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Hydroclimatology of the Kaduna River Basin

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Abstract

This study examined the hydroclimatology of the Kaduna River Basin (KRB) in northern Nigeria. In achieving this, monthly data on temperature (T) and rainfall (P) were sourced from ten hydrometeorological stations across the basin from 1990 to 2018. DrinC (Drought Indices Calculator) software was deployed to calculate Potential Evapotranspiration (PET) adopting Thornthwaite approach. Water Balance (WB) model was used further to estimate other WB components *i.e.* soil moisture (SM), actual evapotranspiration (ET_a), Water surplus (S) and Runoff (R). WB components are used to examine the temporal and spatial variability of the KRB for hydrological years (1990-2018). KRB was divided into two sub-basins (Lower and Upper KRB). The WB analyses indicated the peak of R generally occurs during the wet season (*i.e.* April through October) most especially at the Upper KRB. The study further reveals that the runoff efficiencies imply that <44% of annual P results in R at the upper KRB while <27% of annual P results in R at the lower KRB. The study shows that SM utilization occurs mostly towards the end of the year and at the early months (*i.e.* November through March) across the basin while the majority of S is generated during wet season months, particularly from April through October when ~95% of S occurs on average with the peak S in August. The results of this study provide a baseline understanding of the hydroclimatology of the KRB which can be used as a starting point for further analyses, especially for water resources management.

Keywords

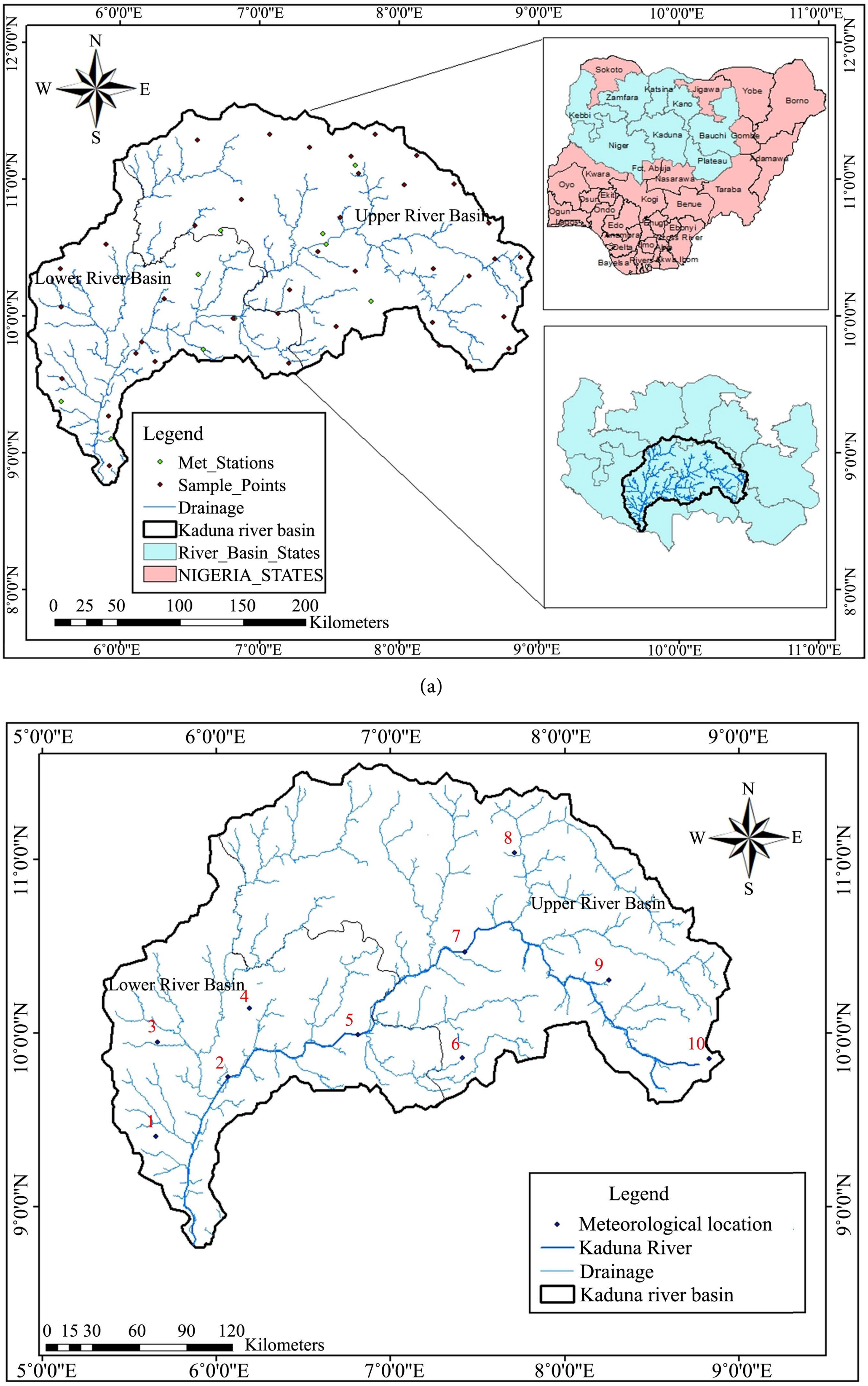
Hydroclimatology, Kaduna River Basin, Water Balance, Nigeria

1. Introduction

The Kaduna River Basin (KRB) is one of the most important river basins in West Africa, accounting for 8% of Nigeria's landmass with 923,768 km^2 (Chinwendu et al., 2017) and drains nearly half of the northern region of Nigeria (**Figure 1**). The 550 km long River Kaduna is the third-longest river in the country after Rivers Niger and Benue flowing through different topographic and geologic zones in the north-west direction towards Kaduna metropolis and thereafter takes a south-west direction turn at Mureji and drains into River Niger at Nupeko. Most of River Kaduna's course passes through open savanna woodland but its lower section cuts several gorges above its entrance into the extensive Niger floodplains. River Kaduna takes its source from Sherri Hills (1280 sl.) in Plateau State. The Kaduna River Basin (KRB) approximately covers 65,878 km^2 area cutting across mainly two States-Niger and Kaduna. The KRB is an important food-producing region, responsible for more than half of Nigeria maize production, among other crops (Agronews, 2019; The Kaduna State Bureau of Statistics, 2019). Additionally, users of the KRB depend on the system for irrigation farming, fishing, industrial uses, drinking water, recreation, navigation, hydroelectricity generation and wildlife habitat. Although its highest headwater is free-flowing and is the only river feeding Shiroro dam (Chinwendu et al., 2017).

Understanding variations and trends of historical and current hydroclimatic variables are relevant to the future development and sustainable management of water resources of a given region (Oguntunde et al., 2016). Information regarding hydroclimatological issues is crucial within the context of water and energy cycles, global warming and the increasing demand for water as a result of urbanization and economic growth (Sankarasubramanian & Vogel, 2002, 2003; Oguntunde et al., 2006; Oguntunde et al., 2016). In most developed countries of the world, hydroclimatology of river basins has been comprehensively studied and the spatial and temporal variability of water balance (WB) components closely monitored (Sankarasubramanian & Vogel, 2002; Oguntunde et al., 2006; Wise et al., 2018; McCabe & Wolock, 2019). Concerted efforts have been made by several scholars to analyze, observe and model hydroclimatic data in the river basins (Sankarasubramanian & Vogel, 2003; Oguntunde et al., 2006, 2016; Wise et al., 2018; McCabe & Wolock, 2019). Some studies have also examined temporal variability and trends of river basins hydroclimate, surface water and energy balances (Milly & Dunne, 2001; Qian et al., 2007). Qian et al. (2007) reported in their study on hydroclimatic trends in the Mississippi River Basin that rainfall trends were the main control of trends in evapotranspiration, while temperature and solar radiation trends had only a little impact. In another study, Frans et al. (2013) employed a macroscale hydrology model to examine the impacts of land use/land cover changes and climate variability on temporal changes in Mississippi River Basin hydroclimate and found that climate change was the major factor driving runoff changes in the basin.

In the developing world, few hydroclimatological studies of river basins have been carried out acknowledging that the present day and future climate in a region like West Africa are gaining ground. However, regional climate modelling studies over the region have mostly focused on model validation and process studies (Afiesimama et al., 2006; 'Bayo Omotosho & Abiodun, 2007; Sylla et al., 2010;



(a)

(b)

Figure 1. (a) The Kaduna river basin; (b) Point locations of meteorological stations. Source: Authors' fieldwork, 2020.

Oguntunde et al., 2016; Ologunorisa & Akinbobola, 2019). Efforts have equally been made to investigate the flow regimes and hydrological variability of some basins in West Africa using hydrological or landsurface models (Andersen et al., 2008; Okpara & Perumal, 2009; Oguntunde & Abiodun, 2013; Durowoju et al., 2018). Conway & Mahe (2009) for example, simulated monthly river flow in three tributaries of the Niger River Basin (NRB) using conceptual water balance (WB) model. In a similar study, Li et al. (2007) applied hydrological routing model and a land surface model to investigate the hydrological variability in sub-catchments of the Lake Chad basin and Niger River basin between 1950 and 1995. Others have reported similar studies for one sub-basin of NRB or the other (Mahe et al., 2005; Mounir et al., 2011; Oguntunde et al., 2014). Siebert & Ward (2014) also explore the frequency of hydroclimate extremes on the River Niger using historical data analysis and Monte Carlo methods and assumed the flow changes reflect varying combinations of the systematic global change (GC), natural multidecadal variability (MDV) and interannual variability (IV).

However, most of these studies are restricted to the river basins in West Africa while no hydroclimatological studies have been carried out on Nigeria's river basins despite the availability of some important river basins. Concerns regarding hydroclimate variability in Nigeria's river basins necessitate this study in order to extenuate the global warming effects which could further be exacerbated by climate change. The aim of this study, therefore, is to analyze the variability and trends in several WB components for the Kaduna River Basin (KRB) (e.g., rainfall, runoff, evapotranspiration) and provide an up-to-date evaluation of the spatial and temporal variability of WB components for the KRB. This study will provide a baseline to which future analyses of variability and trends in KRB hydroclimatic variables can be compared. The choice of KRB is hinged on the fact that the basin is the food basket of the nation producing a considerable quantity of staple diets for the country such as rice, beans, cowpea, maize, millet, sorghum, wheat, carrot, Irish potatoes, sweet potatoes and yam. Also, it is regarded as the major River Basin in the region due to its economic potentials (grain-centric agricultural area) and ecological diversity. Hence, this study is indispensable and has much to offer policymakers in planning.

2. Data and Methods

2.1. Study Area: Kaduna River Basin, Nigeria

This study was conducted in Kaduna River Basin (KRB), the Guinea and Sudan Savannah ecological zone of north-central Nigeria with an absolute location of 8˚45'15"N and 11˚40'5"N and longitudes 5˚25'48"E and 8˚45'36"E. Basically, the basin is divided into two parts (upstream and downstream) in this study. Larger parts of upstream of KRB are found in Kaduna State which is bordered by Katsina and Kano States to the north; Bauchi State to the east; Plateau State to the southeast while the downstream is found in Niger State (**Figure 1**). River Kaduna was dammed at Shiroro in 1990. The Shiroro reservoir (320 km^2) is situated on the eastern part of Niger State and was mainly built to supply energy to nation and the neighbouring countries by improving the country's growing economy (Chinwendu et al., 2017). The basin's general climatic condition is similar to tropical continental (Aw) characterized by a well-defined wet and dry season climate, strong seasonality in rainfall and temperature distributions (Koppen, 1928). The mean annual rainfall can be as high as 2000 mm in wet years and as low as 500 mm in drought years but with a long term average of 1000 mm and an average annual temperature of 27.48˚C (NiMET, 2019).

2.2. Data and Sources

The data used in this research primarily consisted of monthly precipitation and temperature sourced from the available meteorological stations from hydrological year 1990 to 2018 from Nigerian Meteorological Agency (NIMET). The monthly rainfall and temperature data obtained were converted to annual data. DrinC (Drought Indices Calculator) software developed by Tigkas et al. (2015) was deployed to calculate Potential Evapotranspiration (PET) adopting Thornthwaite method.

2.3. Methods

The monthly temperature data were used to determine the values of PET at the 10 locations in the basin using Thornthwaite's method. The method was preferred in this research because is monthly air temperature-based and a widely used empirical method for estimating PET. Also, the method is best suitable for deriving other WB variables (ET_a, SM, Water surplus (S) and runoff (R) unlike other temperature-based methods (Hamon and Hargreaves-Samani) (Rana & Katerji, 1998; Ayoade, 2008; Mccabe & Wolock, 2013, 2019). The method estimates PET based on

$$\text{PET} = 16 \cdot \left(\frac{N}{12}\right) \cdot \left(\frac{m}{30}\right) \cdot \left(10 \cdot \frac{T_{mean}}{I}\right)^{a} \tag{1}$$

T_{mean} is the mean monthly temperature (˚C), N is the mean monthly possible sunshine hours (h/day), m is the number of days of each month and a is given by the equation:

$$a = 6.75 \times 10^{-7} \times I^{3} - 7.71 \times 10^{-5} \times I^{2} + 1.79 \times 10^{-2} \times I + 0.49 \tag{2}$$

where I is a heat index calculated as the summation of the 12 monthly values according to the following equation:

$$I = \sum_{i=1}^{12} \left(\frac{T_{imean}}{5}\right)^{1.514} \tag{3}$$

WB model was used to estimate values of soil moisture (SM), actual evapotranspiration (ET_a) and Runoff (R) among other parameters adopting Thornthwaite and Mather model (Thornthwaite & Mather, 1955; Steenhuis & Van Der Molen, 1986).

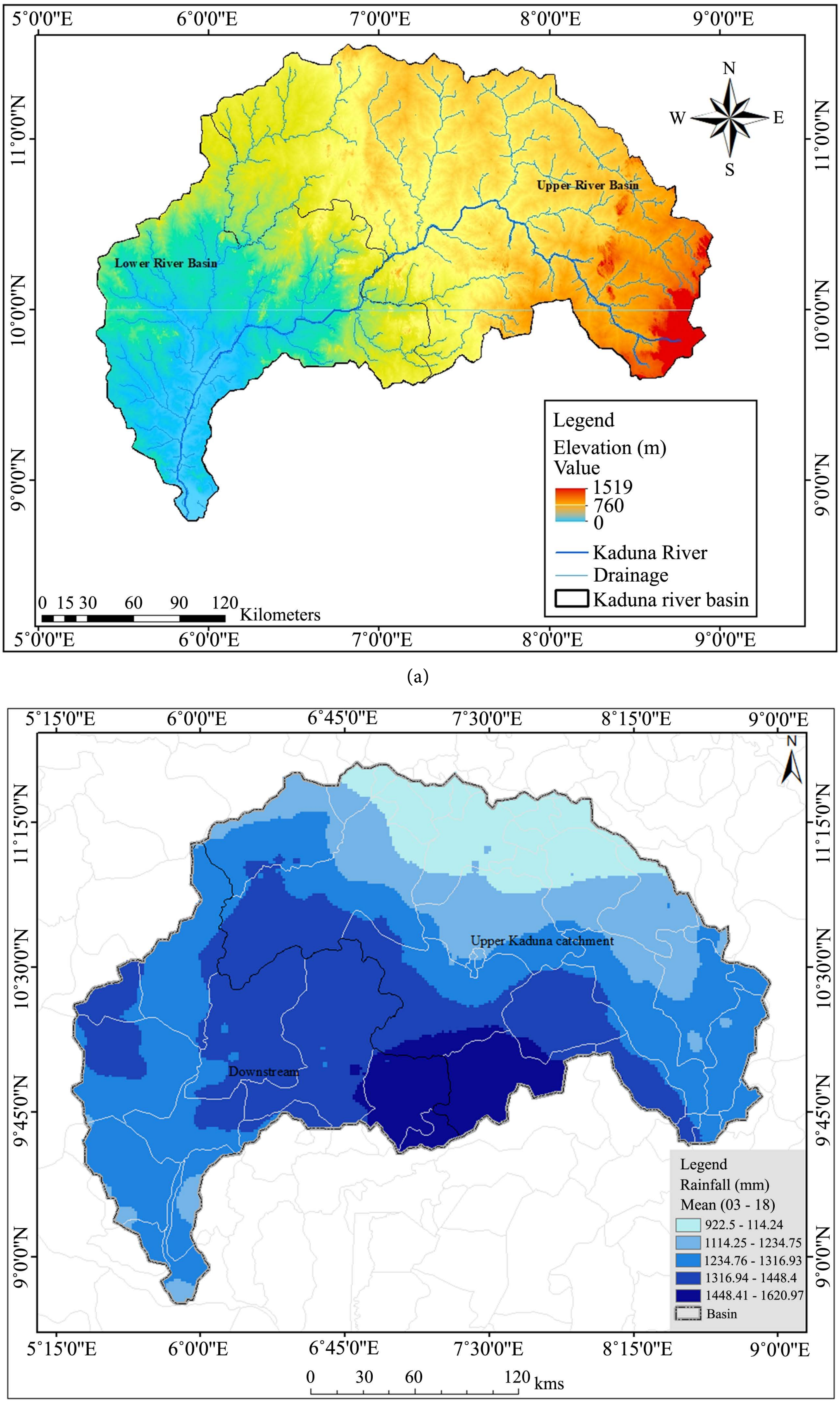
The WB model has been evaluated in several studies to examine the hydroclimatology of a river basin (McCabe & Wolock, 2008, 2011, 2013, 2019). In-depth verifications of WB model and the comparisons between measured and WB-estimated runoff (R) have been carried out in 735 basins across the conterminous United States (CONUS). It was established that the comparison of measured and estimated monthly runoff indicated that the WB model reliably simulated the temporal variability of monthly runoff for most of the stream gauges. It was further stressed that the distribution of correlation values between WB-estimated monthly R and measured monthly R are statistically significant at $p < 0.01$ (McCabe & Wolock, 2013). It is upon this fact, that this study engaged conventional climatic data (precipitation and temperature) from the available meteorological stations to estimate PET, ET_a, SM, Water surplus (S) and runoff (R) with the adoption of WB model by Thornthwaite and Mather method.

In this method, the accumulated potential water loss (APWL) is a summation of negative values of P-PE. Obtain values of water storage corresponding to given values of APWL for a water holding capacity of 250 mm from the appropriate soil moisture retention table. Change in storage (ΔST) is the difference between storage in a given month and that in the preceeding month. And when precipitation (P) is greater or equal to potential evapotranspiration (PET), the soil is saturated and actual evapotranspiration (ET_a) is equal to potential evapotranspiration. But when precipitation is less than PET, the soil begins to dry out and ET_a is less than PET. The ET_a is equal to precipitation plus water withdrawn from the soil, *i.e.* $ET_a = P - \Delta ST$. When the soil is at field capacity, any excess of P over PET is water surplus (S). Only half of the S in a given month actually appears as runoff (R) in that month. While the remaining half is delayed till the succeeding month (Slabbers, 1980; Rana & Katerji, 1998; Ayoade, 2008; Mccabe & Wolock, 2011, 2013, 2019; Durowoju & Olusola, 2017). The mean values of precipitation, temperature, PET, ET_a, SM and R were calculated and were interpolated for each location in the basin using Inverse Distance Weighting (IDW), a spatial statistics extension in ArcGIS 10.1 software (**Figure 2**).

3. Results and Discussion

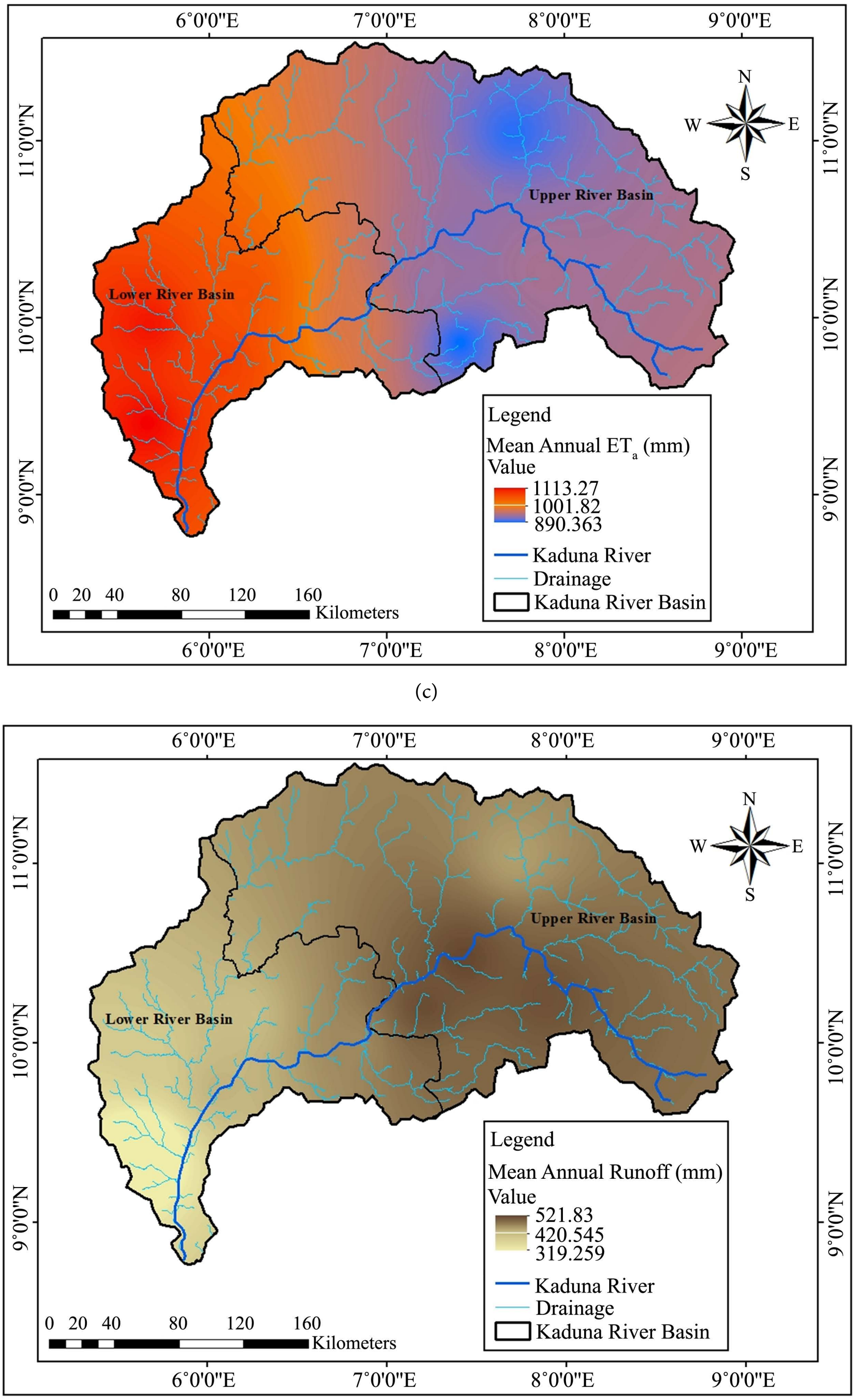
Mean Monthly WBs

Mean monthly WB components (*i.e.* P, PET, ET_a and R) are illustrated for each of the ten locations within the basin (**Figure 3**). In general, P, SM and R are highest during the wet season months (*i.e.* April through October) in KRB. On annual basis, a substantial fraction of P is evaporated and transpired at the temporal phase. The fraction of annual P that becomes ET_a ranges from 0.65 (Location 9) to 0.95 (Location 9) (**Table 1**). The study shows that SM utilization which is the period when ET_a exceeds P occurs mostly towards the end of the year and at the early months (*i.e.* November through March) across the basin (**Figure 3**). At Location 1, SM exceeds P during the peak of the rainy season (*i.e.* May till October). This is attributed to the fact that the location is near to the discharging point into River Niger while result at Location 10 also shows excess SM during the rainy season and this could be related to the fact that the location 10 is very close to River Kaduna's source (Jos Plateau).


5°0'0"E
6°0'0"E
7°0'0"E
8°0'0"E
9°0'0"E
11°0'0"N
10°0'0"N
9°0'0"N
N
W
E
S
Upper River Basin
Lower River Basin
Legend
Elevation (m)
Value
1519
760
0
Kaduna River
Drainage
Kaduna river basin
0 15 30 60 90 120 Kilometers
5°15'0"E
6°0'0"E
6°45'0"E
7°30'0"E
8°15'0"E
9°0'0"E
11°15'0"N
10°30'0"N
9°45'0"N
9°0'0"N
N
Upper Kaduna catchment
Downstream
Legend
Rainfall (mm)
Mean (03 - 18)
922.5 - 114.24
1114.25 - 1234.75
1234.76 - 1316.93
1316.94 - 1448.4
1448.41 - 1620.97
Basin
0 30 60 120 kms

(a)

(b)



(c)

(d)

Figure 2. (a) Mean elevation (ELE in meters [m]); (b) Precipitation (P in mm); (c) Actual Evapotranspiration (ET_a in mm); (d) runoff (R in mm), 1990-2018.

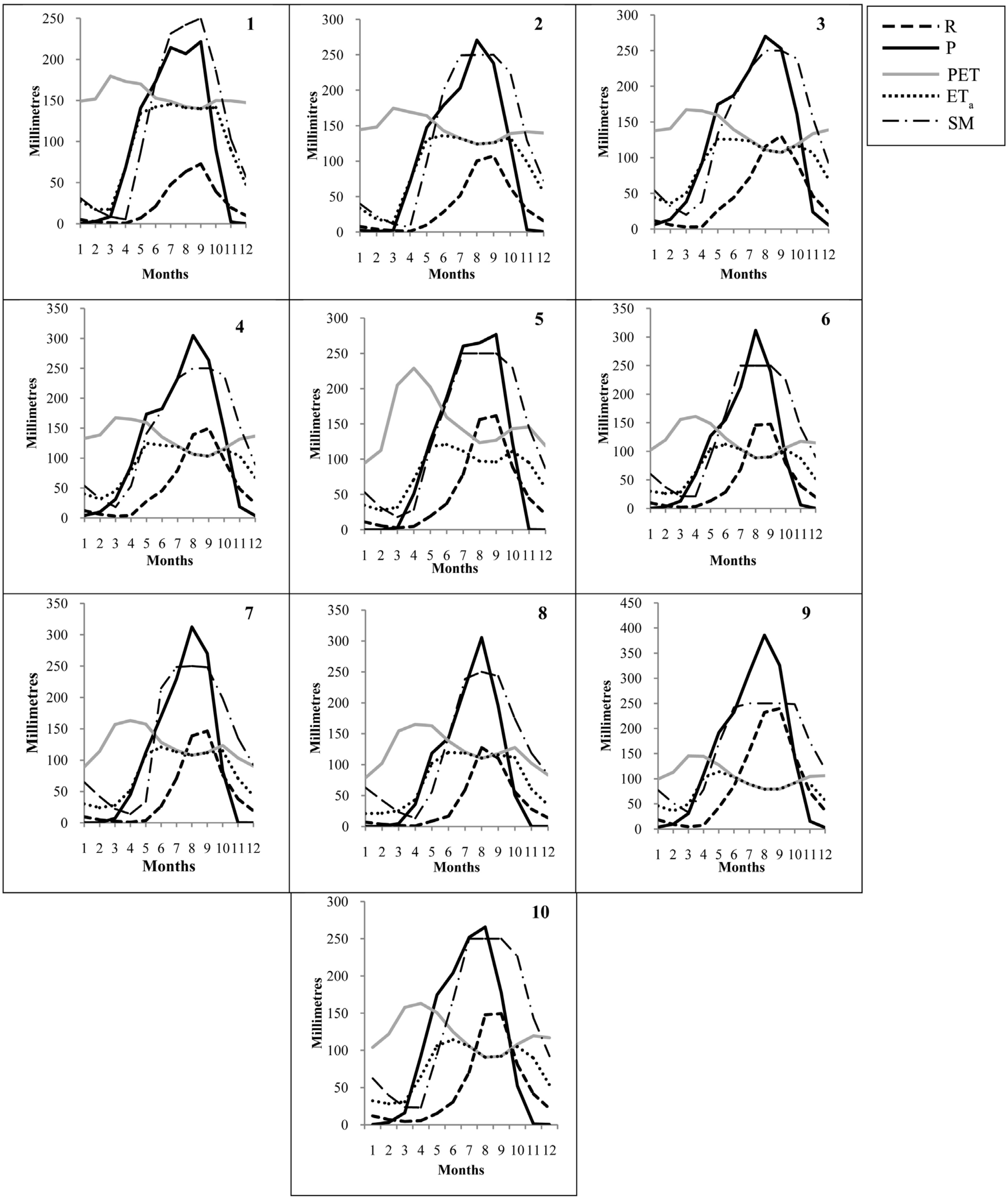


Figure 3. Mean monthly WB components estimated using a WB model for the ten locations in the KRB identified for water years 1990-2018.

For all the locations, PET generally exceeds P during the dry season months (**Figure 3**). Thus, during the dry season most P becomes ET$_a$ and there is little S that can become R. But on an annual basis, P exceeds PET (**Table 1**). Thus, there

Table 1. Mean annual P, PET, ET_a, and R in mm, P-PET in mm, and ratios of PET/P, ET_a/P, R/P and ET_a/PET for the ten locations across KRB.

	Location	P	PET	ET_a	R	P-PET	PET/P	ET_a/P	R/P	ET_a/PET
Lower KRB	1	1174.90	1856.93	1113.29	319.22	−682.02	1.580	0.95	0.27	0.27
	2	1241.12	1750.60	1074.84	427.82	−509.49	1.411	0.87	0.34	0.34
	3	1441.76	1648.18	1107.23	405.53	−206.42	1.143	0.77	0.28	0.28
	4	1454.62	1616.19	1055.18	418.85	−161.57	1.111	0.73	0.29	0.29
	5	1293.00	1799.62	976.25	461.04	−506.62	1.392	0.76	0.36	0.36
Upper KRB	6	1213.52	1437.39	890.33	489.81	−223.87	1.184	0.73	0.40	0.40
	7	1189.57	1462.29	927.88	521.84	−272.72	1.229	0.78	0.44	0.44
	8	1091.29	1468.16	893.93	442.82	−376.87	1.345	0.82	0.41	0.41
	9	1451.23	1598.34	943.45	518.23	−147.11	1.101	0.65	0.36	0.36
	10	1239.30	1442.45	1028.67	425.74	−203.15	1.164	0.83	0.34	0.34

is enough R generated during the rainy season of every year, a perfect characteristics of tropical climate (Oguntunde & Abiodun, 2013; Ologunorisa & Durowoju, 2014; Oguntunde et al., 2014, 2016; Akinbobola et al., 2015; Durowoju et al., 2017). Additionally, for all the locations, the ratio of hydrological-year ET_a to hydrological-year P ranges from 0.65 (Location 9) to 0.95 (Location 1), and the runoff efficiency (hydrological-year R/hydrological-year P) ranges from 0.27 (Location 1) to 0.44 (Location 7) (**Table 1**). Impliedly, the runoff efficiencies indicate that <44% of annual P results in R at the upper KRB while <27% of annual P results in R at the lower KRB.

The magnitude of R that occurs for each location indicates that the largest amounts of R occur most for the northeastern locations (**Figure 4**). A comparison of mean monthly R for each location indicates that the highest R occurs for locations 10, 5, 9 and 6 for most months of the year, with R from location 10 being the highest. In contrast, the lowest R occurs in location 1, 2, 3 and 8. It is also notable that the peak of R generally occurs during the wet season (*i.e.* April through October) most especially at the upper KRB. This occurrence of peak R for most of the locations at the upper basin is related to the soil type (Clayey soil), nature and properties that characterize the location, preventing the direct infiltration of P.

Mean Annual WBs

Examination of time series of hydrological year WB components for the ten locations provides additional information regarding the relative magnitudes and inter-annual variability of the WB components (**Figure 5**). Because PET exceeds P for all the locations, all P is evaporated and transpired while ET_a and P are almost equal in magnitude, resulting in R being consistently generated in the basin every year for the hydrological years under consideration.

Noticeably, locations at the upper basin (*i.e.* 6, 7, 8, 9 and 10) show a marked increase in the total R has compared to locations at the lower basin (*i.e.* 1, 2, 3, 4 and 5). This is due to immediate PET occurring at lower basin (**Figure 5**).

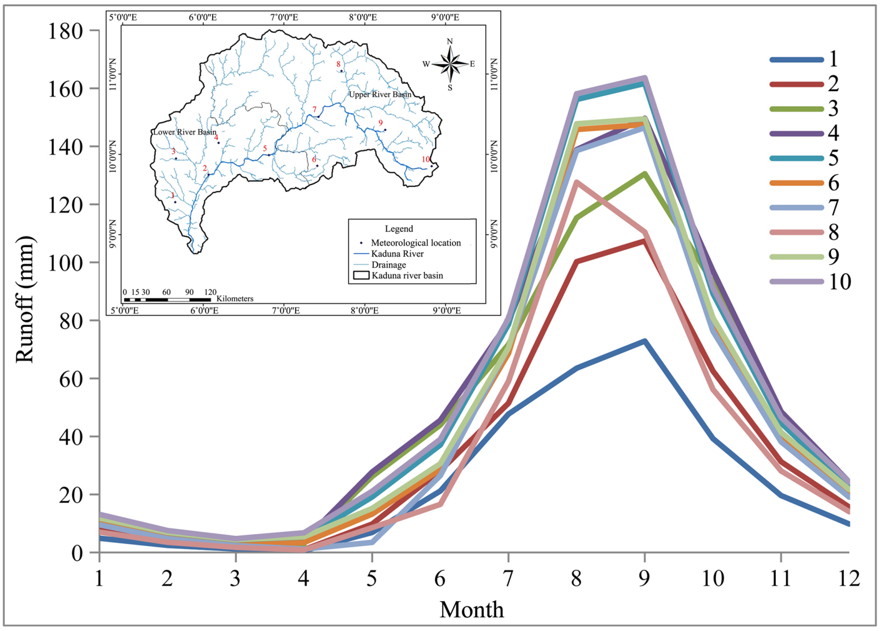


Figure 4. Mean monthly runoff for each of the ten locations in the KRB for hydrological years 1990-2018. (The line colours match the colours of the locations in the inset map and the numbers on the legend).

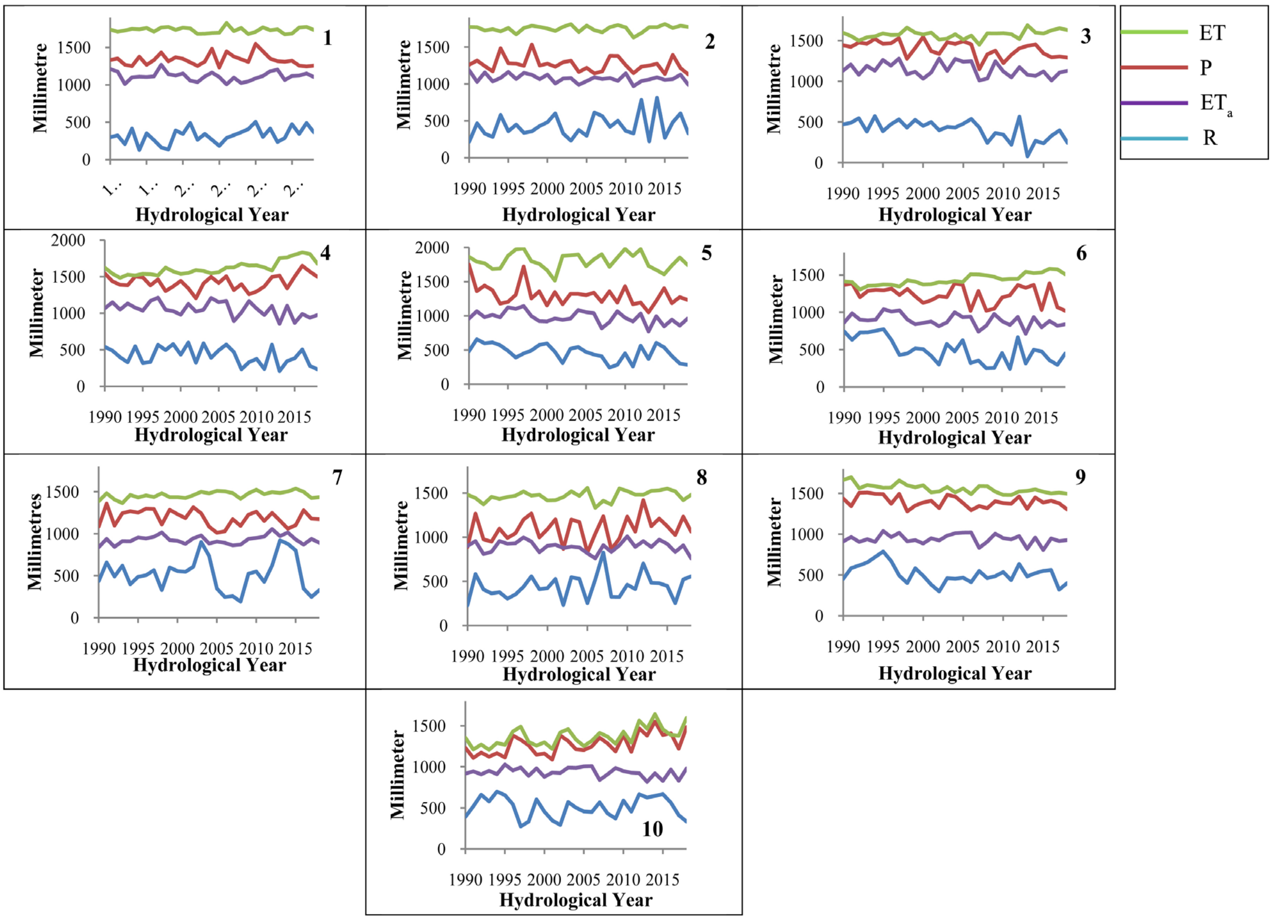


Figure 5. Time series of hydrological year WB components using a WB model for the ten locations in the KRB.

Figure 6 provides a comparison of 3-year moving average Z-scores of mean hydrological-year P, PET, ET_a and R for Lower KRB and Upper KRB. The Z-scores were computed by $Z_i = \frac{X_i - \overline{X}}{\sigma}$, where Z_i is the Z-score for variable

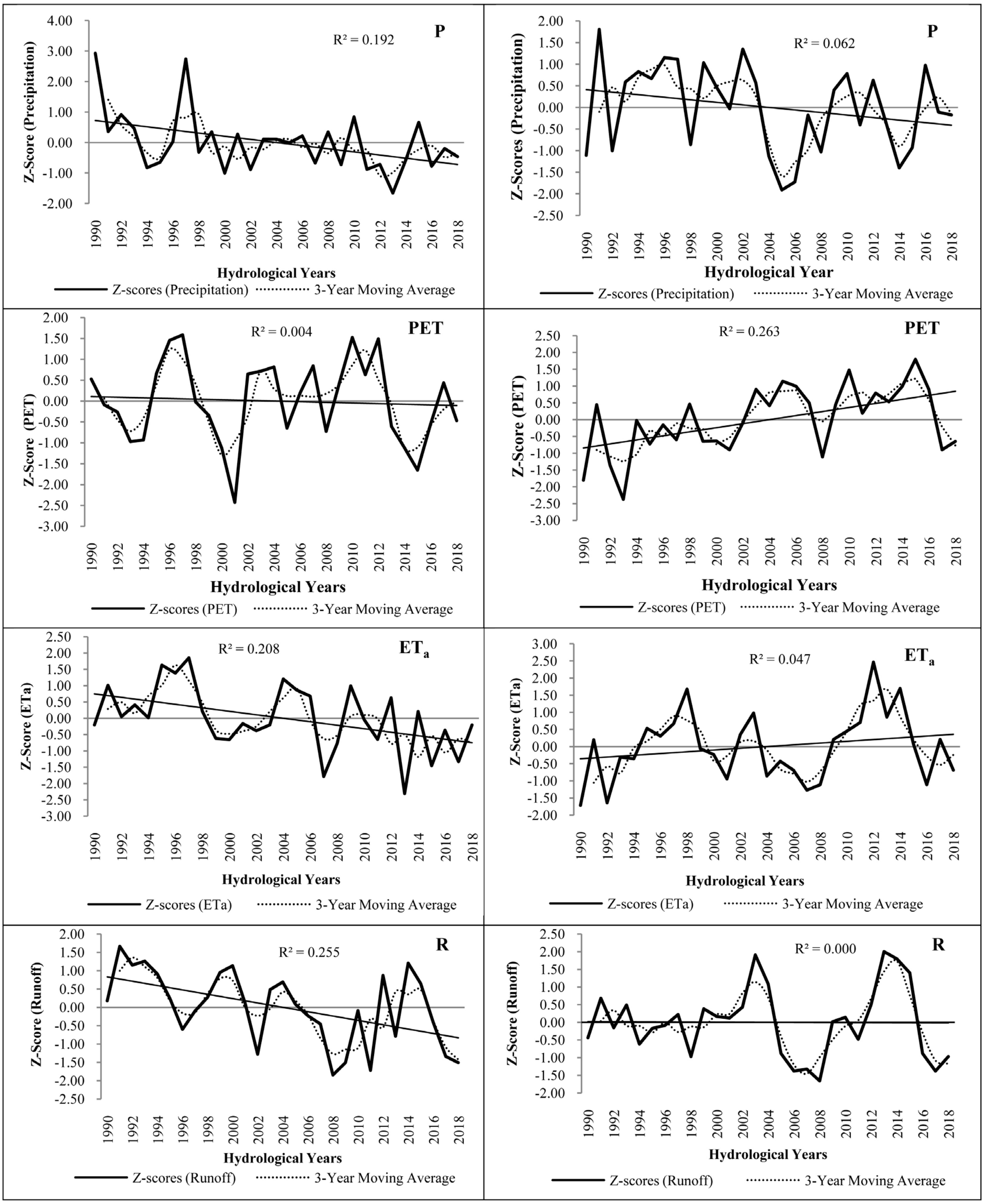


Figure 6. Three-year moving average Z-scores of hydrological year P, PET, ET_a and R using a WB model for both lower KRB and upper KRB.

X and hydrological year *i*, X_i is the raw variable value for year *i*, $\overline{X}$ is the long-term variable mean, and σ is the standard deviation. Time series of Z-scores makes it easier to compare time series for different variables and for different locations because each time series has a mean of zero and a variance of one. The time series were smoothed with 3-year moving average to remove high-frequency variability from the time series.

Examination and comparison of the time series of smoothed Z-scores for the two sub basins indicate substantial variability in the WB components for each basin (**Figure 6**). The negative Z-scores for P, ET_a and R, and the positive Z-scores for PET indicate drought which was reflected in early 2000s. The most notable positive Z-scores for both Lower KRB and Upper KRB of the smoothed P, ET_a and R Z-scores are 1990, 1993, 1994, 1997, 2012 and 2016. P shows slight downward trends in both sub-basins, Lower KRB (R^2 = 0.1921) and Upper KRB (R^2 = 0.0624). From the study also, the ET_a shows a very slight upward trend (R^2 = 0.0474) at the Upper basin while at the Lower basin, ET_a reveals a downward trend (R^2 = 0.208). Runoff (R) reveals a downward trend (R^2 = 0.2552) at the lower basin while the R trend at the upper basin is insignificant (R^2 = 0.0001). The trend of PET at the upper basin show an upward direction (R^2 = 0.2636) and also a slight upward at the lower basin (R^2 = 0.0043). The significant positive Z-scores for PET at the upper basin indicate high rate of water loss leading to frequent drought at the upper KRB (Chinwendu et al., 2017; Animashaun et al., 2020).

Water Surplus (*S*)

Water Surplus (S) is the water that is in excess of PET (the climatic demand for water) and water needed to bring soil moisture storage to capacity (Olusola et al., 2017; Durowoju & Olusola, 2017; Wolock & McCabe, 2018; McCabe & Wolock, 2019). Half of the S in a given month actually becomes R in the month while the remaining half is delayed till the succeeding month (Ayoade, 2008). The majority of S in the KRB is generated during wet season months (**Figure 7**),

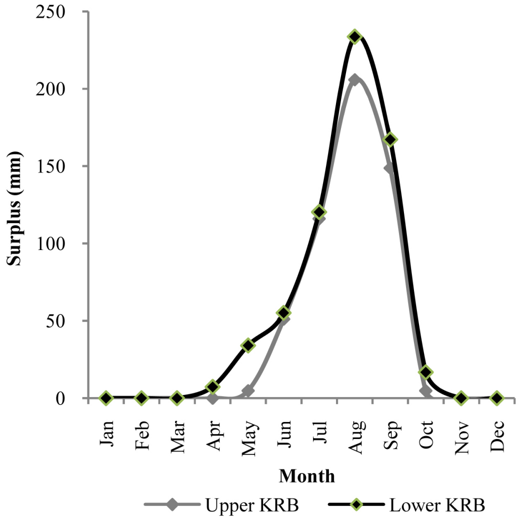


Figure 7. Mean monthly surplus (in mm).

particularly from April through October when ~95% of S occurs on average with the peak in August followed by September. The average annual S for both Lower KRB and Upper KRB are 634.34 mm and 531.14 mm respectively. An indication that the Lower KRB is wetter than the Upper KRB. The result further shows that SM recharges in the month of April at the Lower KRB, earlier than Upper KRB where SM starts recharging in May (**Figure 7**).

4. Conclusion

A monthly water balance model was used to examine the variability and trends of P, PET, ET_a, and R from 1990 to 2018. The analyses indicate that P has been the primary climate factor driving the variability in R, even during periods when PET has increased. This study reveals that PET exceeds P at all the locations and all P is evaporated and transpired while ET_a and P are almost equal in magnitude, resulting in R being consistently generated in the basin every year. It is also notable that the peak of R generally occurs during the wet season (*i.e.* April through October) most especially at the Upper KRB. The occurrence of peak R for most of the locations at the upper basin is related to the soil type (Clayey soil), nature and properties that characterize the location, preventing the direct infiltration of P. The runoff efficiencies indicate that <44% of annual P results in R at the upper KRB while <27% of annual P results in R at the lower KRB.

The negative Z-scores for P, ET_a and R, and the positive Z-scores for PET from the analyses, indicate a high rate of water loss leading to the frequent drought most especially at the Upper KRB in the early 2000s. The study shows that SM utilization occurs mostly towards the end of the year and at the early months (*i.e.* November through March) across the basin while the majority of S is generated during wet season months, particularly from April through October when ~95% of S occurs on average with the peak S in August followed by September.

The results of this study provide a baseline understanding of the hydroclimatology of the KRB which can be used as a starting point for further analyses. In addition, the baseline KRB hydroclimatology depicted in this study can be used to guide the selection of sub-basin within the KRB for specific analyses especially water resources planning and management.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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