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Spatiotemporal analysis of droughts using self-calibrating Palmer's Drought Severity Index in the central region of South Africa

Desalegn C. Edossa[1] · **Yali E. Woyessa**[1] · **Worku A. Welderufael**[1]

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Abstract The loss of life and property from drought events has forced society to focus on the development of reliable early warning systems which may enable farmers and other stakeholders to correctly and timely adapt to the expected impacts of climatic hazard. However, a scientific approach to a reliable early warning system for a region requires, among others, characterisation of drought events in the region in terms of duration, magnitude, intensity and frequency using standard drought indices. Therefore, the objective of this study was to identify and characterise drought events in the Modder River basin, central region of South Africa, using a self-calibrated Palmer's Drought Severity Index (sc-PDSI). Attempts were also made to establish a relationship between meteorological and hydrological drought events in the region. During the period of analysis, the total number of drought episodes identified in the study area ranged between eight and sixteen. It was found that the most severe drought episodes occurred during the period 1992–1995 followed by the period 1982–1987. Results of analysis of seasonal drought events in one of the quaternary catchments (C52A) revealed that peak drought events during the three summer months (November, December and January) occurred in the area in 1993. However, in terms of event magnitude and intensity, the worst drought events were recorded during the period December 1982–July 1987, followed by the event that ensued during December 1989–September 1995. Results of analysis of decadal variation of drought events showed that the number of extreme and moderate drought events recorded in the catchment showed statistically significant increasing trends during the five decades at 5 % significance level. Moreover, spectral analysis of sc-PDSI time series in the region identified periodicities in the time series ranging from 6 years (C52E) to 16 years (C52K). In terms of the spatial extent of extreme drought events, the maximum areal coverage (91 %) was recorded in November 1998, followed by December 1998 and December–January 1999 (43 %). Analysis of the relative frequency of droughts of varying categories revealed that extreme drought events were most prevalent in the C52E (2.72 %) quaternary catchment, followed by C52C (2.21 %). The study also found an average lag time of 10 months between the onsets of meteorological and hydrological drought events in the region.

1 Introduction

Drought is a normal phenomenon of climate in most countries, especially in sub-Saharan Africa, but it has serious economic, environmental and social impacts which affect more people than any other natural hazard – particularly the poor who are more vulnerable. This is a cause of concern as the world is entering a period of unprecedented climate change, which is predicted to result in higher average temperatures, changes in precipitation patterns and more frequent extreme weather events over extensive land areas (Richardson et al. 2007, cited in Vetter 2009; IPCC 2013). Therefore, countries must address the underlying causes of drought vulnerability and improve monitoring and early warning systems. Even though the ensuing damages depend on the exposed populations, economies and societies and their adaptive capacity, drought events entail loss of assets in the form of crops, livestock,

✉ Desalegn C. Edossa
dedossa@cut.ac.za; desalegnchemeda@gmail.com

[1] Department of Civil Engineering, Central University of Technology, Free State (CUT), 20 Pres Brand Street Private Bag X20539, Bloemfontein 9300, South Africa

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infrastructures and other productive capitals as a result of water shortages and related impacts.

In South Africa's arid and semi-arid rangelands, droughts are a frequent occurrence (Vogel 1994, cited in Vetter 2009). Jury and Levey (1993) indicated that drought recurs at intervals of 3.45 and 18.2 years in the Eastern Cape, particularly when March rains fail to materialise. Moreover, Rouault and Richard (2005) reported an increase in the spatial extent of drought in Southern Africa since the 1970s due to stronger relationship between ENSO and the Southern African rainfall, although localised basin-level assessments are lacking. While these droughts may be short-term and followed by recovery during subsequent years of higher rainfall (Ellis and Swift 1988, cited in Vetter 2009), in some cases droughts can trigger substantial and irreversible ecological and socio-economic changes. Model predictions show that reductions in mean annual rainfall, increased inter-annual variation, and more frequent droughts in South Africa, can lead to disproportionately large impacts on livestock production (Burns et al. 2006, cited in Vetter 2009).

The loss of life and property from drought events has caused society to focus on the causes and predictability of drought events. Backeberg and Viljoen (2003) developed a theoretical framework for drought management based on review of literatures. They acknowledged the shortage of research and extension capacity in South Africa to implement reliable early warning systems which may enable farmers and other stakeholders to correctly and timely adapt to the expected changes in the climate and weather. However, a scientific approach to a reliable early warning system for a region requires, among others, characterisation of drought events in the region in terms of duration, magnitude, intensity and frequency using standard drought indices. Seymour and Desmet (2009) suggest that long-term drought research is essential in the country and underlined the importance of a suite of coordinated long-term field observations, experiments and models to inform agricultural policy and conservation planning. Moreover, Durand (2010) underlined the importance of developing social and physical vulnerability indicators of drought for South Africa.

Various drought indices have been developed to characterise drought spatially and temporally based on its magnitude, duration and intensity (e.g. Heim 2000, 2002; Keyantash and Dracup 2002; Vicente-Serrano et al. 2010; Dai 2011). Among them, the Palmer's Drought Severity Index (PDSI) is the most prominent index of meteorological drought used in the USA for drought monitoring and research (Heim 2002). PDSI has been extensively used to study drought climatology and variability in different parts of the world (e.g. Dai 2011; Vasiliades et al. 2011; Vasiliades and Loukas 2009; Burke and Brown 2008; Ceglar et al. 2008; Van der Schrier et al. 2006a, b, 2007; Burke et al. 2006; Mika et al. 2005; Dai et al. 1998, 2004; Lloyd-Hughes and Saunders 2002). However, the standardisation used by Palmer (1965) was based on limited data from the central USA, and the PDSI values are not comparable between diverse climatological regions. To improve the spatial comparability problems associated with PDSI, Wells et al. (2004) proposed what is known as a self-calibrating Palmer's Drought Severity Index (sc-PDSI) by calibrating the PDSI using local conditions, instead of using the empirical constants (coefficients) that were used by Palmer based on data from the central USA. The sc-PDSI automatically calibrates the behaviour of the index at any location by replacing empirical constants in the index computation with dynamically calculated values. The revised model performed better than the original PDSI during the twentieth century over Europe and North America (Van der Schrier et al. 2006a, b, 2007).

Du Pisani et al. (1998) reported a review of various drought assessment techniques that have been developed in South Africa prior to 1998. Rouault and Richard (2003) used Standardised Precipitation Index (SPI) to make a retrospective analysis of the spatial extent and intensity of droughts in South Africa since 1921. Despite its wide applications, the original and modified versions of the PDSI (i.e. PDSI and sc-PDSI) have not been well examined in Africa in general or in South Africa in particular. The objective of this study was, therefore, to characterise droughts in the central region of South Africa both spatially and temporally using sc-PDSI, to establish a relationship between meteorological and hydrological drought events in the region and identify lag time between the two drought events.

2 Materials and methods

2.1 Location of the study area

The study was conducted in the Modder River basin, C52 tertiary catchment. The basin has a total area of 17,380 km^2 and is divided into three sub-basins, namely the Upper Modder, the Middle Modder and the Lower Modder. It is located within the Upper Orange Water Management Area to the east of the city of Bloemfontein and consists of 11 quaternary catchments (Fig. 1). The Upper Modder, which consists of the quaternary catchment C52A, comprises approximately 5 % of the total runoff contributing area. The Middle Modder consists of the second largest portion of the basin area. It covers about 45 % of the total area and includes quaternary catchments C52B, C52C, C52D, C52E, C52F, C52G and C52H. The remaining 50 % of the total area belongs to the Lower Modder basin and is divided into three quaternary catchments, namely C52J, C52K and C52L (Woyessa et al. 2011).

The dominant soil types of the catchment are sandy clay loam and sandy clay. The irrigated agriculture in the basin

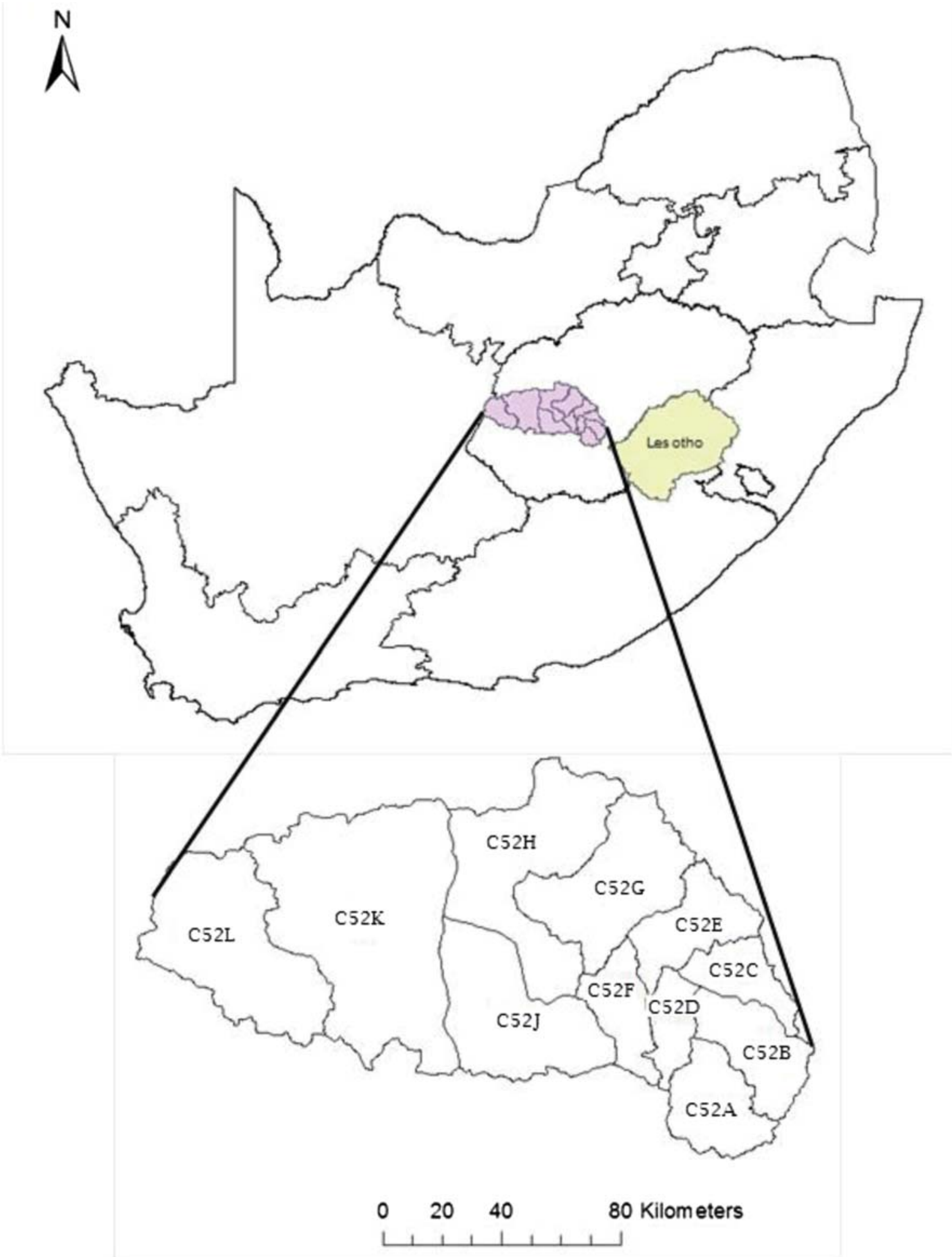

Fig. 1 Location of the study area

mainly uses water supplied by pumping from rivers and weirs. However, many of the rural farmers rely on rain-fed agriculture for crop production. The basin is experiencing intermittent droughts causing shortages of water supply for agriculture, livestock and domestic purposes.

2.2 Preparation of input data

Daily precipitation and temperature data of the quaternary catchments within C52 tertiary catchment were obtained from QCD_DAT.EXE, a self-extracting compressed data file containing 50 years of daily hydroclimatic data pertaining to each of the 1946 quaternary catchments of South Africa compiled by Lynch (2004). In this analysis, the quaternary catchments' databases have been used for spatial and temporal analyses of droughts in the tertiary catchment. Soil types of the study area were obtained from the *South African Atlas of Climatology and Agrohydrology* (Schulze et al. 2008) for the determination of available water-holding capacity (AWC). The programme to calculate monthly sc-PDSI values requires four specifically named input files, namely 'monthly temperature (monthly_T)', 'monthly precipitation (monthly_P)', 'normal temperature (T_normal)' and 'parameter'.

2.3 Monthly temperature

This file holds the temperature data for a quaternary catchment. Each line starts with the year and is followed by 12 temperature entries. The temperature is the average monthly temperature for each of the 12 months of that year.

2.4 Monthly precipitation

This file holds the precipitation data for a quaternary catchment. It is the same format as the temperature files; each line starts with the year and is followed by 12 precipitation values. The precipitation values are the total monthly precipitation for each of the 12 months of that year.

2.5 Normal temperature

This file has the normal temperature data for a quaternary catchment. It has only 12 entries, all in one line. The values in the file are the normal or average temperature over all the years on record for each of the 12 months. This file is named T_normal to comply with the sc-PDSI programme requirement. The programme will open the file named T_normal if it exists and if it contains the correct number of entries.

2.6 Parameter

The parameter file contains two numbers. The first number should always be the AWC. The second number should be the latitude of the station (in this case the centroids of the quaternary catchments). The latitude should be given in decimal degrees.

2.7 Palmer's Drought Severity Index

The PDSI is a moisture balance model in the soil based on supply and demand of the soil moisture at a location. The supply is the amount of moisture in the soil plus the amount that is absorbed into the soil from rainfall. The demand depends on factors affecting the amount of water lose from the soil, such as temperature and the amount of moisture in the soil.

The basis of the soil moisture balance modelling is the calculation of potential evapotranspiration (PET), which is based on Thornthwaite's method. Dai (2011) reported that the choice of the method for calculation of PET only has small effects on sc-PDSI for the twentieth century climate. The model also requires calculation of potential recharge (PR), potential runoff (PRO) and potential loss (PL). The sc-PDSI uses a two-level approach for the computation of soil moisture status. The upper level, the topsoil, can lose all of its moisture. Only once the topsoil has lost all of its moisture does the underlying soil start losing moisture, and then only a fraction is taken out at a time. The detailed procedure for the calculation of original PDSI and its subsequent derivatives can be found in Palmer (1965), Alley (1984) and Kim et al. (2002). In this study, the sc-PDSI programme developed by the Spanish National Research Council (CSIC) was used to generate time series of drought indices for each quaternary catchment in the basin. The sc-PDSI values were categorised based on the classification scale shown in Table 1, which was originally proposed for PDSI.

2.8 Temporal analysis of droughts

A drought event occurs any time the sc-PDSI values are continuously negative and ends when the values become positive. In this study, the number of drought events ensued at each quaternary catchment during the period of analysis was first identified. Each drought event was then characterised based on its duration, magnitude and intensity. Drought duration is

Table 1 Classification of moisture anomaly according to PDSI

PDSI	Classification
≥4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to −0.49	Near normal
−0.50 to −0.99	Incipient drought
−1.00 to −1.99	Mild drought
−2.00 to −2.99	Moderate drought
−3.00 to −3.99	Severe drought
≤4.00	Extreme drought

Source: Thompson (1999)

defined by the beginning and end of the event. The positive sum of the index values for all the months within a drought event is termed as drought magnitude. Therefore, intensity of a drought event is defined as the ratio of event magnitude to its duration. Decadal variation of drought in the basin during the period of analysis is examined by plotting the number of events identified in each decade versus time. Moreover, power spectral analyses were applied to each sc-PDSI time series data corresponding to each quaternary catchment to examine the periodicity of drought events in the region.

2.9 Spatial analysis of droughts

The prime objective of spatial analysis of drought is to identify quaternary catchments in the basin frequently hit by droughts and to depict the areal extent of droughts of different severity levels. The primary software package used to implement the spatial analysis of drought is ArcGIS, which provides ready-to-use functions to display, browse and query geo-referenced data. Attribute tables containing drought frequencies pertaining to the 11 quaternary catchments were geo-referenced/linked to coordinate points of their respective centroids (Table 2). Thus, each polygon representing the quaternary catchment represents the spatial database, while the drought frequencies computed at the respective catchment represent their corresponding attribute databases.

In this study, the spatial databases of monthly precipitation and temperature that were compiled and developed for Southern Africa (Lynch 2004; Schulze 2003) were used as input data for the computation of sc-PDSI values for the 11 quaternary catchments. Therefore, the sc-PDSI outputs and drought frequencies derived from these outputs represent attribute tables for each quaternary catchment. As a result, no interpolation was needed to convert a point meteorological database to spatial database while generating maps in ArcGIS environment.

Table 2 Geo-locations of the mean centres of the quaternary catchments in C52

Quaternary catchment	Geo-location		
	Latitude (dd)	Longitude (dd)	Altitude (metres)
C52A	−29.47	26.65	1529
C52B	−29.29	26.78	1447
C52C	−29.09	26.73	1463
C52D	−29.22	26.49	1383
C52E	−28.92	26.56	1372
C52F	−29.18	26.32	1363
C52G	−28.80	26.28	1306
C52H	−28.75	25.99	1290
C52J	−29.20	25.94	1312
C52K	−28.93	25.44	1199
C52L	−29.00	24.97	1159

dd decimal degrees

A multivariate technique, principal component analysis (PCA), was applied to the sc-PDSI time series data of the quaternary catchments to examine the spatial variability of droughts in the study area. The PCA is a technique for forming new uncorrelated variables that are linear combinations of the original ones (Sharma 1996). The principal components are computed and arranged in a decreasing order of importance based on their loadings (eigenvalues), meaning that the first component explains the maximum possible variance of total data and the last component is the one that least contributes to explain the variance of the original data. The number of principal components (PC) to be retained for spatial analysis is decided based on spree plot of the loadings. Precipitation and drought spatial variability have been studied by many authors through the application of PCA (Bonaccorso et al. 2003; Cannarozzo et al. 2006; Raziei et al. 2008, 2009).

2.10 Standardised Precipitation-Evapotranspiration Index

The calculation of Standardised Preicipitation-Evapotranspiration Index (SPEI) is also based on the original SPI calculation procedure (McKee et al. 1993). However, the SPEI uses the monthly difference between precipitation and PET. This represents a simple climatic water balance which is calculated at different time scales to obtain the SPEI. The monthly PET is calculated based on Thornthwaite (1948).

2.11 Relationship between sc-PDSI and SPEI

Both sc-PDSI and SPEI are meteorological drought indices with different input data requirements—sc-PDSI is data intensive as compared with SPEI. A simple correlation analysis was conducted between the outputs of the two indices in an attempt to explore the application of SPEI under data-scarce conditions.

2.12 Relationship between meteorological and hydrological drought events

Drought forecasting is one of the crucial steps in the development of drought early warning systems for an area. It is evident that there is an inherent time lag between meteorological and hydrological drought events. Identification of this lag can

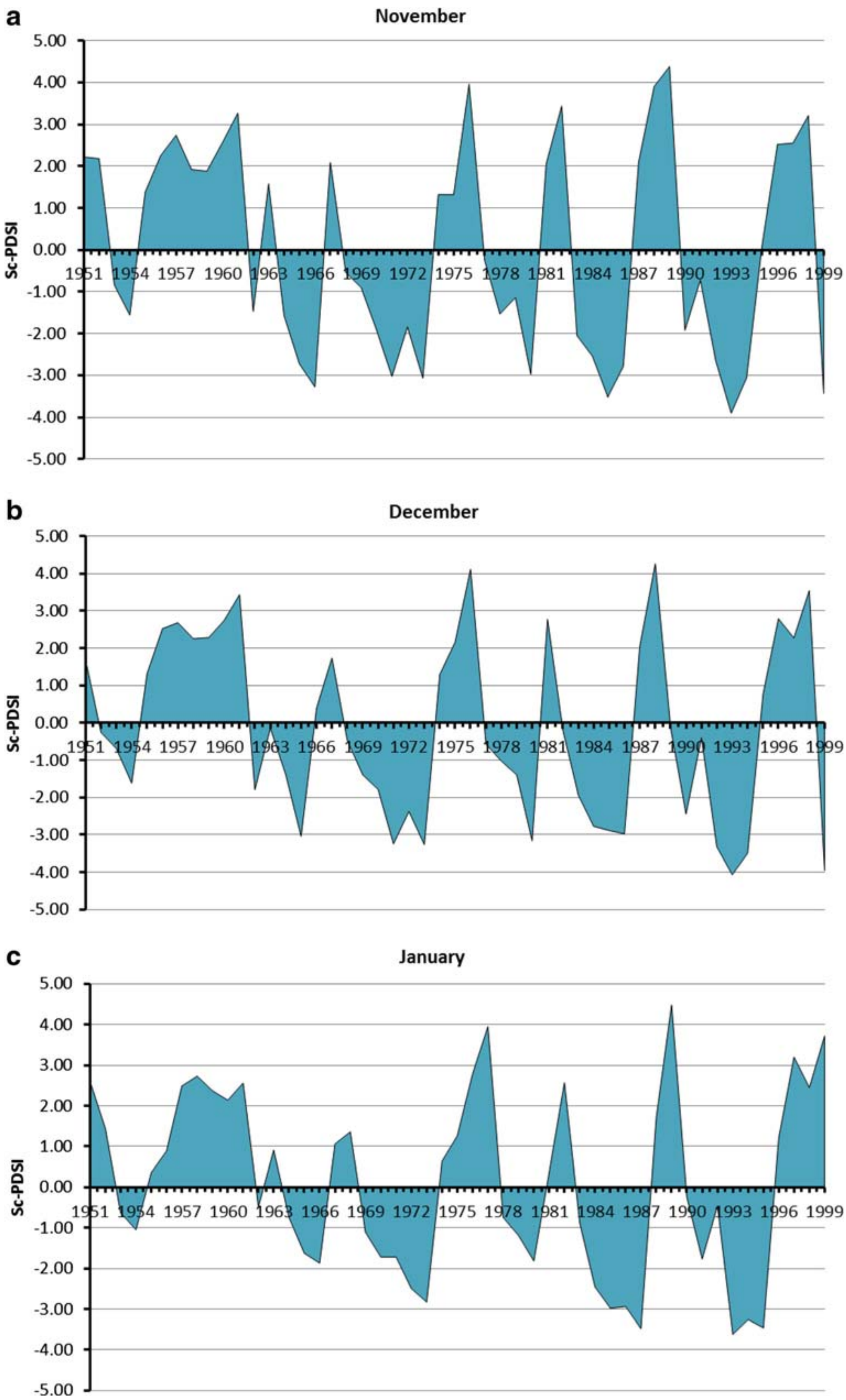

Fig. 2 Temporal variation of drought in the C52A quaternary catchment in the summer months (November–January) based on sc-PDSI

be used in forecasting hydrological droughts in an area. In this study, the average lag time between the two drought events was determined for the C52G quaternary catchment. Streamflow data of the Modder River, measured at the Bultfontein gauging station (outlet of C52G quaternary catchment), were used to identify hydrological drought events, whereas meteorological drought events in the quaternary were identified from the outputs of sc-PDSI.

3 Results and discussions

In this section, results of temporal and spatial analyses of droughts are presented and discussed. Moreover, relationships between different meteorological drought indices (sc-PDSI and SPEI), and between meteorological and hydrological droughts, are explored.

3.1 Temporal analysis of droughts

3.1.1 Identification of drought events

In this study, more emphasis was given to the characterisation of drought events during the three summer months of the year. Figure 2 shows the time series of sc-PDSI values during the three summer months (November, December and January) in the C52A quaternary catchment. Results of this analysis revealed that the number of drought events recorded in the catchment during the period of analysis in the months of November, December and January were 8, 7 and 6, respectively. It is interesting to note that one extreme drought event (in December 1993) was detected during the period of analysis, whereas no extreme drought event was detected in November or January. However, the result revealed that the summer peak drought events were recorded in the year 1993 in all 3 months, indicating that this year was the one of severest drought in the area in terms of both duration and magnitude.

Figure 3 shows plot of time series of monthly sc-PDSI values computed for the C52A quaternary catchment. Results of the characterisation of each drought events that were detected by the model in the quaternary catchment are presented in Table 3 for illustrative purpose. Considering both magnitude and intensity of drought events as indicators of drought severity, the most severe drought event was recorded during the period December 1982–July 1987, followed by the event that ensued during the period December 1989–September 1995. However, in terms of event duration the drought event that was recorded during October 1968–December 1973 was found to be the longest. Widespread and sustained droughts that have periodically afflicted Southern Africa over the past three decades are those in 1964, 1968, 1970, 1982, 1983 and 1984, are often associated with El Niño (Preston-Whyte and Tyson 1988, cited in Dube and Jury 2002).

Table 3 Characterisation of drought events detected in C52A

Onset	End	Duration (months)	Magnitude	Intensity
Dec 1952	Dec 1954	25	−16.17	−0.65
Jan 1962	Dec 1962	12	−11.71	−0.98
Dec 1963	Nov 1966	36	−68.86	−1.91
Oct 1968	Dec 1973	63	−122.07	−1.94
Nov1977	Dec 1980	38	−60.33	−1.59
Dec 1982	Jul 1987	56	−163.75	−2.92
Dec 1989	Sep 1995	70	−159.48	−2.28
Feb 1999	Dec 1999	11	−20.51	−1.86

Figure 4 shows decadal variation of drought events in the C52A quaternary catchment over 50 years. It can be noted from the plot that the number of extreme and moderate drought events recorded in the catchment during these five decades show an increasing trend. However, the numbers of both mild and severe drought events appear to show increasing trends during the first three decades and a declining trend (moderate drought) and cyclical trend (mild drought) afterwards. The Spearman's rank correlation method (with $t_{critical}$ *= 3.18 and df = 3) was used to test whether the trends shown in the plots are statistically significant at 5 % significance level. The observed/calculated values of t for each drought category are shown on the plots (obs. t). Results of the analysis showed that the increasing trends exhibited by both extreme and moderate drought categories are statistically significant at 5 % significance level. However, both mild and severe drought categories showed no significant trend at 5 % significance level.*

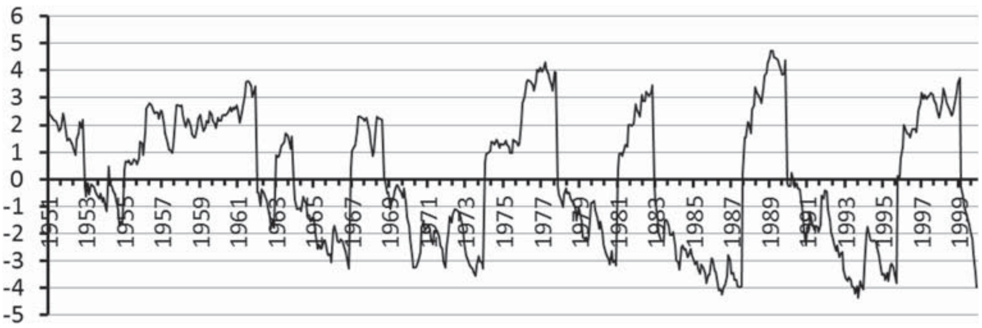

Fig. 3 Time series of sc-PDSI values recorded at C52A

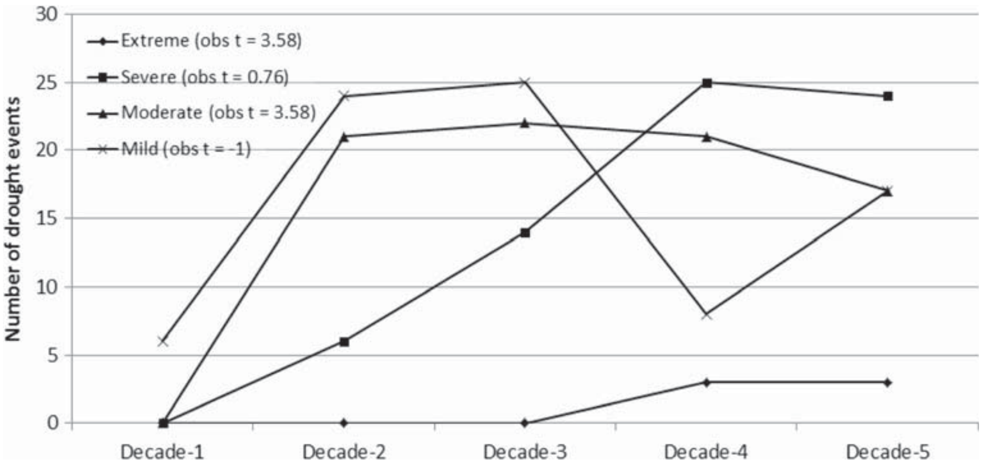

Fig. 4 Decadal variation of drought in the C52A quaternary catchment based on sc-PDSI

3.1.2 Power spectral analysis

Power spectral analyses were applied to each sc-PDSI time series data corresponding to each quaternary catchment to examine the periodicity of drought events in the region. Analysis of Lomb periodogram of sc-PDSI for C52A quaternary catchment shows that the frequency of the strongest peak in the periodogram is 0.01129 cycles/month. This corresponds to a period of 1/(0.01129 cycles/month) ≅ 7 years/cycle. However, it is interesting to note that multiple peaks (varying between 3 and 5) were observed in all quaternary catchments based on both 5 and 1 % significance levels, which might be attributed to the existence of several periodic components in the time series with different periods. Dominant frequencies corresponding to the remaining quaternary catchments in the study area were calculated in similar fashion and these results are presented in Table 4. The dominant periodicities of the sc-PDSI time series in the study area generally vary between 6 years (C52E) and 16 years (C52K).

3.2 Spatial analysis of droughts

3.2.1 Spatial extent/coverage of drought events

Figure 5a–d presents plots of the areal extent (in percentage of the total area of the catchment) of various drought severity classes computed using the index during the years 1950–1999. The results herewith presented for illustrative purposes are for the three summer months. Similar summary results can be produced for the other seasons of the year.

Considering extreme drought events, the maximum areal coverage was recorded in November 1998, followed by December 1998 and January to December 1999. In November 1998, about 91 % of the total area of the basin experienced an extreme drought event. However, during the entire summer months of 1999 about 43 % of the total area of the basin was struck by extreme drought events.

Considering the areal coverage of severe drought events, and the persistence throughout the summer months, the period 1991–1994 was found to be the one of most critical drought years. The maximum areal coverage of severe drought events in the basin was recorded in January 1994 (72 %), followed by December 1991 (61 %). This study revealed that, in general, 50 % or more of the total area of the basin was hit by severe drought events in six summer months during the period of analysis, namely November 1965 (50 %), December 1991 (61 %), November 1993 (58 %), December 1993 (50 %), November 1994 (51 %) and January 1994 (72 %). It can be noted that the number of drought years and months increases with the decreasing severity level, i.e. the number of mild drought years during the time of analysis is highest compared with all other drought categories.

3.2.2 Drought prevalence in the basin

Drought prevalence in the basin was computed based on the relative frequency of drought events in a given category with respect to the total number of events recorded during the period of analysis (Fig. 6). The purpose of this analysis was to identify areas prone to droughts

Table 4 Periodicities of the sc-PDSI time series in the quaternary catchments

Q/catchment	C52A	C52B	C52C	C52D	C52E	C52F	C52G	C52H	C52J	C52K	C52L
Frequency (years)	7	10	10	7	6	7	15	15	7	16	7

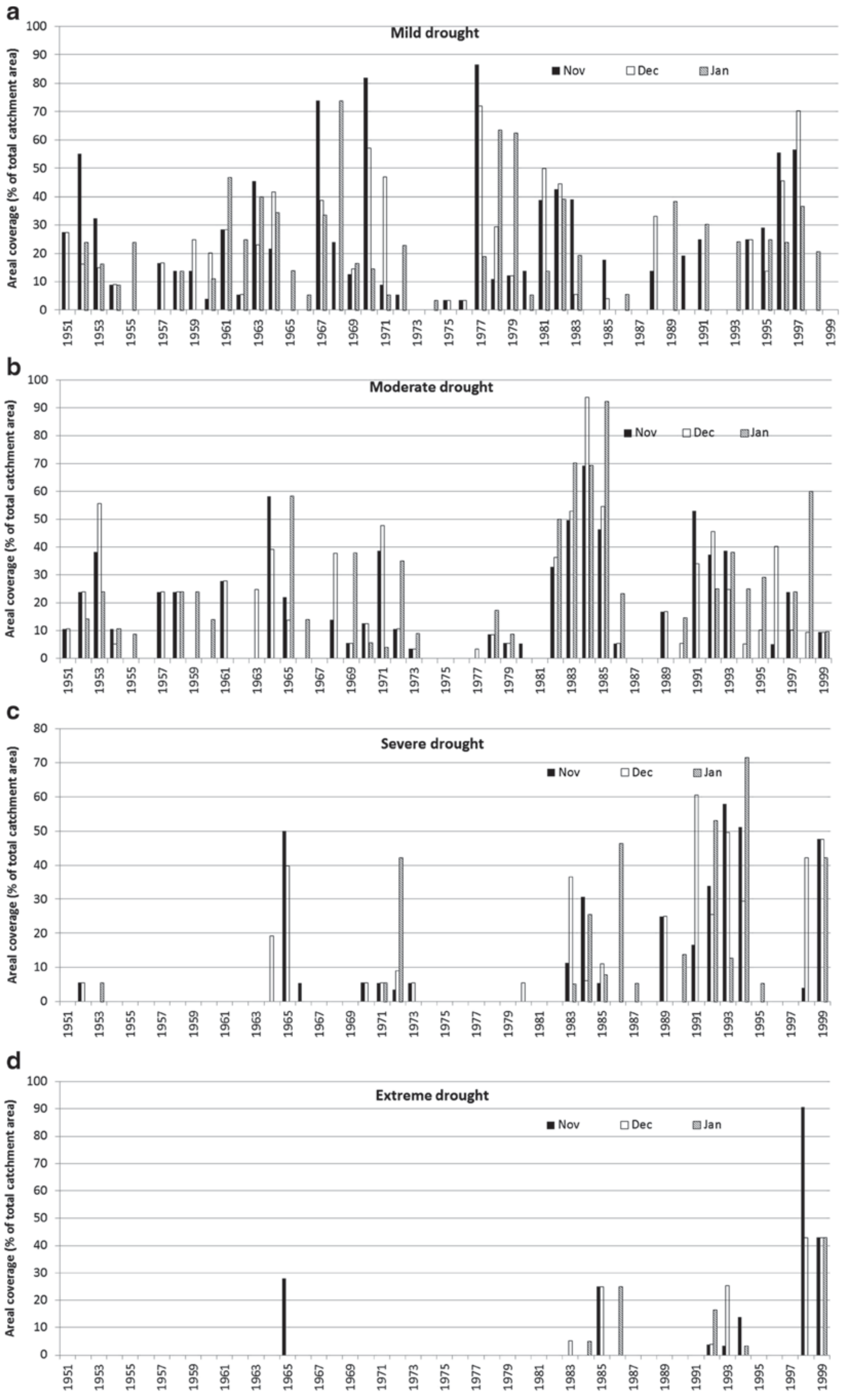

Fig. 5 a–d Areal coverage of droughts of various severity levels during the three summer months.

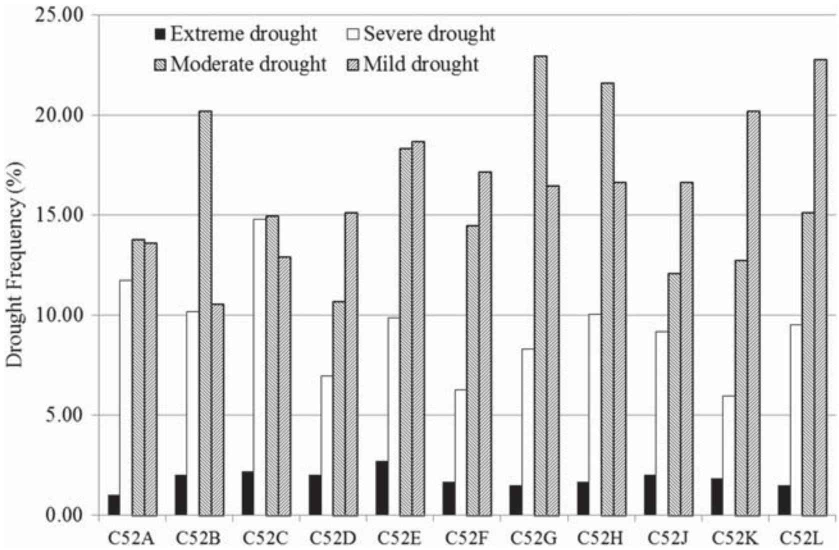

Fig. 6 Relative frequency of drought events in the basin

of various severity levels during the period of analysis. Results of this analysis revealed that extreme drought events occurred most frequently in the C52E (2.72 %) quaternary catchment, followed by C52C (2.21 %). However, the relative frequency of severe drought events is highest in the C52C (14.80 %) quaternary catchment, followed by C52A (11.73 %).

Figure 7 shows the spatial extent of drought frequencies corresponding to the four drought categories based on sc-PDSI. It can be noted that mild drought events are highly frequent in the western section of the catchment and decreases towards the east, whereas frequency of moderate drought events decreases from north to south. However, the frequency of severe and extreme drought events have a similar general distribution—both frequencies decrease from east to west across the catchment area.

3.2.3 Principal component analysis

Following inspection of the scree plot of the eigenvalues of the principal components, two components (PC1 and PC2) were retained for spatial mapping. The cumulative total explained variance by the two retained PCs is 78.54 %—the first PC explained much of the total variance (68.87 %), and the second PC explained 9.67 %. Figure 8 shows the spatial patterns of the loadings over the study catchment. In the case of PC1, the maximum loading (drought variability) is centred in the eastern (C52A), middle (C52F) and northern (C52G and C52H) quaternary catchments and decrease west. Based on PC2 loadings, the maximum loadings are centred in the northern (C52G and C52H) and western (C52L) quaternary catchments and slowly decreases east. It can be noted that drought variability in the northern and middle sections of the catchment follow similar patterns under both PC1 and PC2 loadings.

3.3 Relationship between sc-PDSI and SPEI

Figure 9a–d illustrates the relationships between the outputs of SPEI based on 3-, 6-, 12- and 24-month time scales and sc-PDSI in the C52A quaternary catchment. Results of these analyses (through visualisation of the plots and their correlation coefficients) revealed that the shape of the scatter plots (cloud of points) varies with SPEI time scale. It can be noted that the clustering of points around the best-fit line is loosest in Fig. 9a and tightest in Fig. 9d. In general, the points become more tightly clustered around the best-fit line as the SPEI time-scale increases indicating that the correlation between the indices becomes stronger as the time-scale increases. This confirms the effectiveness of sc-PDSI in monitoring long-term impacts of meteorological droughts such as hydrological droughts (manifested by reduction in streamflow, reservoir level, groundwater table etc). Vicente-Serrano (2014) also reported that the SPEI has shown to correlate well with the sc-PDSI on longer time scales (>18 months).

3.4 Relationship between meteorological and hydrological drought events

Figure 10 shows a plot of the Modder River flow at Bultfontein stream gauging station (1971–1999) at the outlet of C52G quaternary catchment. This analysis was undertaken in order to determine if there is a link between meteorological drought events identified by sc-PDSI and low flows in the Modder River. It is expected that low flows (an indication of hydrological droughts) at Bultfontein gauging station are preceded by meteorological drought events in the upper catchment (C52G). Edossa et al. (2010) reported that hydrological

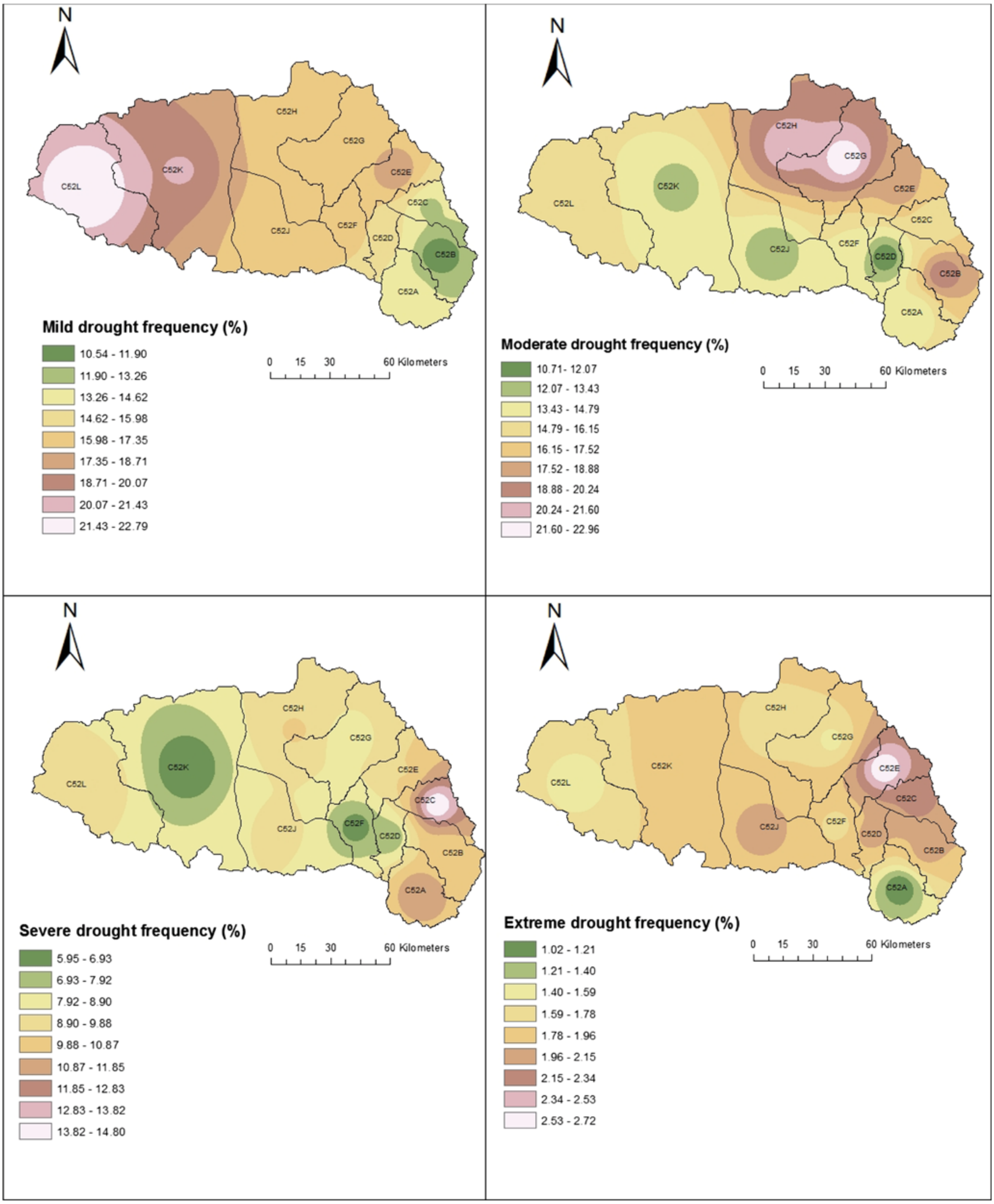

Fig. 7 Spatial variation of drought frequency in the basin based on sc-PDSI

drought events lag behind meteorological drought events by an average of 7 months. Figure 11 shows a plot of sc-PDSI outputs for the same period (1971–1999) for the purpose of comparison.

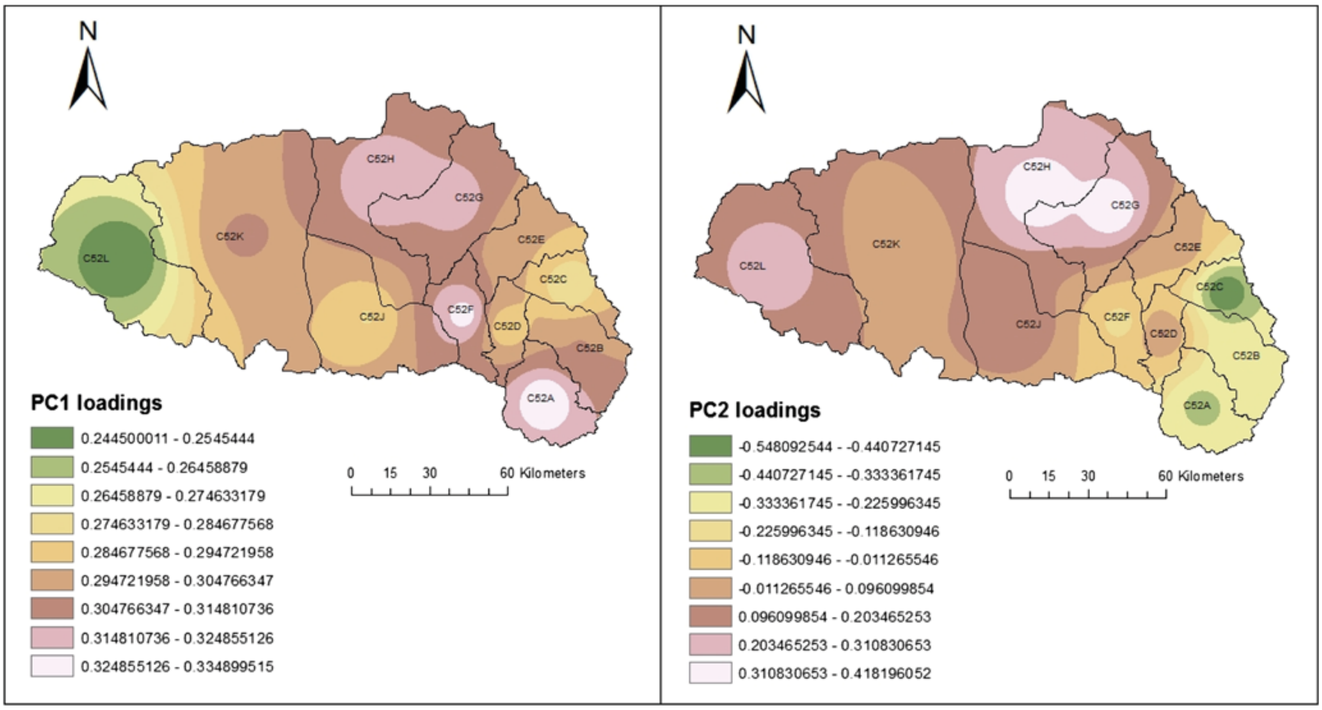

Fig. 8 Spatial patterns of drought in the study catchment based on PC1 (**a**) and PC2 (**b**) loadings

It can be noted that most of the drought events identified by sc-PDSI (see events marked as 1–5 on the Figs. 10 and 11) in the quaternary catchment have been followed by low-flow events at Bultfontein stream gauging station. Results of the analysis of the lag time between the onsets of drought events identified by sc-PDSI and low flows revealed that the lag time between the hydrological and meteorological drought events is in the range of 8 to 14 months (with an average lag time of 10 months). It is interesting to note that the finding of this study agrees fairly with results previously reported by Edossa et al. (2010).

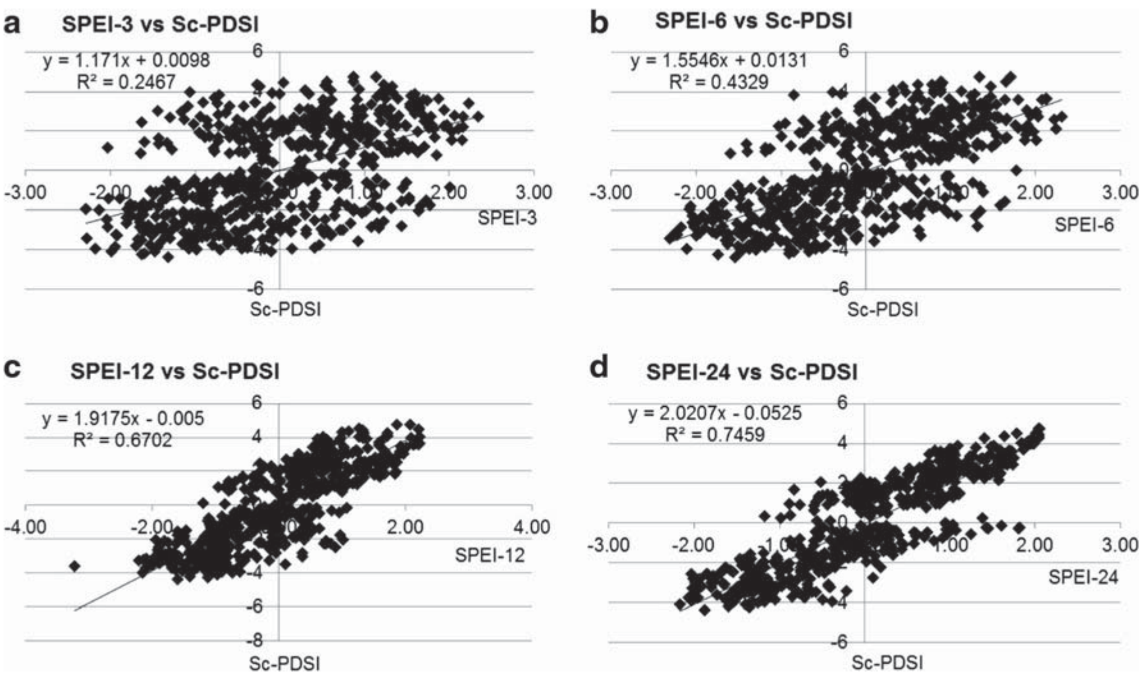

Fig. 9 **a**–**d** Relationship between sc-PDSI and SPEI at various time scales in C52A.

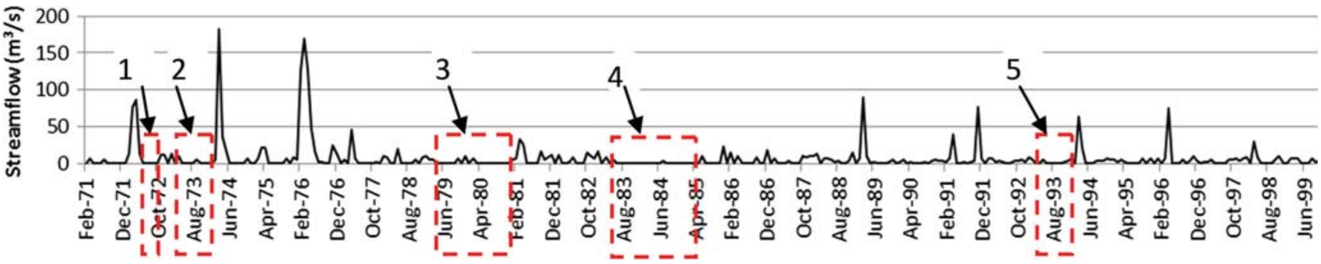

Fig. 10 Plot of Modder River flow at Bultfontein gauging station

4 Conclusion

Long-term historical records (1950–1999) of meteorological data were used in this study to characterise droughts in the central region of South African (Modder River basin) both spatially and temporally using sc-PDSI. Attempts were also made to establish relationships between both sc-PDSI drought indices and meteorological and hydrological droughts. The number of drought events of varying severity levels identified by sc-PDSI in the study area varies from eight (C52A) to sixteen (C52D). Analysis of the seasonal variation of drought events in the C52A quaternary catchment shows that, in all three the summer months, maximum drought events (minimum sc-PDSI values) were detected in 1993. Further analysis of decadal variation of drought events shows that the number of extreme and moderate drought events showed statistically significant increasing trends with time (at 5 % significant level) in the C52A quaternary catchment. Results of a spectral analysis of sc-PDSI time series revealed the existence of periodicities—the dominant periodicities generally vary between 6 years (C52E) and 16 years (C52K). It was also found that the relationship between the two popular meteorological indices (SPEI and sc-PDSI) showed improvements as the SPEI time-scale increases.

The sc-PDSI was also used to analyse the prevalence of drought events of varying categories in the Modder River basin. The study found that the maximum areal coverage of an extreme drought event was detected in November 1998 (97 %), followed by December 1998 and all summer months of 1999 (43 %). In terms of areal coverage and persistence through summer months of severe droughts, the period 1991–1994 was found to be the most critical one. The maximum areal coverage of severe drought events in the basin was recorded in January 1994 (72 %), followed by December 1991 (61 %). It can be noted that the number of drought years and months increases with the decreasing severity level, i.e. the number of mild drought years during the time of analysis is highest compared with all other drought categories.

Results of the spatial analysis of droughts for various categories revealed that mild and moderate droughts occurred most frequently in the Lower (C52L) and Middle (C52G and C52H) Modder, respectively. However, the most frequent severe and extreme drought events were both recorded in the Middle Modder (C52C and C52E, respectively), whereas extreme drought events occurred least frequently in Upper Modder (C52A).

It is quite common that hydrological droughts typically lag behind the occurrence of meteorological and agricultural droughts. More time elapses before precipitation deficiencies show up in the components of the hydrological systems. Results of analysis of the lag time between the onsets of drought events identified by sc-PDSI and low flows revealed that the lag time between the hydrological and meteorological drought events is in the range of 8 to 14 months (with an average lag time of 10 months). It is believed that this lag time can be utilised by policy makers as a planning period for the management of impacts of hydrological droughts.

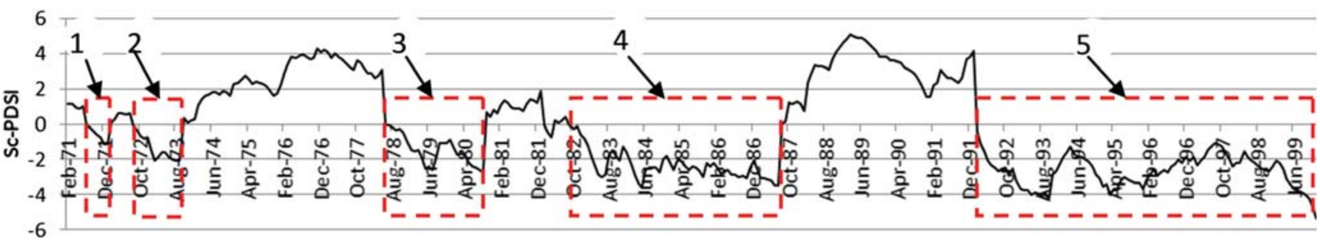

Fig. 11 Plot of sc-PDSI in C52G quaternary catchment

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References

Alley WM (1984) Palmer Drought Severity Index: limitations and assumptions. J Clim Appl Meteorol 23:1100–1109

Backeberg GR, Viljoen M (2003) Drought management in South Africa. Paper presented at a workshop of the ICID Working Group on Irrigation under Drought and Water Scarcity, Tehran, I.R. of Iran, 13–14 July 2003

Bonaccorso B, Bordi I, Cancelliere A, Rossi G, Sutera A (2003) Spatial variability of drought: an analysis of the SPI in Sicily. Water Resour Manag 17:273–296

Burke EJ, Brown SJ (2008) Evaluating uncertainties in the projection of future drought. J Hydrometeorol 9:292–299

Burke EJ, Brown SJ, Christidis N (2006) Modelling the recent evolution of global drought and projections for the twenty-first century with the Hadley centre climate model. J Hydrometeorol 7:1113–1125. doi:10.1175/JHM544.1

Cannarozzo M, Noto LV, Viola F (2006) Spatial distribution of rainfall trends in Sicily (1921–2000). Phys Chem Earth 31: 1201–1211

Ceglar A, Črepinšek Z and Kajfež-Bogataj L (2008) Analysis of meteorological drought in Slovenia with two drought indices. Proceedings of BALWOIS 2008, 27–31 May, 2008, Ohrid, Republic of Macedonia 2008

Dai A (2011) Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. J Geophys Res 116

Dai A, Trenberth KE, Karl TR (1998) Global variations in droughts and wet spells: 1900–1995. Geophys. Res Lett 25:3367–3370

Dai A, Trenberth KE, Qian TT (2004) A global dataset of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. J Hydrometeorol 5:1117–1130

Du Pisani LG, Fouch HJ, Venter JC (1998) Assessing rangeland drought in South Africa. Agri Sys 57(3):367–380

Dube LT, Jury MR (2002) Structure and precursors of the 1992/93 drought in KwaZulu-Natal, South Africa, from NCEP reanalysis data. Water SA 29(2):201–208

Durand W (2010) Drought adaptation measures and risk tolerance of commercial, small-scale and subsistence maize farmers in the Free State and North-West Provinces of South Africa. Available from http://www.docstoc.com/docs/93179035/Drought-adaptation-measures-and-risk-tolerance-of-commercial. Accessed 18 June 2012

Edossa DC, Babel MS, Gupta AD (2010) Drought analysis in the Awash River basin, Ethiopia. Water Resour Manag 24:1441–1460

Heim Jr RR (2000) Drought indices: a review. In: Wilhite DA (ed) Drought: a global assessment. Routledge, London, pp. 159–167

Heim RR (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteorol Soc 83:1149–1165

IPCC (2013) Summary for policy makers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley BM (eds) Climate change 2013: the physical science basis. Cambridge University Press, Cambridge, UK

Jury MR, Levey K (1993) The Eastern Cape drought. Water SA 19(2): 133–137

Keyantash J, Dracup JA (2002) The quantification of drought: an evaluation of drought indices. Bull Am Meteorol Soc 83:1167–1180

Kim TW, Valdes JB, Aparicio J (2002) Frequency and spatial characteristics of droughts in the Conchos river basin, Mexico. Water Int 27(3):420–430

Lloyd-Hughes B, Saunders MA (2002) A drought climatology for Europe. Int J Climatol 22:1571–1592

Lynch SD (2004) The development of a raster database of annual, monthly and daily rainfall for southern Africa. Report to the Water Research Commission. Pretoria, Water Research Commission

McKee TB, Doesken NJ and Kliest J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th conference on applied climatology, 17–22 January, Anaheim, CA. American Meteorological Society, Boston, MA. 179–184

Mika J, Horva'th Sz Makra L, Dunkel Z (2005) The Palmer Drought Severity Index (PDSI) as an indicator of soil moisture. Phys. and Chem. Ear 30:223–230

Palmer WC (1965) *Meteorological droughts*. U.S. Department of Commerce Weather Bureau Research Paper 45:58

Raziei T, Bordi I, Pereira LS (2008) A precipitation-based regionalization for western Iran and regional drought variability. Hydrol Earth Syst Sci 12:1309–1321

Raziei T, Saghafian B, Paulo AA, Pereira LS, Bordi I (2009) Spatial patterns and temporal variability of drought in western Iran. Water Res. Manage 29:439–455

Rouault M, Richard Y (2003) Intensity and spatial extension of drought in South Africa at different time scales. Water SA 29(4):489–500

Rouault M, Richard Y (2005) Intensity and spatial extent of droughts in southern Africa. Geophys Res Lett 32:15

Schulze RE (2003) Development of a database of gridded daily temperatures for Southern Africa. University of Natal, Pietermaritzburg, School of Bioresources Engineering and Environmental Hydrology. ACRUcons Report, 41:82

Schulze RE, Maharaj M, Warbuton ML, Gers CJ, Horan MJC, Kunz RP, Clark DJ (2008) South African Atlas of Climatology and Agrohydrology. Water Research Commission

Seymour C and Desmet P (2009) Coping with drought—do science and policy agree? SA J Sc 105

Sharma S (1996) Applied multivariate techniques. John Wiley & Sons 512

Thompson MW (1999) South African national land cover database project, data users' manual: final report (phases 1, 2, and 3). Client report ENV/P/C 98136. Pretoria: CSIR

Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38:55–94

Van der Schrier G, Efthymiadis D, Briffa KR, Jones PD (2007) European Alpine moisture variability for 1800–2003. Int J Climatol 27:415–427

Van der Schrier G, Briffa KR, Jones PD, Osborn TJ (2006a) Summer moisture variability across Europe. J Clim 19: 2818–2834

Van der Schrier G, Briffa KR, Osborn TJ, Cook ER (2006b) Summer moisture availability across north America. J Geophys Res 111

Vasiliades L and Loukas A (2009) Hydrological response to meteorological drought using the Palmer drought indices in Thessaly, Greece. Proceedings of conference on Water Resources Management: New Approaches and Technologies, 14–16 June 2007, Chania, Greece

Vasiliades L, Loukas A and Liberis N (2011) A water-balance derived drought index for pinios river basin, Greece. Water Resour Manag 25:1087–1101

Vetter S (2009) Drought, change and resilience in South Africa's arid and semi-arid rangelands. SA J Sc 105

Vicente-Serrano SM, Begueria S, Lopez-Moreno JI (2010) A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23:1696–1718

Vicente-Serrano SM (2014) The climate data guide: Standardized Precipitation Evapotranspiration Index (SPEI). Available from https://climatedataguide.ucar.edu/climate-data/standardized-precipitation-evapotranspiration-index-spei. Accessed 19 Nov 2014

Wells N, Goddard S, Hayes MJ (2004) A self-calibrating Palmer Drought Severity Index. J Clim 17:2335–2351

Woyessa YE, Welderufael WA, Kinyua JDM, Kundhlande G and Tsumake OP (2011) Land-water linkages: agent-based modelling of land use and its impact on water resources. Water Research Commission Report No 1753/1/10