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Meteorological drought in Northland, New Zealand: a regional and local analysis using copulas

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Abstract

Meteorological drought, or a prolonged period of below average precipitation, is a significant and recurring hazard in Northland, where eight droughts, all having severe negative impacts, have been recorded since 1900. The cause of drought is usually the persistence of slow-moving or blocking high-pressure systems over Northland during the summer seasons. The reasons for this behaviour and the links between severe drought occurrence and natural climate fluctuations caused by the El Niño-Southern Oscillation, the Interdecadal Pacific Oscillation and the Southern Annular Mode are poorly understood. An analysis of meteorological droughts, characterised by severity, duration, and frequency (return period) is undertaken for the period 1893–2018. Severity is measured by the Standardized Precipitation Index (SPI) and severity-duration-frequency relationships are described for 298 Northland rain gauge sites using copulas.

The worst year in terms of monthly SPI values was 1993 when nearly 25% of all sites were affected by drought. Based on severity alone the worst drought (severity = 21.19 at Whangārei Harbour) occurred in 1987 and had a duration of 10 months and the three worst drought years were (in order) 1987, 1913 and 1990. Based on duration alone the worst drought occurred in 1993 at Topuni with a duration of 16 months and the three worst drought years were (in order) 1993, 1913 and 1986.

Statistical tests of SPI values showed no consistent and significant temporal trend in drought occurrence in the 125-year period. Attempts at contouring and clustering demonstrated that SPI relationships are not spatially dependent, implying that there are no specific drought-prone areas and that drought may occur at any locality and time in Northland (given the appropriate synoptic conditions).

Further work is needed to improve climatological understanding of drought occurrence, along with continued monitoring of drought conditions. Use of multivariate copulas, including extra variables such as minimum SPI values and spatial extent, should provide a more comprehensive description of drought in Northland.

Keywords

meteorological drought; Standardized Precipitation Index; copula; statistical hydrology

Introduction

A drought, or prolonged water shortage, may last for months or years and have substantial impacts on ecosystems, agriculture, the economy and society in the affected region.

Drought is a recurring event in many parts of the world and is defined in four main ways: meteorological, agricultural, hydrological and socio-economic (Wilhite and Glantz, 1985). More recently, Van Loon *et al.* (2016) suggested broadening the definitions to include water shortage caused and modified by human processes.

Despite a history of crippling drought in New Zealand very little is known about drought occurrence and characteristics in general (Singh *et al.*, 2017), although there have been numerous studies and reports on the effects of individual droughts (for example, Woods and McKerchar, 2010). Northland, New Zealand, has experienced both regional and localised droughts with serious impacts. Eight major droughts, defined in different ways, have been recorded since 1900 (Keyte, 1993; Woods and McKerchar, 2010; Porteous and Mullan, 2013), with the most severe in 1914–15, 1945–46, 1982–83 and 2009–10 (Pham and Donaghy, 2017).

Keyte (1993) examined meteorological drought on a regional and local scale, where drought was defined as the occurrence of two or more months of rainfall below the long-term (decadal) 25th percentile for that month. Spatial variation in drought was found to be considerable and drought of a regional nature tended to occur every three or four years.

Here, interest lies in the occurrence of meteorological drought, or a prolonged period of less than average precipitation, on both a regional and local scale. As a measure of drought severity we employ the Standardized Precipitation Index (SPI) (McKee *et al.*, 1993) as recommended by the World Meteorological Organization (WMO, 2011; Svoboda *et al.*, 2012) using data from rain gauges located throughout Northland.

We present reasons for the occurrence of dry spells and droughts, including the effects of natural factors that cause fluctuations in the climate of Northland. Spatial and temporal patterns are sought in terms of the severity, duration and frequency of drought. The aim is to provide planners and managers with information and an analytical approach for decision making in sustainable water resources management. The analysis is based on data measured during the period 1893–2018 and is a synthesis and reworking of separate studies of western and eastern Northland by Singh and Griffiths (2018, 2019, respectively).

Background

Northland has a sub-tropical climate that is generally warm, intermittently dry and humid in summer, mild in winter and rather windy. Rainfall is normally plentiful all year round with occasional heavy falls. Annual rainfall varies significantly across the region. Hilly areas north of Dargaville and Kaikohe receive the most rain at 2000 mm per year on average while the driest part, near Cape Reinga, receives about 900 mm per year on average (Fig. 1). There is substantial year-to-year variation in rainfall, but the evidence of long-term changes in annual rainfall is varied. For example, Dargaville has annual rainfall totals varying from 800 mm to 1600 mm (1951–1985) with a trend showing reduction in rainfall (NIWA, 2016), whereas at Waimatenui, south of Kaikohe, no long-term trend from 1914 to 2000 is evident (NIWA, 2016). Northland often experiences two to three weeks of dry weather in summer due to persistent anticyclones. An anticyclone becomes stationary east of Australia then weakens and a following cold front moves along the southern edge of the anticyclone and over New Zealand bringing cloudy conditions with little or no rainfall. The original anticyclone disappears and is replaced by another and the whole process may repeat several times (Chappell, 2013). This behaviour produces dry spells of about 20 days' duration usually between December and March, perhaps a decade apart on average. The proximate cause of more severe dry spells (i.e., drought) is often the persistence of slow-moving or blocking high-pressure systems over the Tasman Sea and Northland during the summer season (Salinger and Porteous, 2014). The reason for the persistence is still poorly understood but high-pressure systems do not always lead to drought conditions (Porteous and Mullan, 2013).

While three natural fluctuations – the El Niño-Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO) and the Southern Annular Mode (SAM) – lead to long-term quasi-cyclic variations in climate in Northland, shorter-term variations are effectively random or not yet understood. ENSO involves movement of warm ocean water across the Pacific coupled with the movement of rainfall associated with this warm water. It may or may not be a factor in drought (Fowler and Adams, 2004; Caloiero, 2017). During La Niña conditions, which occur on average three to seven years apart, spring and summer easterly anomalies predominate, and dry conditions can evolve in the west of the North Island. However, drought may still happen when the ENSO is in neutral phase, as occurred in the 2012–13 Northland drought (NIWA, 2013). The IPO is a large-scale, long-period oscillation that affects climate variability in New Zealand (Salinger *et al.*, 2001; Salinger and Porteous, 2014). It operates at a multi-decadal scale with phases lasting 20 to 30 years. Positive periods, when westerly winds are stronger, tend to produce drier conditions in Northland. The IPO has been in a negative phase since 1999. The SAM is a ring of atmospheric pressure variability between Antarctic and the mid-latitudes. Positive and negative phases of the SAM generally last only a few weeks. In its positive phase it is associated with relatively light winds and the settled weather that occurs during droughts (Jiang *et al.*, 2013).

Links between severe drought occurrence and ENSO, IPO and SAM behaviour are difficult to establish quantitatively as the three climate oscillations operate at different frequencies. Further climatological investigation is required to understand the cause of droughts and their persistence.

Regarding climate change effects, increases in drought frequency are projected for Northland of about 7% by 2030–50 and 10% by 2070–90 (NIWA, 2016).

Method

Meteorological drought is a function of the amount and duration of the precipitation deficit. Choice of an appropriate drought index depends on available information, type of drought and purpose of drought assessment. A large number of drought indices for meteorological drought (defined on the basis of degree of dryness) exist, each with its own advantages and limitations in terms of assumptions and data requirements. These indices are simply expressed in terms of a rainfall deficit in relation to some average. Widely used indices include the Standardized Precipitation Index (SPI), the Palmer Drought Severity Index (PDSI), the Surface Water Supply Index (SWSI), the Crop Moisture Index (CMI) and rainfall anomalies. Among these, those that have been most commonly used are PDSI and SPI. For these drought indices the value is typically a single number that is interpreted on a scale ranging from abnormally wet to abnormally dry.

In this study, as noted previously, we employ the SPI determined from precipitation records. A drought event is defined here as a period in which the SPI is continuously negative, starting when the SPI reaches a value of -1.0 or less and ends with a positive value of the SPI (McKee

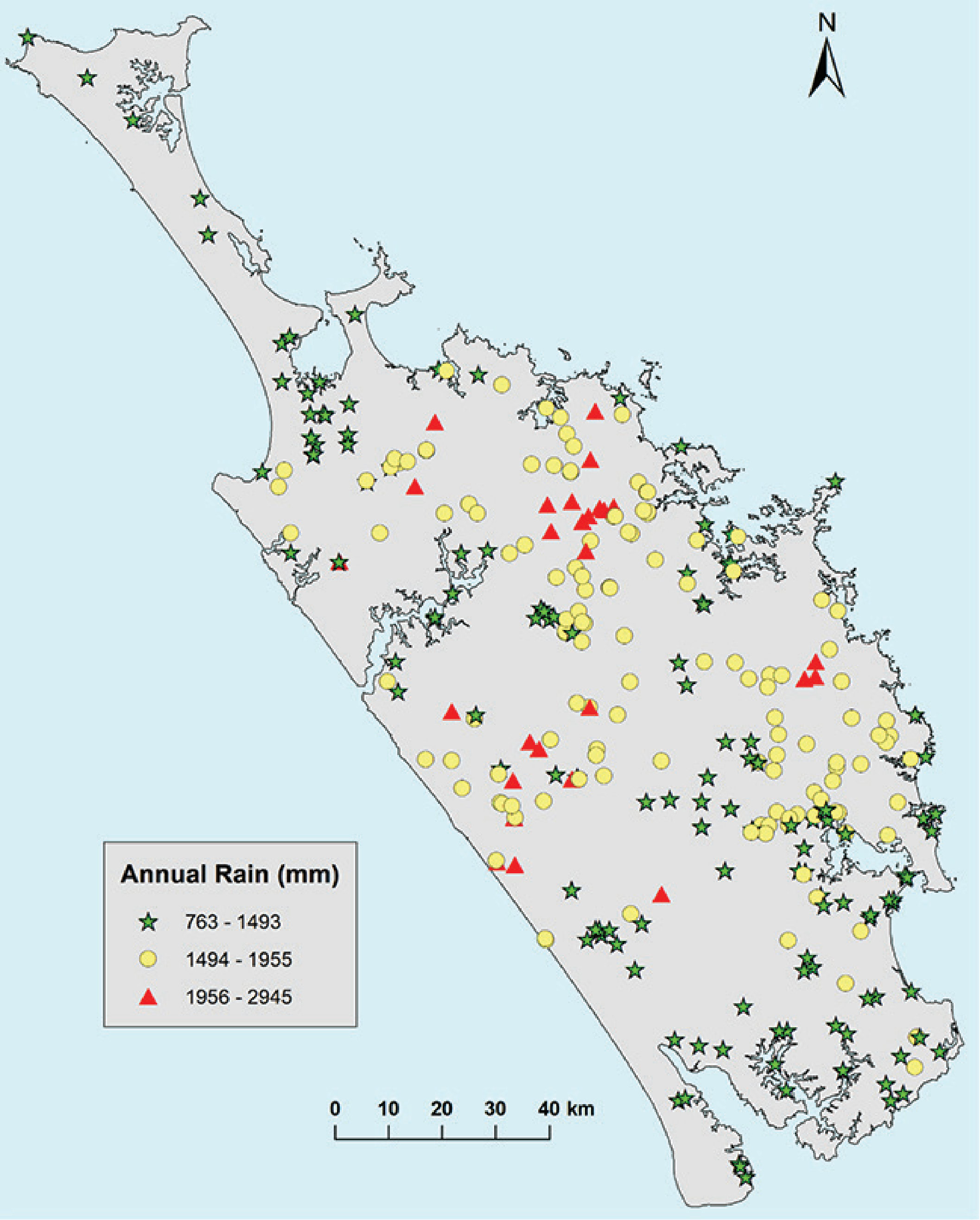

Figure 1 – Location of 298 rain gauges and distribution of mean annual rainfall in Northland.

et al., 1993). Figure 2 illustrates the definition of drought events from an SPI time series. A drought is usually described by employing a combination of three variables, namely severity, duration and frequency (Clausen and Pearson, 1995). These are separately defined and described below along with the methods used to calculate them and to detect trends in the magnitude of SPI values.

Severity

The SPI is a measure of drought severity and is a probability (statistical) index that gives a representation of abnormal wetness or dryness. It is obtained by fitting a gamma or Pearson Type III distribution to monthly precipitation values.

Advantages of the SPI include: (1) it requires only monthly precipitation values; (2) it can be compared across regions with markedly different rainfall regimes; (3) standardization of the SPI allows determination of the rarity of a drought; and (4) it can be calculated for differing periods.

Shortcomings of the SPI, as noted by Trenberth *et al.* (2013), include that SPI values are based on precipitation alone and provide a measure only for water supply, and that long records of rainfall data are needed.

An SPI value is indicative of dryness or wetness. Positive SPI values indicate that the observed precipitation is above median (wet condition), whereas negative SPI values indicate precipitation is below median (dry/drought condition). The wet and dry conditions are further classified as shown in Table 1. A drought event is defined as a period during which the SPI is continuously below zero (McKee *et al.*, 1993). However, in this study, we term any event with a negative SPI (SPI < -1) as a drought, and when the SPI falls below -2 we term it a severe drought. Figure 2 shows an example of an SPI time series indicating wet and drought events.

Table 1 – SPI categories, based on McKee *et al.* (1993).

SPI	**Category**
2.0 and above	Extremely wet
1.5 to 1.99	Very wet
to 1.49	Moderately wet
-0.99 to 0.99	Near Normal
-1.49 to -1.0	Moderately dry
-1.99 to -1.50	Severely dry
-2.0 and below	Extremely dry

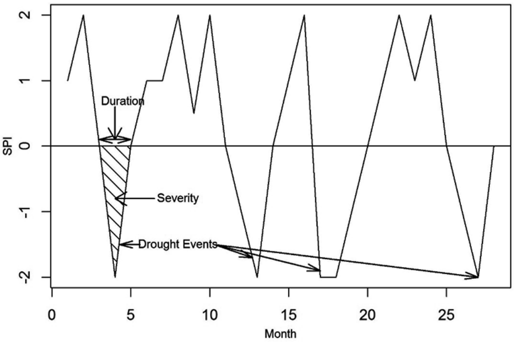

Figure 2 – Example of duration and severity of dry and wet events based on the Standardized Precipitation Index (SPI) (Singh *et al.*, 2017).

Drought severity, S, is quantified by the cumulative SPI for the duration of a drought, defined as

$$S = -\sum_{i=1}^{D} SPI(i) \qquad (1)$$

where D is drought duration (in this case, months) and i is the time step (in this case, monthly).

Duration

Drought duration, D, is taken as the number of consecutive months when the SPI remains below -1. As the SPI is calculated at monthly intervals, the minimum duration of a drought is one month.

Frequency

The frequency of drought events in a given number of years is measured by the arrival rate; that is, the number of drought events divided by the number of years. Arrival rate is independent of severity and duration and is a measure of the propensity of an area to experience dry conditions over time. In drought description, return period (average time between events of a specified magnitude), which is related to the reciprocal of arrival rate or the reciprocal of the frequency, is also used. A rare drought has a low arrival rate and a large return period.

Drought severity and duration are not independent, as severe drought normally lasts a long time. Generally, drought duration and severity are analysed separately and modelled using different distributions. However, separate analyses of duration and severity cannot reveal the significant association between them. As return period is dependent on *S* and *D*, return period was calculated in this study using copulas, an approach widely employed elsewhere (Saghafian *et al.*, 2003; Shiau, 2006; Chen *et al.*, 2012; Halwatura *et al.*, 2015; Masud *et al.*, 2015; Singh *et al.*, 2017). Copula theory offers functions that join or couple multivariate distribution functions into one-dimensional marginal distribution functions, or as multivariate statistical distribution functions whose one-dimensional margins are uniformly distributed on the unit interval.

The interdependence structure of *S* and *D* can be described by two-dimensional copulas by joining their corresponding marginal distributions. The joint return period of severity and duration can be calculated in several ways. For example, it can be estimated by considering the event and or the event **or** , where *D* and *S* refer to a specific event. The first is expressed in terms of the marginal and joint distribution of *D* and *S*, whilst the second depends solely on the joint distribution function. We carried out the analysis considering the second case, as suggested by Shiau (2003). Halwatura *et al.* (2015) illustrate the application of drought severity-duration-frequency (SDF) curves as a risk-based planning tool in the rehabilitation of post-mining landscapes in Australia. Several other examples of the application of drought SDF curves are available in numerous studies (Dalezios *et al.*, 2000; Saghafian *et al.*, 2003; Miller and Durnford, 2005; Shiau and Modarres, 2009; Kim *et al.*, 2011; Reddy and Ganguli, 2012; Todisco *et al.*, 2013; Reddy and Singh, 2014). At-site return periods were calculated using a MATLAB programme yielding SDF curves for various return periods. This programme can also be used to define the return period of any event if *S* and *D* are known.

To assess return periods on a regional basis we first grouped sites using a Hierarchical Affinity Propagation clustering technique (Frey and Dueck, 2007) which employs *S*, *D*, standard deviations of *S* and *D*, and arrival rate as parameters. Calculations were performed using the R package 'apcluster' (Bodenhofer *et al.*, 2012). Affinity Propagation (AP) takes measures of similarity between pairs of data points as input, and simultaneously considers all data points as potential exemplars. Real-valued messages are exchanged between data points until a high-quality set of exemplars and corresponding clusters gradually emerges. An advantage of AP clustering is that it both partitions the objects of a dataset into groups of similar objects and identifies a single object (the 'exemplar') that is most representative for each group. Exemplar-based AP clustering provides an additional advantage for automatically finding the right number of clusters (Bodenhofer *et al.*, 2011). After clustering, we combined all the *S* and *D* values for each site in the group and calculated the return period.

Trends

To ascertain if there were any temporal trends (increasing or decreasing month by month) in the magnitude of the SPI value, we used the non-parametric Mann-Kendall test. This is commonly employed to detect monotonic trends in environmental data series and has been recommended by the World Meteorological Organization for determining the existence of statistically significant trends in climate and hydrologic data time series. The significance of the detected trends can be obtained at different levels of significance (taken here as 0.05). There is no requirement that the measurements be normally distributed or that the trend, if present, is linear. Hirsch *et al.* (1982) state that the Mann-Kendall test is best viewed as exploratory analysis and is most appropriately used to identify stations where changes are significant or of large magnitude and to quantify these findings.

To ascertain if there were any spatial trends in mean severity, mean duration and mean arrival rate we attempted to contour these separate variables and then performed a cluster analysis using a Hierarchical Affinity Propagation technique to look for spatial drought patterns in terms of severity, duration and arrival rate jointly.

Data

Rainfall data were obtained from rain gauges operated by Northland Regional Council, New Zealand Meteorological Service and the National Institute of Water and Atmospheric Research (NIWA). A total of 298 sites, each having a minimum record length of 10 years, were selected (Fig. 1), with relevant statistics listed in Table 2. Lists of rain gauges, record length and mean annual rainfall are given in Singh and Griffiths (2018, 2019). Gaps of three months or less in the data were filled by the mean rainfall total from the record for the relevant missing month. For example, if the record for August 2012 at some site was missing then we would insert the mean of the value for August for all years of the site record as the value for August 2012. This method generally gave more realistic values than using predicted values from correlated sites.

Drought analysis

There are at least seven variables involved in an at-site and regional analysis of drought. They include *S*, *D*, return period (*T*) or arrival rate, time of occurrence within a year, time of occurrence by year and location of affected area. In published studies there are no consistent approaches to the description of drought involving some or all of the variables (Raziei *et al.*, 2009; Cai *et al.*, 2015; Ganguli and Ganguly, 2016; Haslinger and Blöschl, 2017; Juliani and Okawa, 2017). However, it is common practice to hold a number of the variables constant or allow them to range while examining the behaviour of, perhaps, two; for example, the variation of severity at, say, the severely dry level (Table 1) with rain gauge location for a given duration for any time in a year and any return period in a given region. The basis of modern analysis of the spatial and temporal behaviour of droughts is the establishment of an *S-D-F* relationship for each rain gauge site. From this information a great number of at-site or regional statistics can be derived. Among these are rankings of *S* and *D* individually for listed sites and year of occurrence, along with maps of the spatial distribution of mean values of *S* and *D*. Here, we carry out at-site and regional analyses using rain gauge data from Northland to provide an overview of the spatial and temporal properties of droughts.

Table 2 – Details of rainfall records used (1893–2018).

Number of sites	Record length (years)			Mean Annual Rainfall (mm)		
	max	min	mean	max	min	mean
298	118	10	28	2945	763	1567

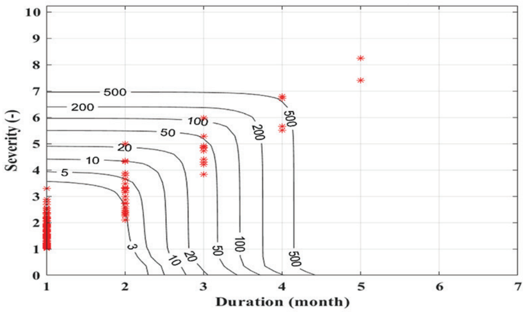

Figure 3 – Typical relationships between severity (*S*), duration (*D*) and return period (*T*, years, as indicated on the curves) determined for each site. If *S* and *D* are specified, then the return period can be determined using the relationships. For example, for $D = 3$ and $S = 6$ then $T = 100$ years.

The main interests are locating drought-prone areas or zones, if any, along with their temporal behaviour and determining whether there are any spatial or temporal trends in drought occurrence.

At-site

SPI values were calculated for all sites using monthly data to determine drought severity, duration and frequency (and return period). Figure 3 displays a typical relationship between these variables. Drought frequency will vary from site to site; that is, some sites will experience more frequent droughts than others for specified *S* and *D*. These site relationships can be employed directly in planning and design for drought management.

Minimum monthly SPI values were calculated at each site along with the month and year of occurrence. The lowest monthly SPI value for any site (-5.35) was that for September 1999 at Dargaville Farm. Table 3 presents a ranking of sites based on *S* values for extremely dry conditions for the 10 sites having highest severity. Table 4 is similar but based on *D* values. Based on *S*, the maximum severity was 21.19 at Whangārei Harbour in a drought that began in May 1987 and lasted 10 months. Based on *D*, the maximum drought duration was 16 months at Topuni, beginning in January 1993.

Considering the whole record for Northland (1893–2018) the percentage of sites experiencing extremely dry conditions from year to year is displayed in Figure 4. The figure also shows the number of sites with data available during those dry events. In the worst year (1993) nearly 25% of sites were affected by extremely dry conditions.

Table 3 – Ranking of top ten sites based on severity (*S*) of drought.

Gauge ID	Rain gauge name	*D* (months)	*S*	Year	Start month	Rank
548212	Whangārei Harbour at N.Z. Refining Co	10	21.19	1987	5	1
545201	Whakapara at Puhipuhi	15	20.91	1913	12	2
541001	Purerua Aws	13	20.69	1990	9	3
643112	Tauhara at Lake Rotokawau	12	17.76	1979	8	4
533501	Kohukohu	9	16.41	1914	6	5
532402	Broadwood	11	16.23	1967	4	6
534503	Rawene 2	11	14.33	1982	5	7
643116	Swan Lake at Bishops	12	14.04	1993	7	8
546103	Ruatangata	11	13.97	1914	4	9
533601	Rangiahua	11	13.66	1914	4	10

Table 4 – Ranking of top ten sites based on duration (*D*) of drought.

Gauge ID	Rain gauge name	*D* (months)	*S*	Year	Start month	Rank
641413	Topuni at Dunn Road (Cook)	16	12.75	1993	1	1
545201	Whakapara at Puhipuhi	15	20.91	1913	12	2
548101	Tangihua	14	12.63	1986	10	3
541001	Purerua Aws	13	20.69	1990	9	4
547223	Otaika at Redwood Orchard	13	8.46	1990	12	5
643112	Tauhara at Lake Rotokawau	12	17.76	1979	8	6
643116	Swan Lake at Bishops	12	14.04	1993	7	7
439201	Waiharara	12	11.85	1973	9	8
530202	Waipapakauri	12	11.37	1986	3	9
546301	Hatea at Glenbervie Forest HQ	12	10.03	1993	10	10

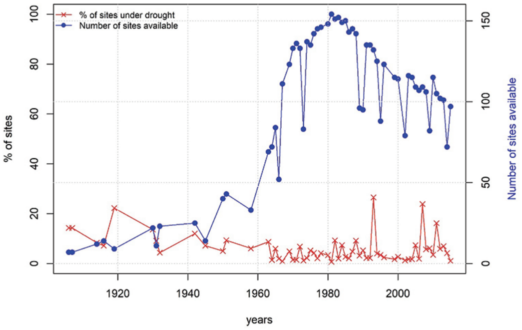

Figure 4 – Percentage of sites with 'extremely dry' conditions, 1890–2018.

Finally, the number of drought events (all sites combined) by SPI category and arrival rate is displayed in Figure 5. The 'moderately dry' category is the most commonly occurring and 21% of all monthly SPI results are 'extremely dry'.

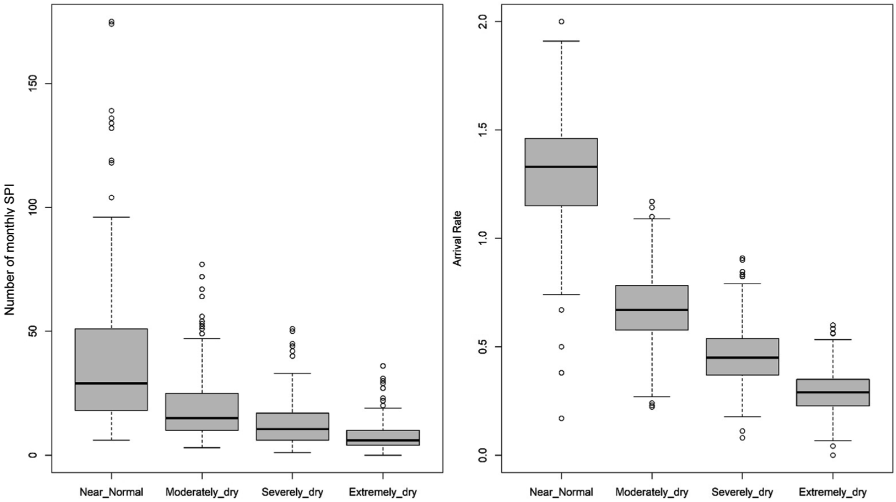

Figure 5 – Number of drought events (left) and arrival rate (right) in each SPI-based drought category (Table 1).

Temporal trend

The statistical significance of overall upward or downward temporal trends was evaluated using the Mann-Kendall test at a significance level of 95%. The test was applied to monthly values of the SPI listed in time order for all months of a site's record. No significant trend was found for 87% of the sites. Some 5% of sites show a downward trend and 8% of sites show an upward trend in SPI. Note that a decrease in SPI over time indicates an increase in the number of drought occurrences (for whatever reason). We could not detect any spatial clustering of temporal trends and hence there is no evidence of a coherent monotonic change in drought occurrence. Although some of the trends might be statistically robust they should not, therefore, be interpreted as indicating regional long-term climate trends.

Regional

We expected to detect a relationship between drought and locality, and that locality might correlate with climate zones based on the spatial distribution of the mean annual rainfall (Fig. 1). The presumed zones were North Cape (low rainfall area), Whangārei (medium rainfall area) and Kaikohe (high rainfall area). However, the spatial distribution of mean severity, that is, the average of all the severity values from moderately dry to extremely dry at a site, exhibits no evident local or region-wide pattern (Fig. 6). That is, there is no geographical dependence of drought severity nor any matching of drought magnitude with climate zone. The same behaviours also occur with mean drought duration and mean drought arrival rate (Fig. 6). In short, the record does not show the presence of any persistent drought-prone areas in Northland. To test this outcome we also examined the spatial distribution of drought for the three 'worst' droughts in the record based on *S* and *D* results. Based on *S* values, the worst droughts were in 1987, 1913 and 1990 and based on *D* values the worst droughts were in 1993, 1913 and 1986.

There are no regional patterns or spatial trends for these six worst droughts except for the 1987 drought based on *S*. These results differ from those of Pham and Donaghy (2017) and Keyte (1993) because of different definitions of drought.

The Hierarchical Affinity Propagation clustering technique was employed to analyse the regional distribution of drought in terms of severity, duration and arrival rate jointly. The results were a division of this cluster of three variables into 24 distinct groups of sites (Fig. 7). Table 5 lists a representative site for each group. These representative sites were obtained based on exemplar sites given by the Hierarchical Affinity Propagation clustering technique.

As shown by Figure 8, as previously, there is no spatial dependence of the various groups. This means that Northland droughts cannot be partitioned geographically or related to the spatial distribution of mean annual rainfall in general.

The severity-duration-return period relationships for all the groups were derived and a typical example is shown in Figure 8. Different return periods are represented by contour lines. If *S* and *D* are specified then the return period can be determined from these relationships. It is important to note that for specific values of *S* and *D* the associated return period may vary dramatically from group to group.

Future work

An improved understanding is needed of climatological drivers of long-term drought occurrence in Northland and the effects of drought persistence. For example, a study of the relationships between climate modes, including ENSO, IPO, SAM, the Indian Ocean Dipole and South Pacific Subtropical Dipole, and climate variables

Table 5 – Optimal representative sites for each group of sites.

Group	Gauge ID	Gauge name
1	439201	Waiharara
2	531411	Victoria at Kitchen
3	531715	Kaeo at Bramley (Manual)
4	531718	Touwai at Weta
5	532801	Taus Falls
6	532812	Maungaparerua at Airstrip
7	532813	Maungaparerua at Flats
8	545213	Waiotu at Hukerenui (Morgans)
9	545310	Whakapara at Opuawhanga
10	546210	Wairua at Matarau 2
11	546411	Ngunguru at Sands
12	547201	Maungatapere
13	548213	Ruakaka at Fosters
14	548310	Ahuroa at Whittles
15	531415	Te Puhi at Mangakawakawa Trig
16	532202	Herekino
17	534503	Rawene 2
18	534711	Opahi at Norwest Corner
19	535501	Wekaweka
20	535510	Waimamaku at Waiora Farm
21	536816	Mangakahia at Twin Bridges
22	537712	Opouteke at Aomarama
23	546031	Puketurua at Pukeiti
24	643118	Kaipara Harbour at Pouto Point

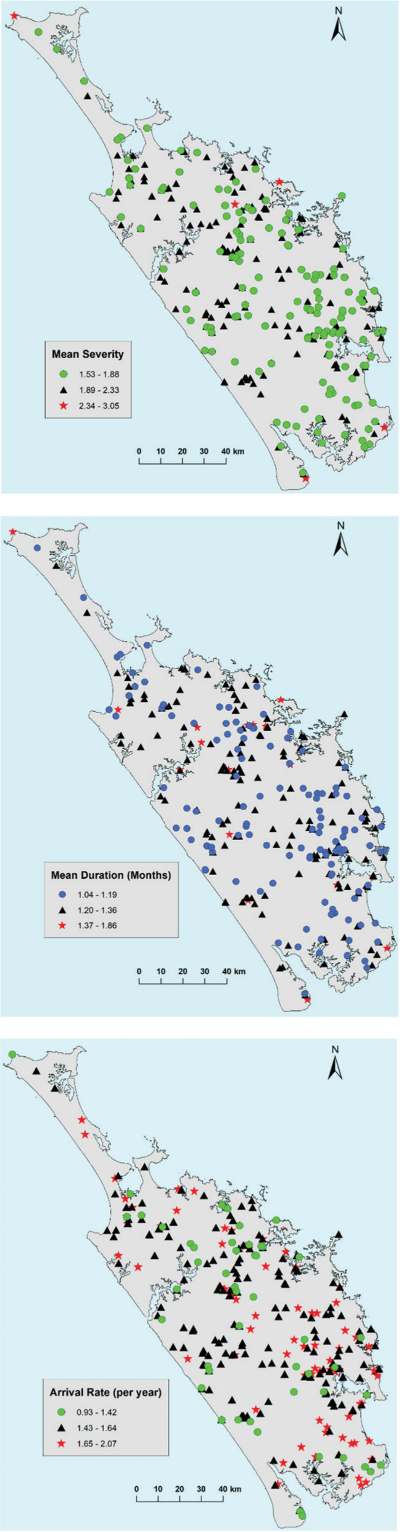

Figure 6 – Mean drought severity, duration and arrival rate for all sites.

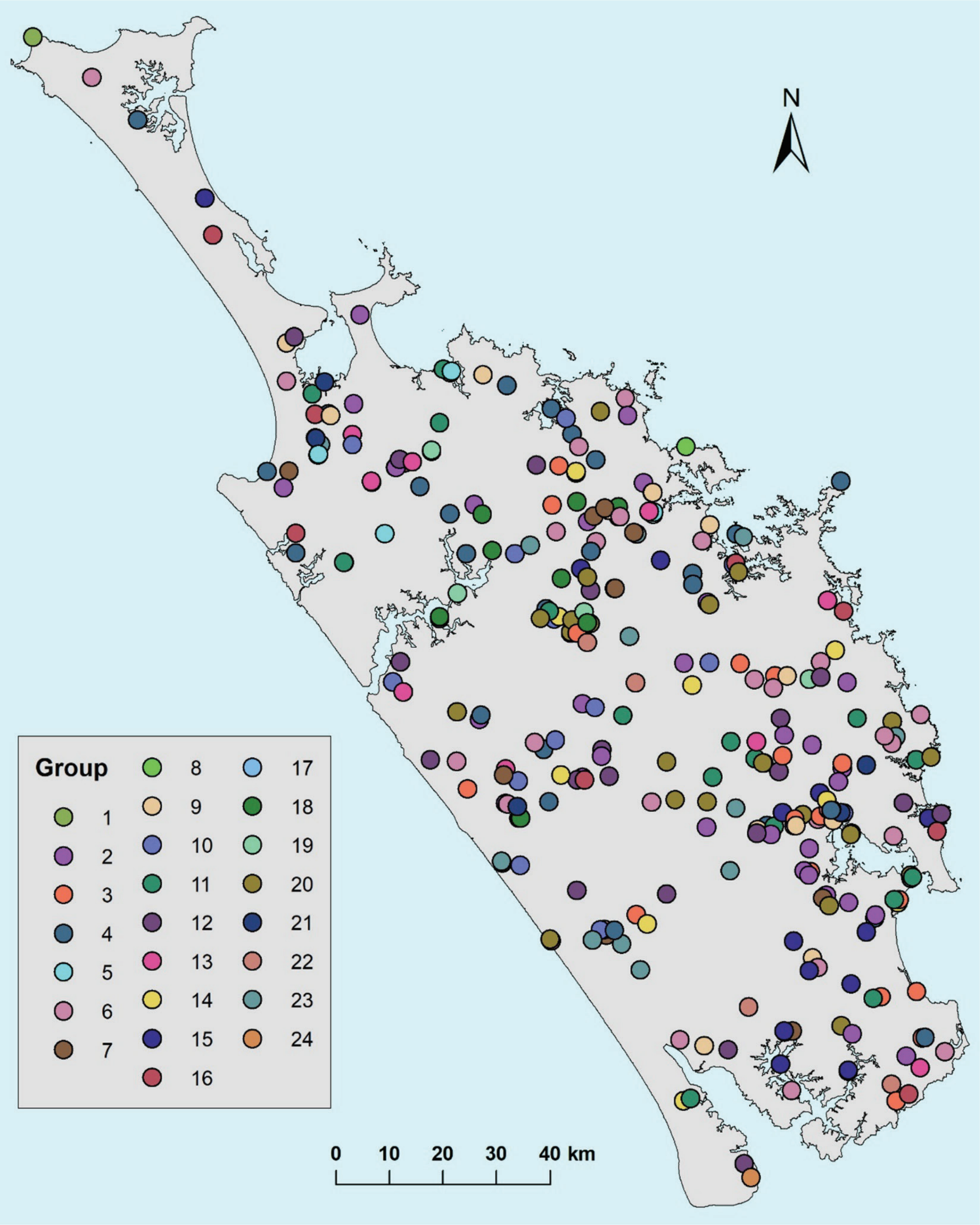

Figure 7 – Clustering of sites by group based on mean severity, mean duration and mean arrival rate.

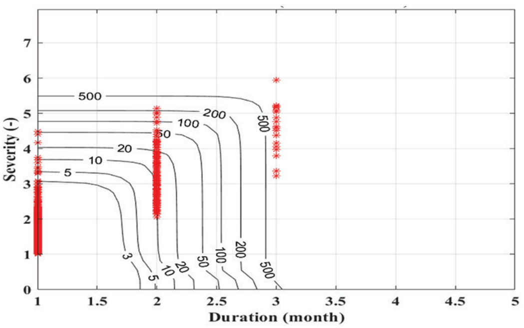

Figure 8 – Severity, duration and return period relationship for Group 13. Return period is labelled on the curves, in years.

(particularly rainfall), as has been undertaken for Wellington and Hawke's Bay (Fedaeff and Fauchereau, 2015; Fauchereau *et al.*, 2018), would be helpful. Additionally, potential effects of topography, geography and microclimate should be investigated. Monitoring of possible or probable drought conditions and indications of trend (temporal and spatial) using the online New Zealand Drought Monitor (NIWA) could be informative for hazard planning. The monitor employs SPI and other drought indices including potential evapotranspiration and soil moisture deficits.

Multivariate (instead of bivariate) copulas could be employed so that extra variables, such as minimum SPI values and drought areal extent, are included to provide a more refined description of drought occurrence. Further analysis employing more sites, more parameters (such as soil moisture, evapotranspiration rate and streamflow) and different drought indices should provide more comprehensive knowledge of drought in Northland.

Conclusions

Present knowledge allows only a broad description of the cause of droughts and their persistence in Northland and links, if any, between natural climatic fluctuation produced by ENSO, IPO and SAM and drought occurrence need to be established. Use of the SPI as a measure of drought severity readily allows determination of at-site severity-duration-return period relationships through bivariate copula analysis. These relationships can be used in design and planning for drought management.

The worst year in the 1893–2018 rainfall record, in terms of SPI values for monthly drought, was 1993 when nearly 25% of all Northland rain gauge sites were affected (see, also, regarding the Auckland water supply crisis, Fowler and Adams, 2004). Based on severity alone the worst drought occurred in 1987 at Whangārei Harbour and had a duration of 10 months; the second and third most severe droughts were in 1913 and 1990, respectively. Based on duration alone the maximum recorded drought duration is 16 months, which occurred at Topuni in 1993; the second and third longest droughts were in 1913 and 1986, respectively.

No consistent temporal or spatial trends in drought occurrence are apparent. Severity-duration relations and severity-duration-return period relations are not spatially dependent; that is, they cannot be locally grouped or zoned geographically. In other words, there are no persistent drought-prone areas and droughts of different severity, duration and return period may occur in the Northland region at any site whenever the appropriate synoptic conditions occur.

Future work is needed to improve climatological understanding of drought occurrence along with continued drought monitoring for hazard management and the use of multivariate copulas to provide a more refined description of drought occurrence. Future work is also needed to improve the current limitations of the existing drought approach, which does not provide characteristic descriptions of intermittent droughts and multi-annual droughts.

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