Severity-Duration-Frequency curves of droughts: An early risk assessment and planning tool for ecosystem establishment in post-mining landscapes

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Abstract

Eastern Australia has considerable mineral and energy resources and areas of high biodiversity value co-occurring over a broad range of agro-climatic environments. Lack of water is the primary abiotic stressor for (agro)ecosystems in many parts of Eastern Australia. In the context of mined land rehabilitation quantifying the severity-duration-frequency (SDF) of droughts is crucial for successful ecosystem rehabilitation to overcome challenges of early vegetation establishment and long-term ecosystem resilience.

The objective of this study was to quantify the SDF of short-term and long-term drought events of 11 selected locations across a broad range of agro-climatic environments in Eastern Australia by using three drought indices at different time scales: the Standardized Precipitation Index (SPI), the Reconnaissance Drought Index (RDI), and the Standardized Precipitation-Evapotranspiration Index (SPEI). Based on the indices we derived bivariate distribution functions of drought severity and duration, and estimated the recurrence intervals of drought events at different time scales. The correlation between the simple SPI and the more complex SPEI or RDI was stronger for the tropical and temperate locations than for the arid locations, indicating that SPEI or RDI can be replaced by SPI if evaporation plays a minor role for plant available water (tropics). Both short-term and long-term droughts were most severe and prolonged, and recurred most frequently in arid regions, but were relatively rare in tropical and temperate regions.

Our approach is similar to intensity-duration-frequency (IDF) analyses of rainfall, which are crucial for the design of hydraulic infrastructure. In this regard, we propose to apply SDF analyses of droughts to design ecosystem components in post-mining landscapes. Together with design rainfalls, design droughts should be used to assess rehabilitation strategies and ecological management based on drought recurrence intervals, thereby minimising the risk of failure of initial ecosystem establishment due to ignorance of fundamental abiotic and site-specific environmental barriers such as flood and drought events.

1 Introduction

Eastern Australia holds vast mineral and energy resources of economic importance and internationally significant biodiversity (Williams et al., 2002; Myers et al., 2000) occurring over a broad range of agro-climatic environments (Hutchinson et al., 2005; Woodhams et al., 2012). There are also extensive areas of cropping and grazing such as in the Brigalow Belt Bioregion (Arnold et al., 2013) and the wheatbelt regions around Kingaroy and Wagga Wagga (Woodhams et al., 2012) (Table 1, Fig. 1). Lack of water availability is a critical factor for the mining industry, agriculture and biodiversity. For example, water deficit reduces agricultural productivity and increases the risk of failure of ecosystem rehabilitation. Likewise, flooding affects mining as a result of soil erosion in rehabilitation areas or flooded mine workings preventing production. For some of the agro-climatic regions in Eastern Australia lack of water is the primary abiotic stressor for (agro)ecosystems throughout the year, whereas for others water availability is at least seasonally limited (Table 1). In the past century regions across Australia have regularly experienced periods of water deficit (Murphy and Timbal, 2008). These drought events are distributed diversely with regard to their duration, severity, and frequency of occurrence over the continent.

Droughts, and associated limitations in plant available water, determine plant distribution in response to climatic conditions. Ecosystem attributes are sensitive to the occurrence of drought events, for example the distribution of native tropical species (Engelbrecht et al., 2007; Kuster et al., 2013), the structure and functioning of forests (Zhang and Jia, 2013; Vargas et al., 2013), biodiversity and ecosystem resilience (Brouwers et al., 2013; Lloret, 2012; Jongen et al., 2013), and the primary productivity and respiration of vegetation (Shi et al., 2014). In the context of mined land rehabilitation, droughts also play a critical role for the early establishment of plants (Nefzaoui and Ben Salem, 2002; Gardner and Bell, 2007) and long-term resilience of novel (Doley et al., 2012; Doley and Audet, 2013) and/or native ecosystems on post-mining land (Bell, 2001). Across the life span of plants, due to their under-developed root system, juvenile vegetation such as seeds, seedlings, and pre-mature plants rather than climax vegetation are especially vulnerable to lacks of water availability (Jahantab et al., 2013; Craven et al., 2013; Arnold et al., 2014a). For climax vegetation, however, medium to long-term drought periods rather than short-term droughts may critically impact ecosystems by altering plant communities' species composition (Mariotte et al., 2013; Ruffault et al., 2013).

Methods for characterising droughts vary in complexity depending on the climatic and environmental (e.g. soil moisture) factors considered. Meteorological or climatological droughts are the simplest and are based on the characterisation of anomalies in rainfall conditions (Anderegg et al., 2013). For meteorological droughts, standardised drought indices such as the Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI) and Standardized Precipitation-Evapotranspiration Index (SPEI) provide the foundation for quantifying the duration and severity, and eventually the frequency or recurrence of drought events (McKee et al., 1993; Tsakiris and Vangelis, 2005; Vicente-Serrano et al., 2010). These indices are commonly used to identify anomalies in rainfall patterns (Heim, 2002). As none of these indices apply universally to any climate region it is best for land managers to use a range of drought indices at various temporal scales (Heim, 2002; Spinoni et al., 2013). In many parts of the world evaporation data are unavailable or incomplete and simple rainfall indices are most commonly used. In this study we compare indices incorporating evaporation (SPEI and RDI) with the simple rainfall index SPI in order to determine the accuracy of using SPI across different climatic regions.

Drought periods can be characterised from a few hours (short-term) to millennia (long-term) depending on the ecological or socio-economic question being addressed. The time lag between the beginning of a period of water scarcity and its impact on socio-economic and/or environmental assets is referred to as the time scale of a drought (Vicente-Serrano et al., 2013). For example, for biochemists and molecular biologists the hourly time scale is of interest while geologists and palaeontologists operate in time scales of millennia. For meteorologists, farmers and agronomists monthly to yearly time scales tend to be of interest (Passioura, 2007). There are three time scales with which drought indices are usually calculated for: short-term droughts of less than three months; medium-term droughts between three to nine months and long-term droughts normally exceeding 12 months. Short-term droughts have an impact on water availability in the vadose zone (National Drought Mitigation Center, 2014; Zargar et al., 2011), while long-term droughts also affect surface and ground water resources (National Drought Mitigation Center, 2014; Zargar et al., 2011).

Of key importance for land managers planning for drought events of any time scale is characterising the return period or frequency of occurrence of rainfall and drought events. The recurrence interval is defined as the average inter-occurrence time of any geophysical phenomena and is calculated with long-term time series data (Loaiciga and Mariño, 1991). Recurrence intervals of rainfall events greater than the average are commonly used by engineers to derive intensity-duration-frequency (IDF) design estimates for building hydraulic infrastructure such as roofs, culverts, stormwater drains, bridges or water dams (Chebbi et al., 2013; Kuo et al., 2013; Hailegeorgis et al., 2013). IDF design rainfalls are crucial for estimating the risk of hydraulic infrastructure failure and for maximising infrastructure efficiencies (Smithers et al., 2002). Similar to the concept of IFD design rainfall, which aims to quantify the recurrence interval if rainfall events based on their intensity and duration, we apply the same concept to quantify the recurrence intervals of droughts based on their severity and duration, and refer to this concept as severity-duration-frequency (SDF) design drought (Shiau, 2006; Shiau et al., 2012). While IFD design rainfalls are a well-established tool in civil engineering and hydrology, we believe SDF design drought could be used in a similar way to assess the risk of ecosystem rehabilitation failure due to droughts.

This approach contrasts current climate classifications methods (Table 1) that are used for the management of agricultural land (e.g. classification of Australian agricultural environments or Australian agro-climatic classes (Hutchinson et al., 2005; Woodhams et al., 2012; Audet et al., 2013). These classifications are based on average climatic conditions and may not be adequate for the management of early re-establishment of vegetation in post-mining landscapes (Audet et al., 2013; Audet et al., 2012) because of the vulnerability of vegetation to drought events. Although droughts play a critical role in post-mining land restoration in Eastern Australia, so far methods for quantifying the frequency of drought events have been rarely applied to assess the risk of failure of ecosystem rehabilitation due to droughts. In the perspective of mined land rehabilitation, specific metrics of site climate or seasonality are surprisingly rare (Audet et al., 2013).

The objective of our study is to quantify the severity, duration, and frequency of short-term and long-term drought events at selected locations across a broad range of agro-climatic environments in Eastern Australia (Table 1). We characterised droughts using the RDI and SPEI for 3 and 12-month time scales respectively, and compared these indices with the SPI at the same time scales. We then linked the univariate distributions of severity and duration calculated with the drought indices to form bivariate distribution functions and estimated the recurrence intervals of droughts. Note, since the estimated recurrence intervals are based on historic rainfall and evaporation data, our results are descriptive rather than predictive. Nevertheless, our findings are crucial to discuss the potential of design droughts to be applied as a management tool to overcome the challenges of early vegetation establishment and long-term ecosystem resilience in post-mining landscapes.

2 Materials and methods

Estimating SDF curves involves uncertainties associated with the length of the observed rainfall data, the applied drought index, the probability distribution functions used to fit the observed severity and duration, and the estimated copula parameter (Hu et al., 2014). To overcome these uncertainties we tested the applicability of drought indices for locations in different climatic regions by calculating the correlation of three selected drought indices. Likewise we used the best fitted probability distribution functions and copula for each site. A flow chart of the processing steps is depicted in a schematic diagram (Fig. 2).

We selected 11 sites for which historical observations of monthly rainfall and evaporation (Table 1) were most comprehensive (i.e., longest and most complete) across Eastern Australia (Bureau of Meteorology, 2013a). The selected locations covered a broad range of climate classes and environments across Eastern Australia (Table 1, Fig. 1).

For each site we compared the simple SPI with the more complex RDI and SPEI drought indices. Amongst the three indices the SPI is the most widely used and simplest drought index, because it is solely based on long-term rainfall for any period of interest (McKee et al., 1993; Guttman, 1999). However, SPI may not adequately characterise drought events due to the lack of other meteorological data (Vicente-Serrano et al., 2010; Mishra and Singh, 2010). Both the RDI and SPEI integrate potential evaporation and thereby better represent the local water balance (Tsakiris, 2004; Tsakiris and Vangelis, 2005; Tsakiris et al., 2007; Vangelis et al., 2013).

The drought indices can be calculated using monthly values of rainfall and/or potential evaporation. Amongst the two indices which incorporate potential evaporation, the RDI represent short and medium time-scale (3 to 6 months) drought events very well (Banimahd and Khalili, 2013), while the SPEI plays a strong role in detecting annual drought events (Egidijus et al., 2013). For short time scales, we compared SPI_3 with RDI_3 (3 months) and at long time scales we compared SPI_{12} with $SPEI_{12}$ (12 months) for each location.

2.1 Step 1: Calculate drought indices

The SPI is derived by fitting a probability distribution to the rainfall record and then transforming that to a normal distribution such that mean and standard deviation of the SPI are zero and one. Positive or negative values of the SPI represent rainfall conditions greater or smaller than average rainfall, respectively (Edwards, 1997). RDI and SPEI are based on the SPI calculation procedure, except the two indices use the quotient or difference of precipitation and potential evaporation, respectively (Tsakiris et al., 2007; Vicente-Serrano et al., 2010). Equations for the three drought indices are shown in Appendix A. We applied two correlation coefficients to assess the correlations between SPI_3 and RDI_3, and SPI_{12} with $SPEI_{12}$ (step 1 in Fig. 2): Kendall's tau to assess the number of concordances and discordances in paired variables (RDI_3 and SPI_3, $SPEI_{12}$ and SPI_{12}), and Pearson's r to measure linear correlation.

2.2 Step 2: Bivariate distribution of drought severity and duration

For each location, we used the estimated drought indices (SPI, RDI, SPEI), hereafter collectively referred to as *I*, to quantify duration *D* and severity *S* (Dracup et al., 1980b, a; Reddy and Ganguli, 2012). The duration of any drought was defined as the period of rainfall deficit, i.e. the cumulative time of negative *I* values preceded and followed by positive *I* values (Fig. 3). The severity of any drought period starting at the i^{th} month was defined as:

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

We fitted the time series of *D* and *S* to a range of cumulative distribution functions (gamma, logistic, extreme value, lognormal, bimodal lognormal, and bimodal logistic) and used the function with the best fit for further investigations (step 2 in Fig. 2).

2.3 Step 3: Estimate copula parameter

We used copulas to link the univariate probability distributions of D and S to construct a bivariate joint distribution of D and S (Shiau and Modarres, 2009; Sklar, 1959) (step 3 in Fig. 2). Copulas have been applied across a range of disciplines such as hydrology (Zhang et al., 2011; Shiau and Shen, 2001; Shiau et al., 2007; Li et al., 2013), engineering (Lebrun and Dutfoy, 2009), meteorology (Liu et al., 2011; Madadgar and Moradkhani, 2011), and economics (Wang et al., 2013; Dajcman, 2013). If $F_{S,D}(s,d)$ is the joint cumulative distribution function with marginal distributions $F_S(s)$, for severity, and $F_D(d)$, for duration, the copula C exists such that:

$$F_{S,D}(s,d) = C\big(F_S(s), F_D(d)\big). \quad (2)$$

The joint probability density function $f_{S,D}(s,d)$ can then be written as

$$f_{S,D}(s,d) = c\big(F_S(s), F_D(d)\big) f_S(s) f_D(d), \quad (3)$$

where c is the double partial derivative of C over u and v, written as

$$c(u,v) = \frac{\partial^2 C(u,v)}{\partial u \partial v}, \quad (4)$$

where u and v denote the two dependent cumulative distribution functions ranging between zero and one. Many well-known systems of bivariate distributions belong to the class of Archimedean copulas such as Gumbel, Ali-Mikhail-Haq-Thélot, Clayton, Frank, or Hougaard (Genest and Rivest, 1993). The present study only focused on the Frank and Gumbel copula (Appendix B), as they perform best when analysing the bivariate drought dependence structure of drought variables such as severity and duration (Ganguli and Reddy, 2012; Reddy and Ganguli, 2012; Shiau, 2006; Lee et al., 2013; Wong et al., 2010; Zhang et al., 2011).

We estimated the copula parameters using the Inference Function for Margins (IFM) (Joe, 1997). The IFM comprises two separate valuation stages. First, the maximum likelihood estimation of each univariate distribution is performed, and then the copula dependence parameter is estimated to derive the joint drought duration and severity distributions (Shiau, 2006; Shiau and Modarres, 2009; Mirabbasi et al., 2012; Shiau et al., 2007).

2.4 Step 4: Derive recurrence intervals

We used the estimated copula parameters to generate random drought events. Severity and duration of the generated random droughts were then fitted to cumulative distribution functions in the same manner as in step 2 (Fig. 2, step 3) to test which estimated copula parameters result in a distribution that best fit the generated random drought variables. The estimated copula parameters were also assessed quantitatively through calculating the correlation between generated random drought events and the estimated gamma (*S*) and logistic (*D*) cumulative distribution functions.

The generated random numbers were then used to calculate the recurrence intervals. Recurrence intervals of bivariate drought events is a standard metric for hydrological frequency analysis (Yoo et al., 2013; Hailegeorgis et al., 2013) and water resources management (Shiau and Modarres, 2009; Mishra and Singh, 2010). For each location, we calculated the recurrence interval of drought events exceeding any severity *or* duration of interest, denoted by the logical operator "∨":

$$T_I^{\vee} = \frac{1}{P(S \geq s \vee D \geq d)} = \frac{1}{1 - C[F_S(s), F_D(d)]}. \quad (5a)$$

where *I* is one of the drought indices of interest, i.e., the 12-monthly $SPEI_{12}$ or SPI_{12}, or the three-monthly RDI_3 or SPI_3. Alternatively, the recurrence interval of drought events exceeding any severity *and* duration of interest, denoted by the logical operator "∧", was calculated as:

$$T_I^{\wedge} = \frac{1}{P(S \geq s \wedge D \geq d)} = \frac{1}{1 - F_S(s) - F_D(d) + C[F_S(s), F_D(d)]}, \quad (5b)$$

For the sake of simplicity, we only present and discuss $T_I^{\vee}$, whereas $T_I^{\wedge}$ is presented in Appendix C.

3 Results

Based on the drought indices RDI_3 and $SPEI_{12}$ we detected distinct drought patterns across the selected sites at short and long-term scales, respectively. As an example of differences between tropical, temperate and arid rainfall conditions, figure 4 depicts calculated time series of RDI_3 and $SPEI_{12}$ for Weipa, Sydney and Quilpie, respectively. For each location RDI_3 detected more drought events (i.e., $RDI_3 < 0$) of short duration and lower severity than $SPEI_{12}$ (Table 2).

Short-term droughts were most severe and prolonged in tropical Weipa and Cairns, and temperate Wagga Wagga (Table 2). However, in contrast to Wagga Wagga, the two tropical locations were characterised by distinct seasonality patterns and very low variation as indicated by the low ratio of winter to summer rainfalls (Table 1) and low coefficients of variation in severity and duration (Table 2). The highest variation in severity was detected in arid Bourke and temperate Brisbane (Table 1).

Long-term droughts were most severe and prolonged in arid Quilpie (Table 2) and rare in temperate Melbourne. Likewise, severity and duration varied most at the two locations, together with arid Bourke. While severity and duration were moderately high in arid Mount Isa and temperate Brisbane, both parameters were low across the other selected temperate and tropical locations (Table 2).

No significant differences were detected ($P > 0.05$ at 95% confident level) between RDI_3 and SPI_3, and $SPEI_{12}$ and SPI_{12} (Fig. 5). Correlation between RDI/SPEI and SPI was greatest for tropical Cairns and Weipa, and lowest for arid Bourke and Quilpie (outliers in Fig. 5). Interestingly, although Mt Isa was being the most arid location (R/PET = 0.13, Table 1) the correlations between drought indices was relatively strong with values of 0.903 (Pearson's r) and 0.759 (Kendalls'tau) for long-term droughts.

For each location, the recurrence intervals of drought events exceeding any severity *or* duration of interest are depicted in figure 6 for short-term droughts (based on RDI_3) and figure 7 for long-term droughts (based on $SPEI_{12}$). Short-term droughts recurred most frequently in arid Mount Isa and were relatively rare in tropical Weipa and Cairns, and temperate Sydney. For example, in Mount Isa a drought with severity of 14 or duration of 17 months[1] recurred once in 50 years, whereas the same drought recurred only once in 100 000 years in Weipa, 300 years in Cairns, and 100 years in Sydney (Fig. 6). Long-term droughts recurred most frequently in arid Quilpie, where droughts with severity of 18 or duration of 10 months recurred once in 2 years. In Kingaroy and Sydney the same design drought recurred only once in 4 and 5 years, respectively (Fig. 7). Interestingly, although average long-term droughts were very severe and prolonged in Melbourne (Table 2), they only recurred once in 30 to 50 years. We found the same qualitative patterns in all locations for recurrence intervals of droughts exceeding any severity *and* duration of interest (Appendix C).

4. Discussion

[1] Drought events are calculated by 3 (short-term) and 12 (long-term) month running precipitation totals (Guttman, 1999).

In this study we estimated the recurrence intervals of short- and long-term droughts based on meteorological drought indices and copulas (i.e., bivariate probability distributions). For both time scales the correlation between the simple SPI (rainfall) and the more complex SPEI or RDI (rainfall and evaporation) was much stronger for the tropical and temperate locations (e.g., Cairns, Weipa, Brigalow) than for the arid locations (e.g., Quilpie, Bourke, Wagga Wagga). Extending a former study on abiotic boundaries affecting ecological development of post-mining landscapes (Audet et al., 2013), our findings have critical implications for assessments of rehabilitation success.

4.1 Extreme events and seasonal rainfall distribution

Across Eastern Australia intense rainfall and severe drought events are predominantly governed by the El Niño-Southern Oscillation (ENSO) (Bureau of Meteorology, 2005). During La Niña moist tropical air is the source of above average rainfall, while during El Niño rainfall stays below average. Climate processes such as El Niño and La Niña and seasonal patterns influence the average severity and duration of short and long-term droughts (Table 2), as well as the seasonal rainfall distribution (Table 1). The short-term drought index (RDI_3) detects most severe and prolonged droughts in the tropics such as Weipa and Cairns (Table 2), where rainfall is low in winter and high in summer. Annually recurring seasonal patterns also explain the low variability of short-term drought severity and duration. The same holds for arid Mount Isa, where in average 23 out of 100 days have no rainfall and most of the rainfall occurs in summer with 14% of storm events being greater than 100 mm (Bureau of Meteorology, 2013a). In contrast the long-term drought index ($SPEI_{12}$) detects most severe and prolonged droughts in arid locations such as Quilpie and Mount Isa, as well as temperate Melbourne (Table 2).

Though drought indices were originally developed for detecting droughts, they can also be used as flood monitoring tool and to assess monsoonal events related to El Niño and La Niña (Du et al., 2013; Wong et al., 2010; Vicente-Serrano et al., 2011). Major El Niño and La Niña events from recent decades coincided with low and high drought indices, respectively (Fig. 4 and Appendix C). Likewise, the $SPEI_{12}$ and RDI_3 are extraordinary low and high during major droughts and floods. However, due to smaller index fluctuations these major events are more pronounced in the context of long-term droughts ($SPEI_{12}$) (Fig. 4, and Appendix C). Moreover, often delayed negative peaks in drought indices occur after El Niño events (Vicente-Serrano et al., 2011), which explains the time lag between negative southern oscillation index and the occurrence of severe droughts (e.g., the 1982/83 El Niño and subsequent drought in Kingaroy). In some cases there was a lack of agreement with major historic droughts as defined by the Australian Bureau of Meteorology because their estimates are based on duration and/or economic losses rather than meteorological drought severity alone (Bureau of Meteorology, 2013b). This difference explains the lack of agreement between major droughts defined by authorities during periods of high negative drought index values (e.g. Cairns, Quilpie, Brisbane (Fig. 4 and Appendix C)). With regard to major flood events, drought indices might not be a good predictor due to development of infrastructure for flood mitigation such as retarding basins, flood levees, etc.

4.2 Implications for ecosystem rehabilitation planning

Across Eastern Australia current post-mining land rehabilitation strategies often do not incorporate site-specific rainfall and drought metrics other than the average annual rainfall depth (Audet et al., 2013). However, regionally extreme rainfall patterns, including both intense rainfall events such as storms or cyclones and prolonged periods of water deficit (droughts), play a critical role in identifying windows of opportunity and/or challenge to the rehabilitation of early-establishment ecosystems (Hinz et al., 2006; Hodgkinson et al., 2010). Furthermore, Audet et al. (2013) suggested that short and long-term ecosystem rehabilitation sensitivity to climate can be effectively determined by the seasonality, regularity, and intensity of weather, combined with both median and standard deviation of periods. In particular prolonged seasonal drought with high variation and frequently occurring intense rainfall can be used as a primary characteristic for determining site sensitivity while regular rainfall and relatively short periods of water deficit are common characteristics of favourable climate conditions. Based on their findings, Audet et al. (2013) revealed how broad scale rainfall patterns outline climate boundaries that drive rehabilitation sensitivity in arid to temperate locations across Eastern Australia. For example, ecosystem rehabilitation in arid regions (Mount Isa, Quilpie, and Bourke) is sensitive to climate as they have heavily variable climates (long spell of droughts and high intensity rainfall), which affect the success of rehabilitation.

Commonly the characterisation of climatic conditions is based on long-term rainfall and do not consider short and long-term drought conditions. Identifying drought and its variables are critical factors in ecosystem rehabilitation because the distribution and health of plant species are vulnerable to droughts and plant available water (Engelbrecht et al., 2007). In our study we presented two sophisticated climate parameters describing the average recurrence intervals of short-term and long-term droughts (Figs. 6, 7 and Appendix D), which can be used instead of the oversimplified parameters of median period without rain and standard deviation normally used (Audet et al., 2013).

The design drought tool proposed in this paper is an adaptation of the intensity-duration-frequency (IDF) analysis of rainfall events, a standard tool used by engineers (Hailegeorgis et al., 2013; Chebbi et al., 2013). Our new term “design droughts”, characterised by drought severity-duration-frequency (SDF), is based on the severity of droughts (negative values of Fig. 3) as opposed to IDF which is based on the intensity of the rainfall (positive values in Fig. 3). Design droughts allow for drought severity, duration and frequency to be considered in order to determine the risk of failure of current mining operations (Mason et al., 2013; Burton et al., 2012), and to design robust ecosystem components in the face of the local climate variability (Audet et al., 2013). For example, certain vegetation types will not establish if there is a drought greater than a specific duration or severity (Arnold et al., 2014a). The recurrence intervals can provide the probability of a drought occurring at this duration or severity, and thus the risk of establishment failure can be assessed. This is important for rehabilitation managers who can conduct a cost-benefit analysis to decide whether costs of constructing mitigation methods such as irrigation are comparable with the costs of potential failure of multiple revegetation attempts.

Together, design rainfalls (IDF) and droughts (SDF) should be the primary determinants of rehabilitation strategies and eventually help to guide rehabilitation planning, where environmental conditions have an impact on current mining operations. In accordance with IDF parameters of similar locations across Eastern Australia (Audet et al., 2013), temperate and tropical environmental conditions (Table 1) are favourable for ecological development, i.e. recurrence intervals of droughts are large (Figs. 6, 7 and Appendix D). By contrast, re-establishment of ecosystems is prone to failure in arid conditions, where droughts recur more frequently (i.e., low recurrence intervals). However, locations with distinct patterns of seasonality such as Weipa, Cairns, or the Brigalow Belt are the exception to this pattern due to the distinct distribution of winter and summer rainfalls (Table 1**).**

The choice of drought indices (SPI versus RDI or SPEI) used to derive SDF depends on the location and its climatic characteristics. Our analysis revealed that Pearsons’r and Kendall’s tau correlations were strong across the selected locations (Fig. 5), indicating the potential of the simple SPI to serve as a surrogate for the more complex RDI and SPEI. For temperate and tropical environments such as Cairns, Weipa, or Brisbane the more complex RDI and SPEI can be replaced by the simple SPI if evaporation data is not available (Fig. 5). By contrast, in arid Bourke, Quilpie, or Mount Isa correlations between SPI and the more complex indices were weaker. In these arid and water-limited locations (Table 1) we recommend using SPEI and RDI and also to conduct intensive monitoring of ecosystem development in relation to empirical weather data to measure evaporation directly, e.g. pan evaporation (Lugato et al., 2013; Clark, 2013), or indirectly, e.g. based on radiative and aerodynamic variables (Allen et al., 1998).

4.3 Application of design droughts to rehabilitation planning

One of the major outcomes of this study is to support land managers and/or rehabilitation practitioners to make fundamental decisions on appropriate management actions in the context of drought frequency. For rehabilitation to be successful in the face of severe and prolonged droughts, there are a range of management domains and management actions that need to be considered in response to recurrence intervals, drought severity, and drought duration (Table 3). These management actions can be categorised into four domains: plant species selection, planting/seeding regime, soil characteristics, and irrigation method.

Selection of suitable plant species based on drought type is one of the key management actions for successful rehabilitation. Some management actions can be applied to all drought types (LS, LP, SS, SP in Table 3). These include (i) planting of drought tolerant species (e.g., *Acacia* spp., *Banksia* spp., *Casuarina* spp.), at (ii) northern aspects to address drier conditions that result from higher solar radiation causing increased evaporation (Sternberg and Shoshany, 2001), and (iii) planting of perennial grasses (*Eragrostis* spp., *Themeda* spp. (Bolger et al., 2005)), which may not be affected by long-term water deficits. At locations with frequently recurring long-term (12 month time scale) droughts of high severity and durations (LS, LP in Table 3), such as Mount Isa and Quilpie, seeding of species with physical/chemical dormancy may increase the probability of germination during favourable periods (Hilhorst, 1995; Arnold et al., 2014b). Additionally, a southern aspect may require drought tolerant species to increase survival of plant communities (Sternberg and Shoshany, 2001). However, these species need to be shade tolerant as southern aspects get less solar radiation in winter. At locations with frequently recurring short-term (3 month time scale) droughts of high severity but short duration, with rainfall throughout the year (SS in Table 3), such as Wagga Wagga, annual grasses and seeds with short germination periods may be suitable.

Soil characteristics play a critical role for plant available water and a number of strategies may need to be employed to make soil more favourable to plant establishment. Except for mulching, all of the management actions within the soil characteristics management domain can be applied to locations with high recurrence of long-term, severe, and prolonged droughts (LS, LP in Table 3), such as Quilpie and Mount Isa. For locations with high recurrence of short-term, and prolonged droughts (SP in Table 3), such as Melbourne, increasing the depth of topsoil can increase water holding capacity (Audet et al., 2013; Bot and Benites, 2005). Similarly, by mixing silt and clay soil in the topsoil and reducing slope gradients may facilitate infiltration and increase soil water retention capacity (Audet et al., 2013). For tropical locations with high recurrence of short-term (3 month time scale), severe, and prolonged droughts (SS, SP in Table 3), such as Cairns and Weipa, ground cover such as mulch and planting fast growing cover (e.g., Buffel grass) may reduce evaporation and maintain soil moisture to allow for the establishment of drought sensitive and slow growing species (Blum, 1996).

Utilising irrigation methods for specific site characteristics is a cost effective strategy for any rehabilitation plan. Regular irrigation with proper drainage systems that distributes water is an effective strategy in locations with high recurrence of long-term, severe, and prolonged droughts (LP, LS in Table 3). For locations with high recurrence of short-term, severe, and prolonged droughts (SS, SP in Table 3), with seasonal rainfall (e.g. Brisbane, Sydney, Kingaroy, Brigalow), seasonal irrigation and irrigation at critical stages of plant growth (Blum, 1996), such as germination, and root or pod development periods are efficient actions to ensure plant survival throughout drought spells.

4.4 Future research

The method outlined in this study provides a useful tool for land managers to address site-based climatic conditions. Future research needs to build on this tool, as well as address the limitations of our method based on meteorological drought indices inferred from point observations. This research may assess: (i) the relationship between meteorological and agricultural drought indices, (ii) regional scale mapping of drought indices and, (iii) the predictive power of design droughts.

While the applied drought indices are robust indicators of meteorological droughts (Mishra and Singh, 2010; Quiring, 2009), they are limited to detecting anomalies from historic rainfall patterns. Soil plays a critical role for any ecosystem development, particularly with regard to ecosystem rehabilitation in post-mining land (Arnold et al., 2013), as soil properties translate rainfall into plant available water (Zhang et al., 2001; Huang et al., 2013). Future drought analysis would benefit from integrating soil properties such as depth, texture, salinity, or organic matter content into drought indices to describe agricultural droughts (Khare et al., 2013; Baldocchi et al., 2004; Woli et al., 2012). Soil texture and depth are critical factors in highly seasonal climates, where the soil forms the water storage to overcome periods of water deficit (Prentice et al., 1992; Bot and Benites, 2005).

Although the selected locations can be considered representative of the agro-climatic environments across Eastern Australia (Fig. 1), our analysis is strictly valid for the selected point data and therefore site-specific. Future work should not only integrate the above mentioned soil component but also extend drought analyses across Australia using gridded weather data from the Bureau of Meteorology (2014). Future investigations could assess possible trends in temporal changes of recurrence intervals by dividing historic time series of rainfall and evaporation into subsets and replicate the analysis for each subset (Li et al., 2014; Darshana et al., 2013; Jacobs et al., 2013).

5 Conclusions

The study revealed site-specific patterns of recurrence intervals of short-term and long-term droughts across Eastern Australia. Severe and prolonged short-term droughts recurred most often in tropical climates and temperate Wagga Wagga, while severe and prolonged short-term droughts recurred most often in arid conditions and temperate Melbourne. Design droughts can be applied to quantify the frequency of drought events – characterised by severity and duration – at different time scales. This is a critical step forward to consider drought in risk assessments for rehabilitation of post-mining ecosystems. Together with design rainfalls, design droughts should be used to assess rehabilitation strategies and ecological management based on drought recurrence intervals, thereby minimising the risk of failure of initial ecosystem establishment due to ignorance of fundamental abiotic and site-specific environmental barriers.

Appendix A. Drought indices

A1 SPI

$$S = -\sum_{i=1}^{D} SPI_i \tag{A1}$$

where D denotes is the drought duration, and S is the drought severity (McKee et al., 1993).

A2 RDI

$$RDI_{st}(k) = \frac{y_k - \bar{y}_k}{\hat{\sigma}_k} \tag{A2}$$

Where,

$$y_k = ln \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j} \tag{A3}$$

RDI_{st} is standardised RDI, $\hat{\sigma}$ is the standard deviation, Y_k is the month k during a year, $\bar{y}_k$ and $\hat{\sigma}_k$ is arithmetic mean of y_k, and $\hat{\sigma}_k$ is the standard deviation of k, P_j and PET_j are precipitation and potential evapotranspiration for the j^{th} month of the hydrological year (Tsakiris and Vangelis, 2005).

A3 SPEI

$$SPEI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \tag{A4}$$

With,

$$W = \sqrt{-2\,ln(P)} \quad for\ P \le 0.5 \tag{A5}$$

Where,

P is the probability of exceeding a determined D value, P = 1- F(x). If $P > 0.5$, then P is replaced by 1 - P and the sign of the resultant SPEI is reversed. The constants are C_0 = 2.515517, C_1 = 0.802853, C_2 = 0.010328, d_1=1.432788, d_2=0.189269, and d_3=0.001308 (Vicente-Serrano et al., 2010).

Appendix B. Mathematical description of Gumbel and Frank copula (Shiau, 2006).

B1 Gumbel copula

$$C(u,v) = exp\left\{- \left[(-ln\, u)^{\theta} + \left(-\, ln\, v\right)^{\theta}\right]^{\frac{1}{\theta}}\right\}\ \theta \geq 1 \tag{B1}$$

$$\mathrm{c}(u,v) = C\ (u,v)\frac{[\ (-1ln\, u)^{\theta}\ (-\, ln\, v)^{\theta-1}]}{uv}\ \ [\ (-1ln\, u)^{\theta}\ (-\, ln\, v)^{\theta}]^{\frac{2}{\theta}-2} \tag{B2}$$

$$.\left\{(\theta-1)\left[(-ln\, u)^{\theta} + \left(-\, ln\, v\right)^{\theta}\right]^{-\frac{1}{\theta}} + 1\right\}$$

B2 Frank copula

$$C\ (u,v) = -\frac{1}{\theta} ln\left[1 + \frac{\left(e^{-\theta u}-1\right)\left(e^{-\theta v}-1\right)}{e^{-\theta}-1}\right], \theta \neq 0 \tag{B3}$$

$$c(u,v) = -\frac{\theta e^{-\theta(u+v)}\ \left(e^{-\theta}-1\right)}{[e^{-\theta(u+v)} - e^{-\theta u} - e^{-\theta v} + e^{-\theta}]^{2}} \tag{B4}$$

Appendix C. Time series of drought indices and major weather events.

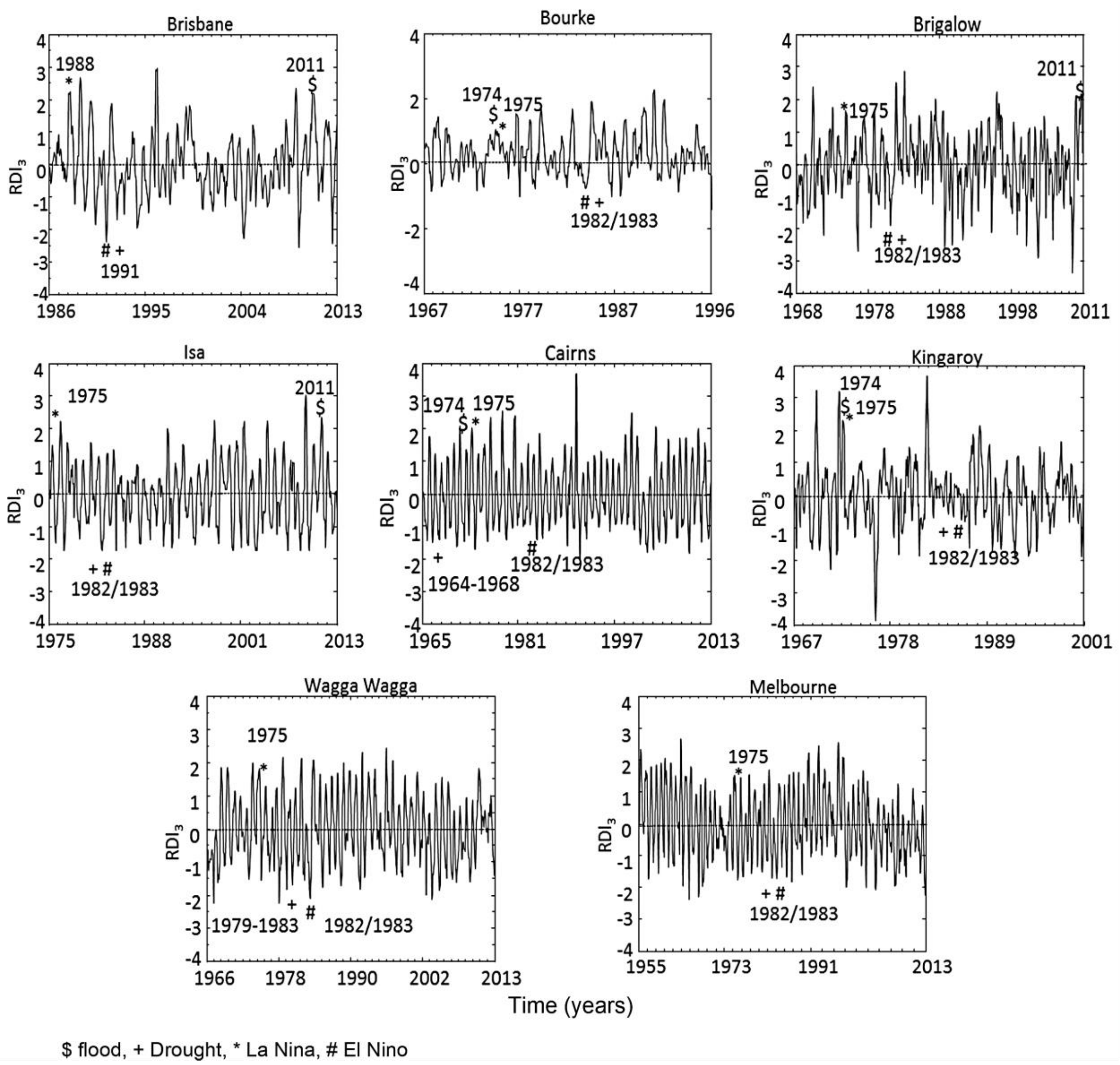

Figure C1. Calculated $SPEI_{12}$ for selected locations across Eastern Australia.

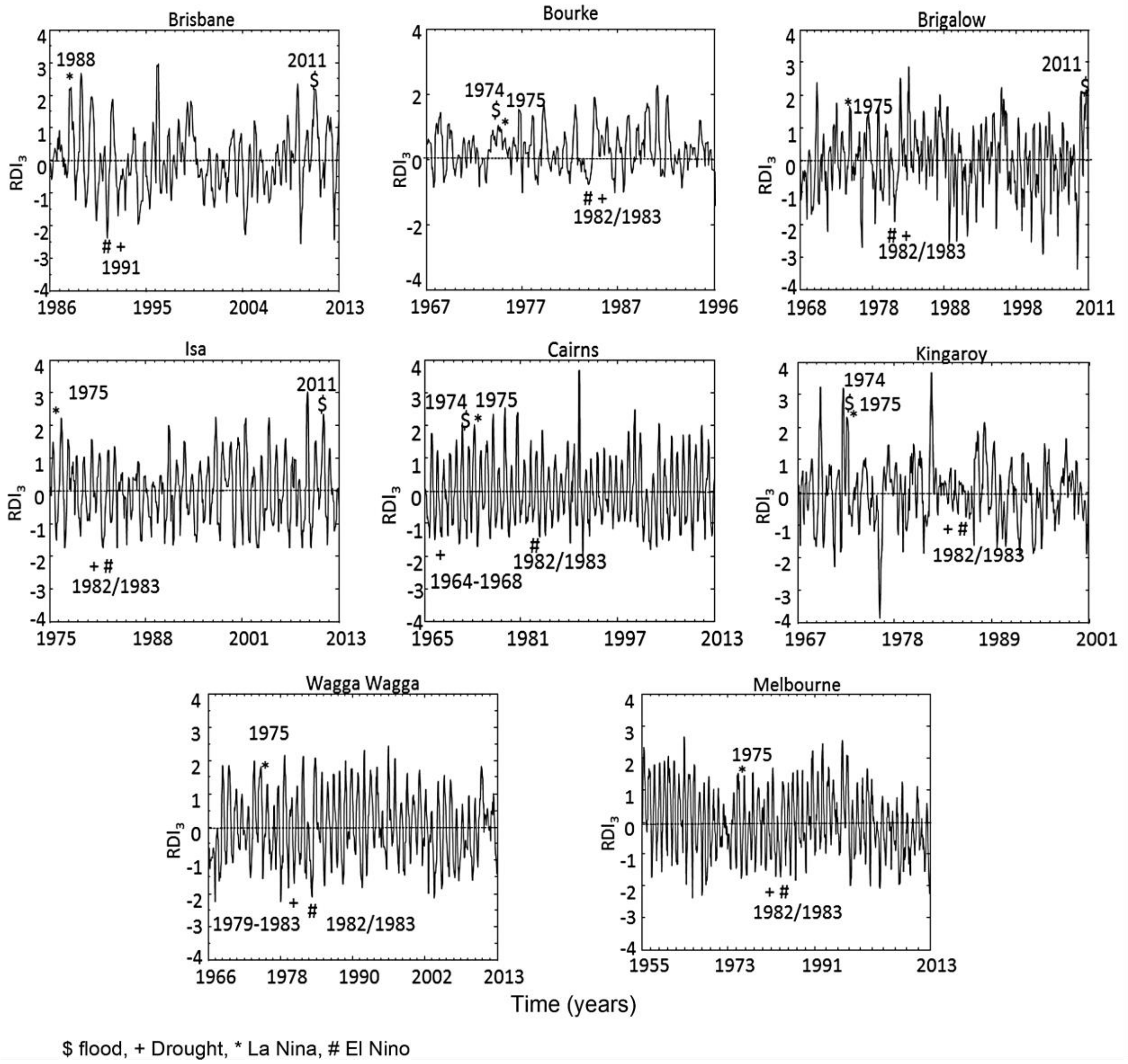

Figure C2. Calculated RDI_3 for selected locations across Eastern Australia.

Appendix D. Recurrence intervals of drought events with any severity *and* duration of interest.

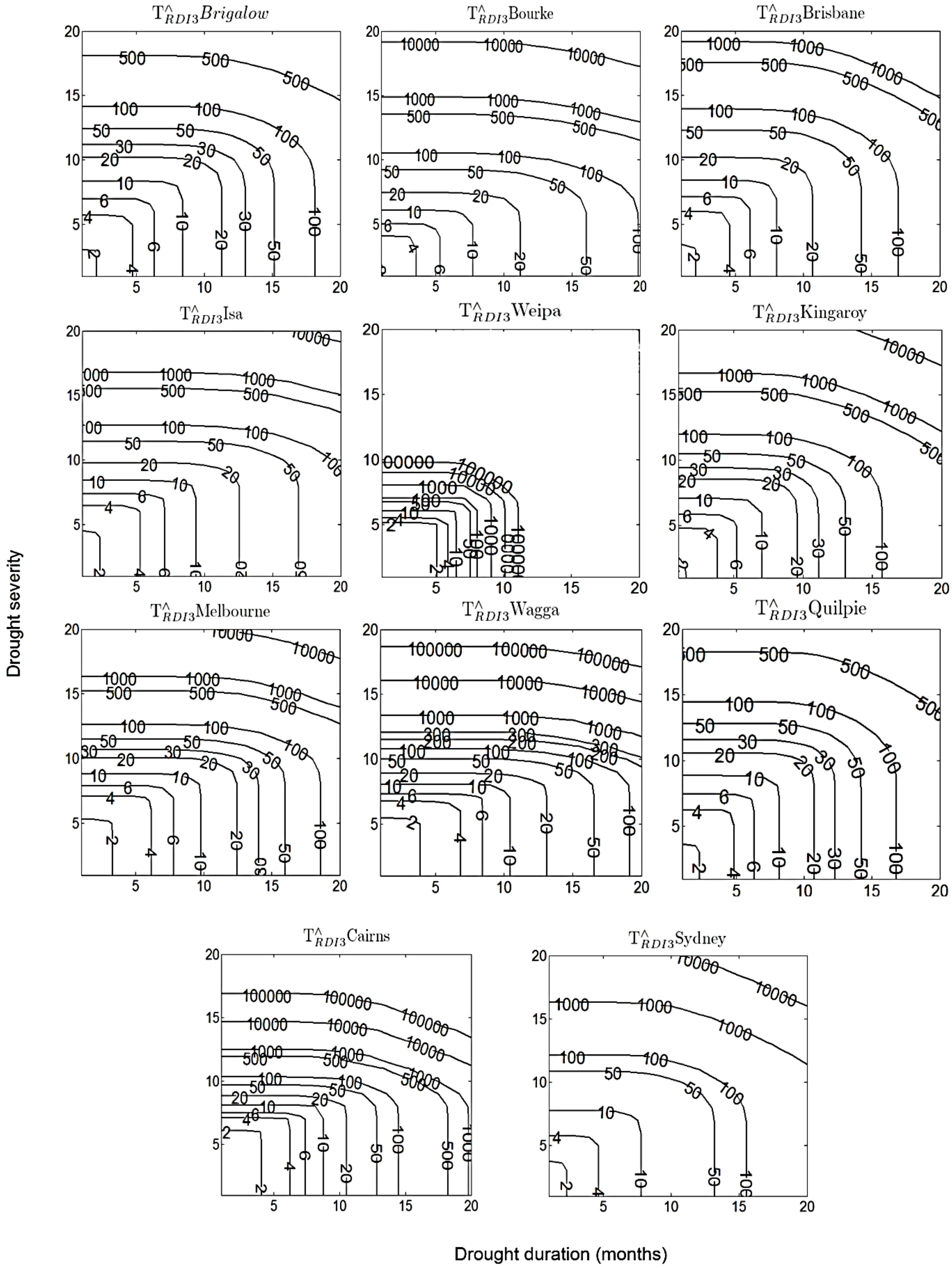

Figure D1. Recurrence intervals T^ (years) of drought events with any severity *and* duration of interest based on RDI_3 (short-term) of historical rainfall.

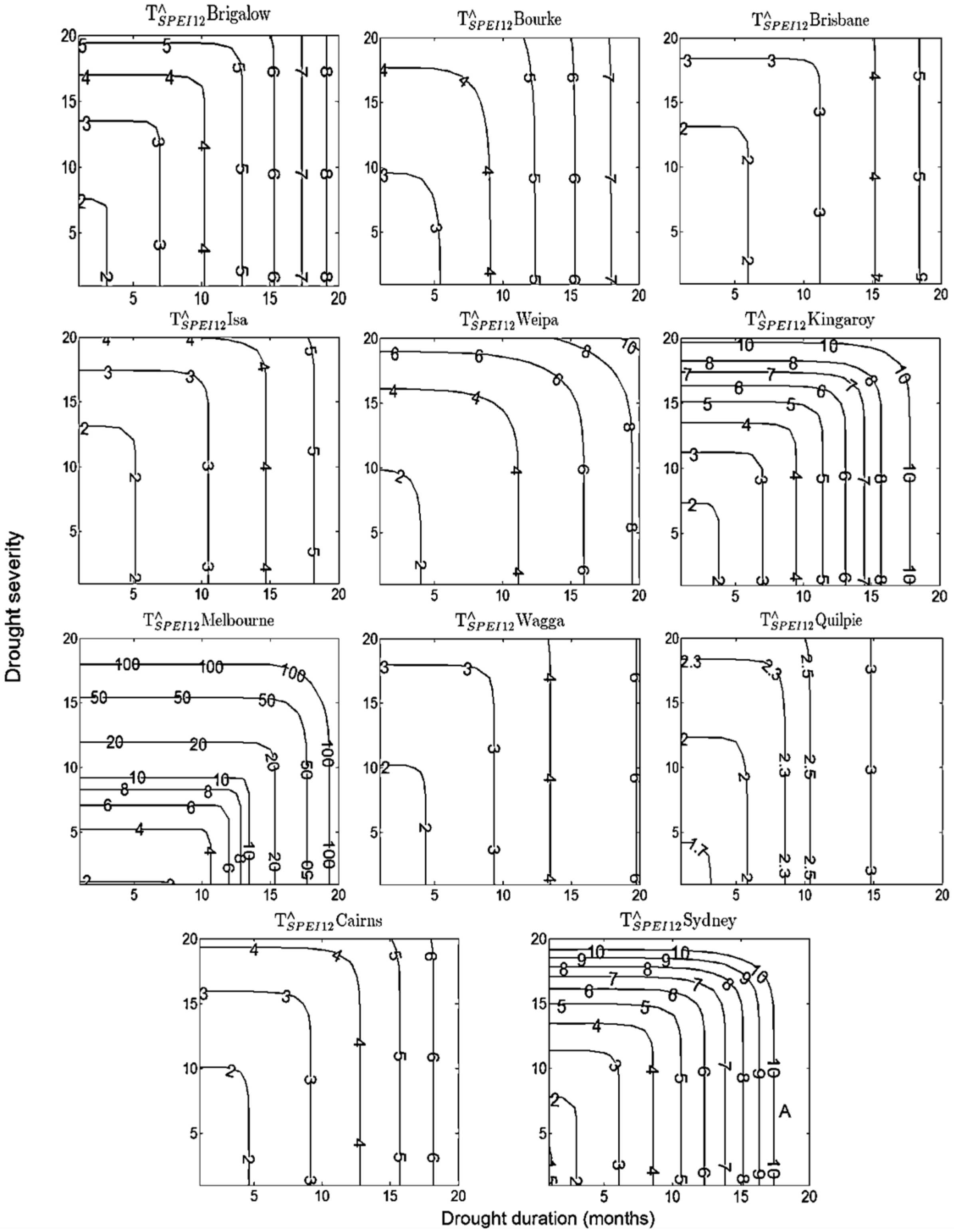

Figure D2. Recurrence intervals T^ (years) of drought events with any severity *and* duration of interest based on $SPEI_{12}$ (long-term) of historical rainfall.

Acknowledgments

This study was made possible by The University of Queensland Post-doctoral Fellowship scheme and Early Career Research Grant awarded to SA, as well as the International Postgraduate Research Scholarship awarded to DH. We thank Tanja Giebner for her dedicated work on deriving the RDI for selected locations. Further, we thank David Doley and Patrick Audet for critical discussions.

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Table 1. Climate indices and classification of selected locations across eastern Australia with focus on rainfall.

Location	Length of meteorological data (years)	Climate index		Climate classification system			
		R/PET[a]	R_w/R_s[b]	Köppen-Geiger[c]	Australian Agricultural Environment[d]	Agro-climatic[e]	potential productive landuse[e,d]
Weipa	1960-1994 (34)	0.99	0.01	Aw – Tropical, savannah	AAE1 – Tropics (wet/dry season)	I1 – wet/dry season (temporally water-limited)	crops, rangeland
Cairns	1965-2013 (48)	0.91	0.10	Aw – Tropical, savannah	AAE2 – Tropical coast (wet)	I3 – wet/dry season (temporally water-limited)	crops, rangeland, sugarcane
Brisbane	1986-2013 (27)	0.55	0.38	Cfa – Temperate, without dry season	AAE6 – Subtropical coast (wet)	F4 – wet	horticulture, pasture, sugarcane
Sydney	1970-1994 (24)	0.53	0.51	Cfb – Temperate, without dry season	AAE10 - Temperate coast east (wet, winter-dominant rainfall)	F3 – wet	crops, horticulture, pasture
Melbourne	1955-2013 (58)	0.51	0.95	Cfb – Temperate, without dry season	AAE10 - Temperate coast east (wet, winter-dominant rainfall)	D5 – wet (moderately water-limited in summer)	crops, forestry, horticulture, pasture
Kingaroy	1967-2001 (34)	0.47	0.34	Cfa – Temperate, without dry season	AAE7 - Wheatbelt downs (summer-dominant/moderate rainfall)	E4 – water-limited	cotton, crops, pasture,
Brigalow Research Station	1968-2011 (43)	0.32	0.27	Cfa – Temperate, without dry season	AAE4 – Subtropical plains (summer-dominant/moderate rainfall)	E4 – water-limited	
Wagga Wagga	1966-2013 (47)	0.30	1.21	Cfb – Temperate, without dry season	AAE14 – Wheatbelt east (winter-dominant rainfall)	E3 – water-limited in summer	crops, horticulture, pasture
Bourke	1967-1996 (29)	0.20	0.61	BSh – Arid, steppe	AAE18 – Arid (dry)	E6 – water-limited	
Quilpie	1970-2013 (43)	0.14	0.36	BSh – Arid, steppe	AAE18 – Arid (dry)	H – water-limited	rangeland, wildland
Mount Isa	1975-2013 (38)	0.13	0.05	BSh – Arid, steppe	AAE18 – Arid (dry)	G – water-limited	

a – (UNEP, 1992)
b – Based on average of three months of rainfall during winter (June – August) and summer (December – February)
c –(Peel et al., 2007)
d –(Woodhams et al., 2012)
e – (Hutchinson et al., 2005)

Table 2. Mean severity μ_S and duration μ_D of selected locations across eastern Australia, and corresponding coefficient of variation CV_S and CV_D for short-term (RDI_3) and long-term ($SPEI_{12}$) droughts.

Location	**RDI_3**				**$SPEI_{12}$**			
	μ_S	**CV_S**	**μ_D**	**CV_D**	**μ_S**	**CV_S**	**μ_D**	**CV_D**
Weipa	5.2	0.2	5.8	0.1	8.4	1.1	10.4	0.8
Cairns	4.7	0.4	6.4	0.3	9.6	1.3	12.5	1.0
Brisbane	3.1	3.3	3.6	0.8	11.2	0.9	13.3	0.8
Sydney	3.4	0.9	4.4	0.6	6.5	1.7	8.9	0.9
Melbourne	4.5	0.7	5.8	0.5	14.5	1.9	18.6	1.6
Kingaroy	2.8	1.2	3.7	0.8	7.0	1.1	8.3	0.8
Brigalow Research Station	3.4	1.0	4.4	0.9	8.0	1.3	10.2	1.0
Wagga Wagga	5.2	0.8	6.2	0.6	8.6	1.8	13.8	1.1
Bourke	2.8	3.9	3.9	1.1	8.2	2.0	9.9	1.5
Quilpie	3.5	1.1	4.6	0.7	18.8	2.1	21.8	1.5
Mount Isa	3.8	0.7	4.9	0.5	11.1	1.2	14.4	0.9

Table 3. Management actions for addressing specific kinds of drought characteristics identified with SDF curves for the southern hemisphere.

Management domain	Management actions	Type of drought
Plant species selection	Drought tolerant species	LS, LP, SP, SS
	Quickly germinating species	SS
	Species with physical/chemical dormancy	LS, LP
	Shade tolerant species on southern aspects	LS, LP
	Light tolerant species on northern aspects	LS, LP, SP, SS
	Annual grasses	SS, SP
	Perennial grasses	LS, LP, SP, SS
	Trees	LS, LP
Planting/seeding regime	Trees require repeated establishment	LS, LP
	Annual/perennial grasses are successful after rain events	SS, SP
Soil characteristics	Deep top soil	LS, LP, SP
	Amendments of silt/clay	LS, LP
	Gentle slopes	LS, LP
	Mulching	SS
Irrigation method	Regular irrigation	LS, LP
	Seasonal irrigation	SS, SP
	Critical stage irrigation	LS,LP,SP,SS
	Drainage system	LS, LP

SS – High recurrence of short time scale (3 month) severe droughts
SP – High recurrence of short time scale (3 month) prolonged droughts
LS – High recurrence of long time scale (12 months) severe droughts
LP – High recurrence of long time scale (12 months) prolonged droughts

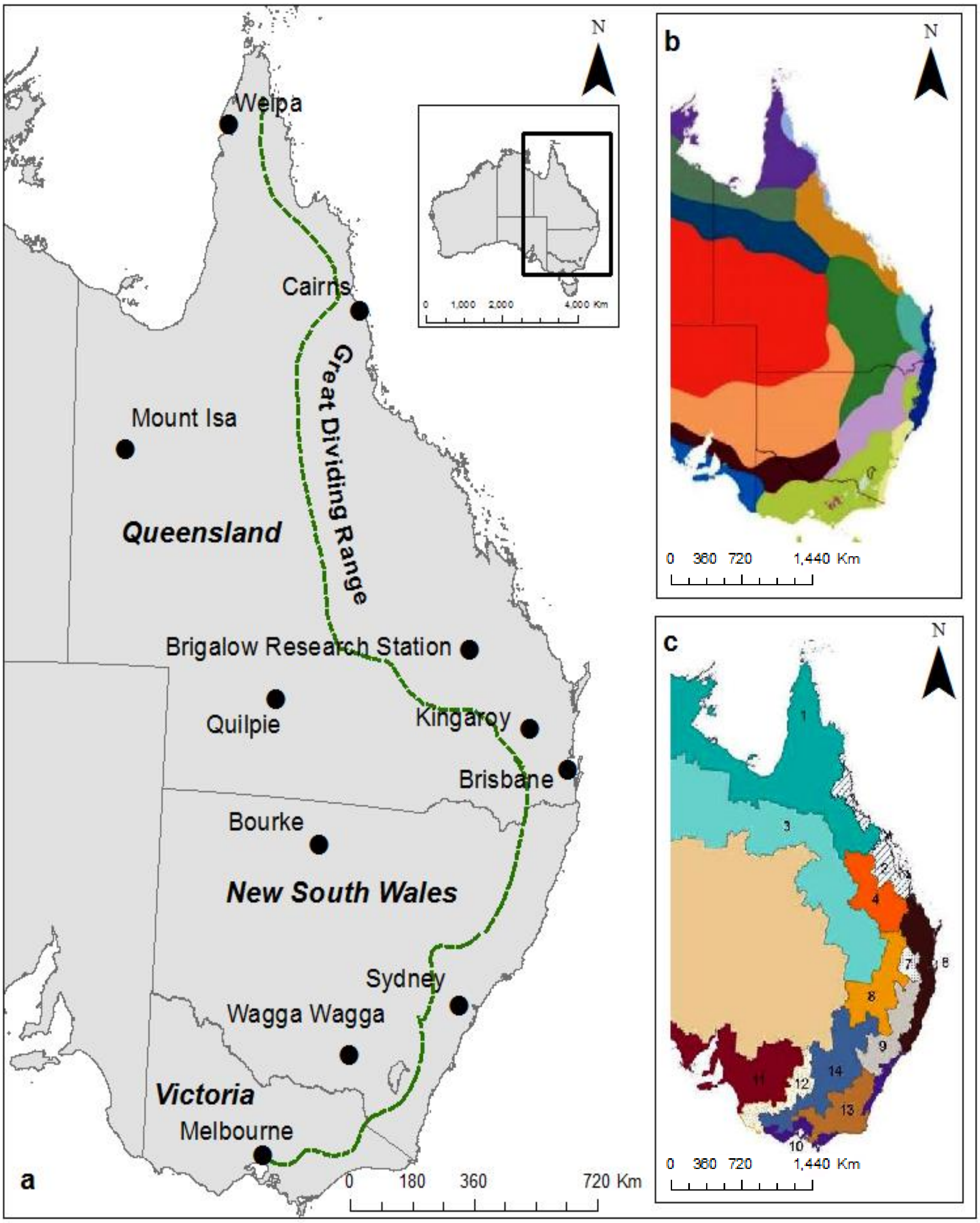
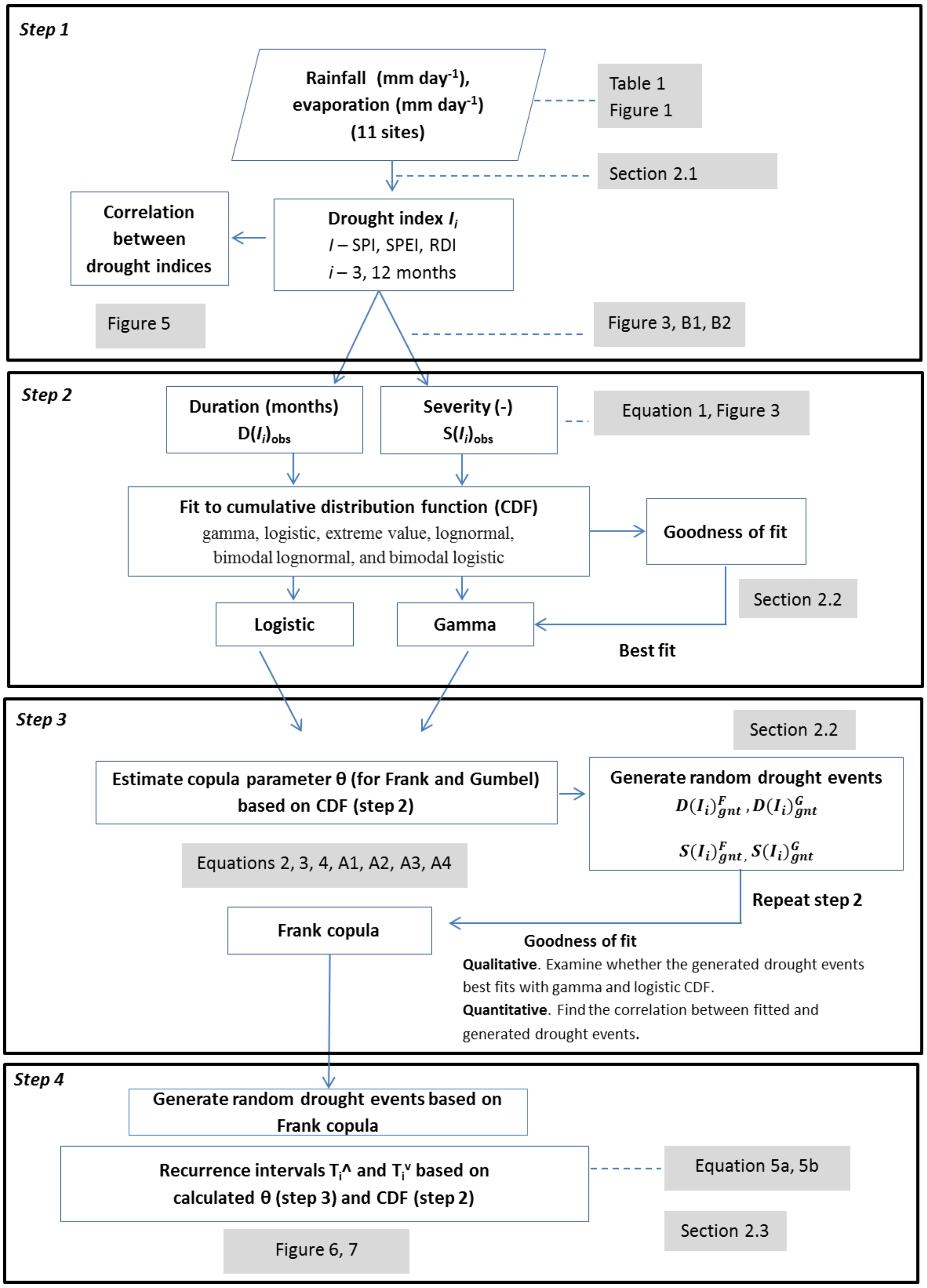


Figure 1. (a) Selected locations of interest with boundaries of (b) agro-climatic classes (Hutchinson et al., 2005) and (c) Australian agricultural environments (Woodhams et al., 2012).



F-Frank copula, G-Gumbel copula, gnt-generated

Figure 2. Schematic diagram of steps applied to estimate recurrence intervals of drought events. See Section 2 for further details. *Step 1.* Calculate drought index based on monthly rainfall (SPI) and evaporation (RDI, SPEI). *Step 2.* Fit cumulative distribution function (CDF) to estimated drought duration and severity. *Step 3.* Estimate copula parameter based on CDFs. *Step 4.* Calculate recurrence intervals based on CDFs of univariate (severity, duration) distributions and bivariate joint distribution (copula).

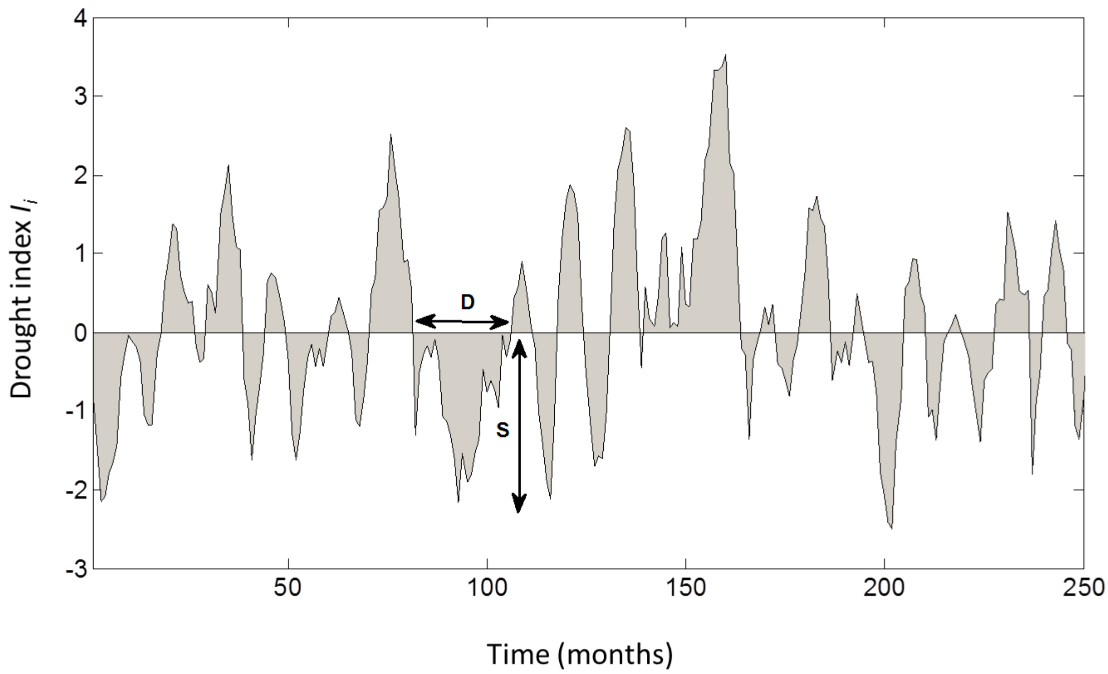


Figure 3. Concept of severity S and duration D of a drought event quantified with drought index I_i, where i refers to any time-scale of interest.

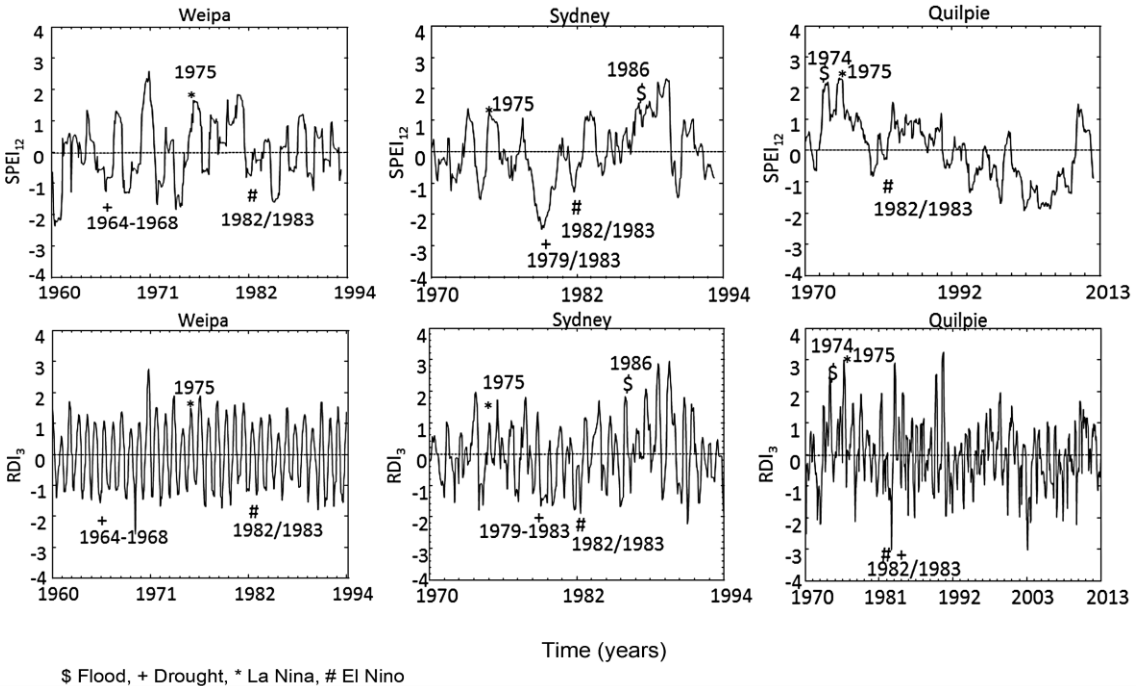


Figure 4. Calculated $SPEI_{12}$ (upper row) and RDI_{3} (lower row) for Weipa, Sydney and Quilpie including major weather events. The same indices are depicted for all other selected locations in Appendix B.

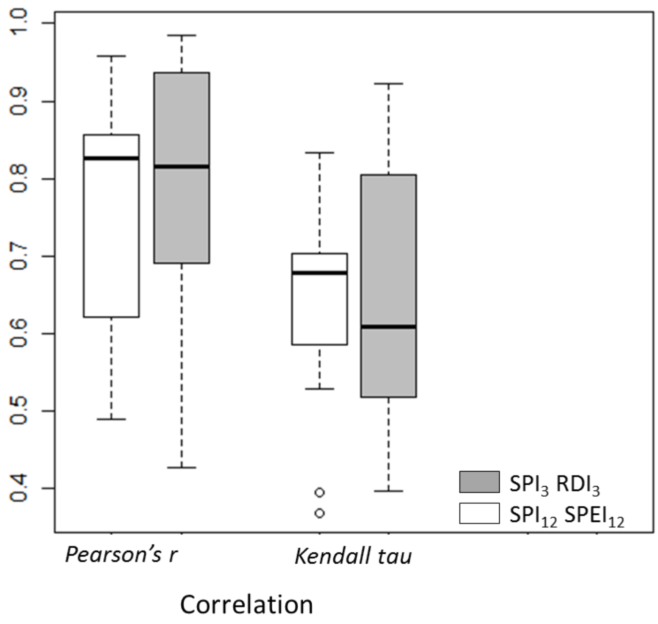


Figure 5. Correlation between SPI_3 and RDI_3, and SPI_{12} and $SPEI_{12}$ based on the correlation coefficient Pearson's r and Kendall tau. The outliers represent the very dry locations of Bourke and Quilpie.

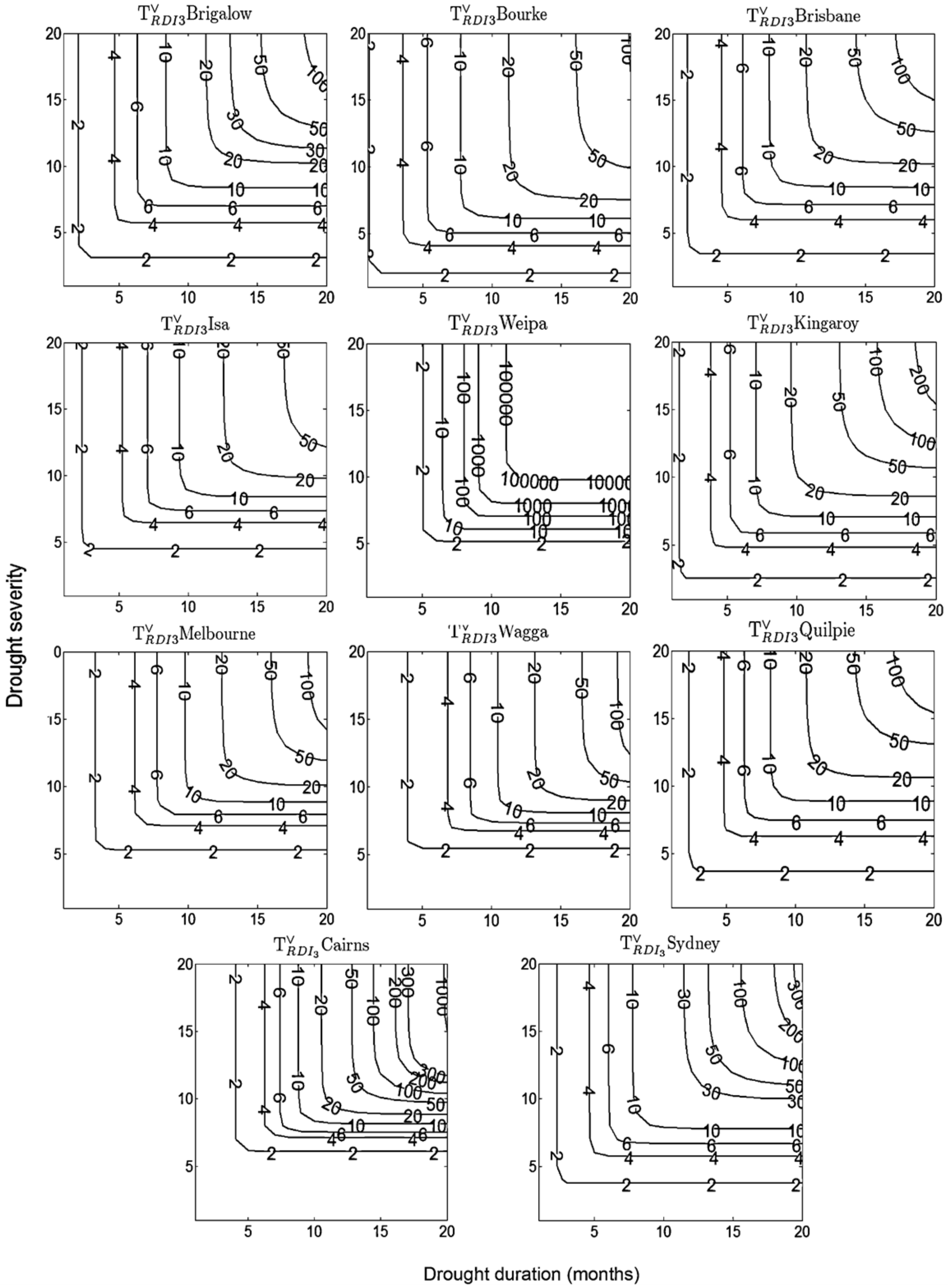


Figure 6. Recurrence interval T^{v} (years) of drought events of any severity *or* duration of interest based on the RDI_3 (short-term) of historical rainfall.

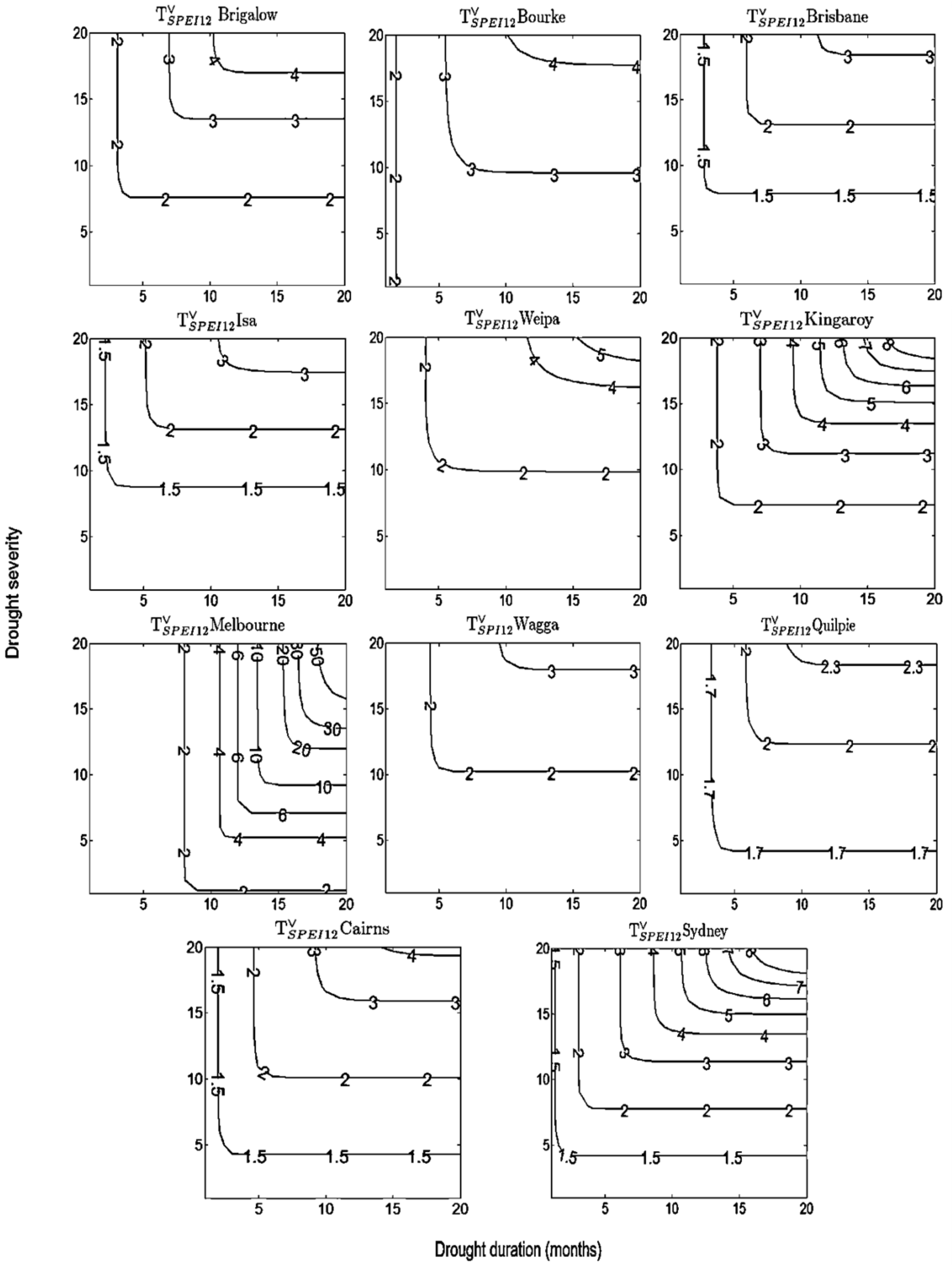


Figure 7. Recurrence interval T^{v} (years) of drought events of any severity *or* duration of interest based on $SPEI_{12}$ (long-term) of historical rainfall.