Supplementary file

Table S1. Mean annual precipitation (mm) and evaporation (mm), mean seasonal maximum and minimum temperatures (°C), altitude, latitude and longitude Global Positioning System (GPS) coordinates of the six magisterial districts of the three study provinces.

Province	Municipality	Mean annual precipitation (mm)	Mean seasonal maximum temperature (°C)	Mean seasonal minimum temperature (°C)	Mean annual evaporation (mm)	Altitude (m)	Latitude and longitude (GPS coordinates)
Free State	Bloemfontein	736	30	14.8	1 946	1 395	-29.1211; 26.2140
	Bethlehem	506	26.3	12.6	2100	1 700	-28.2308; 28.3071
North West	Klerksdorp	481	30	14.8	2 646	1 357	-26.8598, 26.6317
	Schweizer-Reneke	507	31	14.5	1 982	1 312	-27.1833, 25.3333
Mpumalanga	Lydenburg	532	25	15.1	2 233	1 385	-25.0959; 30.4439
	Standerton	750	26.8	12.3	1 400	1 530	-26.9337; 29.2415

"Seasonal" refers to the period from October to March, a period when rainfall is received and crop production takes place in these areas.

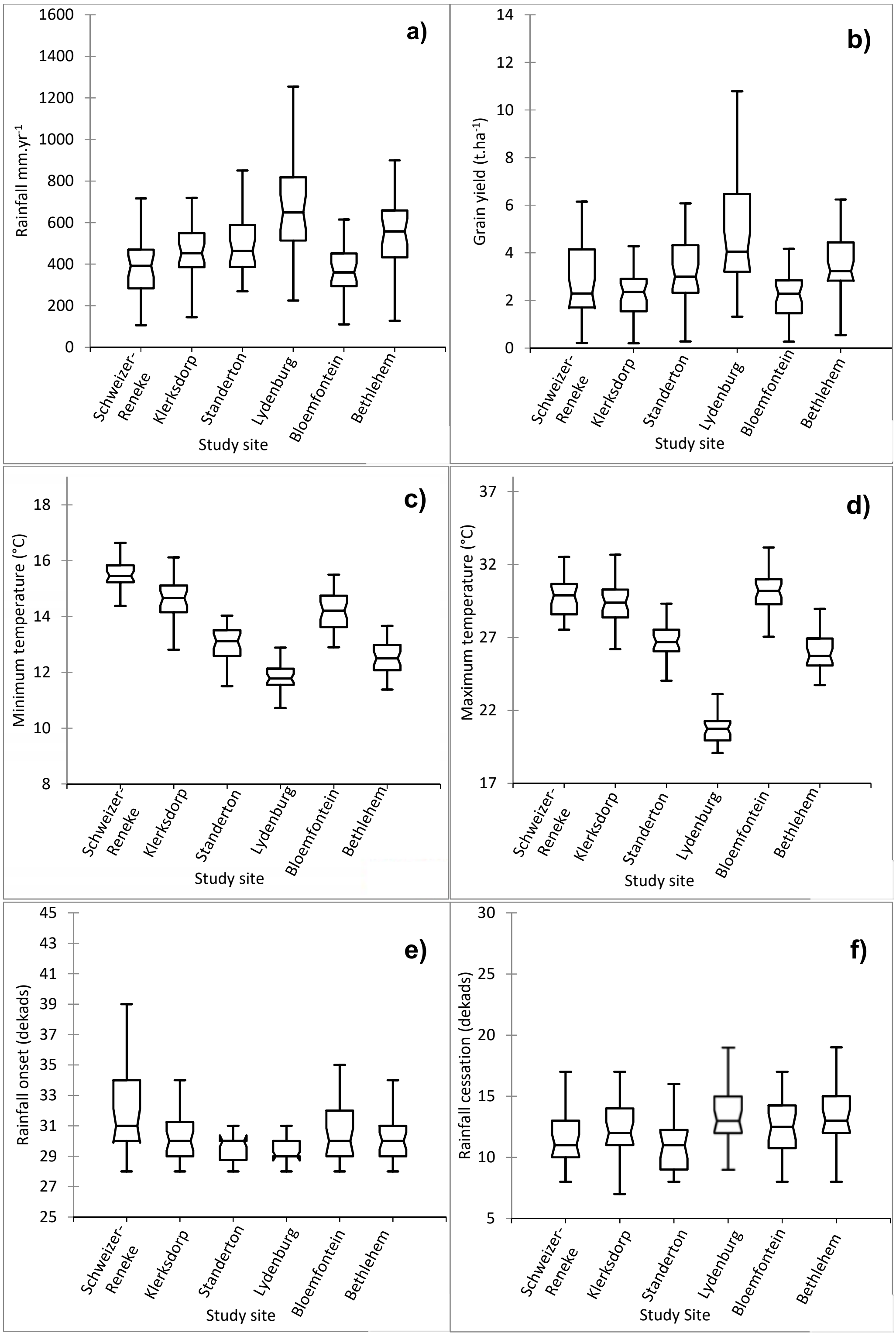

Figure S1. Box plots showing median properties of a) rainfall (mm season^{-1}), b grain yield (t ha^{-1}), minimum temperature (°C), c) maximum temperature (°C), d) rainfall onset and e) rainfall cessation for each study location.

Equations S3.

North West
Schweizer-Reneke:

$$\Delta Y = 0.024 - 0.691 * \Delta\text{Tmax} + 0.158 * \Delta\text{Tmin} + 0.0002 * \Delta\text{Rainfall} - 0.003 * \Delta\text{EHT} - 0.045 * \Delta\text{Ro} - 0.022 * \Delta\text{Rc} \quad (1)$$

Klerksdorp:

$$\Delta Y = 0.076 - 0.703 * \Delta\text{Tmax} + 0.174 * \Delta\text{Tmin} - 0.001 * \Delta\text{Rainfall} - 0.005 * \Delta\text{EHT} - 0.003 * \Delta\text{Ro} - 0.017 * \Delta\text{Rc} \quad (2)$$

Free State
Bethlehem:

$$\Delta Y = 0.039 - 0.551 * \Delta\text{Tmax} + 0.208 * \Delta\text{Tmin} - 0.000 * \Delta\text{Rainfall} + 0.001 * \Delta\text{EHT} + 0.170 * \Delta\text{Ro} - 0.001 * \Delta\text{Rc} \quad (3)$$

Bloemfontein:

$$\Delta Y = 0.065 + 0.057 * \Delta\text{Tmax} - 0.016 * \Delta\text{Tmin} + 0.001 * \Delta\text{Rainfall} - 0.063 * \Delta\text{EHT} + 0.119 * \Delta\text{Ro} - 0.046 * \Delta\text{Rc} \quad (4)$$

Mpumalanga
Standerton:

$$\Delta Y = 0.153 - 0.454 * \Delta\text{Tmax} + 0.674 * \Delta\text{Tmin} - 0.001 * \Delta\text{Rainfall} - 0.001 * \Delta\text{EHT} - 0.021 * \Delta\text{Ro} + 0.046 * \Delta\text{Rc} \quad (5)$$

Lydenburg:

$$\Delta Y = 0.128 - 0.607 * \Delta\text{Tmax} + 0.410 * \Delta\text{Tmin} - 0.001 * \Delta\text{Rainfall} + 0.177 * \Delta\text{EHT} + 0.265 * \Delta\text{Ro} + 0.074 * \Delta\text{Rc} \quad (6)$$

Equations S4

Mann-Kendall Test

The Mann-Kendall test statistics, *S* is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \ldots \quad (1)$$

Where:

n is the number of data points, x_i and x_j are the data values in time series *i* and *j* $(j>i)$, respectively and $sgn(x_j - x_i)$ is the sign functions as:

$$sgn(x_j - x_i) = \begin{cases} +1, if\ x_j - x_i > 0 \\ 0, if\ x_j - x_i = 0 \\ -1, if\ x_j - x_i < 0 \end{cases} \ldots \quad (2)$$

The variance is given as

$$\text{Var(S)} = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18} \quad \ldots\ldots\ldots\ldots (3)$$

Where:

n is the number of data points; m is the number of tied groups and t_i denotes the number of ties of extent i. The test statistics Z_c is computed as follows:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \\ 0, S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, S < 0 \end{cases} \quad \ldots\ldots\ldots\ldots (4)$$

For a sample size n>10, Z_c follows a standard normal distribution. An upward trend is detected when the Z-value is positive, and a negative Z-value reflects a downward trend.

The presence of a seasonal component was identified in the time series data, indicating that the use of a seasonal Mann-Kendall test was appropriate. The seasonal Mann-Kendall test is an extension of the MK test that considers the effects of seasonal components in time series data. The test statistic for the seasonal MK test is given:

$$\hat{S} = \sum_{g=1}^{m} S_g \quad \hat{\sigma}_g^2 = \sum_{g=1}^{m} \sigma_g^2 \quad \ldots\ldots\ldots\ldots (5)$$

Where $\hat{S}$ is the overall **Mann-Kendall** test statistic for the entire dataset over multiple seasons (e.g., months or quarters), S_g represents the individual Mann-Kendall statistic for the g-th season, $\hat{\sigma}_g^2$ **is** the variance for the test statistic for the g-th season, **m** represents the number of seasons (for example, m = 12 for monthly data). The combined test statistic **Ŝ** is the sum of the test statistics for each season, and the combined variance $\hat{\sigma}_g^2$ is the sum of the variances for each season.

Equations S5

Theil-Sen estimator calculations

The Theil-Sen estimator is extensively used for quantifying the rate or magnitude of change in climate and hydrological trend analyses (Abghari et al. 2013; Zamani et al. 2017). This robust technique effectively addresses outliers, rendering it highly reliable for diverse datasets. A significant advantage of the Theil-Sen estimator is its independence from assumptions regarding error distribution, thus offering enhanced flexibility. In contrast to using the mean, it is predicated on the median, which further augments its resilience to outliers. The formula for the Theil-Sen estimator is as follows:

$$d_k = \frac{X_j - X_i}{j - i} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (7)$$

for (1 ≤ i < j ≤ n), where d is the slope, k denotes the variable, n is the number of data, and i, j are indices.

In this study, the seasonal Theil-Sen estimator was employed to account for the effects of seasonality observed in the time series data. The seasonal Theil-Sen estimator, as described by Hirsch et al. (1982), is given by the following equation:

$$d_{ijk} = \frac{X_{ij} - X_{ik}}{j - k} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (8)$$

for each (xij, xik) pair i = 1,.,.,., m, where (1 ≤ k < j ≤ ni and ni is the number of known values in the i−th season.

References

Abghari H, Tabari H, Talaee PH (2013) River flow trends in the west of Iran during the past 40 years: impact of precipitation variability. Global and Planetary Change 101:52–60. https://doi.org/10.1016/j.gloplacha.2012.12.003

Zamani R, Mirabbasi R, Abdollahi S, Jhajharia D (2017) Streamflow trend analysis by considering autocorrelation structure, long-term persistence, and Hurst coefficient in a semi-arid region of Iran. Theoretical and Applied Climatology 129:33–45. https://doi.org/10.1007/s00704-016-1747-4