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ORIGINAL RESEARCH ARTICLE

ANALYZING THE SPATIAL AND TEMPORAL DYNAMICS OF RAINFALL AND DROUGHT IN THE VALL RIVER BASIN, SOUTH AFRICA.

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ABSTRACT

Climate change continues to have devastating effects worldwide, particularly through drought, impacting billions of people. A recent study focused on the Vaal area in South Africa, a semi-arid region reliant on the Vaal River, a vital water resource. Researchers utilized the Standardized Precipitation Index (SPI) and Standardized Precipitation and Evapotranspiration Index (SPEI) to assess rainfall variability, evapotranspiration, drought, and trends over four decades. The results show some characteristics of Rainfall Patterns; such as Peak precipitation occurs during the January to March summer months while Drought Years: 2016 was identified as a hydrologically driest year for the Vaal River based on SPI and SPEI analysis at 12- and 24-month scales. Similarly, Agricultural Drought: Years like 1983, 1999, 2016, and 2019 exhibited agricultural drought, particularly evident in SPEI/SPI -3 and SPEI/SPI -6, crucial for local irrigation and agricultural production. Furthermore, for Temporal Consistency: SPI and SPEI demonstrated increasing temporal consistency with longer timescales until 2019, except for SPEI/SPI-1 and SPEI/SPI-48, which did not accurately represent drought in the Vaal River basin. Interestingly, the study highlights the escalating impact of climate change-induced drought in the Vaal area and underscores the importance of SPEI in assessing drought severity. Therefore, as climate conditions worsen globally, such analyses are vital for informed decision-making and effective water resource management.

1.0 Introduction

Drought is believed to be one of the world's most harmful natural disasters (Zhong, Sun and Di, 2021), its severity has intensified in recent decades due to climate change and associated effects, leading to shifts in climatological patterns like rainfall and temperature. Drought has influenced larger regions when contrasted to other hazards such as floods, which are restricted to floodplains, coastal regions, storm tracks, or fault zones (Svoboda *et al.*, 2015). Drought events are anticipated to rise in the 21st century (Guo, 2012; Huang *et al.* 2016; Bahta and Myeki 2022), necessitating robust monitoring and assessment measures (Pei *et al.*, 2020).

Drought is characterized by a prolonged period of water scarcity resulting from inadequate precipitation and heightened evaporative demand, ultimately leading to substantial environmental and socioeconomic consequences. It can be categorized into four types: meteorological, hydrological, agricultural (or vegetative), and socioeconomic drought. Meteorological drought refers to a lack of precipitation. Hydrological drought occurs when surface and groundwater resources are depleted, affecting rivers, lakes, reservoirs, and aquifers. Agricultural drought arises from precipitation deficits during the growing season, limiting crop growth and development. Droughts have had devastating effects on many nations, leading to declines in agricultural productivity, portable water supply, and economic stability, with severe cases resulting in famine (Tladi, Ndambuki and Salim, 2022). In Southern Africa, drought has been a significant concern since the 1970s, with

El Niño and the Southern Oscillation (ENSO) warm events exacerbating drought impacts (Rouault and Richard, 2005; Cane *et al.*, 1997; Enfield, 1989; Ogallo, 1979).

South Africa, in particular, has faced several drought spells, with notable occurrences in 1964, 1986, 1988, 1990, 1995, 2002–2004, and 2015–2019 (Bhaga *et al.*, 2020; Mishra and Singh, 2010). The 2015–2016 hydrological year marked the worst drought in 23 years, resulting in crop declines, livestock mortality, and water constraints in major cities (Department of Agriculture Forestry and Fisheries, 2010). Rising water demand in South Africa has been exacerbated by recurring droughts, which degrade water quality, disrupt hydrological systems, and stress groundwater recharge. Climate change and variability are expected to increase the frequency and severity of droughts, further straining limited water resources.

This study examines rainfall variability and drought impacts in the Vaal River Basin, a vital water source for agriculture, industry, and domestic use. Understanding the effects of drought is crucial for sustainable water resource management and developing effective mitigation strategies. Drought indices, which quantify drought onset, duration, intensity, and frequency, offer a valuable framework for simplifying complex climate-hydrology interactions and assessing drought severity.

The Standardized Precipitation Index (SPI) and the Standardized Precipitation Evaporation Index (SPEI) are two of the most widely used drought indexes amongst others. The SPI as coined by McKee *et al.* (1993) considered precipitation while the SPEI was first proposed by Vicente-Serrano *et al.* (2010) as an improvement over the Standardized Precipitation Index (SPI), for the reason that it considers variables like temperature and evapotranspiration to effectively provide a water balance standardized result. Compared to SPI, SPEI provides advantages in assessing water balance, standardization for comparability, flexibility across timescales, and broad regional applicability, making it highly effective for drought monitoring and decision-making. Remote sensing (RS) data, such as those from MODIS, provide valuable large-scale observations for drought monitoring, enabling the retrieval of variables like precipitation, evapotranspiration, and vegetation health. This study will evaluate drought occurrences in the Vaal River Basin from 1983 to 2023. The aim is to analyse temporal and spatial drought patterns and their impacts on water resources and the environment, supporting sustainable management in the region. The study main objectives were to utilize SPI and SPEI drought indices to evaluate drought patterns from 1983 – 2023, produce rainfall maps for the Vaal River basin and adjacent provinces, identifying evapotranspiration patterns and assess the extent of drought effects in the study area. This research aims to suggest early warning systems for drought occurrence along the Vaal River basin, essential for ensuring water availability to support the country's economy and population.

2. Materials and Methods

2.1 The Study Area

The Vaal River Basin, located between 26.5 - 28.5°S, 24 - 29.5°E in central South Africa (Fig 1), is the main tributary of the Orange River, which drains into the Atlantic Ocean. Flowing westward near Johannesburg, it spans several provinces, including Gauteng, Free State, Mpumalanga, Northwest, and Eastern Cape, and supplies water to major cities such as Johannesburg, Pretoria, and Bloemfontein. The basin lies within a sub-tropical dry savanna climate, with mean annual evaporation (~1,300 mm) exceeding rainfall (~600 mm). Rainfall varies spatially, from 800–1,000 mm in the east to about 300 mm in the west, with a mean annual temperature of 15 °C. Land use is dominated by agriculture, including the large Vaalharts irrigation scheme, making the basin critical for both water resource management and food production.

2.2 Sources of Data and Data Analysis

Rainfall variability in the Vaal River basin (1983-2023) was analysed using a combination of rain gauged and remotely sensed data. Precipitation and temperature records were obtained from the South African Weather Service, CHIRPS, and MODIS evapotranspiration (MOD16A2). Rainfall mapping and study area delineation was performed using ArcGIS 10.1, while drought indices were calculated using R. Rainfall trend analysis was conducted using the Mann-Kendall Trend Test and Sen's Slope estimator. The Mann-Kendall test results, including the test statistic (Z), p-value, and Sen's slope (Q), were calculated using R.

The Standardized Precipitation Index (SPI) was based solely on precipitation, whereas the Standardized Precipitation Evapotranspiration Index (SPEI) incorporated both precipitation and Potential Evapotranspiration (PET), estimated using the Hargreaves method. Data from six meteorological stations were averaged to represent the drought severity and duration along the lower, middle, and upper Vaal River basins using the

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SPI and SPEI indices. Drought assessment was conducted across multiple timescales (1-48 months), with shorter timescales capturing rapid changes and longer timescales reflecting extended drought conditions.

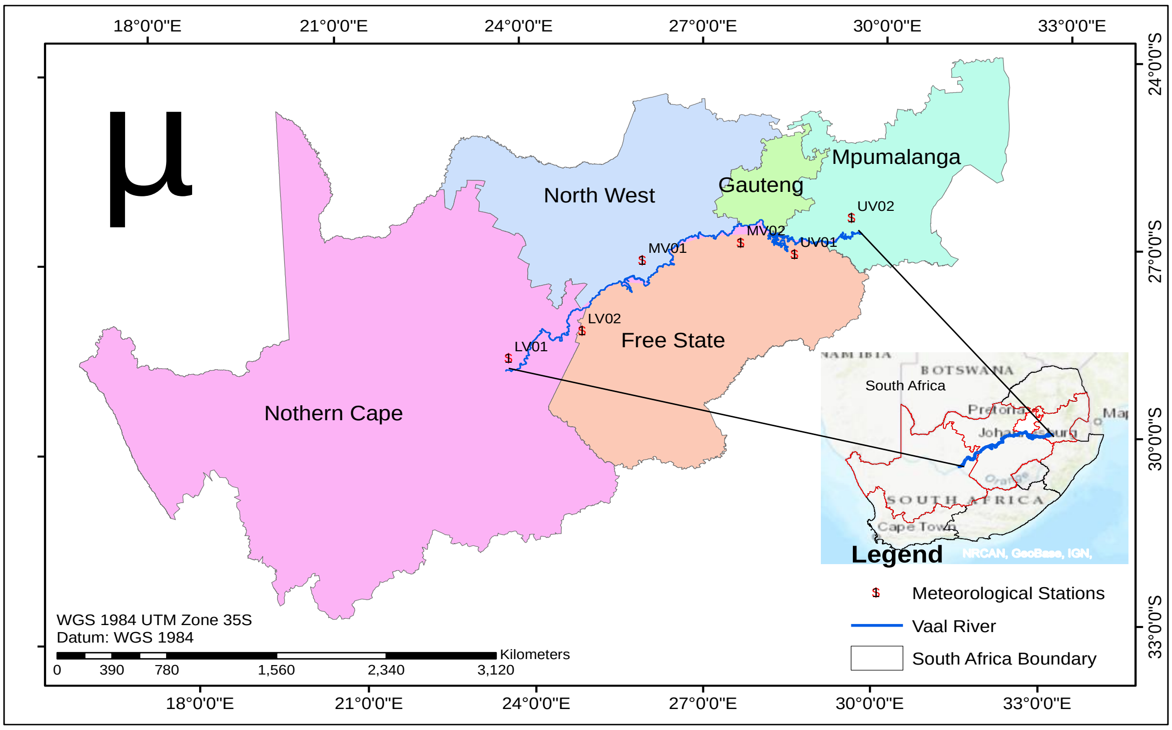

Figure 1: Study Area

2.3 SPI and SPEI Indices

The SPI was offered by Mc Kee, Doesken and Leist in 1993. The Index is based on analysing precipitation as the sole variable been considered making its evaluation easier. It can be calculated over different time scales and is suitable to calculate drought among different time regions (Cacciamani *et al.*, 2007). It can be calculated as given in the equation 1.

$$SPI = \frac{p - p^*}{\sigma_p} \quad 1$$

Where p = observed monthly precipitation, p^* = mean of monthly precipitation and σ_p = standard deviation of observed precipitation.

The SPEI was proposed as an improvement over the Standardized Precipitation Index (SPI). It is built on the water balance principle, utilizing the difference between precipitation (P) and potential evapotranspiration (PET) as input conditions to estimate the wet and dry conditions of an area (Tirivarombo, Osupile and Eliasson, 2018). A comprehensive explanation of the SPEI theory was offered by Vicente-Serrano *et al.* (2010) and the climate-water balance was calculated:

$$D_i = P_i - PET_i \quad 2$$

Where D_I is the moisture deficit (mm) at the month *i*, P_i is the precipitation (mm) at the month *i, and* PET_i is the potential evapotranspiration (mm) at the month *i*.

As can be seen, there are various approaches to analyse drought, SPI, which uses only precipitation data, and SPEI, which uses PET and precipitation simultaneously, are notable among the most widely used methods in the literature (Tirivarombo, Osupile and Eliasson, 2018; Eris *et al.*, 2020; Pei *et al.*, 2020). Although these two methods use different input parameters, their calculations are similar (Danandeh *et al.*,, 2022). Due to their similarity in results, the study used the more recent indices which is the SPEI. The formula below has been used to calculate SPEI.

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

$$W = -\sqrt{2\ln(P)} \quad for\ P \leq 0.5 \quad 4$$

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$$C_0 = 2.515517, C_1 = 0.802853, C_2 = 0.010328$$

$$d_1 = 1.432788, d_2 = 0.189269, d_3 = 0.001308$$

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. Table 1 indicates the drought severity classification adopted for the study.

Table 1: Drought severity classification for SPEI and SPI (Soydan Oksal, 2023)

Class	SPEI Value	SPI Value
Extremely wet	$\geq$ 2.0	$\geq$ 2.0
Severely wet	1.5 to 1.99	1.5 to 1.99
Moderately wet	1.0 to 1.49	1.0 to 1.49
Near normal	-0.99 to 0.99	-0.99 to 0.99
Moderately dry	-1 to -1.49	-1 to -1.49
Severely dry	-1.5 to -1.99	-1.5 to -1.99
Extremely dry	$\leq$ - 2.0	$\leq$ - 2.0

The SPEI drought index has been globally recognised and used. It can be calculated at various timescales such as 1-, 3-, 6-, 12-, 24- and 48-months to represent different drought conditions. According to Mishra and Singh (2010), a short timescale (1 or 3 months) is appropriate to estimate meteorological drought; a 3-month or 6-months timescale is generally used for agricultural drought, whereas a larger timescale such as 12 or 24 months is more suitable for evaluating hydrological drought and water resources. This study will focus more on the results from the 12-, 24-month timescale to adequately understand drought frequency and magnitude in the Vaal River basin.

3. Results and Discussion

3.1 Seasonal Variation of Rainfall

3.1.1 Dry season rainfall trends in the Vaal River and its surrounding provinces.

During the dry season, average rainfall in the Vaal River Basin and surrounding provinces was generally low, with notable variability and lowest rainfall recorded in 1983, 2003, and 2013, especially in Mpumalanga. Similarly Rouault and Richard (2003), indicated rainfall in the region of South Africa is highly variable and unevenly distributed. Rainfall along the river decreased from the upper to lower Vaal, while the Northern Cape in the lower western basin often received the highest precipitation (Figure 2). In 1983, rainfall along the Vaal peaked at 64.8 mm in Mpumalanga. Additionally, Mukhawana *et al.* (2023) found out that winter rainfall was approximately 30 and 70mm around the North-western cape and southwestern Cape. Rainfall along the Vaal remained near 0–5.3 mm, while the Northern Cape recorded up to 106.7 mm. In 2023, the Vaal experienced 1.75–40.7 mm of rain, and surrounding provinces ranged from 1 mm to 117.8 mm in the Northern Cape.

3.1.2 Wet season rainfall trends in the Vaal River and its surrounding provinces.

Figure 3 confirms that the wet season in the Vaal River and surrounding provinces is relatively wetter than the dry season, consistent with expectations. This is consistent with Mukhawana *et al.* (2023) whose study acknowledged summer maximum rainfall for the region. During this season, the results revealed that the year with the highest rainfall is 2023 peaking at 117.8mm. In 1983, average precipitation in the Vaal was highest at about 47.46mm. In 1993, precipitation was more evenly distributed across the Vaal River Basin, encompassing Mpumalanga, Free State, and parts of the Northern Cape (Figure 3). Notably, some years exhibited higher rainfall north of the river, particularly in Gauteng, Mpumalanga, and parts of Northwest, compared to the Northern Cape. Conversely, 2013 was identified as the driest year, with rainfall concentrated in the northern middle Vaal region, specifically Northwest and Mpumalanga.

Analysis of seasonal patterns revealed that during the dry season, rainfall was more prevalent in the Northern Cape, whereas during the wet season, it was predominantly observed in Mpumalanga, Free State, Gauteng, and Northwest provinces comparable with what Rouault and Richard, (2003) found out indicating maximum

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rainfall around that Kwazulu-Natal area(close to Free State and Mpumalanga) with a maximum of 130mm in the wet season.

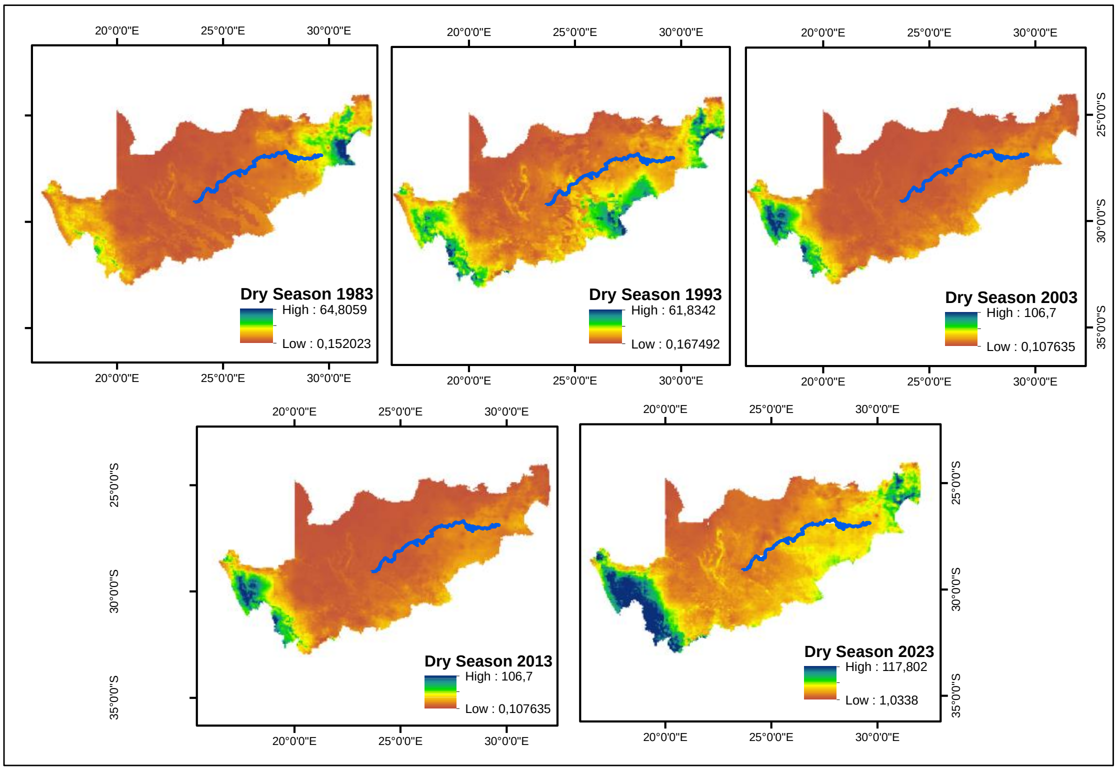

Figure 2: Dry season rainfall trends of the Vaal River basin and its surrounding provinces from 1983 – 2023.

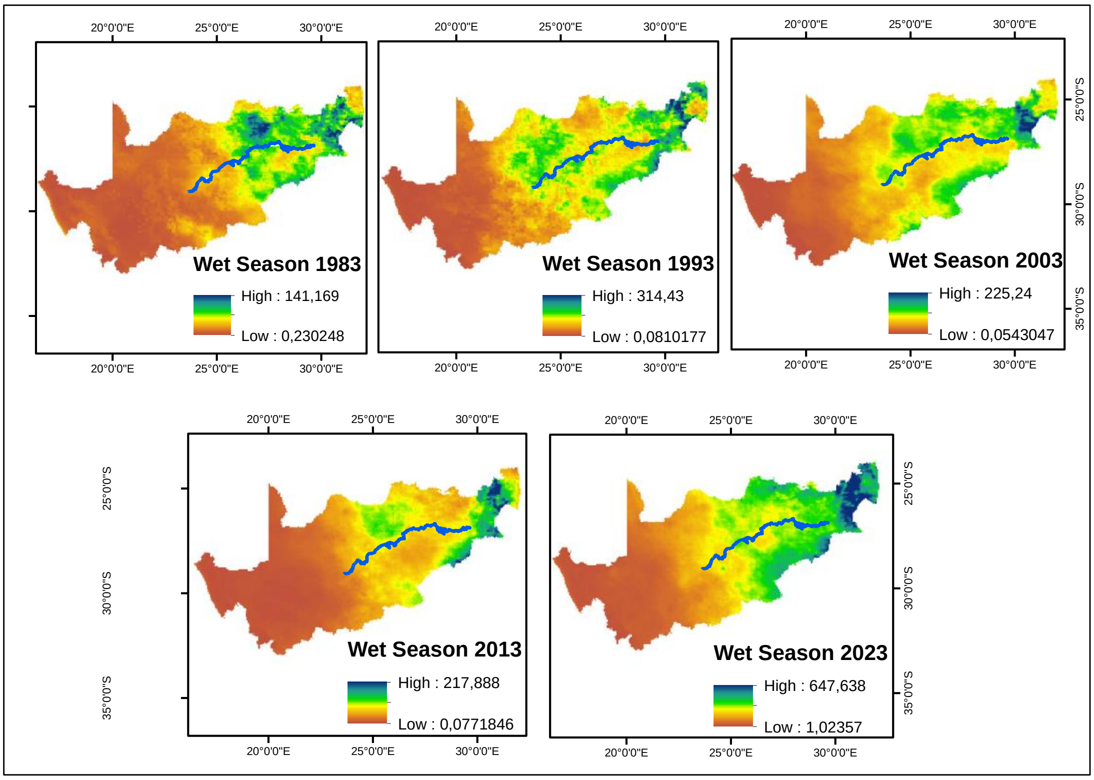

Figure 3: Wet season rainfall trends of the Vaal River basin and its surrounding provinces from 1983 – 2023.

3.1.3 Mean Rainfall Variation in the Vaal River Basin from 1983 to 2023.

Figure 5 illustrates the mean rainfall time series chart for the Vaal River from 1983 to 2023, revealing fluctuating trends. Notably, rainfall volumes were lowest during the dry season (June to August) and peaked during the wet season (January to March). Over the four-decade study period, the highest average rainfall volume in the Vaal River basin ranged between 50 mm and 60 mm. These were seen in 1988, 1991, 1996, 2011 and 2021. Average rainfall recorded to have the least volume was observed in 1983, 1986, 1987, 1990, 1992, 2001 - 2004, 2007 - 2008, 2012 - 2013, 2015, and 2016 (Figure 4).

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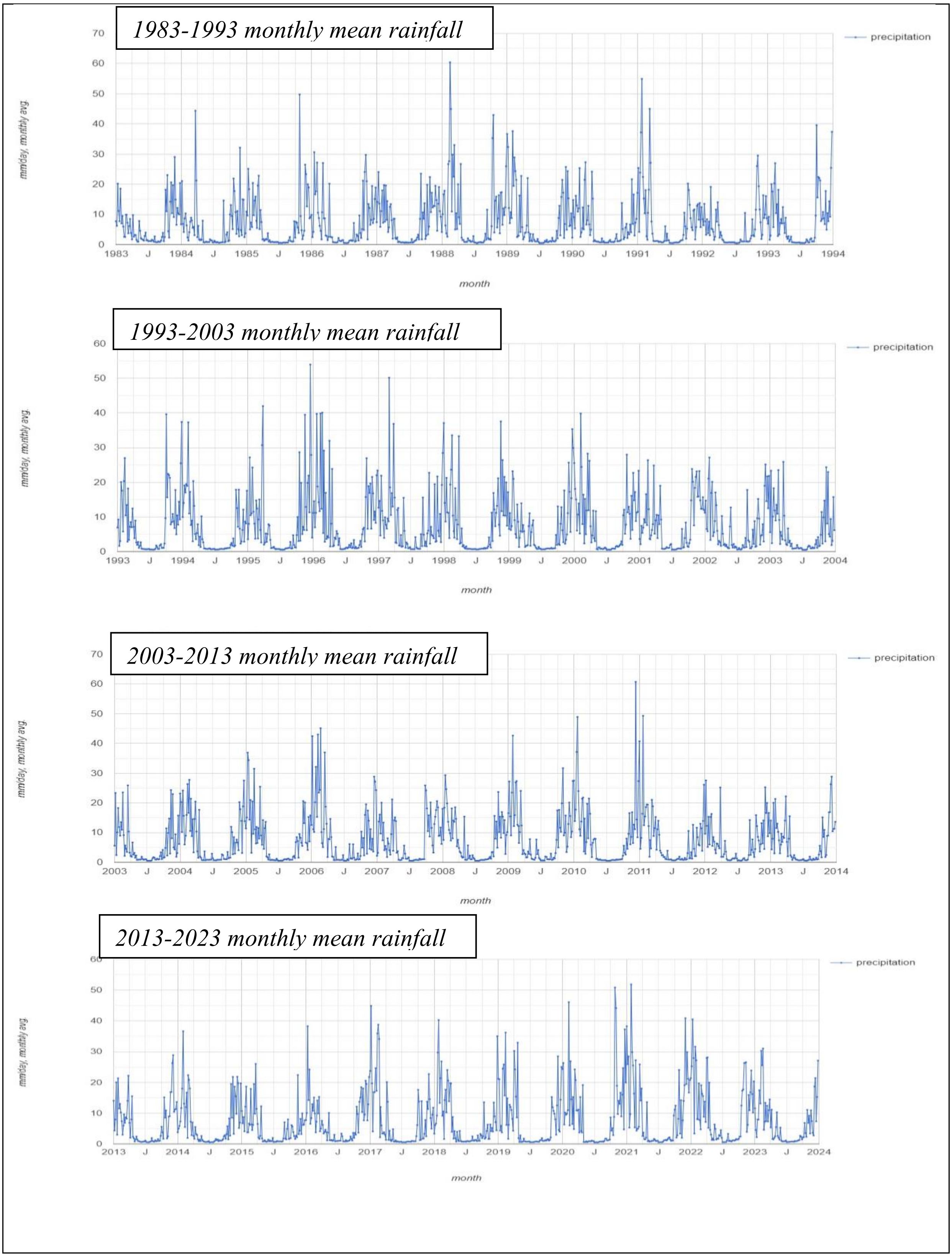

Figure 4: Monthly mean rainfall variation in the Vaal River basin between 1983 – 2023.

3.2 Comparing the mean rainfall and mean evapotranspiration in the Vaal River basin

Figure 5 illustrates the variability in annual average precipitation and evapotranspiration over several years. Notably, the annual average evapotranspiration consistently exceeds the annual average precipitation, indicating a surplus of evapotranspiration over rainfall in the Vaal River basin. This trend suggests that evapotranspiration surpasses rainfall in the study area, highlighting the importance of understanding this dynamic for water resource management.

The trend analysis revealed varying degrees of downward trends in rainfall across the Vaal River regions: weak in the Lower Vaal, strong in the Middle Vaal, and moderate in the Upper Vaal. Although the p-values exceeded the 0.05 significance threshold, indicating a lack of statistical significance, the results suggest a downward trend in rainfall per year.

Table 1: The Mann-Kendal Sens rainfall slope table of the Lower, Middle and Upper Vaal.

Location	Z-Value	Shift	P-value	Sig. level	Sens slope	Result	Trend
Lower Vaal	-0.68528	Downward	0.4932	P>0.05	-0.88	Negative	Decreasing
Middle Vaal	-4.218000	Downward	0.9284	P>0.05	-0.130626	Negative	Decreasing
Upper Vaal	-1.6517	Downward	0.0986	P>0.05	-3.388852	Negative	Decreasing

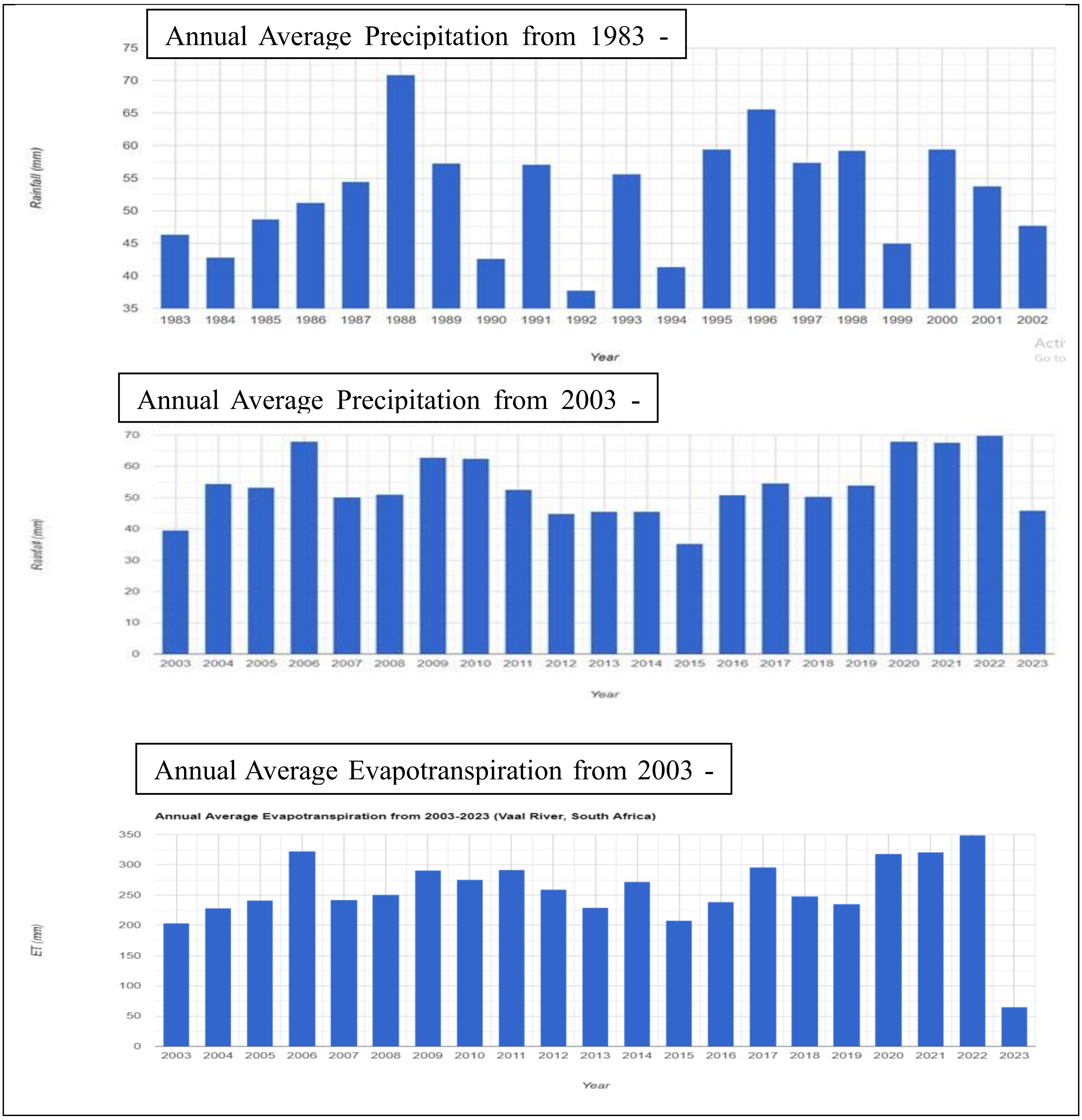

Figure 5: Long-term mean rainfall and mean evapotranspiration in the Vaal River Basin.

3.3 Drought Trends

Drought severity and duration across the Vaal River Basin were analysed using the Standardized Precipitation Evapotranspiration Index (SPEI) and the Standardized Precipitation Index (SPI) at multiple timescales (1-, 3-, 6-, 12-, 24-, and 48-month intervals). The results revealed distinct spatial and temporal variability in drought intensity and persistence across the lower, middle, and upper Vaal regions between 1983 and 2023.

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3.3.1 SPEI-Based Drought Trends

The SPEI results showed that short-term indices (SPEI-1 and SPEI-3) captured frequent drought events, notably in 1983, 1999, 2001–2006, and 2016, with variation among stations. Rouault and Richard, (2003) in their study revealed extreme dryness in the summer rainy season in Dec 1982 to March 1983. Intermediate and longer timescales (SPEI-6, SPEI-12, and SPEI-24) confirmed 2016–2019 as the most severe and prolonged drought period, particularly in the lower Vaal where SPEI-24 reached −3.20 in 2016. These longer timescales provided a more accurate depiction of hydrological drought, reflecting cumulative water deficits rather than short-term meteorological fluctuations. Similar findings were reported by Mathbout *et al.* (2018) and Tirivarombo *et al.* (2018), who noted that drought severity and duration increase with longer timescales in arid and semi-arid regions.

3.3.2 SPI-Based Drought Trends

The SPI results corroborated the SPEI analysis, identifying severe droughts in 1992, 2007, 2014–2016, and 2018. SPI-12 and SPI-24 showed the strongest drought intensities in 2015–2016 (up to −3.03), aligning with South Africa's worst drought in over two decades (Bhaga *et al.*, 2020). Drought frequency and intensity increased markedly after 2013, particularly between 2013 and 2018, a trend consistent with growing climatic instability. Both indices demonstrated that the 12- and 24-month timescales were the most reliable for detecting hydrological droughts, while shorter scales (1–3 months) reflected transient meteorological droughts. These observations align with Pei *et al.* (2020), who emphasized the suitability of intermediate timescales for drought monitoring in semi-arid basins.

3.4 Temporal and Spatial Patterns

Across the basin, drought events were more frequent and severe in the middle and upper Vaal regions compared to the lower Vaal. The consistent identification of 2016 as a hydrologically dry year by both indices underscores the influence of climatic variability on regional water resources. Eris *et al.* (2020) and Kumar and Gautam (2021) observed that multi-scalar drought indices, when applied together, enhance temporal drought characterization accuracy.

3.5 Climate Change and Implications

The recurrence of extreme droughts—especially between 2015 and 2019—highlights the growing influence of climate change on the Vaal River system. These findings are consistent with projections by Serdeczny *et al.* (2017), who predicted declining rainfall and increased drought frequency in southern Africa under warming conditions. Drought impacts extend beyond hydrology; they threaten agricultural productivity, water security, and livelihoods in one of South Africa's most economically vital regions. The Vaalharts Irrigation Scheme, the country's largest, is particularly vulnerable to such droughts (Department of Water Affairs and Sanitation, 2015). Reduced precipitation and rising evapotranspiration rates directly affect irrigation supply and crop yields, echoing the findings of Waseem *et al.* (2022), who linked precipitation deficits to yield declines.

3.6 Synthesis and Implications for Water Resource Management

Overall, the SPI and SPEI indices demonstrated strong agreement in identifying the major drought periods of 1983, 1999, 2016, and 2019, just as found in the studies of Bhaga *et al.* (2020); Mishra and Singh (2010), with 2016 emerging as the most severe hydrological drought. This is similar with the findings of Department of Agriculture Forestry and Fisheries South Africa (2010) indicating that the 2015-2016 was the worst drought resulting in decline in livestock and water constraints in cities. The results highlight a clear intensification of drought frequency and duration over recent decades, influenced by rising temperatures and changing rainfall patterns. These trends align with the work of Engelbrecht and Engelbrecht (2016) and Jury (2016), who documented climate-driven hydrological changes in the Vaal catchment affecting agricultural and industrial water use. The findings emphasize the need for adaptive water management strategies, including enhanced drought monitoring, improved reservoir operation, and sustainable irrigation practices. Integrating multi-scalar drought indices like SPEI and SPI provides a robust framework for understanding drought evolution, supporting early warning systems and resilience planning in the Vaal River Basin.

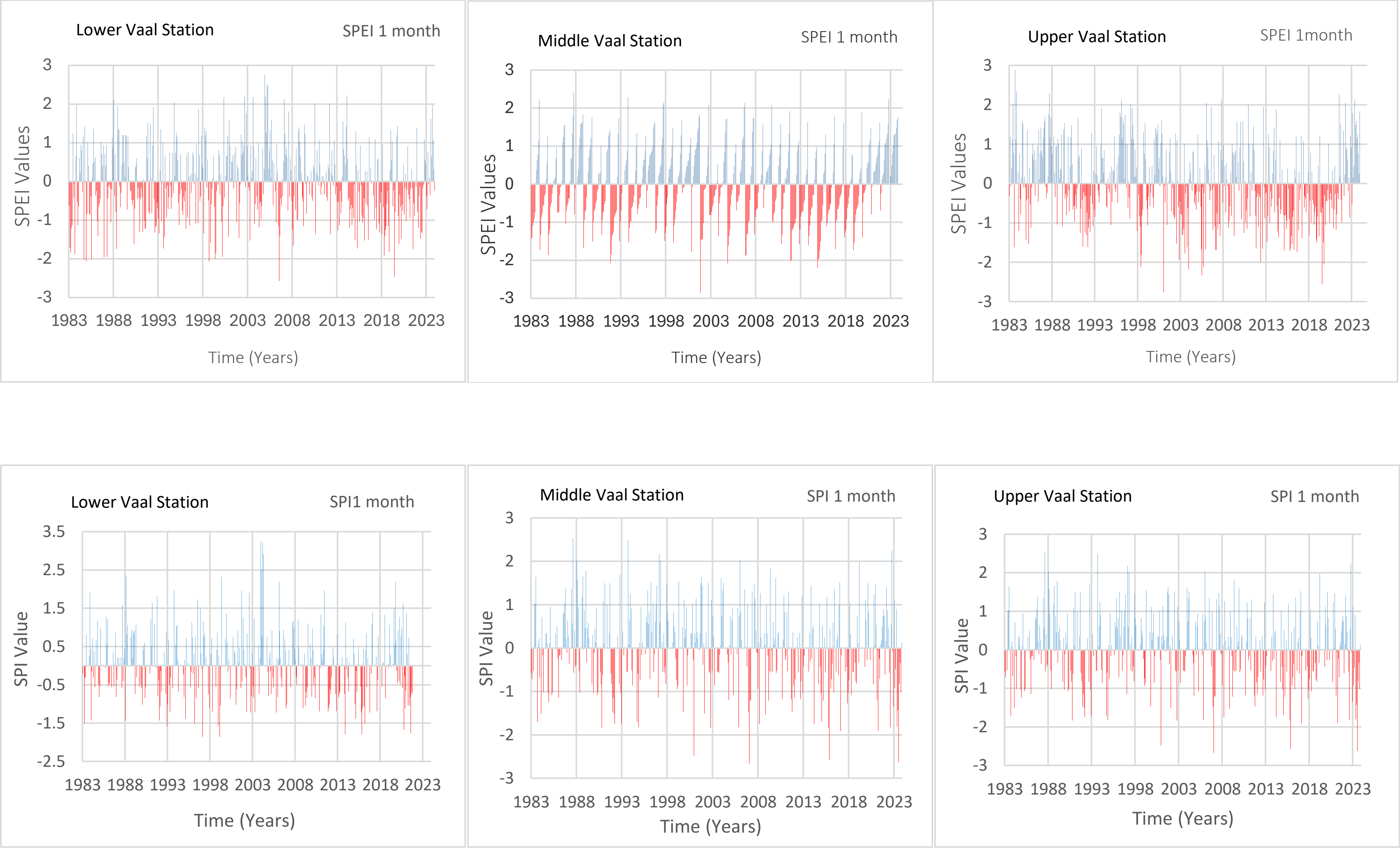

Figure 6. Dispersion of SPEI-1 and SPI-1 values in the Lower Vaal, Middle Vaal, and Upper Vaal meteorological stations 1983 - 2023.

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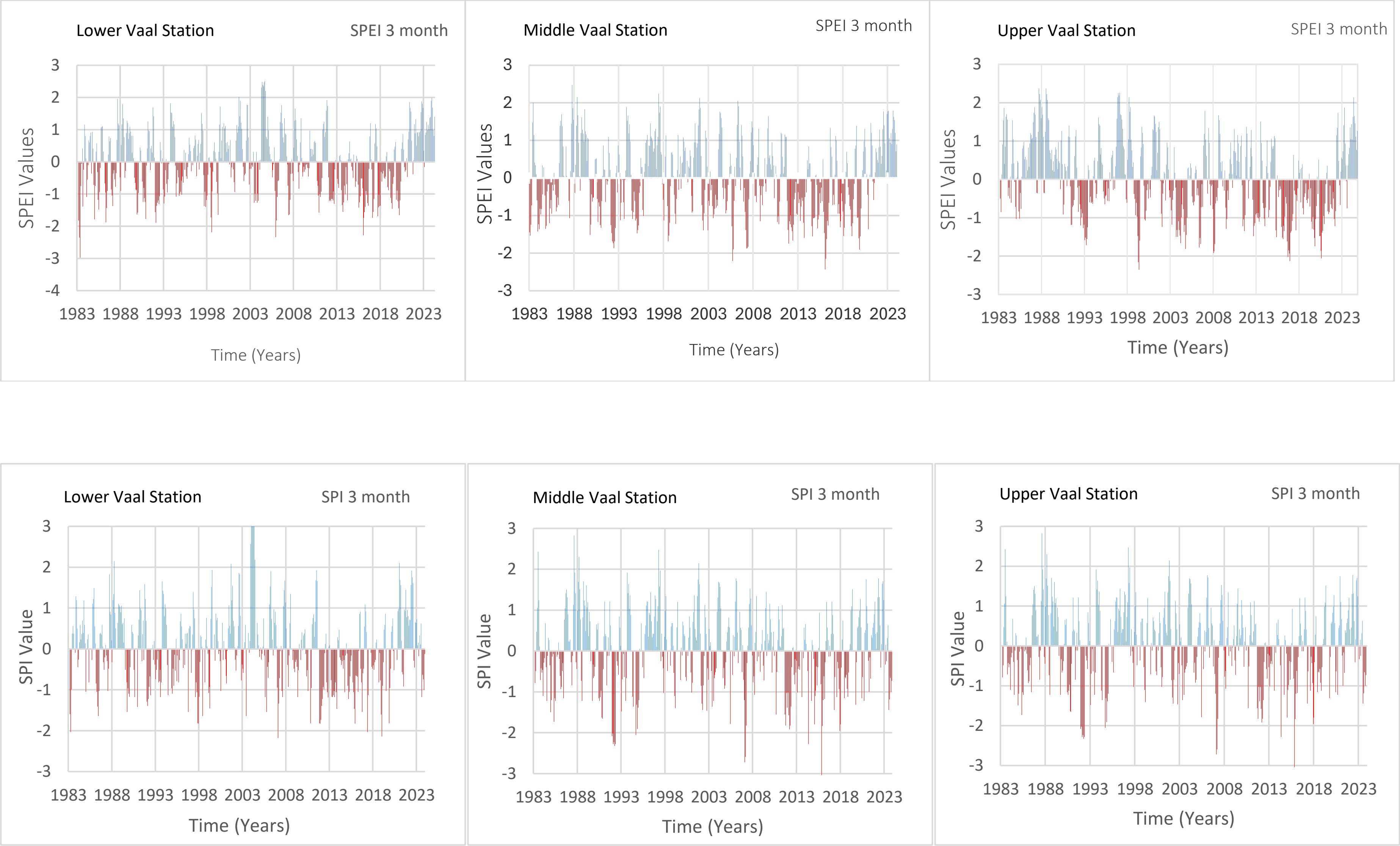

Figure 7. Dispersion of SPEI-3 and SPI-3 values in the Lower Vaal, Middle Vaal, and Upper Vaal meteorological stations 1983 - 2023.

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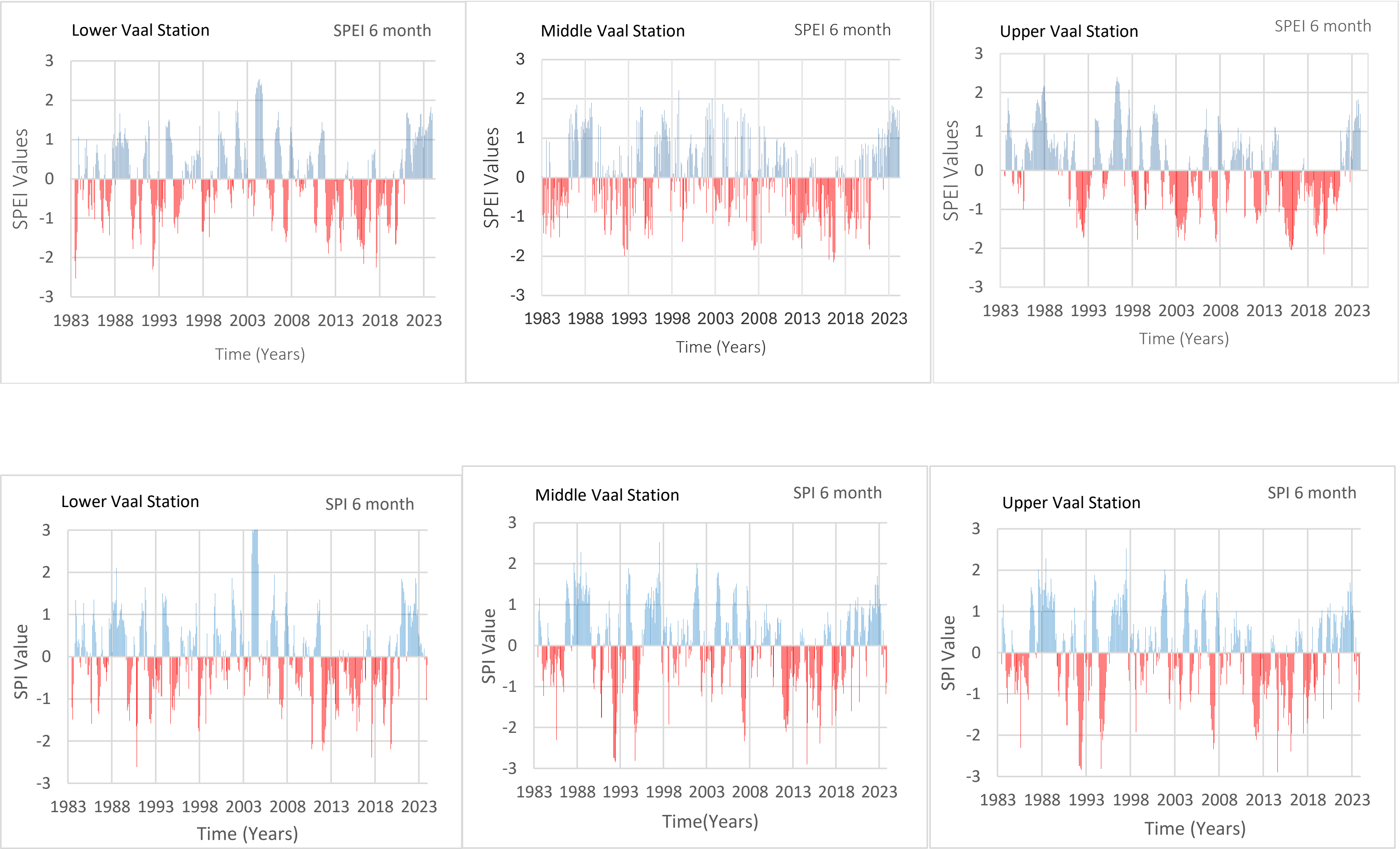

Figure 8. Dispersion of SPEI-6 and SPI-6 values in the Lower Vaal, Middle Vaal, and Upper Vaal meteorological stations 1983 - 2023.

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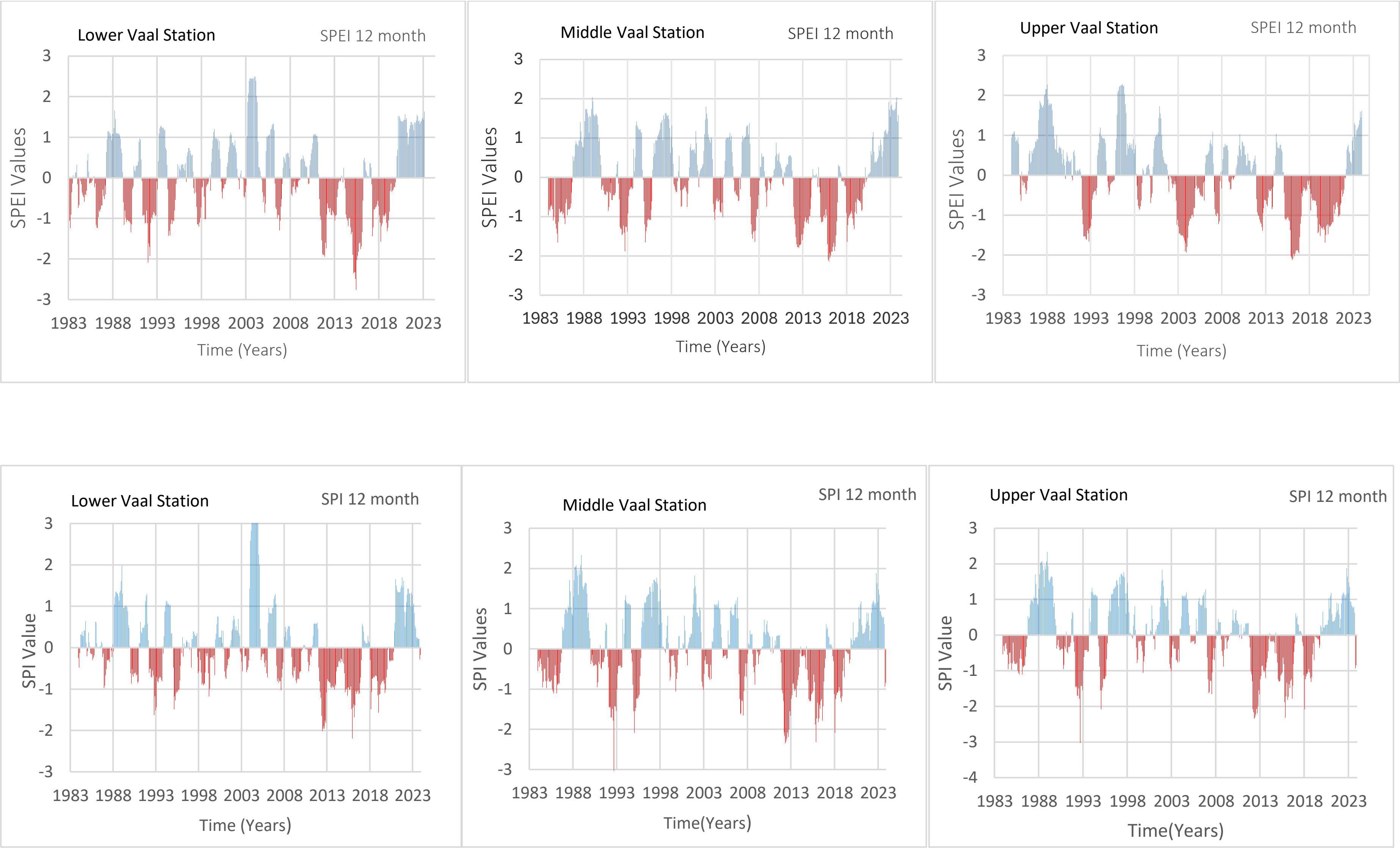

Figure 9. Dispersion of SPEI-12 and SPI-12 values in the Lower Vaal, Middle Vaal, and Upper Vaal meteorological stations 1983 - 2023.

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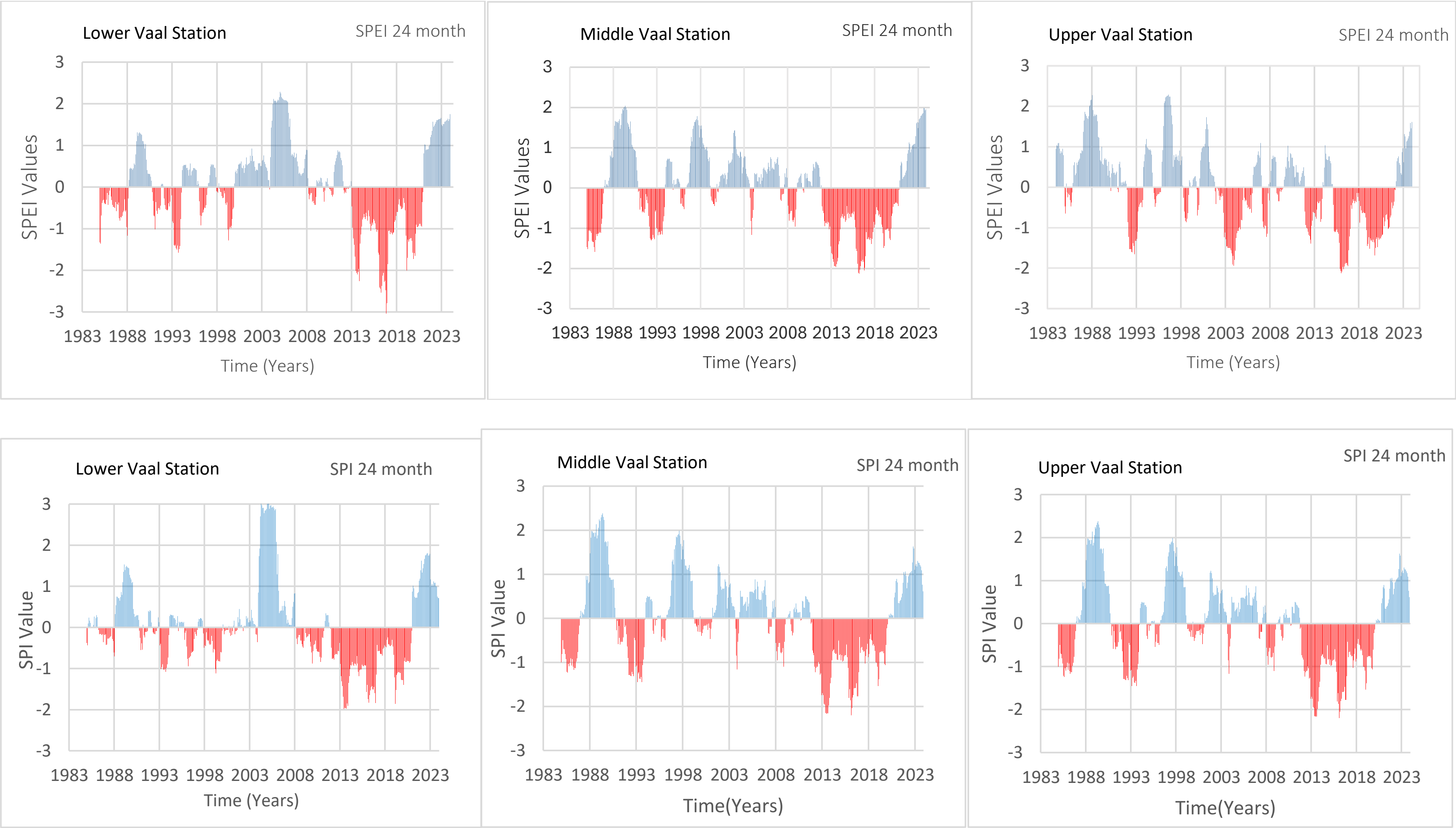

Figure 10. Dispersion of SPEI-24 and SPI-24 values in the Lower Vaal, Middle Vaal, and Upper Vaal meteorological stations 1983 - 2023.

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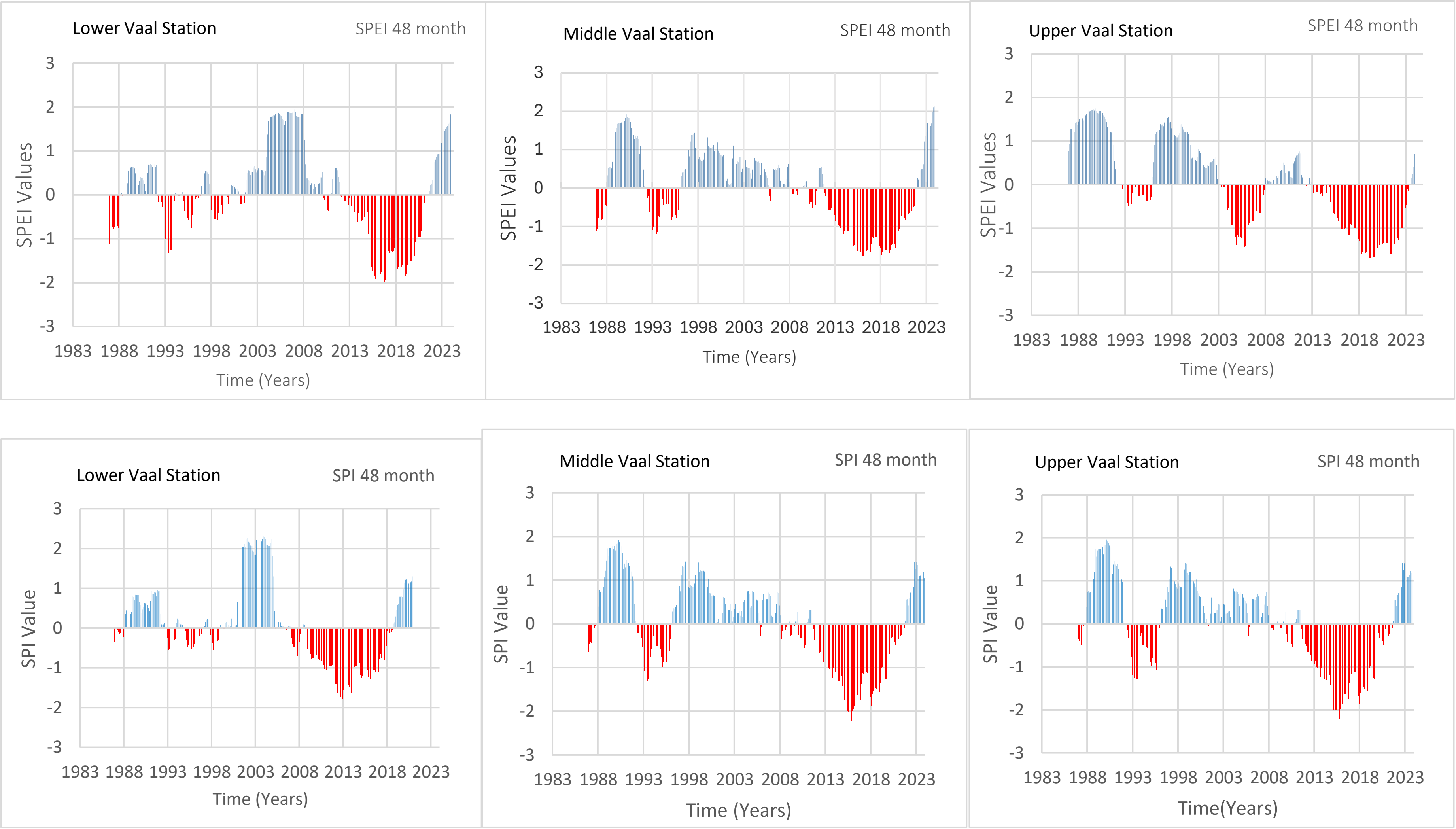

Figure 11. Dispersion of SPEI-48 and SPI-48 values in the Lower Vaal, Middle Vaal, and Upper Vaal meteorological stations 1983 - 2023.

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4. Conclusion

This study conducted a comprehensive analysis of drought patterns in the Vaal River, South Africa, utilizing the Standardized Precipitation Evapotranspiration Index (SPEI) and the Standardized Precipitation Index (SPI). We examined precipitation patterns and evapotranspiration dynamics in the basin to assess their correlation with SPEI and SPI findings. By applying SPEI and SPI drought indices at monthly scales ranging from 1 to 48 months between 1983 and 2023, we explored the spatiotemporal variability of rainfall and drought, revealing significant patterns.

Our analysis identified drought periods, with short-scale indices (3 and 6 months) indicating meteorological drought and longer timescales associated with hydrological drought, the latter being the primary focus of our study. The results showed severe and prolonged extreme drought in the Vaal River basin, particularly prevalent from 2016 to 2018. The years most affected by hydrological drought from 1983 to 2023 in the lower Vaal, middle Vaal, and Upper Vaal River basins, as indicated by SPEI/SPI-12 and SPEI/SPI-24, were 1983-1985, 1992, 1995, 2003, 2004, 2007, and 2012-2016. The study's findings are significant, integrating temperature and Potential Evapotranspiration (PET) values into drought index calculations. However, a notable limitation was the use of only the Hargreaves method for PET calculation. The observed disparity between lower rainfall and higher evapotranspiration in the Vaal River basin suggests potential impacts on various sectors, including agriculture, mining, industry, municipal water users, and economic development. This underscores the importance of considering short-term timescales (3 and 6 months) in drought mitigation strategies, as suggested by previous studies.

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