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Quantifying the effects of Climate and Environmental changes on Evapotranspiration Variability in the Sahel

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Highlights:

- Significant increasing trends in annual ET in most parts of the Sahelian belt.
- Precipitation, humidity, and vapour pressure (climatic factors), and soil moisture and NDVI (environmental factors) are the most important variables controlling increase in ET.
- Vapour pressure has the highest positive elasticity score (2.58) while net radiation has the highest negative elasticity score (-9.58) on ET.
- The study covers the whole Sahelian belt from west to east making it to stand out from previous studies in the region that cover mostly the western Sahel.

Abstract

Whilst considerable research has been carried out to understand the effects of reforestation on evapotranspiration (ET), such studies are generally absent in the Sahel even though the region is currently undergoing extensive reforestation to halt desertification and land degradation. The objective of this study is to identify and quantify the dominant climatic and environmental factors influencing ET variability in the Sahel. However, achieving this goal in the Sahel is hindered by a lack of in situ monitoring data. To overcome this challenge, this study adopts geospatial datasets along with analytical methods to assess the climatic and environmental factors affecting ET in 45 watersheds in the Sahel over a period of four decades (1982-2021). Analyses show significant increasing trends in annual ET in more than 90% of the watersheds. Precipitation and mean temperature show significant increasing trends in all watersheds while windspeed, vapour pressure, solar radiation, specific humidity, and atmospheric evaporative demand show mixed results with both increasing and decreasing trends in different watersheds. Environmental variables including soil moisture, and vegetation cover measured using the normalised difference vegetative index (NDVI) also show consistent increasing trends in all watersheds. Statistical analyses further show that climatic and environmental factors contribute about 80% of ET variance. The relative contribution of climatic variables on ET variance is 75.11% while that of environmental variables is 24.71%. This suggests that climatic factors have a higher influence on ET variability than environmental factors. Analyses using the double logarithm elasticity model show that vapour pressure has the highest positive elasticity coefficient (2.58) on ET while net radiation has the highest negative elasticity coefficient (-9.58). This is the first study to cover the whole Sahelian belt from west to east and the results may be crucial for adopting climate-smart reforestation policies, enhance regional water management and improve our knowledge of vegetation-hydrology-climate interactions in the Sahel.

Keywords: analytical methods; elasticity concept; partial correlation coefficient, least square and double logarithm elasticity models; great green wall initiative; NDVI.

1. Introduction

Due to increased vulnerability caused by climate change and population growth, many dryland areas are exposed to desertification and land degradation risk and ensuing contradiction between humans and land (Sun *et al.*, 2023). To achieve land degradation neutrality -which is one of the sustainable development goals (SDGs) and enhance carbon sequestration, many dryland areas are undergoing extensive reforestation/afforestation (Arneth *et al.*, 2021; Schulze *et al.*, 2021). Considering the vulnerability of the Sahel to desertification and land degradation (Mbow *et al.*, 2017), the region is currently undergoing vast reforestation through the Great Green Wall Initiative (GGWI) (Mbow, 2017). The objective of the GGWI is to restore 100 million hectares of degraded land through reforestation, sequester 250 million tons of carbon and create 10 million green jobs by 2030 (Mbow, 2017; Goffner *et al.*, 2019). Whilst many studies have been conducted in other regions undergoing reforestation to understand the factors influencing actual evapotranspiration (ET) variability (Teuling *et al.*, 2019; Yang *et al.*, 2022; Zheng *et al.*, 2022), such studies are generally lacking in the Sahel. ET is an important component of regional energy cycle representing the complex interaction between vegetation, climate, and landscape characteristics (Zhang *et al.*, 2019; Yang *et al.*, 2021). It is also an important component of the water cycle with a strong influence on runoff and soil moisture availability and groundwater recharge (Guo *et al.*, 2017; Yinglan *et al.*, 2019; Condon *et al.*, 2020). Therefore, to achieve consistent, evidence-based allocation and management of water resources in the context of the GGWI, it is crucial to identify and quantify the climatic (abiotic) and environmental (biotic) factors influencing ET variability in the Sahel. Such information may be crucial for adopting climate-smart reforestation policies to support the implementation of the GGWI, enhance water management given the strong links between water scarcity and violent conflicts in the Sahel (Nkiaka *et al.*, 2024) and improve our knowledge of vegetation-hydrology-climate interactions in the Sahel.

Several studies have assessed the climatic and environmental factors influencing ET variability at different scales. For example, Feng *et al.* (2020) showed that ET is strongly influenced by precipitation at the global scale, while potential evapotranspiration, terrestrial water storage, and catchment characteristics influence ET variability in energy-limited environments, arid and humid regions respectively. Yang *et al.* (2022) reported that precipitation, temperature, and vegetation cover are the dominant factors influencing ET variability in northwest China. Li *et al.* (2022) found that precipitation, net radiation, and vapour pressure deficit exert greater control on ET variability in dry climates, tropical regions, and boreal mid-latitude regions respectively. Land use change, precipitation, and potential evapotranspiration were found to be the main factors influencing evapotranspiration across Europe (Teuling *et al.*, 2019). Changing precipitation patterns and land cover have been reported to be the dominant factors affecting the components of the hydrological cycle in the Amazon (Heerspink *et al.*, 2020).

Different approaches have been used to study the effects of climatic and environmental factors influencing ET. For example, Zheng *et al.* (2022) used the partial least squares structural equation model to explore the relationship between ET and climatic and environmental factors. Other studies adopted the Budyko framework (Teuling *et al.*, 2019; Feng *et al.*, 2020; Li *et al.*, 2022), the elasticity concept (Wang *et al.*, 2020; Yang *et al.*, 2022) and the complementary relationship (Brutsaert, 2015; Li *et al.*, 2021) to analyse the effects of climate and vegetation changes on ET. Adeyeri and Ishola (2021) applied the time-frequency wavelet decomposition method and partial correlation analysis to reveal the factors influencing ET in West Africa. Ndehedehe *et al.* (2018) used the independent component analysis to explore ET dynamics in sub-Saharan Africa. Overall, most of the methods used for studying the relationship between ET and climatic and environmental factors are data-driven analytical methods. Analytical methods use mathematical equations based on the assumption that the catchment water balance remains under steady-state over a long period of time (Dey and Mishra, 2017; Zhang *et al.*, 2023). Advantages of analytical methods include: (1) simple model structure and (2) require minimum input data to produce results that are practically useful for most hydrological applications (Hasan *et al.*, 2018).

Despite the high sensitivity of Sahelian vegetation to climate variability and environmental change (Leroux *et al.*, 2017), very few studies have investigated the factors influencing ET variability in the Sahel while existing studies have focused mostly on the western Sahel. Meanwhile, the effects of vegetation on ET are conspicuously ignored in exiting studies. For example, Adeyeri and Ishola (2021) showed that precipitation and atmospheric evaporative demand (AED) had a greater influence on ET in the western Sahel. Ndiaye *et al.* (2021) revealed that ET in the western Sahel is more sensitive to relative humidity, maximum temperature, and solar radiation. Ndehedehe *et al.* (2018) attributed ET variability in the western Sahel to changes in precipitation, soil moisture and temperature. The limited number of studies addressing this issue in the Sahel suggests that there is a dearth of knowledge on the vegetation-hydrology-climate interactions which hampers the development of climate-smart reforestation practices in the context of the GGWI and regional water management. To overcome the challenge of widespread in situ data scarcity in the region, this study leverages on the availability of a wide range of satellite-derived and reanalysis data. The main advantage of such data is that they can provide high spatial resolution and long-term homogeneous data for previously unmonitored regions at scales that are suitable for studying changes in the hydrological cycle (Sheffield *et al.*, 2018).

From the above, the objectives of this study are to: (1) analyse trends in annual ET, climatic and environmental (soil moisture and vegetation cover) variables, (2) identify the main climatic and environmental factors influencing ET and, (3) quantify the impact of climate and vegetation changes on ET across the Sahel.

2. Materials and Methods

2.1. Study area.

The Sahel stretches from Senegal to Eritrea with a length of about 8,000 km. It is a transitional zone located between the Sahara Desert to the north and the Sudanian-savanna to the south covering ten countries with a population of about 150 million (Figure 1). It is one of the world's largest water-limited environments and ranked amongst the most fragile ecosystems in the world (Ghins *et al.*, 2022). The Sahel is remarkable because of a mega drought that affected the region from the 1970s to mid-1990 attracting much media coverage because of the humanitarian crisis that ensued from the drought (Nicholson *et al.*, 1998; Dai *et al.*, 2004). Precipitation estimates from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) over four decades (1982-2021) show that annual precipitation varies from 71-200 mm/year in the north to about 700-1000 mm/year in the south. The present study covers 45 watersheds nested within six major hydrological basins including Senegal, Volta, Niger, Lake Chad, Nile, and Red Sea (Figure 1). The total surface area covered by all the watersheds is about 3,021,412 km^2 ranging in size from 4095 km^2 (Senegal 4) to 541,267 km^2 (Dallol Bosso). Most of the watersheds lie between Latitudes 12°N and 20°N. A full list of the watersheds and their characteristics is available in Appendix A. Shapefiles of the watersheds are collected from HydroSHEDs which provides a seamless global coverage of consistently sized and hierarchically nested sub-basins using the high-resolution Shuttle Radar Topographic Mission digital elevation model (Lehner and Grill, 2013). HydroSHEDs shapefiles have been used in several studies e.g., (Gebrechorkos *et al.*, 2022; Zhang *et al.*, 2023; Nkiaka and Okafor, 2024).

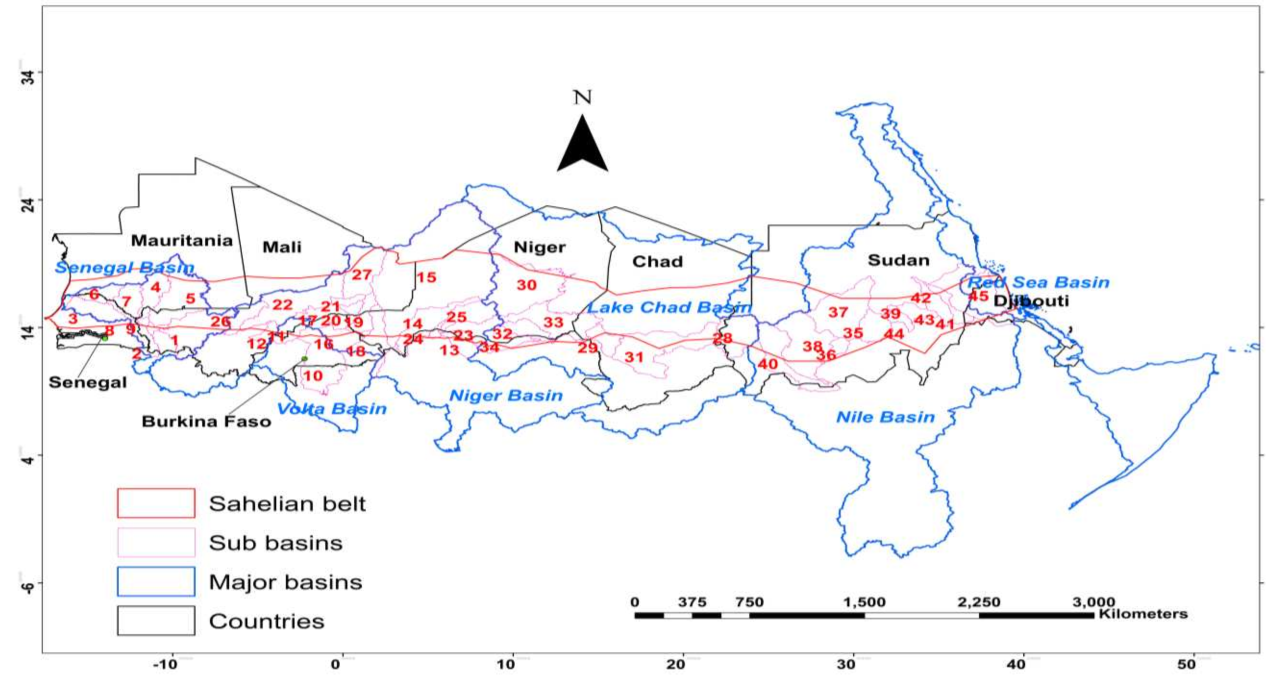

Figure 1: Map of the study region showing the different countries, major hydrological basins, and nested sub-basins and the Sahelian belt. Sub-basins are numbered from left to right. A full list of the sub-basins and their characteristics is available in Appendix 1.

2.2. Data and aggregation

Table 1 summarises the characteristics of the different datasets used in the study. The ET data used in the study has been validated in previous studies e.g., (Nkiaka *et al.*, 2022) and also used in several studies in the Sahel e.g., (Gbohoui *et al.*, 2021; Hernández *et al.*, 2021). CHIRPS, AgERA5, GLEAM Soil moisture and NDVI data from MODIS have been validated and also used extensively in other studies in the region e.g., (Fensholt *et al.*, 2009; Wang *et al.*, 2023; Asante *et al.*, 2022; Dembélé *et al.*, 2020). A complete description of the different datasets is available in their respective references provided in Table 1.

Table 1: Characteristics of products and data used in the study.

Variable type	Product name and reference	Spatial resolution	Temporal resolution
Sub-basin (km^2)	HydroSHEDs, (Lehner and Grill, 2013)	-	-
Precipitation	CHIRPS (Funk *et al.*, 2015)	0.05°	Daily
Evapotranspiration (ET)	TerraClimate (Abatzoglou *et al.*, 2018)	0.041°	Monthly
Atmospheric evaporative demand (AED)	TerraClimate (Abatzoglou *et al.*, 2018)	0.041°	Monthly
Mean temperature	AgERA5 (Boogaard, 2020)	0.1°	Daily
Solar radiation		0.1°	Daily
Windspeed		0.1°	Daily
Vapour pressure		0.1	Daily
Specific humidity	CFSR (Saha *et al.*, 2014)	0.19°	Daily
Soil moisture (0-100 cm)	GLEAM (Martens *et al.*, 2017)	0.25°	Daily
Vegetation cover (NDVI)	MOD13A1 V6 (Didan, 2015)	500m	16 days

The climatic and environmental variables were downloaded at annual timescale at their respective native spatial resolutions using the Climate Engine research App [https://app.climateengine.com] (Huntington et al., 2017). Watersheds shapefiles can be uploaded to Climate Engine directly from a computer folder or using the Google Earth Engine interface through a custom user account. Soil moisture data are downloaded from GLEAM and processed using OriginPro software. All the data were downloaded as spatial average over each watershed.

2.3. Trend analyses

The non-parametric Mann-Kendall test and Sen's slope estimator are used respectively for trend analysis and to quantify trend magnitude and significance. The Mann-Kendall test and Sen slope estimator are widely used for detecting the presence of statistically significant increasing or decreasing trends in hydroclimatic time series and have been used in several studies in the region e.g., (Nkiaka *et al.*, 2017). Although several different Mann-Kendall tests exist, e.g., (Güçlü, 2020), the study adopted the classical Mann-Kendall test. The period 1982–2021 is adopted for climate variables while 2000–2021 is used for vegetation change (NDVI). Trend analyses are conducted at the 5% significance level.

2.4. Identifying the factors influencing evapotranspiration (ET) variability

The study uses three statistical methods to assess the factors influencing ET in the Sahel. Considering that collinearity and interactions among the different independent variables cannot be overlooked, partial correlation coefficient (PCC) is used to determine the relationship between each independent variable (climate and environmental variables) and the dependent variable (ET) while controlling for the effects of all the other independent variables. PCC is calculated using the following equation (Engström and Ekman, 2010) and has been used in several studies e.g., (Yang *et al.*, 2022; Adeyeri and Ishola, 2021).

$$\rho_{X,ET(Y)} = \frac{\rho_{X,ET} - \rho_{X,Y}\rho_{Y,ET}}{\sqrt{1-\rho_{X,Y^2}}\sqrt{1-\rho_{Y,ET^2}}} \quad (1)$$

Where $\rho_{X,ET(Y)}$ is the partial correlation coefficient between X & ET considering the effect of variable Y; $\rho_{X,ET}$ and $\rho_{Y,ET}$ are the correlation coefficients between ET and X & Y, respectively, and $\rho_{X,Y}$ is the correlation coefficient between X and Y. In the second step, Pearson correlation was used to establish how change in the independent variable affects the dependent variable. In the third step, multiple linear regression analysis is conducted between the rate of change of each independent variable and the rate of change of the dependent variable to determine the relative contributions of each independent variable on the dependent variable. This was achieved using multivariable regression at 5% significance level using equation (2). The relative contributions of the change in each independent variable to the rate of change in ET was then estimated from the multivariable regression coefficients using equation (3). Equations (2) and (3) have been used in several previous studies to estimate the relative contribution of independent variables on the dependent variable e.g., (Chen *et al.*, 2022; Yang *et al.*, 2022).

$$Y = aX_1 + bX_2 + cX_3 + \cdots dX_n \tag{2}$$

$$r_x = \frac{|a|}{|a| + |b| + |c| + \cdots |d|}\ X\ 100\% \tag{3}$$

Where *Y* is the standardized dependent variable (ET), *X1, X2, X3,* and *Xn* are the standardized independent variables (precipitation, soil moisture, mean temperature, windspeed, net radiation, humidity, vapour pressure, AED and NDVI); r_x is the relative contribution of each independent variable to ET and *a, b, c*, …. & *d* are the regression coefficients of the independent variables.

2.5. Quantifying the effects of climate and vegetation changes on evapotranspiration.

Analytical method based on the Elasticity concept was used to quantify the effect of climate and vegetation changes on ET.

2.5.1. Attribution of ET change

The elasticity concept is useful for quantifying how a relative change in one variable affects the other variable (Ahiablame *et al.*, 2017; Tan *et al.*, 2020). The elasticity concept is widely used in hydrology due to its clear physical meaning and simple formulation (Sankarasubramanian *et al.*, 2001). Due to its limited input data requirements, the elasticity concept has been extended to investigate the sensitivity of runoff, baseflow and ET to climate and vegetation changes (Ahiablame *et al.*, 2017; Chen *et al.*, 2022; Tan *et al.*, 2020). Since its original formulation, several other elasticity models have been proposed such as the least square elasticity model (Zheng *et al.*, 2009), the multivariable double logarithm, and multivariable transformation analyses models (Tsai, 2017). This study adopts two elasticity models: (1) the least square elasticity (LSE) model because it can overcome the problem associated with small sample size and (2) the double logarithm elasticity

(DLE) model which has previously been used exclusively for quantifying the impact of climate and vegetation changes on streamflow (Tsai, 2017; Khan *et al.*, 2022). The aim of using the two elasticity models is to ensure that our results are robust.

The LSE model is expressed as:

$$\varepsilon = \frac{\bar{X}}{\overline{\overline{ET}}} \cdot \frac{\sum(X_i - \bar{X})(ET_i - \overline{ET})}{\sum(X_i - \bar{X})^2} = \rho_{X,Q} \cdot {}^{C_Q}\!/_{C_X} \tag{4}$$

Where *ET* is evapotranspiration and *X* represent the annual climate or environment variable (precipitation, soil moisture, mean temperature, solar radiation, windspeed, specific humidity, AED and NDVI) and $\bar{X}$ and $\overline{ET}$ represent the multiyear annual mean climatic/environmental variable and ET values respectively. $\rho_{X,Q}$ is the correlation coefficient between the climatic/environment variable and ET and C_X and C_{ET} are coefficients of variation of climatic and environmental variables and ET, respectively.

The DLE model is built on the premise that evapotranspiration (ET) is influenced by multiple factor elasticities in the form of regression coefficients of a multivariable regression model. The multivariable function describing the influence of climatic and environmental variables on ET is expressed as:

$$ET = f(P, SM, T, H, S, W, VP, AED, NDVI) \tag{5}$$

Where *P, SM, T, H, S, W, VP, AED, NDVI* represent precipitation, soil moisture, mean temperature, solar radiation, windspeed, specific humidity, AED and NDVI. We then modify equation (5) using the approach proposed by Tsai (2017) as follows:

$$ET = P^{\beta 1} SM^{\beta 2} T^{\beta 3} H^{\beta 4} S^{\beta 5} W^{\beta 6} VP^{\beta 7} AED^{\beta 87} NDVI^{\beta 9} \tag{6}$$

Taking logarithm of both sides of equation (6) produces the following equation:

$$LogET = \beta 1 LogP + \beta 2 LogSM + \beta 3 LogT + \beta 4 LogH + \beta 5 LogS + \beta 6 LogW + \beta 7 LogVP + \beta 8 LogAED + \beta 9 LogNNDVI \tag{7}$$

Where β_n is the elasticity coefficient of the different climatic and environmental variables. In our approach, we estimated the elasticity coefficient of each independent variable on ET separately. The elasticities are then estimated as coefficients of the ordinary least squares (OLS) regression analysis between ET and each of the independent variables. In running the regression analysis, the intercept term was left unadjusted (i.e., assumed to be zero).

After estimating the elasticity coefficients using the two methods, we used linear correlation analysis to measure the strength of the relationship between the elasticity coefficients obtained using the two models. To determine which elasticity model to be adopted for further analysis and interpretation, we conducted a linear regression analysis between ET and the different independent variables. We conducted the same analysis for their log-transformed counterparts (ET and climatic and environmental variables). Lastly, we used the adjusted R^2 values obtained from both linear regression models to assess the regression goodness of fit for the log transformed and least square elasticity models (Tsai, 2017; Khan *et al.*, 2022). We adopted the adjusted R^2 because it provides a better overall performance of a regression model by considering the number of predictors in the model. We estimated the mean of the adjusted R^2 obtained from both models and adopted the model with highest mean adjusted R^2.

3. Results

3.1. Trend analysis

Figure 2 shows the mean annual ET estimates and trends across Sahelian watersheds over a period of 4 decades (1982 -2021). It can be observed that there is a strong spatial variability in mean annual ET across the study area varying from 50-850 mm/year. High annual ET occur mostly in the southern fringes of the Sahel while low annual ET occur in watersheds around the central and eastern Sahel (Figure 2a). Trend analysis also shows a strong spatial heterogeneity with statistically significant increasing trends visible around watersheds in the western and central Sahel (0.5-4.5mm/year) and statistically significant decreasing trends observed in the far eastern Sahel (Figure 2b).

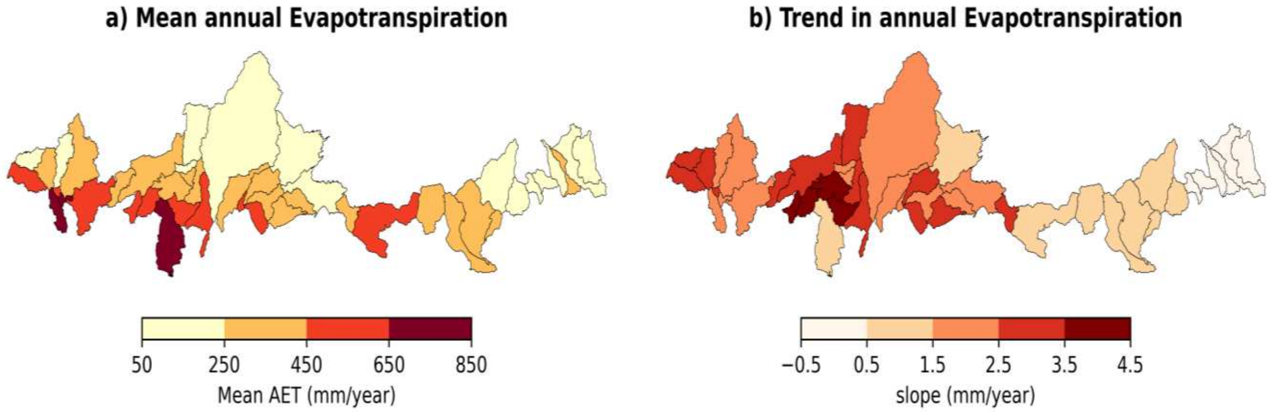

Figure 2: Mean annual ET (a) and trends in annual ET across the Sahelian belt.

Mean annual estimates of all the climatic and environmental variables are shown in Figure 3. There is a strong spatial heterogeneity in precipitation and soil moisture across the study area (Figure 3a & b). Mean temperature is quasi uniform in the western and central Sahel but shows strong spatial heterogeneity in the eastern Sahel (Figure 3c). Windspeed and net radiation are higher in the northern Sahel compared to the south while relative humidity appears to be uniform across the region with a strong spatial heterogeneity observable around the far eastern Sahel (Figure 3d, e, & f). There is also a strong spatial heterogeneity in vapour pressure and AED across the study area (Figure 3g & h). NDVI scores are higher in watersheds located in the southern fringers of the Sahel compared to those in the north and eastern Sahel (Figure 3i)

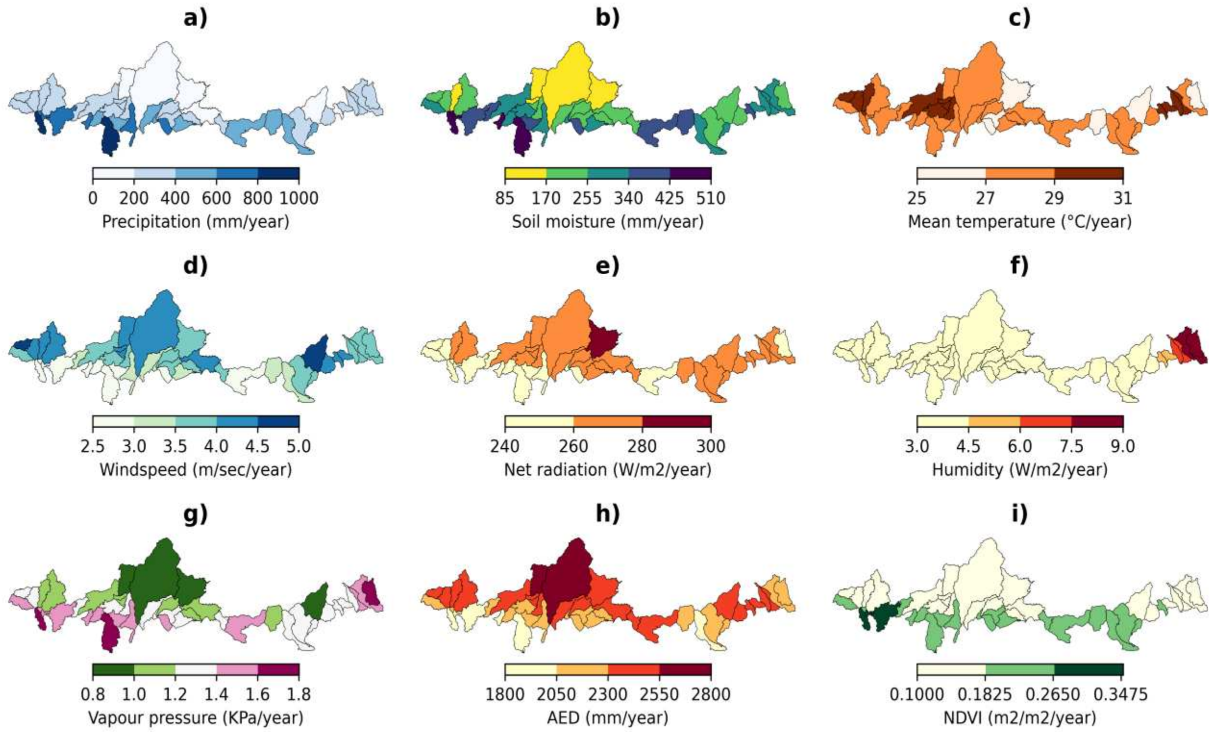

Figure 3: Mean annual estimates of climate and environmental variables.

Figure 4 shows the results of trend analysis for all the other climatic variables over a period of four decades (1981-2021) and NDVI over two decades (2000-2021). Trend analyses show statistically significant increasing trends in annual precipitation, soil moisture and mean temperature across the region (Figure 4a, b & c). Other climate variables show both statistically significant increasing and decreasing trends, however, there is a strong spatial heterogeneity in trend magnitudes. For example, increasing and decreasing trends in windspeed are perceptible in the eastern Sahel and western Sahel respectively (Figure 4d). Decreasing trends in net radiation are also perceptible around the central Sahel (Figure 4e). Statistically significant increasing trends in specific humidity are visible in the western and central Sahel while decreasing trends occur in the eastern Sahel (Figure 4f). Decreasing trends in vapour pressure occur in the eastern Sahel while increasing trends are clearly visible in the central and western Sahel. There is also a strong spatial heterogeneity in AED trends with statistically significant increasing trends clearly visible in the eastern Sahel (6 mm/year) while statistically significant negative trends occur in the western Sahel. (Figure 4h). There is a consistent increase in NDVI across all watersheds with statistically significant trends occurring in a few watersheds (Figure 4i).

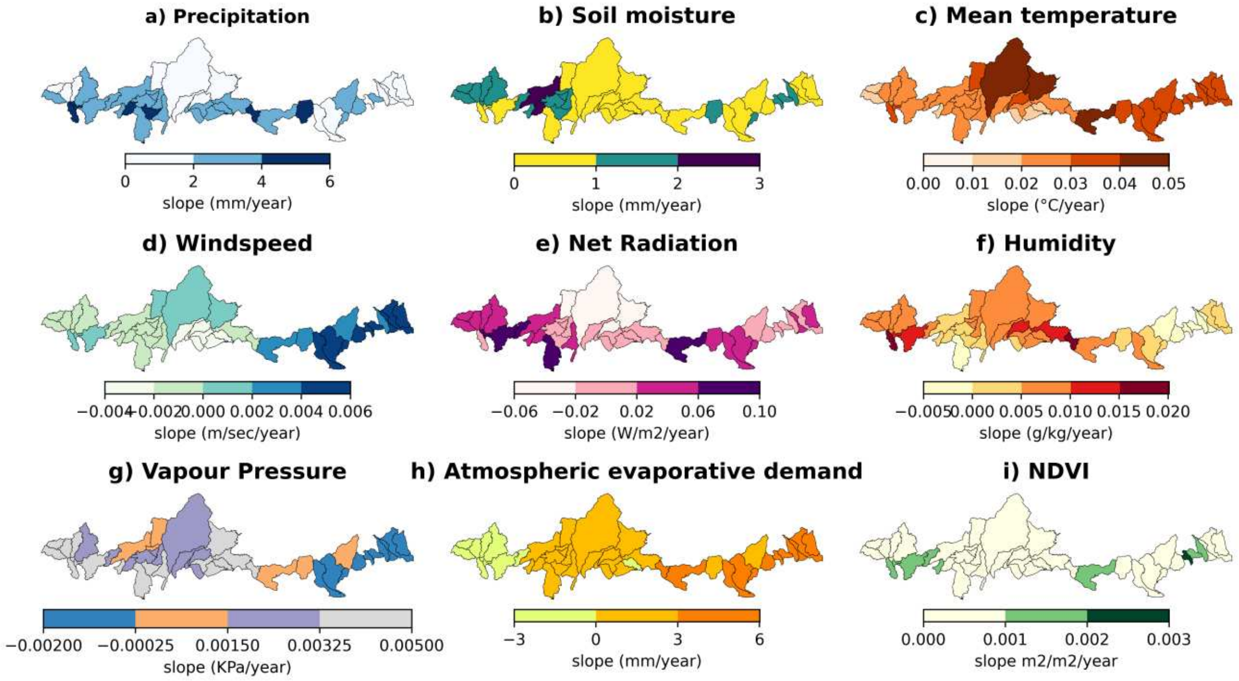

Figure 4: Trends in annual climatic variables and environmental variables across the Sahel

3.2. Factors influencing ET.

Table 2 shows the results of PCC between ET and each independent variable while controlling for the effect of all the other variables. PCC scores show that precipitation, mean temperature, net radiation, specific humidity, vapour pressure and NDVI have statistically significant correlations with ET. Results of Pearson correlation between the rate of change in each independent variable and the rate of change in the dependent variable (ET) are also available in Table 2 and in Figure 4.

Table 2: Identifying the factors influencing ET variability.

Variable	Partial correlation	Pearson Correlation	Multivariable Regression	
			Relative weight	Relative contribution (%)
Precipitation	0.85**	0.38**	0.0367	4.61
Soil moisture	0.06	0.51**	0.1681	21.12
Mean temp	-0.35**	-0.72**	0.1225	15.39
Windspeed	-0.02	-0.74**	0.1629	20.46
Net radiation	-0.64**	0.13	0.5540	6.96
Humidity	0.71**	0.37**	0.0126	1.58
Vapour pressure	0.41**	0.67**	0.0994	12.39
AED	0.004	-0.72**	0.1093	13.72
NDVI	0.28*	0.25*	0.0292	3.67

** Indicates statistically significant at 5% significance; *indicates statistically significant at 1% significance level.

Multivariable regression indicate that the independent variables contributed about 80% of the ET variance (R^2=0.80 and adjusted R^2=0.75). The relative contributions of soil moisture, mean temperature, windspeed, AED and vapour pressure were 21.12%, 20.46%, 15.39%, 13.72% and 12.49% respectively suggesting that these are the main variables influencing ET in the Sahel (Table 2). Pearson correlation analysis also indicate that a positive change in precipitation, soil moisture, specific humidity, vapour pressure and NDVI lead to a positive change in ET (Figure 4 a, b, e, f, & i). In contrast, a positive change in mean temperature, windspeed, and AED leads to a decline in ET (Figure 4 c, d, & h). Among the climatic variables, vapour pressure has the strongest positive Pearson correlation coefficient (*r=0.67, p<0.05*) while mean temperature, windspeed and AED have the strongest negative Pearson correlation coefficients (*r>-0.70, p<0.05*) with ET.

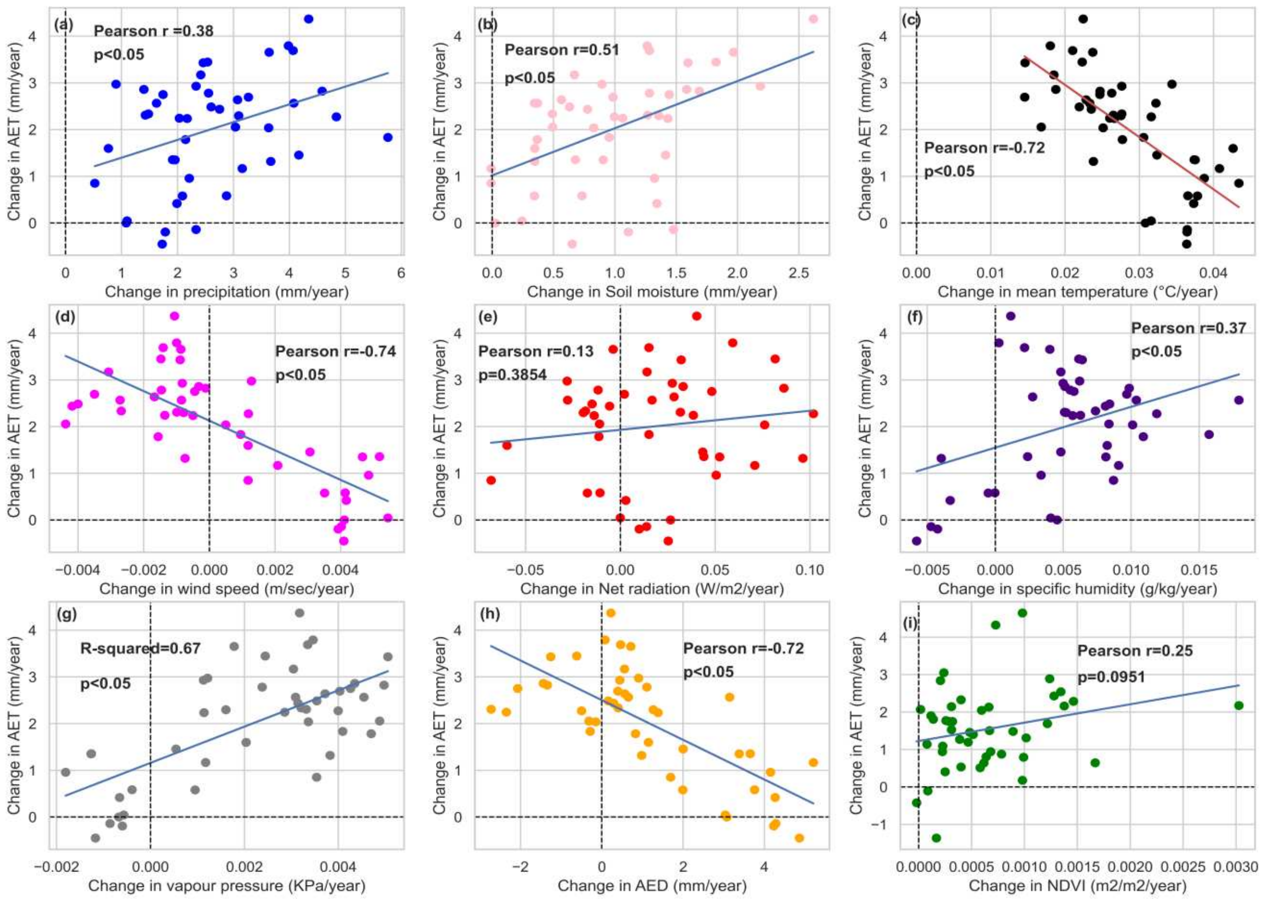

Figure 5: Response of ET to climate and environmental factors: (a) precipitation, (b) soil moisture, (c) mean temperature (d) windspeed, (d) net radiation, (f) specific humidity, (g) vapour pressure, (h) AED and (i) NDVI. Each dot in the plot denotes a watershed.

3.3. Quantifying the effects of climate and vegetation changes on ET

The LSE and DLE models were used to calculate the elasticity coefficients of the independent variables on ET. Results of the Pearson correlation between the elasticity coefficients from both models are shown in Figure 6.

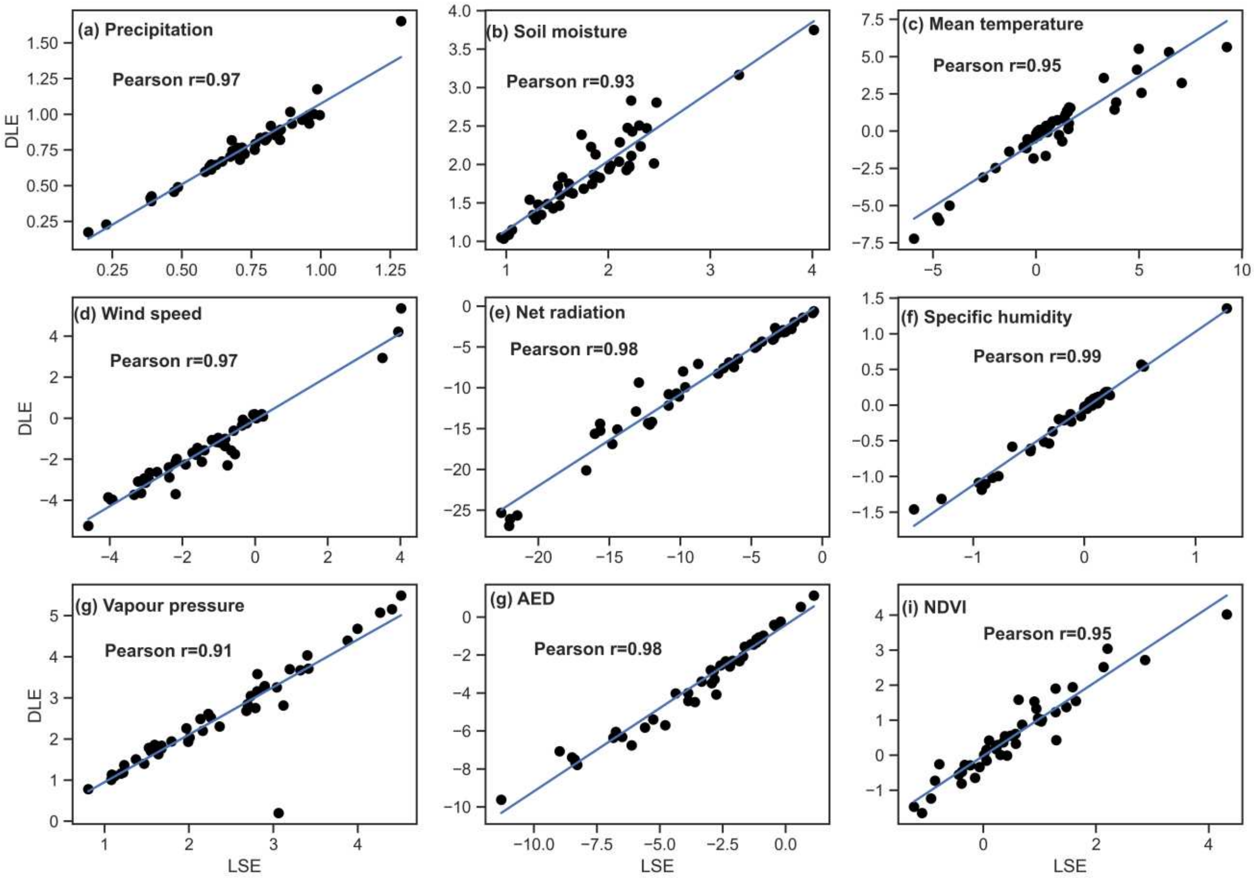

Figure 6: Relationship between elasticity coefficients produced by both models. DLE: double logarithm elasticity and LSE: least square elasticity.

Pearson correlation coefficients between the elasticity coefficients produced by both models are substantially high (*$r>0.91$, $p<0.05$*) for all variables suggesting that both models have similar performance (Figure 6). To determine which of the models to be adopted for further analyses, we used the adjusted R^2 values obtained from the linear regression analysis between ET and the different independent variables, and their log-transformed counterparts as explained in the methods section. Adjusted R^2 values obtained from LSE and DLE models are available in Figure 7 for all the watersheds.

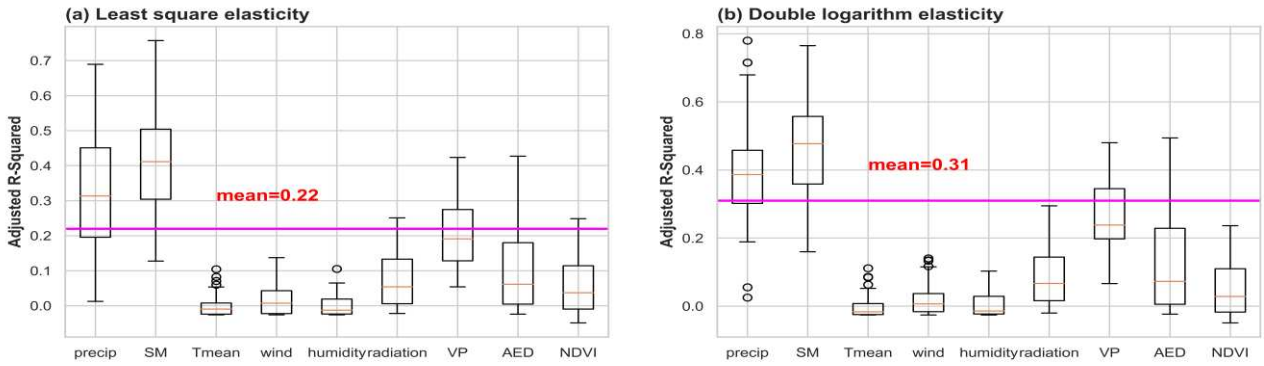

Figure 7: Comparison of adjusted R^2 values using the LSE and DLE models for all the watersheds in the Sahel. Precip: precipitation; SM: soil moisture; VP: vapour pressure, AED: atmospheric evaporative demand; NDVI: normalised difference vegetation index. The horizontal magenta-coloured lines represent the mean adjusted R^2 obtained using each method while the values in red represent the mean adjusted R^2 for all watersheds.

Analyses indicate that the mean adjusted R^2 from the DLE model is (0.31) while that from the LSE is (0.22) (Figure 7). Since the adjusted R^2 from DLE is higher than that of LSE, the elasticity coefficients from DLE are presented and discussed throughout the rest of this paper.

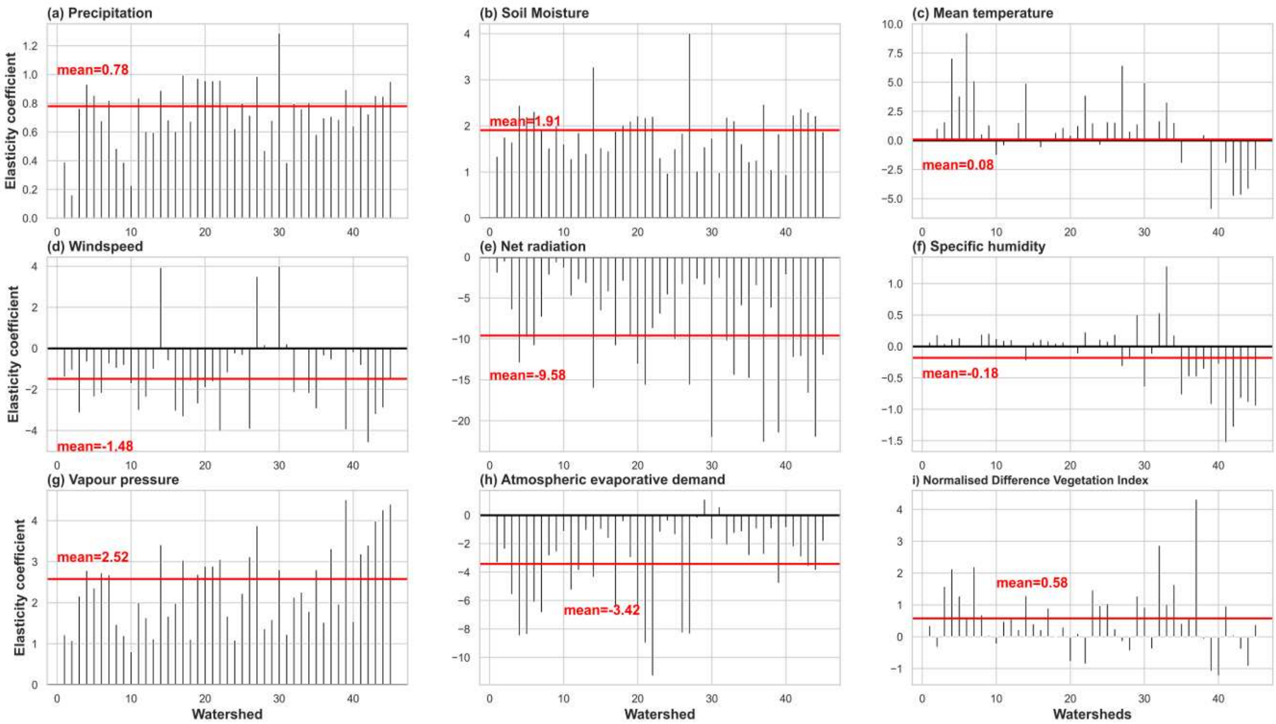

Figure 8: Elasticity coefficients of the independent variables on ET in all the watersheds in the Sahel. Each vertical line represents a watershed while the red horizontal line is the mean elasticity coefficient value for all the watersheds. The values in red are mean elasticity coefficients.

Figure 8 shows the elasticity coefficients of climate and environmental factors on ET. Results from the analyses show that precipitation, soil moisture, and vapour pressure produced positive elasticity coefficients on ET across all the watersheds while mean temperature and NDVI produced positive elasticity coefficients in about 80% of the watersheds (Figure 8a, b, g & i). Other independent variables produce mixed scores (positive and negative elasticity coefficients) across the watersheds. Elasticity coefficients range from (0.17 to 165), (1.03 to 3.75), (8.55 to -5.65), (-5.25 to 5.35), (-26.92 to -0.61), (1.46 to 1.36), (0.19 to 5.49), (-9.92 to 1.13) and (-1.65 to 4.09) with corresponding means of 0.78, 1.90, 0.08, -1.48, -9.58, -0.18, 2.52, -3.41, & 0.57 for precipitation, soil moisture, mean temperature, windspeed, net radiation, specific humidity, vapour pressure, AED and NDVI, respectively. Elasticity coefficients obtained suggest that climatic factors produced higher elasticity coefficients on ET than environmental factors (Figure 8). Furthermore, vapour pressure has a greater positive influence on ET than soil moisture and precipitation (Figure 8a, b & g). Conversely, net radiation shows a greater negative effect on ET compared to other climate variables (Figure 8e).

4. Discussion

4.1. Mean annual estimates.

Generally, higher AED values recorded around the central Sahel may be attributed to higher mean temperature, windspeed, net radiation and vapour pressure which all have different modulating effects on AED. On the other hand, higher NDVI values observed in watersheds around the southern fringes of the Sahel may be attributed to higher annual precipitation and soil moisture availability.

4.2. Trend analysis

The results of trend analysis are consistent with those from other studies around the Sahel. For example, Ndehedehe *et al.* (2018) and Adeyeri and Ishola (2021) found increasing trends in annual ET across the western and central Sahel using data derived from MODIS and GLEAM respectively. Using reanalysis data obtained from the Modern-Era Retrospective analysis for Research and Applications (MERRA), Ndiaye *et al.* (2020) also reported increasing trends in solar radiation, and specific humidity and decreasing trends in windspeed in the western Sahel. Cook *et al.* (2022)

reported increasing trends in mean temperature across the Sahel, reduced (increased) windspeed in the western (eastern) Sahel and increased specific humidity in the central Sahel and our analysis are consistent with their results. Declining trends in ET in parts of the Sahel are also consistent with results from a global study which attributed the decline to changes in specific humidity (Yang *et al.*, 2019). Increasing trends in precipitation and mean temperature follow results reported in several studies in the region e.g., (Nkiaka *et al.*, 2017; Ilori and Ajayi, 2020; Dembélé *et al.*, 2022). Increasing trends in annual precipitation in the Sahel have been attributed to changes in global circulation patterns such as sea surface temperatures and increased moisture recycling in the region (Yu *et al.*, 2017; Biasutti, 2019). Increasing mean annual temperature follow a global pattern that has been attributed to global warming (Hegerl *et al.*, 2019). Decreasing trends in incoming solar radiation around the central Sahel may be due to increasing precipitation which increases cloud cover over the region which in-turn reduces incoming solar radiation at the surface (Giannini, 2010; Cook *et al.*, 2022). Increasing specific humidity in parts of the Sahel have been attributed to increasing surface temperatures and stronger monsoon winds carrying more moisture from the Gulf of Guinea (Cook *et al.*, 2022). Increasing trends in AED parts of the Sahel reflect the increasing trends in mean temperature in those areas which is also consistent with results from another study in the region (Abiye *et al.*, 2019). Many studies in the Sahel attributed increasing trends in NDVI to precipitation increase (Yu *et al.*, 2017; Ogutu *et al.*, 2021; Jiang *et al.*, 2022). However, there is a strong spatial heterogeneity in the distribution of NDVI trends across the region. Overall, our analyses suggest that increasing trends in annual ET across the Sahel may be attributed to different climatic and environmental factors. This is the first study to assess the effects of vegetation cover on ET in the Sahel and as the GGWI is still under implementation, it not yet known how increasing tree cover in the Sahel will affect the vegetation-hydrology-climate interactions especially as the trees become mature in the decades to come. As such, more studies are needed in the region to understand vegetation-hydrology-climate interactions under different alternative scenarios.

4.3. Factors influencing ET.

4.3.1. Climatic (abiotic) factors

The study uses several climatic variables including precipitation, mean temperature, windspeed, net radiation, specific humidity, vapour pressure and AED to assess the factors influencing ET variability in the Sahel. The three statistical methods including PCC which considers the collinearity and interactions among the different independent variables revealed that precipitation, vapour pressure and humidity are climatic variables with the strongest influence on ET. Multivariable regression analyses show that the climatic factors contribute about 75.11% of the ET variance with mean temperature, windspeed, vapour pressure and AED contributing the highest to ET variance. Results from our analyses are consistent with those from previous studies in the western Sahel (Adeyeri and Ishola, 2021; Ndiaye *et al.*, 2021). Multivariable regression analyses also indicate that mean temperature and windspeed have a greater negative influence on ET than AED because of their higher relative contributions to ET variance. It is worth highlighting that AED reflects the atmospheric drying power and is influenced by all the other climate variables except precipitation. This implies that the different climate variables have varying modulating effects on AED which may influence the relationship between ET and AED. Nevertheless, the strong negative Pearson correlation between ET and AED suggest that there may be a complimentary relationship between them as suggested in a previous study (Brutsaert, 2015). This has been attributed to the fact that AED in dryland areas is higher than precipitation and ET combined, and as such, ET is limited by water availability (Yang *et al.*, 2019).

Positive Pearson correlations between ET and precipitation, net radiation and specific humidity and the negative relationship between ET and mean temperature and AED have also been observed in other dryland regions e.g., (Li *et al.*, 2022). Precipitation is the main supplier of water for ET consumption while net radiation provides the energy needed for ET to occur. The negative correlation between mean temperature and ET may be attributed to rising global temperatures which in-turn enhance soil moisture depletion leading to limited water for soil evaporation and vegetation growth which both influence ET in water-limited environments (Jung *et al.*, 2010).

4.3.2. Environmental (biotic) factors

Results of our analyses indicate that biotic factors (soil moisture and NDVI) have less influence on ET compared to abiotic factors (climatic variables) with a relative contribution of 24.79% to ET variance. The PCC between ET and NDVI shows a weak score ($r=0.28$, $p<0.01$) even though statistically significant at 1% significance level (Table 2). This is consistent with results obtained in other dryland regions (Chen *et al.*, 2022; Zheng *et al.*, 2022). The low relative contribution of vegetation cover to ET may be attributed to the fact that vegetation covers varies seasonally and also depends on the characteristics of the vegetation structure such as leaf area index (LAI), root depth, vegetation coverage, physiology, age and vegetation type e.g., forest, agriculture, or grassland (Odongo *et al.*, 2019). The present study was conducted at an annual timescale which may mask the strong seasonal correlations between ET and NDVI in the rainy season when ET is not limited by water supply. Nevertheless, Pearson correlation between ET and NDVI shows that a positive change in NDVI leads to a corresponding positive change in ET which is in-line with results from other studies e.g., (Chen *et al.*, 2022; Zheng *et al.*, 2022). This suggest that as vegetation cover increases in the Sahel, this may likely increase the rate of ET in the region. The low PCC score between ET and soil moisture may be attributed to increasing global temperatures which depletes the amount of soil moisture available for soil evaporation and transpiration.

4.4. Quantitative attribution of ET change

The impact of climate variability and vegetation change on ET in the Sahel was quantified using the double logarithm elasticity model. Mean elasticity coefficients were 0.78, 1.90, 0.08, -1.48, -9.58, -0.18, 2.52, -3.41, & 0.57 for precipitation, soil moisture, mean temperature, windspeed, net radiation, specific humidity, vapour pressure, AED and NDVI, respectively. This implies that a 10% increase in precipitation, soil moisture, mean temperature, vapour pressure and NDVI will increase ET by approximately 8%, 19%, 0.8%, 25% & 6% respectively. Vapour pressure contributes substantially to ET variance and also produced the highest positive elasticity coefficient on ET which is consistent with results obtained from other dryland regions (Ma *et al.*, 2019). The greater positive effect of vapour pressure on ET in water-limited environments may be attributed to the fact that this variable can influence plant stomatal activity and canopy photosynthesis (Yang *et al.*, 2022). In contrast, a 10% increase in windspeed, net radiation, and AED leads to a decline in ET by approximately 15%, 95%, & 34%, respectively. This is consistent with results from another study in the region which showed that net radiation, and mean temperature had a negative impact on ET (Yang *et al.*, 2019). Vapour pressure, soil moisture, precipitation and NDVI produced the highest positive elasticity coefficients while net radiation and AED had the highest negative elasticity coefficients on ET.

NDVI also produced positive elasticity coefficients across most watersheds suggesting that increasing vegetation greenness in the Sahel may enhance ET. However, increasing vegetation greenness in the Sahel may lead to water scarcity as more water may be lost to the atmosphere through the ET. Additional research is needed to investigate vegetation-hydrology-climate interaction in the Sahel as suggested at the end of section 4.2 above. This is very crucial considering that enhance vegetation greenness has been shown to exacerbate water scarcity in some regions (Vicente-Serrano *et al.*, 2021).

Although results from previous studies reported that precipitation is the dominant climatic factor controlling ET in many regions (Feng *et al.*, 2020; Yang *et al.*, 2022), results from the present study show that soil moisture has a stronger positive effect on ET than precipitation with a higher mean elasticity coefficient (1.91) compared to precipitation (0.78). Moreover, the Pearson correlation coefficient between soil moisture and ET is stronger (0.51) than that between precipitation and ET (0.38). Furthermore, soil moisture had a higher relative contribution (21.12%) to ET variance compared to precipitation (4.61%). This is in-line with results from a previous study showing stronger positive correlations between soil moisture and ET compared to precipitation (Yinglan *et al.*, 2019). In contrast the PCC between soil moisture and ET is (0.06) when controlling for precipitation and other variables. This suggests that although precipitation is the main source of water supply for ET, it would appear that across the Sahel, most of the precipitation is lost through infiltration into the soil and therefore contributes indirectly to ET through transpiration (Yang *et al.*, 2019; Wang *et al.*, 2020). In fact, several studies have attributed the decline in ET in many areas to limited soil moisture, thereby highlighting the fact that soil moisture is an important variable driving ET in many regions (Jung *et al.*, 2010; Ndehedehe *et al.*, 2018; Zhou *et al.*, 2021). Furthermore, moisture recycling in the Sahel has been identified as an important factor influencing ET in the region (Yu *et al.*, 2017). Results of the different analyses conducted in this study suggest that the mechanisms controlling ET variability in the Sahel are complex and could transcend natural climate variability and vegetation change.

Whilst all the datasets used in the study have been validated and used extensively in previous studies in the Sahel, we wish to acknowledge that satellite-derived and reanalysis data have inherent uncertainties which may influence the results of the analyses reported in this study. Therefore, we wish to caution that results from this study should be regarded with a bit of caution. We also wish to acknowledge that the number of climatic and environmental factors analysed in the study are non-exhaustive. However, the different factors are selected based on the results from previous studies conducted around the world and in other dryland regions as highlighted in the introduction section of this article. We acknowledge that there may be other important factors that may have been inadvertently left out which could influence the results of the analyses reported herein which is another weakness of the study.

5. Conclusions

The present study used analytical methods to assess the effects of climate and environmental changes on ET in the Sahel over the period (1981-2021) for climate variables and (2000-2021) for vegetation cover change. Results from our analyses show increasing trends in annual ET in the western, central and parts of the eastern Sahel. Precipitation, soil moisture, mean temperature, and NDVI also show increasing trends across the whole region while the other variables show both increasing and decreasing trends in the different watersheds with a strong spatial heterogeneity in trend magnitudes. Multivariable regression analyses show that both climatic and environmental factors contribute about 80% of the ET variance. However, the relative contribution of climatic variables is 75.11% while that of environmental variables is 24.71%. Vapour pressure had the highest mean positive elasticity coefficient (2.58) while net radiation had the highest mean negative elasticity coefficient (-9.58) on ET. Taking together, results from the different analyses carried out in the present study suggest that the mechanisms controlling ET variability in the Sahel are complex and may transcend climate and environmental changes. The LSE and DLE models produced similar elasticity coefficients with strong Pearson correlations coefficients (>0.91) between the elasticity coefficients from both models. This suggest that both models may be used to quantify the impact of climate variability and vegetation change on ET in other regions. Results from the present results may be crucial for adopting climate-smart reforestation policies and enhance water resources management in Sahel. This is the first study to assess the effects of vegetation cover on ET in the Sahel. As the GGWI is still ongoing, it not yet fully known how increasing tree cover will affect the vegetation-hydrology-climate interactions especially as the trees become mature in the decades to come. Therefore, more studies are needed in the region to disentangle the relationship between vegetation-hydrology-climate under different alternative scenarios.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement:

All data used to perform the analyses reported in this paper are freely available for download through the Climate Engine Research App [https://app.climateengine.com] through a custom user account. Shapefiles for the major basins and their sub-basins are freely available at www.hydrosheds.org/hydrosheds-v2. Soil moisture data from GLEAM are freely available for download at https://www.gleam.eu/.

CRediT authorship contribution statement:

Elias Nkiaka: Conceptualization, Data Curation, Methodology, Investigation, Resources, Writing-Review & Editing, Funding acquisition.

Robert G. Bryant: Methodology, Investigation, Writing-Review & Editing.

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Appendix A: Characteristics of the watersheds in the Sahelian belt

Major Basin	Sub-basin	Number	Area (km^2)
Senegal	Bakoy	1	101,792
	Faleme	2	29,880
	Ferlo	3	45,131
	Karakoro	4	47,574
	Kolinbine	5	124,013
	Senegal 1	6	30,152
	Senegal 2	7	43,436
	Senegal 3	8	4,094
	Senegal 4	9	7,086
Volta	Nakambe	10	110,851
	Sourou	11	31,072
Niger	Bani 1	12	18,610
	Bunsuru	13	31,043
	Dallol Maouri	14	71,197
	Dallol Bosso	15	541,267
	Faga	16	39,113
	Gorouol	17	53,944
	Niger 10	18	31,167
	Niger 11	19	11,467
	Niger 12	20	12,352
	Niger 13	21	123,166
	Niger 9	22	60,907
	N' kaba	23	38,787
	Rima	24	6,585
	Tarka	25	48,140
	Tchegue	26	32,872
	Tilemsi	27	87,033
Lake Chad	Bahr Azum	28	77,960
	Bouluo	29	31,407
	Dillia	30	162,385
	Fitri	31	143,576
	Komadugu Yobe	32	33,318
	Komadugu Yobe	33	97,568
	Koramas	34	43,751
Nile	Abu Hut	35	45,971
	Al Ghallah	36	17,948
	Al Malik	37	125,049
	Bandah	38	129,875
	Blue Nile 1	39	23,014
	Gelha	40	90,900
	Nahr Atbarah 1	41	25,088
	Mereb Wenz	42	73,113
	Wadi Atshan	43	33,722
	White Nile 1	44	17,690
Red Sea	Nahr al Qash	45	66,346

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