Statistical and spatial variability of climate data in the Mareb-Gash river basin in Eritrea

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ABSTRACT

Introduction. Global reanalysis products are extensively used for hydrologic applications in sparse data regions. The establishment of inputs for hydrologic modelling from such global reanalysis requires prior checking and analyses.

Materials and methods. The present study attempts to utilize Climate Forecast System Reanalysis (CFSR) datasets for the Mereb-Gash river basin in Eritrea, to prepare the input data for forthcoming hydrological modelling studies. The activities include statistical analyses, computation of PET, and drought indices using different methods so as to understand basin characteristics through the use of geospatial and geostatistical tools.

Results. The results of statistical analyses indicated that there was predominantly a significant monotonic trend in the majority of the data. Precipitation (P) and relative humidity tend to decrease, whereas temperature (T) and potential evapotranspiration (PET) tend to increase. Among the PET estimation methods, the Thornthwaite method gave inconsistent results as compared to Hargreaves and Penman-Monteith methods, the former being highly dependent on the elevation of the station. In most cases, it was found that Penman-Monteith produced the highest PET values.

Conclusions. Besides, Standardized Precipitation and Evapotranspiration Index (SPEI) analyses in the basin indicate persistent dry conditions over the period 2000–2013 and predominantly humid conditions over the period 1979–2000. The study concluded that the presence of a significant trend in most of the climatic variables and persistent drought conditions in recent years were found to be congruent with global and regional climatic studies that are highly likely linked to human and climate influence on the environment.

KEYWORDS: global reanalysis, potential evapotranspiration, standardized precipitation and evapotranspiration index, Mereb-Gash river basin

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Статистическая и пространственная изменчивость климатических данных в бассейне реки Марек-Гаш в Эритрее

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АННОТАЦИЯ

Введение. Продукты глобального реанализа имеют широкое применение в гидрологии при недостаточности исходных данных. Формирование исходной информации для гидрологического моделирования на основе такого глобального реанализа требует предварительной проверки и анализа.

Материалы и методы. Предпринята попытка использовать массивы данных реанализа системы климатических прогнозов (CFSR) для условий бассейна реки Марек-Гаш в Эритрее с целью подготовки исходных данных для предстоящих исследований в области гидрологического моделирования. Это исследование включило в себя статистический анализ, расчет индексов потенциальной эвапотранспирации (ПЭТ) и засухи на основе применения различных методов с целью изучения характеристик речного бассейна с использованием геопространственных и геостатистических инструментов.

Результаты. Результаты статистического анализа показали, что в большинстве массивов данных в значительной степени преобладают монотонные тенденции: осадки (P) и относительная влажность имеют тенденцию к уменьшению, тогда как температура воздуха (T) и ПЭТ — тенденцию к увеличению. Среди методов оценки ПЭТ метод Торнтуэйта

дал неоднозначные результаты по сравнению с методами Харгривза и Пенмана-Монтейта, причем использование первого метода сильно зависело от высотного положения метеостанции. В большинстве случаев было обнаружено, что по методу Пенмана-Монтейта получались самые большие значения ПЭТ.

Выводы. Анализ стандартизированного индекса осадков и эвапотранспирации (SPEI) по методу Пенмана-Монтейта в исследуемом речном бассейне указал на устойчивые засушливые условия в период с 2000 по 2013 г. и преимущественно влажные условия в период с 1979 по 2000 г. Сделан вывод о том, что имеющиеся тенденции для большинства климатических характеристик и устойчивого развития условий засухи в последние годы хорошо согласуются с результатами глобальных и региональных климатических исследований, и, по всей вероятности, связаны с влиянием на окружающую среду воздействия человека и изменения климата.

КЛЮЧЕВЫЕ СЛОВА: глобальный реанализ, потенциальная эвапотранспирация, стандартизированный индекс осадков и эвапотранспирации, бассейн реки Мереб-Гаш

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INTRODUCTION

In any hydrological modelling process that intends to make predictions from ungauged catchments, three types of data are needed: runoff data, climatic data, and basin characteristics. The most widely used models that make use of such data include statistical, process-based or a combination, of both [1]. Hence, runoff Predictions for Ungauged Basins (PUB) (e.g., [2, 3]) recommended the assessment of available data and the information that can be obtained from such data to be the starting point in any hydrological studies. Different data sources for runoff PUB are available: global, local, and regional data sources followed by field observations [4]. If the resources are available, the most accurate runoff predictions can be obtained by utilising very local data describing the specific characteristics and behaviour of the system. While global or regional data can be useful for annual runoff prediction, more intensive local data can be needed for hydrograph prediction [1].

So far, limited hydrological studies have been carried out in the Mereb-Gash river basin in Eritrea. These limited studies (e.g.¹, [5–8]) have sought to understand the hydrology of the area. Others (e.g., [9, 10]) have assessed the environmental repercussions due to flooding and possible mitigation mechanisms at the outlet of the basin. These modelling efforts have ranged from simple conceptual models to complex, physically-based distributed hydrological models. One of the main challenges highlighted in all these studies is the acute shortage of historical hydrometeorological data, suggestions for improved data collection and management system to increase the reliability of hydrological modelling efforts. Global reanalysis products are extensively used

for hydrologic applications in sparse data regions (e.g., [11–15]). For example, [14] evaluated ERA-5, CFSR, ERA-Interim, Modern-Era Retrospective analysis for Research and Applications (MERRA), and Japanese 55-year Reanalysis (JRA-55) for stream flow and annual water budget for two basins located in the diverse climatic settings in India. The results showed that these reanalysis products yielded satisfactory performance. Likewise, [15] evaluated three widely used global high-resolution precipitation products, namely Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSIANN-CDR), Tropical Rainfall Measuring Mission 3B42 Version 7 (TRMM 3B42V7), and CFSR against gauge observations and investigated their reliability as inputs in Soil and Water Assessment Tool (SWAT) to simulate streamflows. Results showed the potentiality of PERSIANN-CDR and 3B42V7 for streamflow prediction on at daily and monthly scale, respectively, over the two humid regions. At the same time, the performance of NCEP-CFSR for hydrological applications varies from basin to basin [11, 13, 16] used CFSR data for hydrological modelling in tropical and semi-tropical basins. The spatially interpolated CFSR data performed as well or better than single ground observations made further than 20–30 km, and sometimes better than individual weather stations less than 10 km from the basin centroid. This study further revealed the usefulness of CFSR data as a means to supplement ground records and consistently determine a baseline for hydrologic model performance. Fuka and others [13] used the CFSR to obtain historical weather data. They demonstrated its application to modelling five watersheds representing different hydroclimatic regimes in Ethiopia and the United States of America. Moreover, [16] assessed the applicability of CFSR climate data in model-

¹ Euroconsult. Sector study on national water resources and irrigation potential: component 1 report surface water resources. Arnhem, Netherlands, 1998.

ling the hydrology of the Upper Blue Nile, Ethiopia. Results reveal that utilizing the CFSR precipitation and temperature data to force a watershed model provides stream discharge simulations that are as good as or better than models forced using conventional weather stations.

The satellite-based global CFSR climatic dataset for the period 1979–2013 on a daily basis might be used for hydrologic modelling to predict streamflow from the poorly gauged Mareb-Gash river basin. However, prior to usage of the global climatic datasets as input to hydrological modelling, various statistical processes should be undertaken the fact that this is the first attempt to utilize global climatic data for the aforementioned purpose in the study area. Such activities are essential to understand the human and climate variability impact on the environment under the influence of natural fluctuations in temperature, precipitation, and other factors. In this regard, the non-parametric Mann-Kendall (MK) and Sen's Slope (SS) estimator are used to estimate the magnitude of the trend for the reference time series of 32 global satellite-based stations. Moreover, the determination of PET and other variables and parameters are inevitable procedures, because they are not only inputs to hydrological modelling but also help to understand the basin characteristics. Therefore, the present study focuses on the statistical analyses, computation of PET and drought indices using different methods. In addition, analyses of spatio-temporal variability and distribution of various climatic parameters and

variables would be carried out, aiming at understanding basin characteristics. The authors strongly believe that this study will contribute to future hydrologic modelling studies in the area.

METHODS AND MATERIALS

Study area

Water resources of Eritrea are divided into five major river basin systems: Mereb-Gash, Barka-Anseba, Danakil, Setit, and the Red Sea. The Mereb-Gash river basin, originating from the Eritrean highlands and the Ethiopian plateau, is a transboundary river basin that crosses two political borders; Ethiopia and Sudan. It is known by Mereb and Gash in the upstream and downstream areas, respectively; hence the name Mereb-Gash that represents the whole basin is commonly used. Figure 1 shows the geographical location of the Mereb-Gash river basin. Its outlet is at Kassalatown (Sudan), which is located at 36°23'20" E longitude and 15°26'50" N latitude, having an area and main channel length of 22,900 km² and 500 km, respectively. According to Euroconsult¹, out of the total area 17,400 km² lies in the Eritrean territory. It is a long, narrow basin, having a basin shape factor and average basin slope of 11 and 7 %, respectively. The flow of the Mereb-Gash does not usually reach the Nile River; rather, it is lost in the sands of the eastern plains of Sudan. Even though the river basin has limited streamflow data, it is believed to be one of the basins with the highest potential for

Fig. 1. Geographical location of the study area

modern technology-based irrigation that can provide sustainable agricultural development in the region.

The river flow has high variation during the wet season. The mean annual flow is estimated to be 680 million m³ [9] and maximum flow 1,000 m³s⁻¹ [10]. It is dry for much of the year (November–April) but subjected to flash floods, transporting 40 million m³ of sediment [10] during the rainy season. The rainy season usually starts in June and ends in September with a series of flood flows. The flash floods are mainly due to mountainous and dissected topography of the upper-third and partly the middle-third of the basin, poor vegetation cover, unfavourable geological formations which are associated with poor soil formation and low infiltration rates. The downstream plains in the lower-third of the basin have been experiencing recurrent flooding; for example [9, 10] reported that the recurrence interval of severe floods for Kassala town is 1 to 5 years. Likewise, the western plain areas, e.g., the town of Tesseney, had been repeatedly exposed to flooding [17]. The long-term annual rainfall in the area is highly variable, usually ranging from over 900 mm to less than 300 mm [18]. The temperature in the area is also highly variable that depends on the season of the year; it is the highest in April and May and lowers in December and January. Typically minimum and maximum temperatures range from less than 10 °C in the highlands to more than 45 °C in the lowlands.

Data sources

Climatic data, which are available globally at 38 km resolution, were obtained from the CFSR over a 35 years period (1979–2013) on a daily basis. These datasets include precipitation (P), minimum and maximum temperatures, wind speed, relative humidity, and solar radiation. Moreover, a high-resolution digital elevation dataset for the study area was acquired from The Shuttle Radar Topography Mission (SRTM) at 1 arc-second global resolution. The spatio-temporal analyses were done with the help of the Quantum Geographic Information System (QGIS).

Data analyses

Non-parametric monotonic trendtest

To test the CFSR dataset for monotonic trend, MK and SS are employed in this study. Non-parametric MK test is commonly employed to detect monotonic trends in a series of environmental, climatic, or hydrological data. The MK trend test assumes that under the null hypothesis of no trend, the time series is independent and identically distributed. The null hypothesis H_0 is that the data come from a population with independent realizations and are identically distributed. The alternative hypothesis H_A is that the data follow a monotonic trend. The univariate MK for a monotone trend in a time series $(X_j, j = 1, 2, 3, \dots, n)$ of data is based on the test statistic S defined as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(X_j - X_k), \quad (1)$$

where X_j are the sequential data values, n the length of the data set, and

$$\text{sgn}(x) = \begin{cases} 1 & \text{if } x > 0, \\ 0 & \text{if } x = 0, \\ -1 & \text{if } x < 0. \end{cases} \quad (2)$$

Mann [18] and Kendall [19] have documented that when $n \geq 8$, S is approximately normally distributed with mean, $E(S) = 0$ and variance σ^2 given by

$$\sigma^2 = \left\{ n(n-1)(2n+5) - \sum_{j=1}^p t_j(t_j-1)(2t_j+5) \right\} / 18, \quad (3)$$

where p is the number of the ties of the extent i and t_j is the number of data points in the j^{th} tied group. The statistic S is approximately normally distributed, provided that the following Z-transformation is employed:

$$Z = \begin{cases} \frac{S-1}{\sigma} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \frac{S+1}{\sigma} & \text{if } S < 0. \end{cases} \quad (4)$$

S is closely related to Kendall's τ as given by:

$$\tau = \frac{S}{D}, \quad (5)$$

where

$$D = \left[\frac{1}{2}(n-1) - \frac{1}{2} \sum_{j=1}^p t_j(t_j-1) \right]^{1/2} \left[\frac{1}{2}n(n-1) \right]^{1/2}. \quad (6)$$

The magnitude of the slope of trend proposed by Sen [19] is estimated by:

$$b = \text{Median} \left(\frac{x_j - x_l}{j - l} \right), \quad \forall l < j, \quad (7)$$

where b is the estimate of the slope of trend and x_j is the j^{th} observation. The slope determined by equation (7) is a robust estimate of the magnitude of the monotonic trend. Negative values indicate a decreasing trend, 0 values no trend, and positive values indicate an increasing trend.

Potential evapotranspiration (PET)

There are several temperatures and radiation-based formulae for calculating PET, such as Blaney-Criddle, Turc, Penman-Monteith, Thornthwaite, Hargreaves, and so on. Three of these methods, which are built-in in the “SPEI” package in R-programming language that uses user-selected input data, have been selected for the determination of PET. The first method computes the monthly PET according to the Thornthwaite [20] equation. It is the simplest of the three methods and can be used when only temperature data are available. But, variables that can affect PET, such as wind speed, surface humidity, and solar radiation, are not account-

ed for. In cases where more data are available, a more advanced method to calculate PET is often preferred to make a more complete accounting of drought variability. However, these additional variables can have significant uncertainties. The second method uses the Hargreaves [21] equation that computes the monthly reference evapotranspiration ET_0 of a grass crop. This method requires data on the mean external radiation. If such data are not available, it can be estimated from the latitude and the month of the year. The third method calculates the monthly reference evapotranspiration ET_0 of a hypothetical reference crop according to the FAO-56 Penman-Monteith equation described in [22]. The original parameterization of Allen et al. [22] is used, corresponding to a short reference crop of 0.12 m height. The method requires data on the incoming solar radiation or sunshine hours or cloud cover, relative humidity, minimum and maximum temperature, wind speed, and geographical information.

Drought characterization

A drought is a natural phenomenon that occurs over a variable period as a result of prolonged shortages in the water supply². It can have a substantial impact on many economic sectors and people. Drought indicators or indices are often used to help monitor droughts. According to World Meteorological Organization (WMO)², there are numerous types of drought indicators and indices; Aridity Anomaly Index (AAI), Aridity Index (AI), Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI), Rainfall Anomaly Index (RAI), Standardized Precipitation Evapotranspiration Index (SPEI) are some among others. A list of such methods, along with their strengths and limitations, is presented in². To assess the degree of droughts in the study area, SPEI based on 32 global satellite-based stations, within and around the Mareb-Gash basin, have been considered. The spatial and temporal comparisons of droughts are prepared by analysing the historical droughts by the characteristics of duration, severity, and magnitude.

The SPEI, a climate drought index which was proposed by [23] and modified by [24], was designed to take into account both precipitation and potential evapotranspiration (PET) in determining drought on a range of timescales. SPEI uses the basis of SPI [25] but includes a temperature component, allowing the index to account for the effect of temperature on drought development through a basic water balance calculation. Vicente-Serrano and others [23] showed that SPEI has the advantage of combining multi-scalar character with the capacity to include the effects of temperature

variability on drought assessment. Ever since its development, SPEI has been used in an increasing number of climatologic and hydrologic studies [24] based on 30–50 years climatic database.

SPEI uses the monthly (or weekly) difference between precipitation and PET. This represents a simple climatic water balance, which is calculated at different time scales to obtain the SPEI. For given values of P_i and PET_i , the climatic water balance D_i that provides a simple measure of the water surplus or deficit for the analysed month is calculated as:

$$D_i = P_i - PET_i, \quad (8)$$

The calculated D_i values could be aggregated at different time scales using the same procedure as that of SPI [23]. The probability density function of a three-parameter log-logistic distributed variable is given by:

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x-\gamma}{\alpha} \right)^{\beta-1} \left[1 + \left(\frac{x-\gamma}{\alpha} \right)^{\beta} \right]^{-2}, \quad (9)$$

where α , β , and γ are scale, shape and origin parameters, respectively, for D values in the range ($\gamma > D < \infty$).

Parameters of the log-logistic distribution can be obtained following different procedures. The L -moment procedure is the most robust and easy approach [26]. When L -moments are calculated, the parameters of the log-logistic distribution are given by [27] as follows:

$$\beta = \frac{2w_1 - w_0}{6w_1 - w_0 - 6w_2}, \quad (10)$$

$$\alpha = \frac{(w_0 - 2w_1)\beta}{\Gamma(1+1/\beta)\Gamma(1-1/\beta)}, \quad (11)$$

$$\gamma = w_0 - \alpha\Gamma\left(1 + \frac{1}{\beta}\right)\Gamma\left(1 - \frac{1}{\beta}\right), \quad (12)$$

where $\Gamma(\beta)$ is the gamma function of β .

In Vicente – Serrano and others [23], when the log-logistic α , β , and γ distribution parameters were calculated, the probability-weighted moments (PWMs) method is used, based on the plotting-position approach [28], where the PWMs of orders are calculated as:

$$w_s = \frac{1}{N} \sum_{i=1}^N (1-F_i)^s D_i, \quad (13a)$$

where F_i is a frequency estimator following the approach of Hosking [28]:

$$F_i = \frac{i-0.35}{N}, \quad (13b)$$

where i is the range of observations arranged in increasing order and N is the number of data, and D_i is the difference between precipitation and potential evapo-

² WMO and GWP, *Integrated Drought Management Programme Handbook of Drought Indicators and Indices*. 2016; 1173.

transpiration for the month i . The unbiased PWMs are obtained according to:

$$w_s = \frac{1}{N} \sum_{i=1}^N \left[\left(\frac{N-i}{s} \right) / \left(\frac{N-1}{s} \right) \right]. \quad (14)$$

The probability distribution function of D according to the log-logistic distribution is then given by:

$$F(x) = \int_0^x f(x) dx = \left[1 + \left(\frac{\alpha}{x-\gamma} \right)^\beta \right]^{-1}. \quad (15)$$

With $F(x)$ the SPEI can easily be obtained as the standardized values of $F(x)$ as given in Vicente – Serrano [23]:

$$SPEI = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3}, \quad (16)$$

where

$$W = \sqrt{-2 \ln(p)} \text{ for } p \leq 0.5 \quad (17)$$

p is the probability of exceeding a determined D value, $p = 1 - F(x)$. If $p \geq 0.5$, p is replaced by $1 - p$ and the sign of the resultant SPEI is reversed, $C_0 = 2.525517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 0.432788$, $d_2 = 0.189269$ and $d_3 = 0.0011308$. SPEI has an intensity scale in which both positive and negative values are calculated, identifying wet and dry events (Table 1). The average value of the SPEI is 0, and the standard deviation is 1. SPEI of 0 indicates a value corresponding to 50 % of the cumulative probability of D , according to a log-logistic distribution.

Table 1. SPEI classification of dry and wet conditions

Category	SPEI	Probability, %
Extreme wet	$SPEI \geq 2.0$	2.3
Severe wet	$1.5 \leq SPEI < 2.0$	4.4
Moderate wet	$1.0 \leq SPEI < 1.5$	9.2
Normal	$-1.0 < SPEI < 1.0$	68.2
Moderate dry	$-1.5 < SPEI \leq -1.0$	9.2
Severe dry	$-2.0 < SPEI \leq -1.5$	4.4
Extreme dry	$SPEI \leq -2.0$	2.3

RESULTS AND DISCUSSION

Precipitation data of 35 years on a daily basis from CFSR has been processed to find out the monthly, seasonally, and annual variability by using non-parametric statistical analyses. Fig. 2 shows the spatial variability of the long-term annual rainfall for the Mereb-Gash basin. It can be observed that rainfall is highly variable that comply with^{3,4}, ranging from over 1,100 mm in the upper-third to less than 500–700 mm in the lower-third and middle-third of the basin. A small area within the territory of the basin, which is located at the remotest part in the Ethiopian-Eritrean highlands, receives the highest rainfall. Visual comparison of the annual rain-

³ INC, Eritrea: Initial national communication, Asmara, Eritrea, 2001.

⁴ IWRM, Action Plan for Integrated Water Resources Management (IWRM) in Eritrea, Asmara, Eritrea, 2008.

Fig. 2. Spatial variability of long-term rainfall based on CFSR dataset for Mereb-Gash

fall from CFSR data with the one presented in various documents (e.g.³, [30]) shows that the former gives higher precipitation values. Substantial areas in the upper-third and lower-third receive rainfall, ranging from 330–715 mm. Fig. 3, *a* shows the seasonal cycle of the mean monthly rainfall at selected global station near the Gherset dam. The seasonal cycle of monthly rainfall of all the stations is about the same except for variability in magnitude; rainfall is peak during the rainy (summer) season, in the month of either July or August. Fig. 3, *b*, *c*, and *d*) shows linear regression trend analyses of long-term annual relative humidity, precipitation, and maximum temperature, respectively, for the selected station near the Gherset dam. The relative humidity and precipitation regression analyses indicate a decreasing trend, whereas maximum temperature shows an increasing

trend. Similar trends were observed in almost all the other global satellite-based stations.

MK and Sen's slope (SS) monotonic trend analysis methods are applied to long-term annual precipitation (P), temperature (T), and PET to P ratio, as shown in Table 2. MK's p-values of P, T and PET/P are higher than the significance level ($\alpha = 0.05$) at 95 % confidence interval for 34.4, 37.5 and 31.3 % of the stations, respectively. Hence the null hypothesis of no significant monotonic trend in the series is accepted. On the contrary, the p-value of P, T and PET/P are less than the significance level ($\alpha = 0.05$) at 95 % confidence interval for 65.6, 62.5 and 68.7 % of the stations, respectively; hence, the alternative hypothesis of the presence of significant monotonic trend is true. Moreover, SS results of P of all the stations are less than 0 at a 95 % confidence

Fig. 3. Regression analyses on long-term climatic data of a selected station near Gherset dam, Mereb-Gash: *a* — mean monthly rainfall; *b* — mean annual relative humidity; *c* — precipitation; *d* — maximum temperature

Table 2. MK p -values and SS for various climatic variables

Station code	Elevation, m	P		T		PET	PET/P	
		MK	SS	MK	SS	mm y^{-1}	MK	SS
142381	1596	0.13	−13.02	0.26	0.02	2159.8	0.19	0.02
142384	1816	0.18	−6.60	0.16	0.02	2105.7	0.15	0.03
142388	1762	0.35	−3.00	0.10	0.03	1970.1	0.32	0.09
142391	2021	0.00	−13.00	0.01	0.03	1895.9	0.00	0.08
142394	2797	0.07	−11.73	0.00	0.04	1483.1	0.02	0.01
145378	1057	0.00	−27.30	0.08	0.03	2178.0	0.00	0.04
145381	1238	0.13	−6.00	0.06	0.03	2446.3	0.14	0.20
145384	1708	0.05	−8.10	0.02	0.03	2087.1	0.05	0.05
145384	1163	0.00	−20.83	0.00	0.05	1994.2	0.00	0.23
145388	1413	0.00	−6.60	0.00	0.03	2108.5	0.00	0.18
145391	1670	0.00	−16.03	0.00	0.05	1906.4	0.00	0.08
145394	2331	0.06	−11.40	0.00	0.04	1593.7	0.03	0.02
148369**	835	0.00	−24.10	0.03	0.03	2330.8	0.00	0.10
148372	1155	0.00	−34.10	0.05	0.03	2266.8	0.00	0.08
148375	843	0.00	−33.80	0.01	0.03	2257.1	0.00	0.09
148378	1163	0.01	−17.34	0.05	0.03	2221.7	0.01	0.04
148381	1270	0.01	−13.90	0.10	0.03	2129.2	0.03	0.04
148384	1634	0.00	−11.60	0.05	0.03	1912.5	0.00	0.05
148388	1762	0.00	−15.40	0.01	0.03	1970.1	0.32	0.10
148391	1545	0.00	−14.90	0.00	0.05	1854.1	0.00	0.07
148394	2324	0.35	−5.10	0.01	0.03	1779.6	0.27	0.03
151366	581	0.00	−20.80	0.00	0.04	2405.7	0.00	0.24
151369†	635	0.00	−27.40	0.00	0.04	2322.4	0.00	0.15
151372	878	0.00	−25.80	0.00	0.03	2324.8	0.00	0.10
151375††	917	0.01	−11.34	0.03	0.03	2409.2	0.01	0.09
151378	972	0.13	−6.00	0.06	0.03	2394.6	0.13	0.19
151381	995	0.01	−8.34	0.06	0.03	2293.4	0.01	0.18
151388*	2430	0.35	−8.63	0.05	0.03	1758.5	0.38	0.01
151391	1644	0.48	−4.20	0.02	0.03	1824.2	0.57	0.02
155366	555	0.00	−18.00	0.00	0.03	2381.4	0.00	0.31
155369	833	0.00	−20.36	0.00	0.03	2435.2	0.00	0.20
155372	833	0.00	−20.36	0.00	0.03	2350.5	0.00	0.20

NB: Station codes with asterisk represent stations that are used hereafter for illustration purposes; *near Adi-Halo dam, **near Gherasetdam, †near Fanco dam, and ††near Haikota town.

level, indicating a significant decreasing trend. But, the statistical analyses of whole reference time series data of T and PET/P highlight that the trends look predominantly increasing at a 95 % confidence level.

Other credible studies in the area could not verify these results, but regional studies give more or less similar indications. For example, a regional study on precipitation and temperature variables in the Horn of

Africa [31] over the period 1930–2014 showed that statistically, the trend of precipitation decreased insignificantly; the trend of temperature was observed to drop very significantly between 1930 and 1969, but it was dramatically elevated from 1970 to 2014. These overall trends are in line with the global predictions that revealed increased land surface air temperature and evapotranspiration and decreased precipitation amount,

in interaction with climate variability and human activities, leading to desertification in Sub-Saharan Africa (where the study area is located), parts of East and Central Asia, and Australia⁵.

Using the Thornthwaite, Hargreaves, and Penman-Monteith methods from the “SPEI” package in R programming language, monthly and annual PET were calculated for all the 32 stations. Fig. 4 shows the comparison of PET estimation methods at different times of the year at two stations in the upper-third near the Adi-Halo dam and lower-third near the Gherset dam. The stations near Adi-Halo and Gherset dams are located at different elevations; 2,430 and 835 m above mean sea level, respectively. The Thornthwaite method was found to be highly dependent on the elevation of the station; it produced much lower PET values in loca-

tions at higher altitudes as compared to the other two methods. Fig. 4, *a* shows PET of the three methods at a station near the Adi-Halo dam with the Thornthwaite and Penman-Monteith method providing the lowest and highest values, respectively, whereas Hargreaves-based PET for the most part standing between the two methods. For example, in January, it can be seen that the Thornthwaite method is giving PET of 49.6 and 61.8 % lower than Hargreaves, and Penman-Monteith, respectively and the same is more or less true for the remaining months. Hargreaves and Penman-Monteith methods do not show such noticeable dependence on the elevation of a station and produced consistent PET, as shown in Fig. 4, *a* and *b*. In almost all cases, Penman-Monteith happens to be with the highest PET values.

Regression analyses were carried out to establish a relationship between the two methods with respect to Penman-Monteith. The results show a polynomial line of 2nd degree, having a coefficient of determination R^2 equal to 0.877 and 0.781 for Hargreaves vs. Penman-Monteith and Thornthwaite vs. Penman-Monteith,

Fig. 4. Comparison of PET estimation methods in Mereb-Gash basin: *a* — at the upper third of the basin near Adi-Halo dam; *b* — at the lower third of the basin near the Gherset dam

Fig. 5. Example on the relationship between PET estimation methods at a station near Adi-Halo dam: a — Hargreaves vs. Penman-Monteith; b — residual plot of Hargreaves vs. Penman-Monteith; c — Thornthwaite vs. Penman-Monteith; d — residual plot of Thornthwaite vs. Penman-Monteith

respectively (Fig. 5, *a* and *c*). Similarly, the residual plots shown in Fig. 5, *b* and *d* demonstrate randomly dispersed points around the horizontal axis, indicating a linear regression model could be appropriate for the data. It is obvious that such relationships could not be established for areas with different climatic and topographic conditions. For example [32], obtained various relations for different climatic conditions. Fig. 6 shows

the spatial variability of long-term annual PET of the Mereb-Gash basin for the values presented in Table 2. The upper-third of the area has the lowest PET, which is logical and continues to increase as we move towards the middle-third and lower-third portions of the basin.

Fig. 7 provides information about drought conditions at shorter and longer time scales (1, 3, 6, and 12 months) SPEI at a station near the Fanco dam in

Fig. 6. Spatial variability of PET in Mereb-Gash basin

Fig. 7. The SPEI at lower-third of the Mereb-Gash basin near the Fanco dam at different time scales: *a* — 1 month; *b* — 3 months; *c* — 6 months; *d* — 12 months

Mereb-Gash. The period until the late 1990's show quasi-continuous humid conditions, with some minor drought periods. The persistent drought conditions during 2000–2013 are also clearly identified by the SPEI, independent of the time scale. Remarkably enough, the SPEI values of all the stations show similar trends. The spatial variability of the annual SPEI for the driest year (2003) for the whole basin is presented in Fig. 8. Unfortunately, the whole area had been exposed to severe and extreme drought conditions the fact that SPEI values are < -1.0 .

The same procedure was employed to the wettest year (1998), providing positive SPEI values (Fig. 9). As per the SPEI classification (Table 1), the basin was predominantly under normal and moderate wet conditions.

These findings are in congruence with global, regional, and local studies. For example, intergovernmental panel on climate change, IPCC⁵ showed that over the period 1961–2013, the annual area of drylands has increased with sizeable inter-annual variability. Also, the frequency and intensity of droughts have increased in

Fig. 8. Spatial variability of the SPEI for the driest year (2003)

Fig. 9. Spatial variability of the SPEI for the wettest year (1998)

some regions, including the Mediterranean, West Asia, many parts of South America, much of Africa, and north-eastern Asia. A regional study on drought in the Horn of Africa [31] over the period 1930–2014 using the SPEI showed that the region experienced from mild to moderate drought throughout the study period with severe to extreme drought in some regions, particularly in 1943, 1984, 1991, and 2009. Thus, it would be necessary to consider the IPCC⁵ recommendation on actions that should be taken in the near-term, based on existing knowledge, to address desertification, land degradation, and food security while supporting longer-term responses that enable adaptation and mitigation to climate change. These include actions to build individual and institutional capacity, accelerate knowledge transfer, enhance technology transfer, and deployment, enable financial mechanisms, implement early warning systems and undertake risk management.

CONCLUSIONS

Conclusions inferred from this study could be summarized in the following statements:

The statistical analyses of the satellite-based global CFSR climatic data show that there is predominantly a significant monotonic trend. MK's p -values of precipitation, temperature, and potential evapotranspiration are less than the significance level ($\alpha = 0.05$) at a 95 % confidence interval for the majority of the stations. Hence, the null hypothesis of no significant monotonic trend is

rejected. Moreover, SS analyzes son precipitation from all the stations are less than 0 at a 95 % confidence level, indicating a decreasing trend. But, temperature and potential evapotranspiration trends were found to be predominantly increasing at a 95 % confidence level.

Among the potential evapotranspiration estimation methods, the Thornthwaite method was highly dependent on the elevation of the station. It produced much lower potential evapotranspiration values in locations at higher altitudes than at lower altitudes as compared to Hargreaves and Penman-Monteith. On the other hand, latter methods did not show such noticeable dependence on the elevation of a station and produced consistent estimation. In most parts of the cases, it was found that Penman-Monteith was providing the highest potential evapotranspiration estimations among the three methods.

The SPEI drought index of all stations shows sustained dry conditions during 2000–2013 and predominantly wet conditions during 1979–2000.

Finally, the reasons for the presence of significant trend in most of the climatic variables and persistent drought conditions in recent years in the study area in particular and in the region, in general, are highly likely to be linked to human activities and climate variability. That resulted from the land-use change, the land-use intensification and climate change contributing to desertification, and land degradation. Hence, concerted efforts are badly needed to reverse these human and climate-driven environmental repercussions.

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