARI	217.8	178.0		217.0	199.4	173.0

During the past 20 years less extreme rainfall occurred in the Auckland Region than in the 20 years previous. LPIII rainfall frequency distribution analyses of four rainfall gauges with 18 to 19 years of rainfall data show very low design rainfall depths compared to TP108, HIRDS V3 and HIRDS V4 design rainfall depths (refer to Table 3). TP108 and HIRDS V3 frequency analysis did not have the last 20 years of rainfall data, as a result predict higher design rainfall depths.

Table 3: 24-hour rainfall depths at 4 gauges (18-19 years of rainfall data)

ARI	24-hour Rainfall Depth (mm)				
	Albany @ Hts Rd (19 years of rainfall data)				
	1999-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	104.1	100.3	80.0	90.1	80.5
5-year ARI	119.4	122.7	116.0	116.3	104.0
10-year ARI	126.4	133.4	139.0	137.6	122.0
20-year ARI	131.4	139.8	160.0	161.9	140.0
50-year ARI	136.6		185.0	199.6	165.0
100-year ARI	139.6		209.0	233.6	184.0
	Cox's Bay Park (18 years of rainfall data)				
	2000-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	85.7	85.6	77.0	81.8	70.1
5-year ARI	103.0	102.9	109.0	106.3	91.1
10-year ARI	114.4	126.4	128.0	126.4	107.0
20-year ARI	125.4	126.9	148.0	149.2	123.0
50-year ARI	139.6		173.0	185.0	145.0
100-year ARI	150.5		192.0	217.3	162.0
	Kumeu @ Waitakere Domain (18 years of rainfall data)				
	2000-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	81.9	79.4	87.0	80.6	75.7
5-year ARI	94.0	97.4	114.0	103.4	97.1
10-year ARI	101.7	107.1	130.0	122.0	113.0
20-year ARI	109.0	109.0	147.0	142.9	129.0
50-year ARI	118.1		168.0	175.4	150.0
100-year ARI	124.9		184.0	204.5	167.0
	Opanuku @ Candia Road (18 years of rainfall data)				
	2000-2017	Ranked Data	TP108	HIRDS V3	HIRDS V4
2-year ARI	84.0	82.9	87.0	79.6	77.1
5-year ARI	95.0	99.7	116.0	102.5	99.2
10-year ARI	102.4	102.0	137.0	121.1	116.0
20-year ARI	109.7	116.7	150.0	142.2	132.0
50-year ARI	119.2		175.0	175.0	155.0
100-year ARI	126.5		192.0	204.5	172.0

4 RAINFALL TREND ANALYSIS

Rainfall trend analyses were carried out based on frequency analyses for moving 20-year interval of rainfall data bins at six rainfall gauges within the Auckland Region with rainfall records ranging from 34 to 72 years of data. Rainfall trend analyses show higher design rainfall depths during the 1978-1999 period and lower design rainfall depths during the 2000-2017 period (refer to Figure 1, Figure 2 and Table 4). These are because of the impact of phase changes in the IPO on rainfall trends i.e. higher rainfall in the positive phase (1978 – 1999) of the IPO and lower rainfall in the negative phase (2000 – 2017) of the IPO. This relationship is not uniform across New Zealand. During the positive IPO phase, rainfall increased in the southwest of the South Island, but decreased in the north and east of the North Island, relative to the earlier negative IPO phase (MfE, 2008).

Figure 1 and 2 shows the IPO has strong influence on rare rainfall events (e.g. 100-year ARI) and week influence on 2-year ARI event. That is why only the estimated LPIII 2-year ARI design rainfall depths are higher compared to TP108 or HIRDS V3 design rainfall depths (refer to Table 1 and 2).

Figure 1: Rainfall trends at Whenuapai rainfall gauge (72 years of rainfall data)

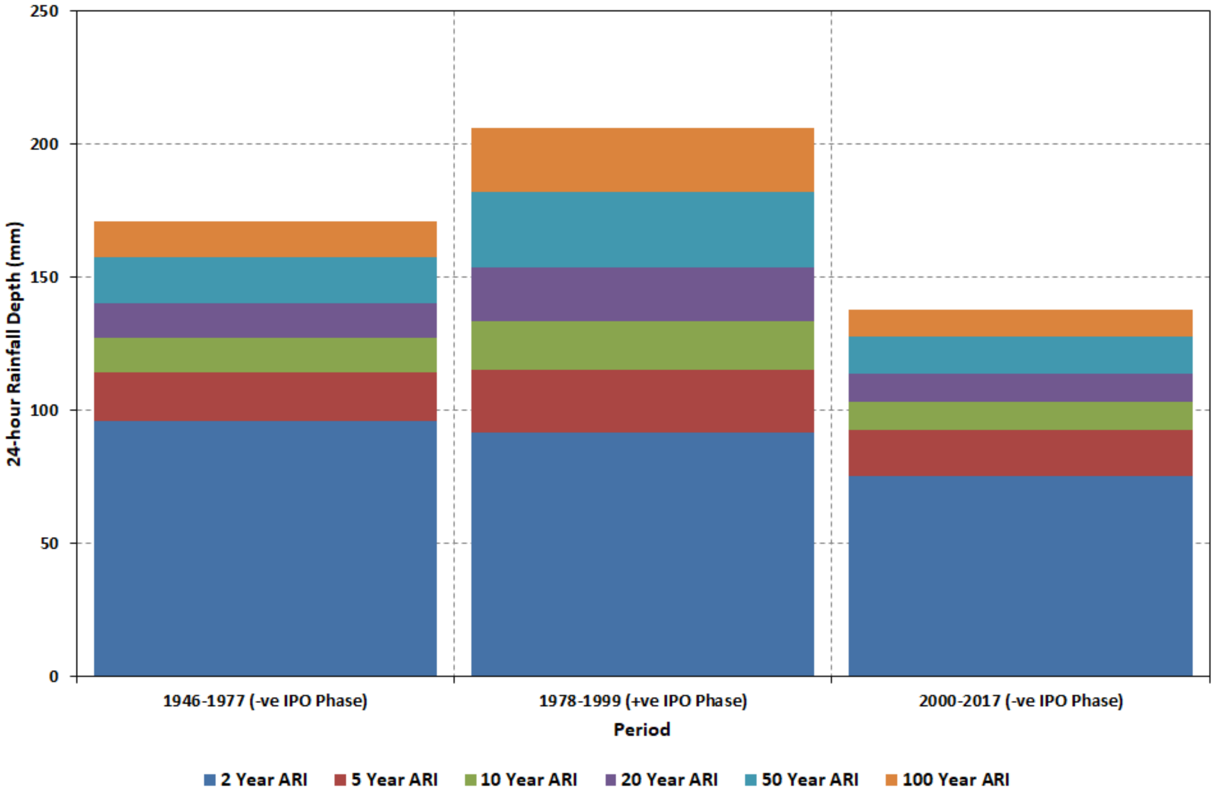


Figure 2: Rainfall trends at Wairau rainfall gauge (44 years of rainfall data)

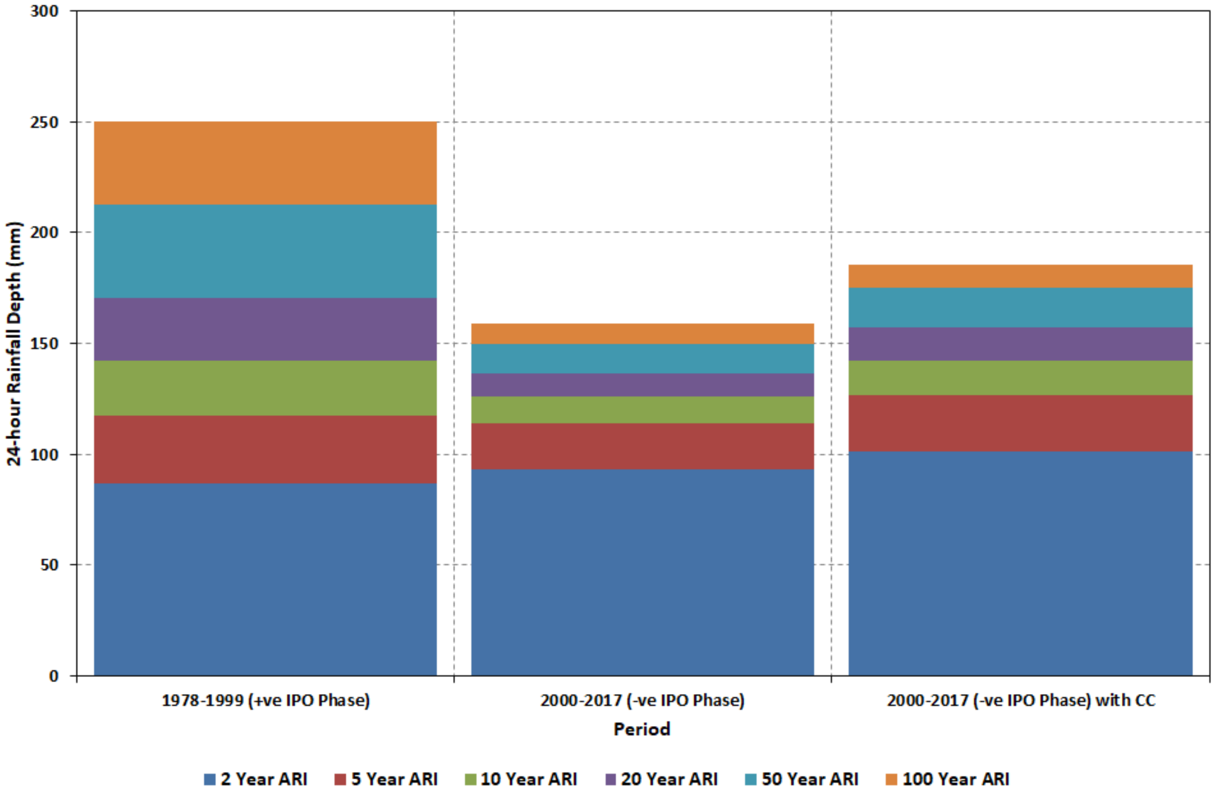
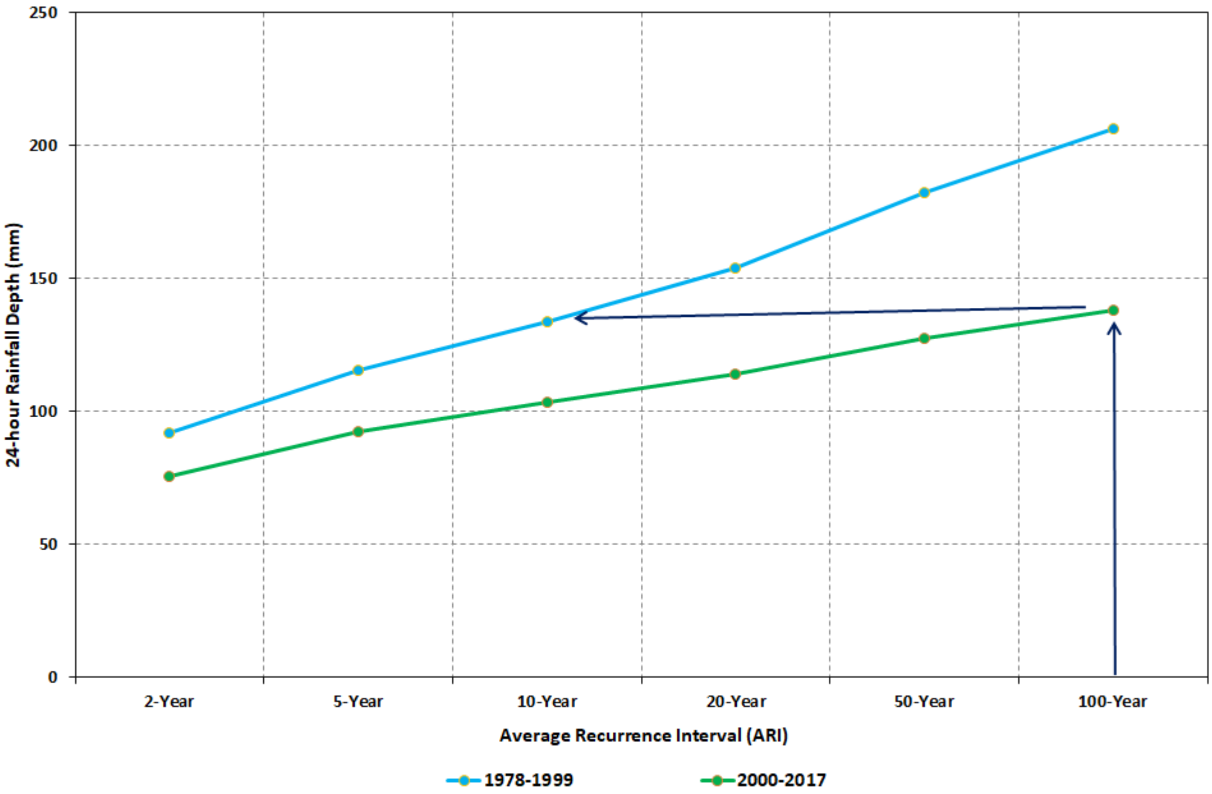


Figure 2 also compares the future design rainfall depths during the negative IPO phase (2000-2017) due to the climate change effects (MfE, 2008). It demonstrates that the natural climatological variability of rainfall extremes is much greater than climate change effects e.g. future 100-year ARI design rainfall depth (185.7mm) during the negative IPO phase (2000-2017) at Wairau rain gauge has an ARI of approximately 30-years during the positive IPO phase (1978–1999).

The LPIII rainfall frequency distribution analysis at Whenuapai rain gauge showed very marked changes in the frequency of extreme 24-hour rainfall depths with the phase of the IPO (Figure 3), the 24-hour rainfall depth with 100-year ARI during the negative IPO phase (2000–2017) has a ARI of approximately 10-year during the positive IPO phase (1978–1999).

Figure 3: Rainfall frequency at Whenuapai rainfall gauge for the positive IPO phase (upper line) and the negative IPO phase (lower line)



The IPO has been found to have a strong influence on extreme rainfall event estimation, e.g. at Wairau rain gauge the 100-year ARI rainfall depth is estimated to be 250mm in positive IPO phase (1978-1999) and 159mm in negative IPO phase (2000-2017), about 57% difference (refer to Table 4). If the rainfall record is long enough to include a negative and a positive IPO phase, the design rainfall depth would be calculated as 212mm (refer to Table 1).

Table 4: Rainfall trends at 6 rainfall gauges (34-72 years of rainfall data)

ARI	24-hour Rainfall Depth (mm)				
	Whenuapai @ Airbase			Puhinui @ Botanics	
	1946-1977	1978-1999	2000-2017	1984-1999	2000-2017
2-year ARI	96.2	91.8	75.4	88.5	81.8
5-year ARI	114.4	115.3	92.4	113.7	96.7
10-year ARI	127.2	133.7	103.4	133.9	106.0
20-year ARI	140.1	153.7	114.0	156.5	114.6
50-year ARI	157.3	182.1	127.7	189.3	125.4
100-year	170.9	206.3	138.0	217.8	133.3
	Wairau at Testing Station			Wairoa @ Hunua Nursery/Bowling	
	1978-1999	2000-2017		1980-1999	2000-2017
2-year ARI	86.8	93.2		88.2	90.4
5-year ARI	117.5	113.8		109.4	106.7
10-year ARI	142.5	125.9		126.9	117.6
20-year ARI	170.8	136.7		146.8	128.5
50-year ARI	212.9	149.8		175.9	142.5
100-year	250.2	159.0		201.4	153.5
	Hoteo @ Oldfields			Rangitopuni @ Walkers	
	1979-1999	2000-2017		1979-1999	2000-2017
2-year ARI	97.5	99.3		97.3	94.4
5-year ARI	125.6	123.3		129.3	109.8
10-year ARI	147.3	138.8		156.2	118.0
20-year ARI	170.8	153.4		187.1	124.7
50-year ARI	204.3	172.1		233.7	132.4
100-year	232.8	186.1		275.6	137.5

Notes: numbers in red are maximum values and numbers in green are minimum values

5 DESIGN RAINFALL PLOTS

The estimated LPIII 24-hour 2-year and 5-year ARI design rainfall depths at 6 rainfall gauges within the Auckland Region are plotted in Figure 4 and Figure 5 with rainfall records ranging from 34 to 72 years of data. The TP108 24-hour 2-year and 5-year ARI design rainfall depth contours are also compared. As 34 to 72 years of rainfall data are used for at-sites LPIII frequency distribution analysis, the estimated 2-year and 5-year ARI design rainfall depths are expected to be reliable.

In general, 2-year ARI design rainfall depths are higher and 5-year ARI design rainfall depths are lower compared to TP108 design rainfall depths. Figure 3 and 4 shows minor variability of the estimated LPIII 24-hour 2-year and 5-year ARI design rainfall depths across the Auckland Region as there are no overlaps between the 2-year ARI estimates (83.8-97.4) and 5-year ARI estimates (103.4-122.9) of design rainfall depths.

Figure 4: 24-hour 2-year ARI design rainfall depths at 6 rainfall gauges

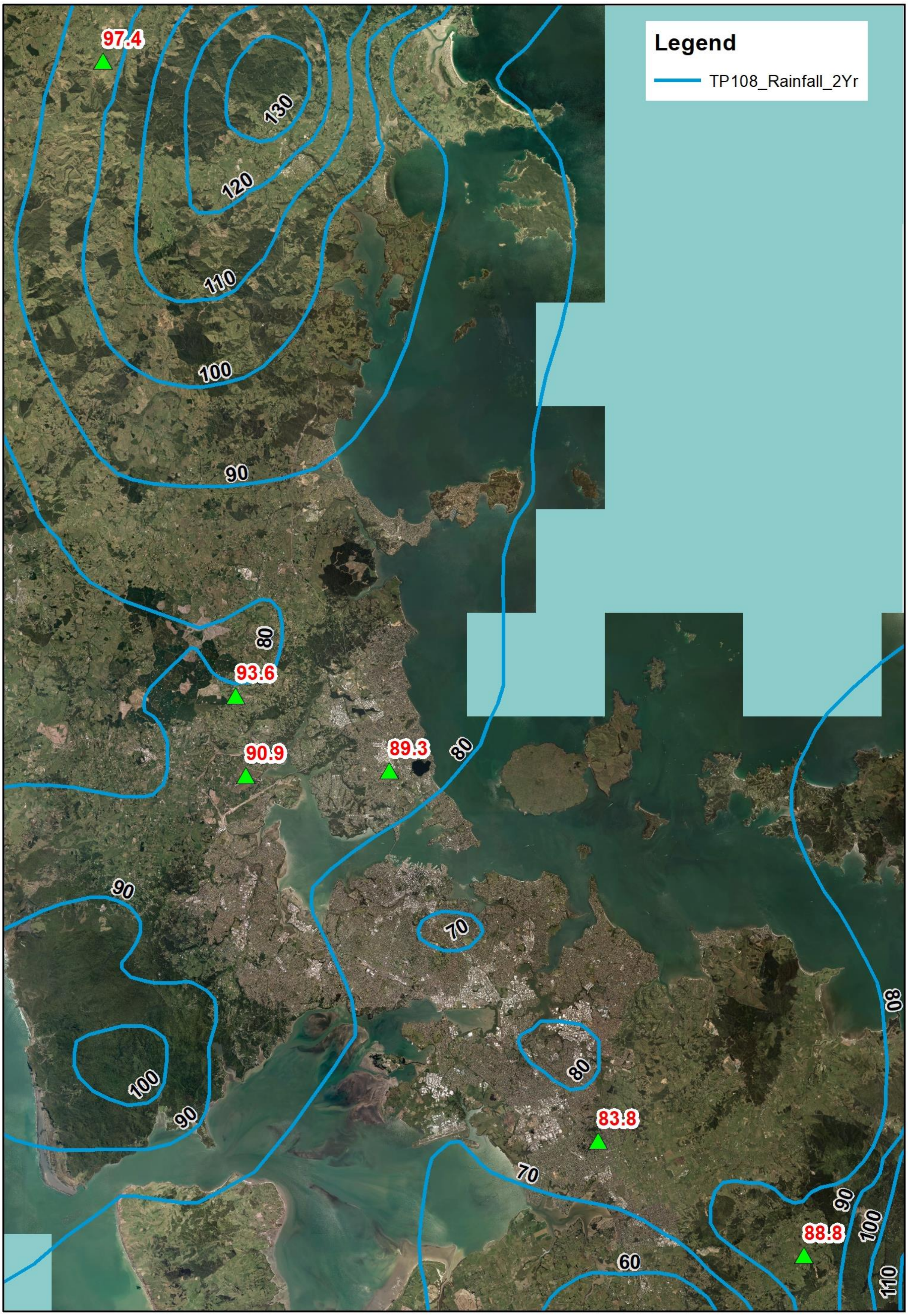
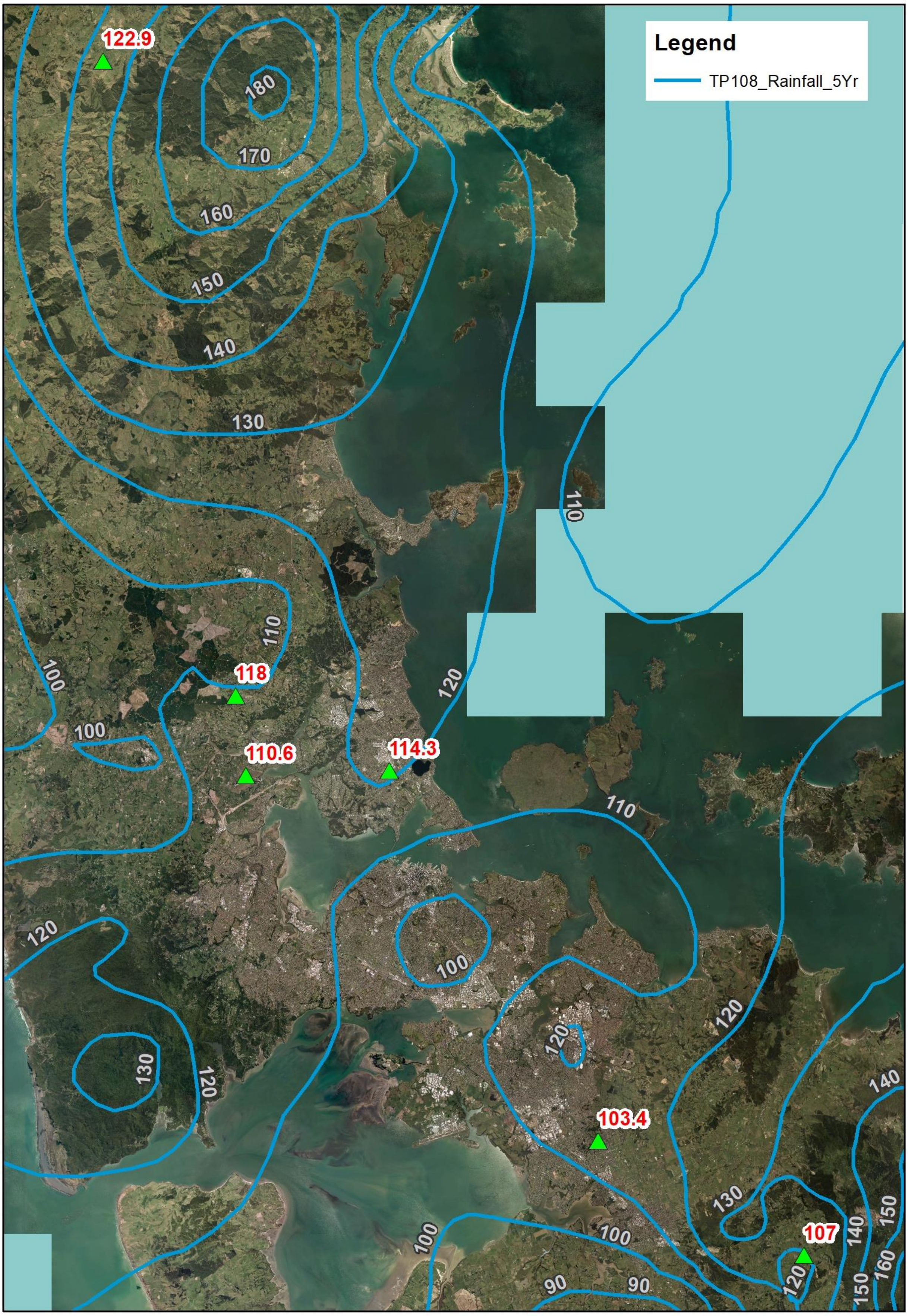


Figure 5: 24-hour 5-year ARI design rainfall depths at 6 rainfall gauges



6 ISSUES AND SOLUTIONS

Rainfall data shows that 80% of the total rainfall record in the Auckland region has been recorded in the past 19 years during the negative IPO phase. So if these data were used in a regional rainfall frequency analysis the extreme event statistics could be skewed by the preponderance of recent data.

Over the short term the natural climatological variability of rainfall extremes is greater than climate change effects. If a short period of record is used to extrapolate extreme event rainfall the underlying climatology of that period skews the extreme event estimates. The skew can mean a pipe designed now to have a 10% AEP capacity may in fact only have a 50% AEP capacity.

The predictability of the IPO and its effects in local climate is still a topic of active research (MfE, 2008). The underlying climatological cause-and-effect mechanisms are complex and it has opposite effects in different locations within New Zealand. During the positive IPO phase, rainfall increased in the southwest of the South Island, but decreased in the north and east of the North Island, relative to the earlier negative IPO phase (MfE, 2008). The strong influences of the IPO on extreme rainfall event estimations were not considered in HIRDS V4 regional frequency analysis.

The key assumption of regional frequency analysis is that sites within a given region form a homogeneous region. The concept of regionalization is to supplement the at-site limited rainfall records by incorporation of spatial randomness using data from various sites in a homogeneous region. The basic principle of this approach is to define statistically homogeneous regions containing sites with similar frequency distributions apart from a scaling factor or index variable (NIWA, 2018).

In general, near neighbor rainfalls tend to show high inter-site correlations, as such in HIRDS V4 rainfall sites within 500m of each other were merged into composite site series. The median annual maximum rainfall was used for the scaling factor or the index variable and the Generalised Extreme Value distribution was used to model the frequency distribution or growth curve (NIWA, 2018).

In order to achieve reliable and accurate estimates of extreme rainfall statistics, rainfall data series should be adjusted (bias correction) for the negative IPO phase or rainfall gauges with less than 20 years of rainfall records should be removed for the Auckland regional rainfall frequency analysis. Currently NIWA is undertaking regional frequency analysis for Auckland Council using rainfall gauges with greater than 40 years of rainfall records and to compare with the HIRDS V4 estimated design rainfall depths to ascertain the impact of rainfall gauges with less than 20 years of rainfall records on the regional frequency analysis method.

The outcome of this analysis is not intended to be a validation of HIRDS V4 per se, but rather a sensitivity test to show the relative impact of including additional short-term rainfall gauges records. Differences between the two versions are to be expected and are not necessarily indicative of problems or errors in the original HIRDS V4 analysis.

7 CONCLUSIONS

The following conclusions can be made from this study:

- Comparisons of 24-hour design rainfall depth for various ARIs show that in general HIRDS V4 24-hour design rainfall depths are lower compared to HIRDS V3, Gauge LPIII, and TP108 design rainfall depths. This is likely due in part to HIRDS V4 including more rainfall data from the negative IPO phase.

- LPIII rainfall frequency distribution analyses of four rainfall gauges with 18 to 19 years of rainfall data show very low design rainfall depths compared to TP108, HIRDS V3 and HIRDS V4 design rainfall depths. TP108 and HIRDS V3 frequency analysis did not have the last 20 years of rainfall data, as a result predict higher design rainfall depths.

- LPIII rainfall frequency distribution analyses of six rainfall gauges with 34 to 72 years of rainfall data show minor variability of the estimated LPIII 24-hour 2-year and 5-year ARI design rainfall depths across the Auckland Region as there are no overlapping between 2-year ARI and 5-year ARI design rainfall depths.

- Rainfall trend analyses show higher design rainfall depths during the positive IPO phase and lower rainfall in the negative IPO phase. IPO has strong influence on the 100-year ARI event and week influence on 2-year ARI event for the Auckland Region.

- Rainfall trend analyses demonstrate that the natural climatological variability of rainfall extremes is much greater than climate change effects.

- Rainfall data shows that 80% of the total rainfall record in the Auckland region has been recorded in the past 19 years during the negative IPO phase. So if these data were used in a regional rainfall frequency analysis (HIRDS V4) the extreme event statistics could be skewed by the preponderance of recent data.

Rainfall data series should be adjusted (bias corrected) for the negative IPO phase or rainfall gauges with less than 20 years of rainfall records should be removed for the Auckland regional rainfall frequency analysis. This would provide reliable and locally relevant estimates of extreme rainfall statistics which is important for accurate prediction of flood risk and design of flood control and drainage infrastructure.

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