Spatial Relationship between Precipitation and Runoff in Africa

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Abstract. ~~Lack~~Apart from the challenges of ~~sufficient and reliable hydrological information is a key hindrance to water resource planning and management~~runoff prediction in ~~Africa.~~ungauged watersheds around different parts of the world, the direct use of river discharges on non-catchment regional studies (i.e.: country scale) also seems to be an unrealistic method that requires scientific precautions. Hence, ~~the objective of~~ this ~~research is~~study intends to ~~examine~~estimate the relationship between precipitation and runoff ~~at three spatial scales, including the whole continent,~~within 25 major basins and all 55 countries. ~~For this purpose,~~ of the ~~long-term monthly~~African continent. Initially, observed runoff ~~coefficient (R_c)~~coefficients were estimated ~~using the long-term~~from monthly runoff (R) data ~~(R)~~ calculated from historical streamflow records provided by the Global Runoff Data Centre (GRDC) ~~streamflow records and~~ and monthly precipitation (P) datasets from the Global Precipitation Climatology Centre (GPCC) ~~precipitation datasets~~ for the period ~~of time~~ spanning from 1901 to ~~2017~~2016. Subsequently, the observed ~~R_c data were interpolated in order to estimate R_c over the ungauged basins under guidance of~~ runoff coefficients for 535 catchments covering about 47.43% of the whole continent were downscaled at 0.5° grid scale based on grids' direct runoff contributions to their corresponding basins estimated following the Natural Resources Conservation Service (NRCS) runoff curve number (CN) approach. NRCS-CN involves the land use and land cover (LULC) information, soil hydrological characteristics, antecedent soil moisture condition (AMC) estimated according to an antecedent precipitation index (API) and precipitation. Predictions in ungauged basins (PUB) were achieved using the inter-gauged and ungauged basin parameter transfer method based on spatial hydrologic similarities. Monthly hydrologic similarity's feature datasets were developed from the key runoff controlling factors, including ~~the land~~-AMC, CN, terrestrial water storage change (TWSC), surface temperature (T), ~~precipitation (P) and potential runoff coefficient (C_o) inferred from the land use and land cover, slope~~and topographic parameters (topographic wetness index (TWI), and ~~soil texture information.~~slope). The results ~~show~~indicated that ~~16~~14% of the annual mean ~~precipitation (672.52~~P (671.88 mm~~) becomes runoff (105.72~~ $\cdot yr^{-1}$) became R (94.9 mm~~), with a runoff coefficient of 0.16,~~ $\cdot yr^{-1}$), and the remaining ~~84% (566.80~~86% (576.98 mm~~) evapotranspirates~~ $\cdot yr^{-1}$) evapotranspirated over the continent ~~during 1901 – 2017~~. Spatial analysis reveals that the ~~precipitation-runoff~~monthly and annual P-R relationship ~~varies~~varied significantly among different basins and countries, mainly ~~dependent on~~due to their

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climatic conditions ~~and its inter-annual variability.~~ Generally, ~~high~~the highest runoff depths and runoff coefficients ~~are~~were observed ~~over~~in humid tropical ~~basins and countries~~regions associated with ~~high~~higher precipitation ~~intensity~~intensities compared to ~~those located in~~ subtropical and temperate drylands.

Keywords: Africa; basin; ~~evapotranspiration; GIS~~runoff curve number; precipitation; runoff coefficient; water balance.

1 Introduction

In the 21st century water resources management becomes a major concern to human life and environmental protection (Cosgrove and Loucks, 2015). It is well-known that precipitation is the source of freshwater on our planet, and its intensity varies from one region to another. ~~Lacking precipitation often causes droughts which would further induces severe environment degradation, social conflicts and hunger crisis (Messer et al., 2001; Clover, 2003).~~ Precipitation-to-runoff is the main source of water for rivers, lakes and ocean replenishment (Edwards et al., 2015). ~~Precipitation~~Water scarcity aggravates poverty to an estimate of 300 million people living in the ~~Eastern and Western~~ drylands of Africa and the number is expected to increase by 65-80% in 2030 (Cervigni and Morris, 2016). By 2050, it is estimated that 40% of the global population will be exposed to river basins that experience severe water stress, particularly in Africa and Asia (UNISDR, 2015). ~~On the other hand, storm water runoffs cause significant hazards and disasters such as soil erosion, floods, landslides, water pollution, and infrastructure damage (Goudie, 2000; Weng, 2001; Karamage et al., 2017a). For instance, the population exposed to flood threats~~Droughts further induce severe environment degradation, social conflicts and hunger crisis (Messer et al., 2001;Clover, 2003). On the other hand, intensive runoffs cause significant damages such as soil erosion, floods, landslides, water pollution, and infrastructure destructions (Goudie, 2000;Weng, 2001;Karamage et al., 2017a). For instance, the population exposed to floods increased from 0.5 to 1.8 million between 1970 and 2010 in Sub-Saharan Africa (UNISDR, 2011). Water-related problems have far-reaching effects in Africa, where, limited financial funds, sparse hydrological data and reliable scientific information bothers sustainable planning and management of water resources and related disasters (Oyebande, 2001; Karamage et al., 2016; Urroz et al., 2001).

~~Although runoff studies have been conducted at global scale and in some local areas in Africa (Hong et al., 2007; Fekete et al., 2002), there is no study yet indicating the spatial relationship between precipitation and runoff within all African basins and countries. In this context, current study analyzed the precipitation-runoff relationship, using an indicative runoff coefficient within 25 major basins and 55 countries in Africa. Besides, this study proposed a novel method for estimating runoff coefficient over ungauged areas based on the environmental characteristics of gauged and ungauged basins. This method derived runoff coefficient by taking consideration of its major controlling factors, which might be useful to the scientists and water resource planners. The runoff coefficient is the ratio of runoff depth to rainfall intensity within a specific watershed (Kadioglu and ŞEN, 2001) and it varies between 0 and 1 (Blume et al., 2007). It is used to indicate how much waterflow converted from precipitation within a given time and catchment. In addition, runoff coefficient is very useful for catchment~~

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~~scale land use and flood management in any catchment (Sriwongsitanon and Taesombat, 2011). Geographical Information System (GIS) has evolved since its introduction in the 1960s, and now becomes a widely used tool able to deal with multiple variables regarding basin management. However, hydrological GIS-based studies rely strongly on databases (Terakawa, 2003). In this respect, this study generated R_e based on monthly runoff calculated from the Global Runoff Data Centre (GRDC) discharges (GRDC, 2018) and Global Precipitation Climatology Centre (GPCC) precipitation products for 1901 to 2017 (Becker et al., 2013; Schamm et al., 2014) in gauged basins. The R_e data were then interpolated to the ungauged areas using the key factors such as land surface temperature (T), Precipitation (P) and potential runoff coefficient (C_e) estimated from the land use and land cover, soil texture and slope information by using GIS spatial analysis techniques. These environmental factors are critical to the estimation of runoff coefficient (Sriwongsitanon and Taesombat, 2011; Chen et al., 2007) . Impervious surfaces generally correspond to higher runoff coefficient and larger runoff volume than previous surfaces (Weng, 2001). Urbanization and cropland expansion reduces infiltration capacity and boosts the generation of surface water runoff (Goudie, 2000; Weng, 2001). Evapotranspiration is generally less than precipitation in wet seasons, that is positive water balance due to groundwater accumulation, which results in an increased surface runoff. In dry seasons evapotranspiration exceeds precipitation because the plants absorb underground water and cause a water deficit. However, underground water can be ignored in the long-term annual mean water balance estimation due to a variety of wet and dry seasons (Long et al., 2014).~~

Geographical Information System (GIS) has evolved since its introduction in the 1960s, and now becomes a widely used tool able to deal with multiple variables regarding basin management. However, GIS-based hydrological studies rely strongly on databases (Terakawa, 2003). Various runoff-related studies have been carried out with different purposes such as, for example, runoff depth estimation at global scale (Hong et al., 2007;Fekete et al., 2002a) (Hong et al., 2007;Fekete et al., 2002b;Ruess, 2015;Smakhtin, 2004) and water stress assessment at country and global scales (Ruess, 2015;Smakhtin, 2004), modelling blue and green water availability in Africa (Schuol et al., 2008) and runoff predictions in different parts of Africa (Tesemma et al., 2010;Olang and Fürst, 2011;Jaleta et al., 2017;Mahmoud, 2014;Karamage et al., 2017a). However, based on our knowledge, there is no available detailed study on the relationship between precipitation and runoff in Africa indicating how river discharges available at catchment scale can be downscaled at small unity of land or grid scale which could be utilized reasonably to estimate P-R correlation at a non-catchment spatial scales (i.e.: countries, etc.), taking into consideration well-known key runoff controlling factors such as land use, climate, soil characteristics, etc. Briefly, this study aims at assessing the relationship between precipitation and runoff within 55 African countries and 25 major drainage basins. As scientific contribution, this study highlighted step by step how the Natural Resources Conservation Service (NRCS) runoff curve number (CN) can be a prominent proxy for the basin's river discharge downscaling at a grid scale which can be reasonably utilized on the non-catchment regional studies (i.e.: Country scale). Actually, runoff-related studies are often conducted at a drainage basin scale, but, hydrological studies on the grid and country scales are very useful at national level since each government has own policies for water resource management. For instance, it has been noticed that runoff discharges are useful in water stress analysis on country scale (Ruess, 2015;Smakhtin, 2004). Integration of NRCS-CN in downscaling the runoff discharges do not alter the quantity of observed runoff at a catchment scale, but it redistributes catchment's discharged runoff volume to its

grids proportionally according to their respective climate and physical conditions. NRCS-CN is very useful in various hydrological studies mainly in predicting the direct runoff discharges by incorporating the land use and land cover (LULC) information, soil hydrological characteristics, antecedent soil moisture condition (AMC) and precipitation (Hawkins, 1993). Besides this, the prediction of the P-R relationship in ungauged regions was achieved utilizing the inter-gauged and ungauged basin parameter transfer method that was previously recommended in other hydrological studies as a reliable approach for parameter predictions in ungauged basins (PUB) (Bárdossy, 2007;Blöschl, 2006). Using this method, the gridded observed runoff coefficients (Or_c) were transferred to ungauged regions according to their hydrologic similarity. Monthly hydrologic similarity's feature datasets were established from key runoff controlling factors such as: (i) AMC, (ii) NRCS-CN, (iii) terrestrial water storage change (TWSC), (iv) land-surface temperature (T), and (v) topographic parameters (topographic wetness index (TWI) and slope). The present study developed a unique monthly hydrologic similarity feature dataset with multiple zones. Each zone is composed by a set of grids with similar climatic and physical characteristics. The runoff controlling factors were firstly classified into ranges, converted to non-simplified polygons and stacked together using an overlay (intersect) analysis technique (Zhu, 2016) performed with the "intersect tool" available in "overlay tools", one of the "Analysis tools" in ArcMap v.10.5. After that, the mean observed runoff coefficients were transferred to ungauged regions employing the "Zonal Statistics as Table Tool" available in "Zonal tool" of the "Spatial Analyst Tools" in ArcMap v.10.5" where, hydrologic similarity dataset were considered as "Input raster or feature zone data", and gridded observed runoff coefficient as "Input value raster". Inter-gauged and ungauged basin parameter transfer approach was chosen to be used in this study because of its simplicity and reasonable prediction in ungauged regions, yielding the results representing a real-world phenomenon occurring in the same region. This method can be considered as one of the hybrid interpolation or gaps filling techniques which are very useful in developing various datasets such as temperature, precipitation, soil, etc.

2 Data inputs and Methods

2.1 Study area

Africa (Figure 1) is the world's second-largest continent (≃ 30.3 million km²) accounting for 6% of Earth's surface area and 20.4 % of land area (Sayre and Pulley, 1999; Mawere, 2017). It is the second-most-populous continent (1,256 million people) after Asia (4,504 million people) as of 2017 (UN-DESA, 2017).

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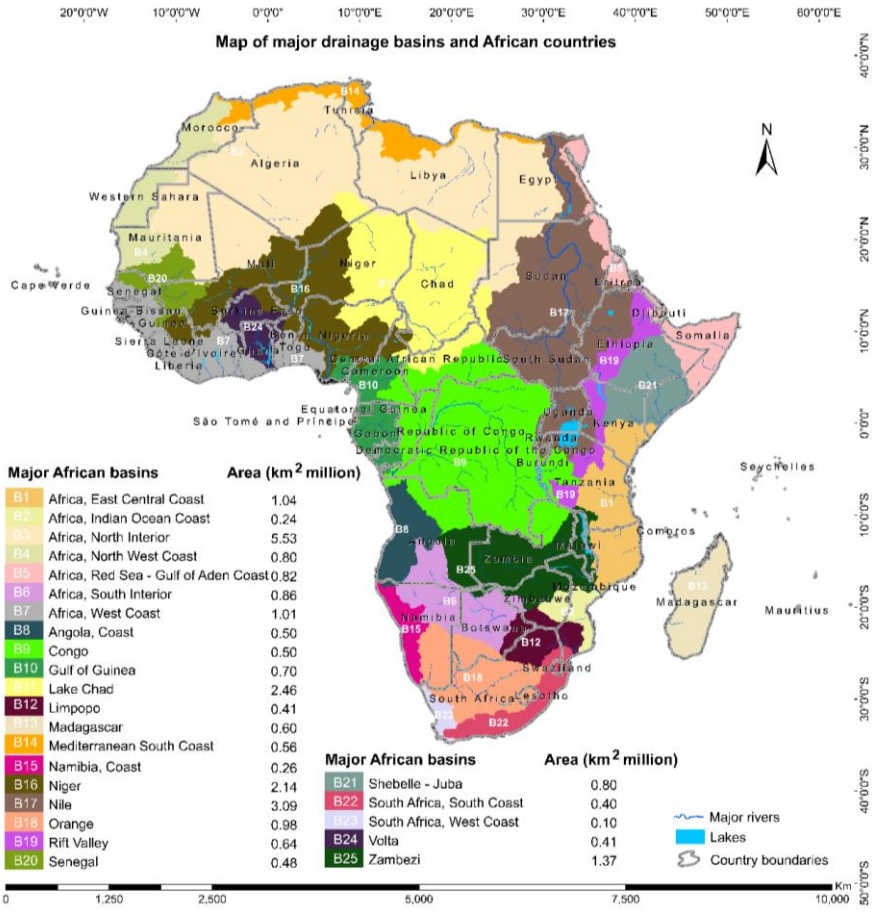

Statistical computation from the~~**Figure 1.** Hydrological map showing major rivers, lakes, 25 major basins and 55 countries of Africa.~~

~~The~~ European Space Agency (ESA) Climate Change Initiative (CCI) land cover (LC) map 2015 (ESA-CCI, 2017) ~~indicates~~showed that Africa is comprised of forests (24.52%), grassland (24.51%), cropland (16.14%), built-up areas (0.16%), wetlands (0.84%), inland water (0.99%), and bare areas (32.84%).

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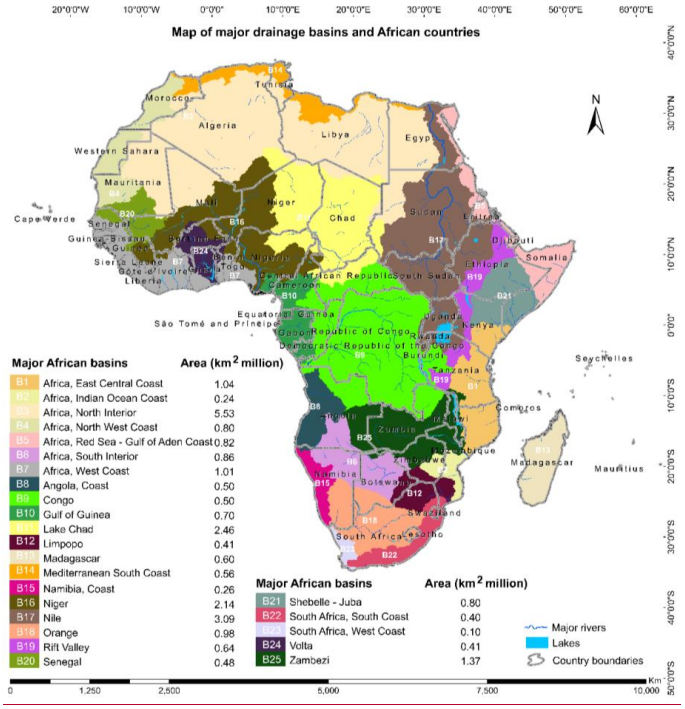

Figure 1. Hydrological map showing major rivers, lakes, 25 major basins (FAO, 2009) and 55 countries of Africa (GADM, 2015).

Over 60% of the soil is dominated by hot, arid or immature soil assemblages: Arenosols (22%), Leptosols (18%), Cambisols (11%), Calcisols (5%), Regosols (3%) and Solonchacks/Solonetz (2%). Another 20% is characterized by tropical or sub-tropical features: Ferralsols (10%), Plinthisols (5%), Lixisols (4%) and Nitisols (2%) (Dewitte et al., 2013). Based on the Climatic Research Unit Timeseries (CRU TS) land-surface temperature ~~dataset~~datasets (1901 – 2016) (Harris et al., 2014), and the GPCC ~~dataset~~datasets (1901 – ~~2017~~2016) ~~(Becker et al., 2013; Schamm et al., 2014)~~(Markus et al., 2018), the African continent has an overall long-term mean ~~annual~~ surface temperature (T) of 24^{o}C·yr^{-1} and mean precipitation (P) of ~~672.52~~671.88 mm~~. It~~·yr^{-1}. Africa has three major climate types including tropical (T = 25^{o}C·yr^{-1}; P = ~~835~~836.36 mm·yr^{-1}), subtropical (T = 22^{o}C·yr^{-1}; P = ~~156~~146.23 mm·yr^{-1}) and temperate zones (T = 18^{o}C·yr^{-1}; P = ~~261~~257.34 mm·yr^{-1}). The topography is characterized by large-scale extensional features such as the East African Rift, anomalously subsided basins and uplifted domes (Moucha and Forte, 2011). The continent is divided into 25 major hydrological basins according to its hydrological characteristics (FAO, 2009). ~~Drainage patterns are controlled by the distribution of basins and swells, about 95%~~

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~~is drained through permanent or ephemeral rivers. However, in arid areas (i.e., Northwest Sahara Desert and Somalia), drainage is sometimes absent or masked by sand seas.~~ Approximately, 60% of the African continent is drained by 10 large rivers (Congo, Limpopo, Niger, Nile, Ogooue, Orange, Senegal, Shebelle, Volta and Zambezi) and their tributaries (Paul et al., 2014).

2.2 Datasets and Application

~~As presented by a conceptual framework (Figure 2), the goal of this study is achieved primarily using two types of data inputs (river discharge data and precipitation) in monitored basins and further auxiliary datasets comprising the land surface temperature, precipitation and potential runoff coefficient established based on the land use and land cover (LULC) maps, Digital Elevation Model (DEM) and soil properties employed to improve the interpolation accuracy of observed runoff coefficient (R_c). The data are processed and analyzed~~The data were processed and analysed using the Esri ArcGIS software version 10.5, SDMToolbox version 2.2 (Brown et al., 2017) and Excel VBA (Visual Basic for Applications) (Walkenbach, 2010). Figure 2 demonstrates the conceptual framework used to analyze the relationship between precipitation and runoff in Africa.

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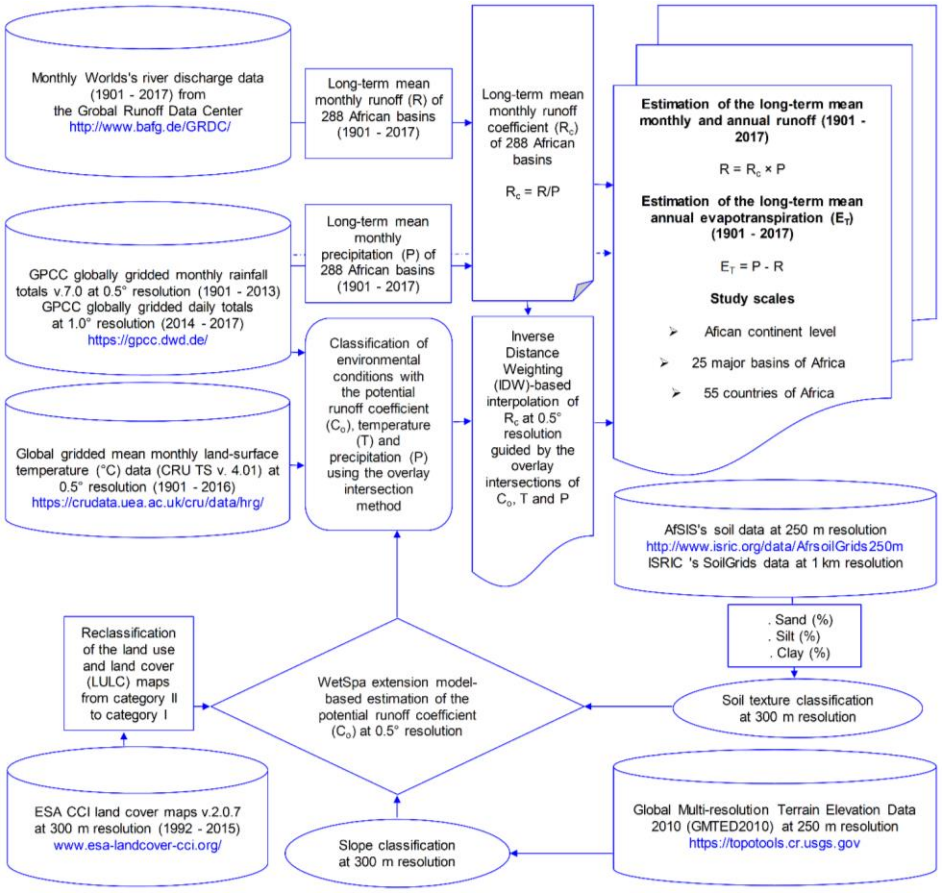
Monthly Worlds's river discharge data (1901 - 2017) from the Grobal Runoff Data Center http://www.bafg.de/GRDC/
Long-term mean monthly runoff (R) of 288 African basins (1901 - 2017)
Long-term mean monthly runoff coefficient (R_c) of 288 African basins
$R_c = R/P$
GPCC globally gridded monthly rainfall totals v.7.0 at 0.5° resolution (1901 - 2013) GPCC globally gridded daily totals at 1.0° resolution (2014 - 2017) https://gpcc.dwd.de/
Long-term mean monthly precipitation (P) of 288 African basins (1901 - 2017)
Global gridded mean monthly land-surface temperature (°C) data (CRU TS v. 4.01) at 0.5° resolution (1901 - 2016) https://crudata.uea.ac.uk/cru/data/hrg/
Classification of environmental conditions with the potential runoff coefficient (C_o), temperature (T) and precipitation (P) using the overlay intersection method
Inverse Distance Weighting (IDW)-based interpolation of R_c at 0.5° resolution guided by the overlay intersections of C_o, T and P
Estimation of the long-term mean monthly and annual runoff (1901 - 2017)
$R = R_c \times P$
Estimation of the long-term mean annual evapotranspiration (E_T) (1901 - 2017)
$E_T = P - R$
Study scales
African continent level
25 major basins of Africa
55 countries of Africa
AfSIS's soil data at 250 m resolution http://www.isric.org/data/AfrsoilGrids250m ISRIC 's SoilGrids data at 1 km resolution
. Sand (%)
. Silt (%)
. Clay (%)
Soil texture classification at 300 m resolution
Reclassification of the land use and land cover (LULC) maps from category II to category I
WetSpa extension model-based estimation of the potential runoff coefficient (C_o) at 0.5° resolution
ESA CCI land cover maps v.2.0.7 at 300 m resolution (1992 - 2015) www.esa-landcover-cci.org/
Slope classification at 300 m resolution
Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) at 250 m resolution https://topotools.cr.usgs.gov

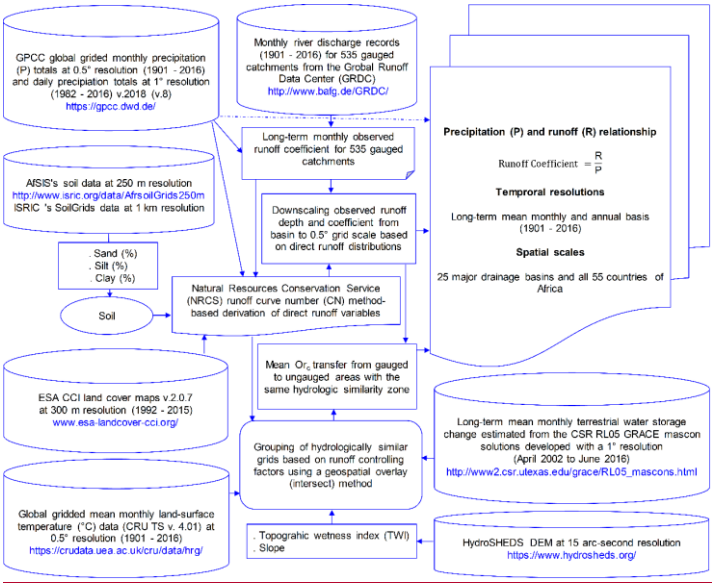

Figure 2. A conceptual framework used for analyzing the precipitation-runoff relationship in Africa.

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2.2.1 Runoff ~~coefficient~~ estimation in gauged ~~basins~~catchments

The runoff ~~coefficient in monitored basins is~~ coefficients over gauged catchments were estimated ~~from~~with two types of data: (1) the monthly time series of river discharge data for ~~341~~535 African ~~river basins (~~catchments (Figure 3) discontinuously recorded since 1901 ~~—2017)~~until 2016 were provided by request from the Global Runoff Data Centre (GRDC~~)~~). The GRDC is an international organization based in Germany, a branch of the World Meteorological Organization (WMO) that was established in 1988 to support scientific studies on global climate change and water resources management (GRDC, 2018) ~~and (2) monthly precipitation datasets acquired from the Global Precipitation Climatology Project (GPCP) (Becker et al., 2013). The GRDC is an international organization based in Germany, a branch of the World Meteorological Organization (WMO) that was established in 1988 to support scientific studies on global climate change and water resources management (GRDC, 2018). Figure 3 shows ungauged areas and gauged catchments of Africa under consideration of a complete set of 12 months in a year (from January to December) during the period of 117 years (1901 – 2017). The shapefile of 25 major African basins was provided by the Food and Agriculture Organization of the United Nations (FAO) (FAO, 2009).~~

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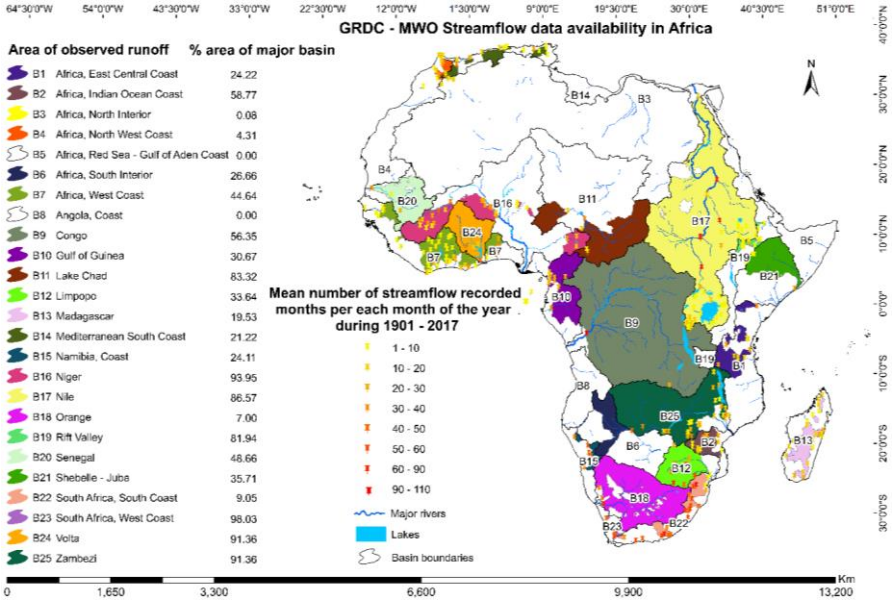

Figure 3. Land area coverage of observed GRDC-WMO streamflow records within 25 major basins of Africa.

, and (2) monthly precipitation datasets acquired from the Global Precipitation Climatology Centre (GPCC) Full Data Gridded Monthly Totals Version 2018 (V.8) at 0.5° resolution for the period 1901–2016. GPCC product is a Rain-Gauges built on GTS-based and Historical Data that is operated by the German Weather Service (DWD) under the auspices of the World Meteorological Organization (WMO) (Markus et al., 2018).

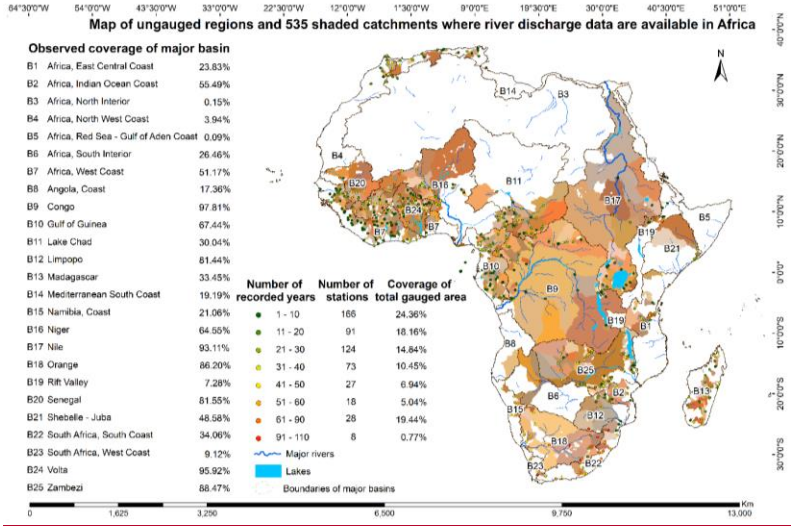

Figure 3. Distribution of 535 GRDC gauged catchments (covering ≃ 47.43% of the total African continent) and streamflow gauging stations (GRDC, 2018) within 25 major basins of Africa (FAO, 2009).

On account of discharge data that were discontinuously recorded ~~in different months and various stations, and~~ which could not allow the possibility of monthly or annual accurate trend analysis, the final results of the present study ~~was carried out using~~ were generated at the long-term monthly and annual mean ~~monthly runoff and their corresponding rainfall input for the period 1901 – 2017. This method enabled us to obtain the streamflow records for all 12 months of the year and maximize the number of monitored basins, covering a total surface area of 12.37 million km² (≃ 41.4% of the total African continent). Given that, streamflow records were provided in cubic meter per second ($m^3 \cdot S^{-1}$), monthly runoff depths at basin scale were calculated by Eq. (1):~~

~~$$R = \frac{(Q \cdot 1000 \cdot 24 \cdot n \cdot 3600)}{A} \quad (1)$$~~

~~where, R is an average runoff depth ($mm \cdot month^{-1}$) for the drainage area or basin of interest A; A is a drainage area (basin) in m^2; Q is river discharge ($m^3 \cdot S^{-1}$) drained from the basin of interest A (m^2); n is the number of days in each month.~~

~~The long-term mean precipitation was computed from the Global Precipitation Climatology Centre (GPCC) version 7.0 at 0.5° resolution (Becker et al., 2013). This is the centennial GPCC Full Data Reanalysis of monthly global land-surface precipitation with a duration record of 10 years or longer from 75,000 stations worldwide. The~~ temporal ~~coverage of the dataset ranges from January 1901 to December 2013. The GPCC Full Data Reanalysis is the most accurate in situ precipitation dataset which~~

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~~supports studies on regional climate monitoring, model validation, and water resources assessment (Becker et al., 2013). The remaining period starting from 2014 to 2017 was completed by monthly total precipitation calculated and resampled at 0.5° from the GPCC First Guess Product at 1° resolution of daily global land-surface precipitation based on the station database (SYNOP) available via the Global Telecommunication System (GTS) of the World Meteorological Organization (WMO) at the time of analysis (3 – 5 days after the end of the analysis month). This product contains the daily totals for a month on a regular latitude/longitude grid with a spatial resolution of 1° x 1° latitude by longitude (Schamm et al., 2014).~~

. By following Eq. (~~2~~1) (Kadioglu and ŞEN, 2001), ~~we estimated the long-term monthly a~~ runoff coefficient is estimated as the ratio of ~~long-term~~mean runoff depth to ~~long-term~~rainfall intensity for each catchment. The monthly runoff coefficients were estimated for each month whenever runoff discharge was recorred. Then, all historical monthly ~~precipitation for the study period 1901 – 2017~~coefficients were summed and divided by the number of recorded months to obtain the long-term monthly average runoff coefficient for each station.

~~$R_c = \frac{R}{P}$ (2)~~

The annual runoff depth (mm·yr-1) is the total of monthly runoff depths for all 12 months of a year. The average annual runoff coefficient is estimated as the ratio of annual runoff depth (mm·yr^{-1}) to the annual precipitation intensity (mm·yr^{-1}).

$$Orc_b = \frac{Or_b}{P} \quad (1)$$

where, ~~R_c is a~~Orc_b is the basin's observed average monthly runoff coefficient (dimensionless~~); R~~), Or_b is ~~a~~the basin's observed runoff depth (mm·month^{-1}) and P is precipitation intensity (mm~~)~~·month^{-1}).

The runoff coefficient is usually a suitable proxy to assess the correlation between precipitation and runoff due to its absolute capability to indicate the ratio of runoff (R) generated by the total precipitation (P) amount within a catchment (Kadioglu and ŞEN, 2001), it has values varying from 0 (low P-R correlation) to 1 (high P-R correlation) (Blume et al., 2007). In addition, runoff coefficient is very useful for rainfall runoff management in different land cover types since it can easily identify the ratio of rainwater flowed from each land use type under heterogeneous climate and physical conditions among different grids of the catchment. It may help to locate areas with high potential runoff risk which require special practices of stormwater management (Chen et al., 2007). Higher runoff coefficient values are often observed on impervious surfaces and unwell-managed croplands due to their low infiltration capacity compared to other land use classes such for example grasslands and forests (Goudie, 2000; Weng, 2001). Areas with low runoff coefficients are those with a relatively higher infiltration and/or evapotranspiration (E_T) rates. Underground water storage change also plays significant role in runoff generation process throughout the alteration of soil moisture condition. However, in the long-term annual mean basis of water balance analysis, the estimation of terrestrial water storage change provides approximately zero values due to a variety of wet and dry seasons (Long et al., 2014).

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2.2.2 Runoff ~~coefficient~~ estimation in ungauged ~~basins~~catchments

~~Numerous studies have established different climatic geospatial datasets such as precipitation and surface temperature, etc., using interpolation algorithms based on a certain number of recorded locations directed by the other auxiliary variables (i.e.: DEM) to improve the results~~ Runoff coefficients over ungauged regions were estimated using the inter-gauged and ungauged parameter transfer method based on the hydrologic similarity feature zones established by means of overlay (intersect) technique applied to major runoff controlling factors, including AMC, CN, TWSC, T, TWI and slope that were selected among others based on their potential effect in runoff generation process as previously revealed by different researchers ~~(Ahmed et al., 2014; Huang and Hu, 2009; Sanabria et al., 2013)~~(Liu and De Smedt, 2004;Bárdossy, 2007;Yuting et al., 2011;McCabe and Wolock, 2011)~~. In this sense, the present study developed a hybrid interpolation method to estimate the R_c in ungauged basins of Africa using the Inverse Distance Weighting (IDW) interpolation algorithm directed by major runoff controlling factors (Potential runoff coefficient, surface temperature and precipitation). The potential runoff coefficient was estimated using the WetSpa (Water and Energy Transfer between Soil, Plants and Atmosphere) extension model (Liu and De Smedt, 2004) which incorporates three types of data inputs including land use and land cover, slope and soil texture classes as synthesized by a Table 1 (Liu and De Smedt, 2004). The soil texture and slope rasters were resampled to the same spatial resolution (300 m) of LULC maps and initial resolution of potential runoff coefficient, which is also resampled at 0.5° resolution (the original resolution of the temperature and precipitation datasets) using the zonal statistic method. The potential runoff coefficient for impervious surfaces (IMP was estimated using Eq. (3) (Liu and De Smedt, 2004).~~

~~$C_u = IMP + (1 - IMP)\, C_{grass}$ (3)~~

~~where, C_u is the potential runoff coefficient for built-up areas, C_{grass} is the potential runoff coefficient for grassland, and IMP is 0.50 that presents the percentage of impervious surfaces recommended for built-up zones.~~

~~The LULC maps (Figure 4) used in this study were reclassified from time series of annual global Climate Change Initiative Land Cover (CCI-LC) maps at 300 m spatial resolution covering a period of 24 years (1992 – 2015) (ESA-CCI, 2017).~~

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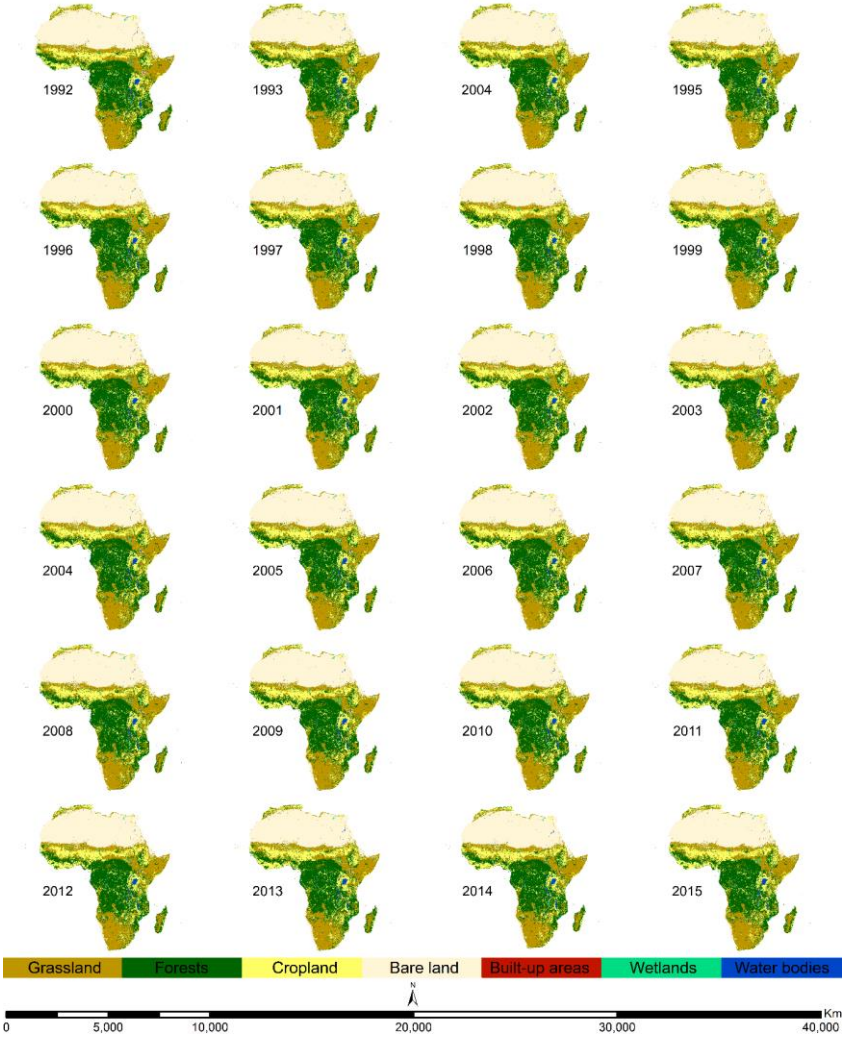

Figure 4. A time series of annual land cover maps of Africa with 7 classes (1992 – 2015).

. Inter-gauged and ungauged parameter transfer method is one of acceptable approach for parameter predictions in ungauged Basins (PUB) recommended in different hydrological studies (Bárdossy, 2007;Blöschl, 2006;Chiew et al., 2018). Several hydrologic models are available and utilized in different projects; but, most of them limited either due to their different input parameter requirements, a lot of time required for preparing input data, and complexity model setting (Lim et al., 2006). Ungauged regions accounting 52.57% of the total continent of Africa seems to be larger extent compared to the recorded catchments (47.43% of African continent) (Figure 3) due to 31% of the continent occupied by the desert of Sahara (Cook and Vizy, 2015) where the runoff depths and runoff coefficient is approximately 0 due to absence of precipitation in this region. The remaining ungauged regions account only 21.57% of the total African continent and are distributed in different climatic zones where it is possible to predict their hydrologic conditions based on the observed parameters of neighbouring gauged catchments. Using any other model for P-R correlation assessment it might be a double task since it would be necessary to calibrate the results using almost the same method of hydrologic similarity analysis.

2.2.2.1 Estimation of direct runoff using the NRCS-CN method

NRCS-CN is one of the ancient popular and efficient empirical hydrologic approaches adopted by various researchers worldwide for water resources planning and assessment, especially estimating the direct rainfall-runoff. It was developed in 1956 by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) (Cronshey, 1986;Silveira et al., 2000). This method is easily understandable, simple and useful for direct runoff prediction over ungauged catchments (Mishra et al., 2006). CN is generally considered as a major input parameter in many hydrologic models such as for example the Long-Term Hydrologic Impact Assessment (L-THIA) model (Lim et al., 2006), the Hydrologic Modelling System (HEC-HMS) (Engineers, 2008;Halwatura and Najim, 2013), The Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel and Douglas-Mankin, 2012), Simulation of Production and Utilization of Rangelands (SPUR) model (Wright and Skiles, 1987). NRCS-CN method predicts the Dr_c and Dr by involving the land use and land cover (LULC) data, soil hydrological characteristics and antecedent soil moisture condition, according to an antecedent precipitation index (API) and precipitation (Cronshey, 1986). The LULC maps (Figure 4) used in this study were reclassified from time series of annual global Climate Change Initiative Land Cover (CCI-LC) maps at 300 m spatial resolution covering a period of 24 years (1992 – 2015) (ESA-CCI, 2017).

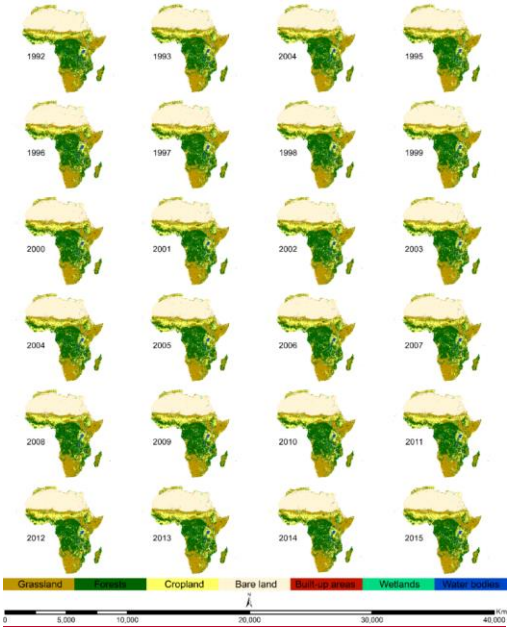

Figure 4. A time series of annual land cover maps (ESA-CCI, 2017) of Africa with reclassified 7 classes (1992 – 2015).

These land cover maps were originally classified from the landcover imagery captured by five different satellites, including the Advanced Very High-Resolution Radiometer (AVHRR), Medium Resolution Imaging Spectrometer Full Resolution and Reduced Resolution (MERIS FR and RR), SPOT-Vegetation (SPOT-VGT), Project for On-Board Autonomy, with the V standing for Vegetation (PROBA-V), Environmental Satellite-Advanced Synthetic Aperture Radar (ENVISAT-ASAR). The CCI-LC map 2015 was validated using the GlobCover map 2009 with two overall accuracy levels of 71.45% and 75.4% (ESA-CCI, 2017). Based on the CCI-LC product manual version 2.0 (ESA-CCI, 2017), we have reclassified all 24 CCI-LC maps ~~were reclassified~~ from the LCCS (Land Cover Classification System) legend to IPCC (Intergovernmental Panel on Climate Change) legend (Penman et al., 2003) that ~~is consistent with a Table 1 of the Wetspa's potential runoff coefficient (Liu and De Smedt, 2004).~~are more compatible with the NRCS-CN structure.

~~**Table 1.** Potential runoff coefficient for different land use and land cover types, slope and soil texture classes (Liu and De Smedt, 2004). Sa: Sand, LoSa: Loamy sand, SaLo: Sandy loam, Lo: Loam, SiLo: Silty loam, Si: Silt, SaClLo: Sandy clay loam, ClLo: Clay loam, SiClLo: Silty clay loam, SaCl: Sandy clay, SiCl: Silty clay, Cl: Clay.~~

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The recent updated dataset of sand, clay, and silt fractions available at ≃ 250 m resolution were downloaded from the Africa Soil Information Service (AfSIS) database (Hengl et al., 2015) and used to classify the soil texture dataset of Africa (Figure 5). Soil texture data were utilized in conjunction with LULC maps (Figure 4) for the development of hydrologic soil group (HSG) and CN dataset (Figure 5) following the studies of Yeo et al. (2004) , Cronshey (1986), and Sumarauw and Ohgushi (2012) (Table 2). Because the AfSIS data have gaps over the Sahara desert, in this region the soil texture was classified from the WorldGrids' s sand, clay, and silt fractions available at ≃ 1 km spatial resolution (Hengl et al., 2014). Soil texture was classified referring to table 1 adapted from the soil textural triangle developed by the United States Department of Agriculture (USDA) (Fernandez-Illescas et al., 2001).

Table 1. Soil texture classes adapted from the USDA' s soil textural triangle (Fernandez-Illescas et al., 2001).

Land useSoil Texture Name	SlopeSand (%)	SaSilt (%)	LoSaClay (%)	SaLo	Lo	SiLo	Si	SaClLo	ClLo	SiClLo	SaCl	SiCl	Cl
ForestlandSand (Sa)	< 0.585 – 100	0.03 – 15	0.07	0. – 10	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40
Loamy sand (LoSa)	0.5 – 570 – 90	0.07 – 30	0.11 – 15	0.14	0.17	0.21	0.24	0.27	0.31	0.34	0.37	0.41	0.44
Sandy loam (SaLo)	5 – 10 0.13 0.17 0.20 0.23 0.27 0.30	0.33	0.37	0.40	0.43 – 80		0.47				0. – 50		0 – 20
-	> 10	0.25	0.29	0.32	0.35	0.39	0.42	0.45	0.49	0.52	0.55	0.59	0.62
GrasslandLoam (Lo)	< 0.5	0.13	0.17	0.20	0.23 – 52	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.28 – 50	7 – 27
	0.5 – 5	0.17	0.21	0.24	0.27	0.31	0.34	0.37	0.41	0.44	0.47	0.51	0.54
Silty loam (SiLo)	5 – 100 – 50	0.23 50 – 88	0. – 27	0.30	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60

Silt (Si)			0 – 20	88 – 100								0 –12		
Sandy clay loam (SaClLo)	≥ 10	0.35	0.39	0.42	0.45 – 80	0.49 – 28	0.522 0 – 35	0.55	0.59	0.62	0.65	0.69	0.72	
Croplands Clay loam (ClLo)					< 0.520 – 45	0.231 5 – 53	0.27 – 40	0.30	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60
Silty clay loam (SiClLo)		0.5 – 5 5 – 20	0.27 0.334 0 – 73	0.31	0.34	0.37	0.41 0.2 7 – 40	0.44	0.47	0.51	0.54	0.57	0.61	0.64
Sandy clay (SaCl)	≥ 10		0.45 – 65		0.49 – 20		0.5 235 = 45	0.55	0.59	0.62	0.65	0.69	0.72	0.75
Bare lands Silty clay (SiCl)	< 0.5 = 20	0	0	0.4 0 – 60	0.4 3	0	0	0	0.40 – 60	0.63	0.67	0.70		
Clay (Cl)		0.5 – 5 – 45				0.37 – 40	0.4 140 = 100	0.44	0.47	0.51	0.54	0.57	0.61	0.64
	5 – 10	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70	0.73	0.77	0.80	
-	> 10	0.55	0.59	0.62	0.65	0.69	0.72	0.75	0.79	0.82	0.85	0.89	0.92	
Built-up areas	< 0.5	0.57	0.59	0.60	0.62	0.64	0.65	0.67	0.69	0.70	0.72	0.74	0.75	
	0.5 - 5	0.59	0.61	0.62	0.64	0.66	0.67	0.69	0.71	0.72	0.74	0.76	0.77	
	5 – 10	0.62	0.64	0.65	0.67	0.69	0.70	0.72	0.74	0.75	0.77	0.79	0.80	
-	> 10	0.68	0.70	0.71	0.73	0.75	0.76	0.78	0.80	0.81	0.83	0.85	0.86	
Wetlands & Water		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Referring to the soil textural triangle developed by the United States Department of Agriculture (USDA) (Fernandez-Illescas et al., 2001), the soil texture dataset at 300 m resolution (Figure 5) was estimated based on sand, clay, and silt fractions available at 250 m resolution from the Africa Soil Information Service (AfSIS) (Hengl et al., 2015). Because the AfSIS data

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~~have gaps over the Sahara desert, in this region the soil texture was classified from the WorldGrids' s sand, clay, and silt fractions available at 1 km spatial resolution (Hengl et al., 2014). The slope map at 300 m resolution (Figure 5) was established from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) available at 250 m spatial resolution of the U.S. Geological Survey (USGS) and the National Geospatial-Intelligence Agency (NGA) (Danielson and Gesch, 2011).~~

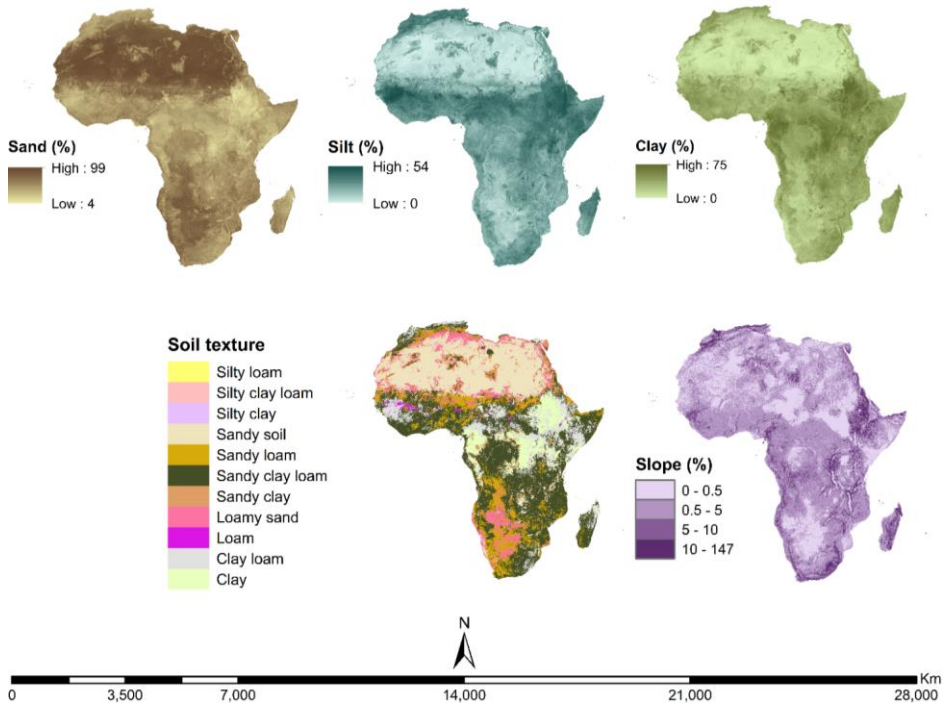

Table 2. LULC classes and their corresponding HSG, soil texture and CN (adapted from (Yeo et al., 2004;Cronshey, 1986;Sumarauw and Ohgushi, 2012).

LULC	Soil Texture	HSG	CN
Grass	Sand, loamy sand, or sandy loam	A	35

	Silt loam or loam	B	56
	Sandy clay loam	C	70
	Clay loam, silty clay loam, sandy clay, silty clay, or clay	D	77
Forrest	Sand, loamy sand, or sandy loam	A	30
	Silt loam or loam	B	55
	Sandy clay loam	C	70
	Clay loam, silty clay loam, sandy clay, silty clay, or clay	D	77
Agriculture	Sand, loamy sand, or sandy loam	A	64
	Silt loam or loam	B	75
	Sandy clay loam	C	82
	Clay loam, silty clay loam, sandy clay, silty clay, or clay	D	85
Barren	Sand, loamy sand, or sandy loam	A	77
	Silt loam or loam	B	86
	Sandy clay loam	C	91
	Clay loam, silty clay loam, sandy clay, silty clay, or clay	D	94
Urban	Sand, loamy sand, or sandy loam	A	81
	Silt loam or loam	B	88
	Sandy clay loam	C	91
	Clay loam, silty clay loam, sandy clay, silty clay, or clay	D	93
Wetland	Sand, loamy sand, or sandy loam	A	0
	Silt loam or loam	B	62
	Sandy clay loam	C	74
	Clay loam, silty clay loam, sandy clay, silty clay, or clay	D	85
Water	Sand, loamy sand, or sandy loam	A	100
	Silt loam or loam	B	100
	Sandy clay loam	C	100
	Clay loam, silty clay loam, sandy clay, silty clay, or clay	D	100

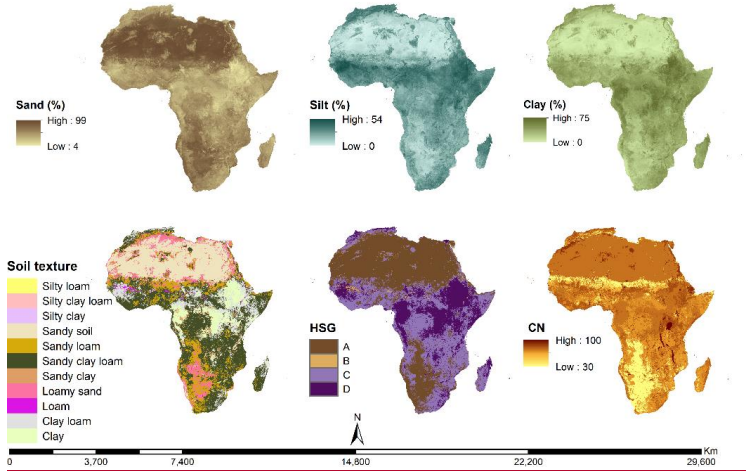

Figure 5. Maps of sand, clay, and silt fractions, soil texture ~~and slope of Africa.~~, hydrological soil group (HSG) and long-term mean curve number (CN) unadjusted by AMC (1992 – 2015).

~~The long-term monthly land-surface temperature (Figure 6)~~Adjusted long-term monthly CN maps (Figure 6) were obtained employing antecedent soil moisture condition (AMC) (Figure 6) using equations (2) and (3) (Hong et al., 2007;Zeng et al., 2017).

$$CN_i^I = \frac{CN_i^{II}}{2.281 - 0.01281 * CN_i^{II}} \quad (2)$$

$$CN_i^{III} = \frac{CN_i^{II}}{0.427 - 0.00573 * CN_i^{II}} \quad (3)$$

C^I, CN^{II}, and C^{III} are corresponding to AMC I (dry), AMC II (normal), and AMC III (wet), respectively, determined utilizing total 5-day antecedent precipitation index (API) and season types (dormant or passive and active or growing seasons) (Table 3) (Silveira et al., 2000;Hong et al., 2007). The glowing season is considered as the active (wet) season with the precipitation intensity > 100 mm·month^{-1}, whilst, the passive (dry) season has a precipitation intensity < 100 mm·month^{-1} (Murray-Tortarolo et al., 2017).

Table 3. Seasonal rainfall limits for AMC (Silveira et al., 2000;Hong et al., 2007;Mishra and Singh, 2006).

AMC group	Total 5-day API (mm)	
	Dormant (passive) season	Growing (active) season
I	< 13	< 36
II	13 – 28	36 – 53
III	> 28	> 53

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Five-day API was estimated using the GPCC Full Data Daily Product V.2018 of daily global land-surface precipitation totals. This product is available at a regular latitude/longitude grid with a spatial resolution of 1° and covers the time period from January 1982 to December 2016 (Anja et al., 2018). The API was estimated following Eq. (4) (Kohler and Linsley, 1951;Heggen, 2001).

$$\text{API} = \sum_{t=1}^{-i} P_t * k^{-t} \quad (4)$$

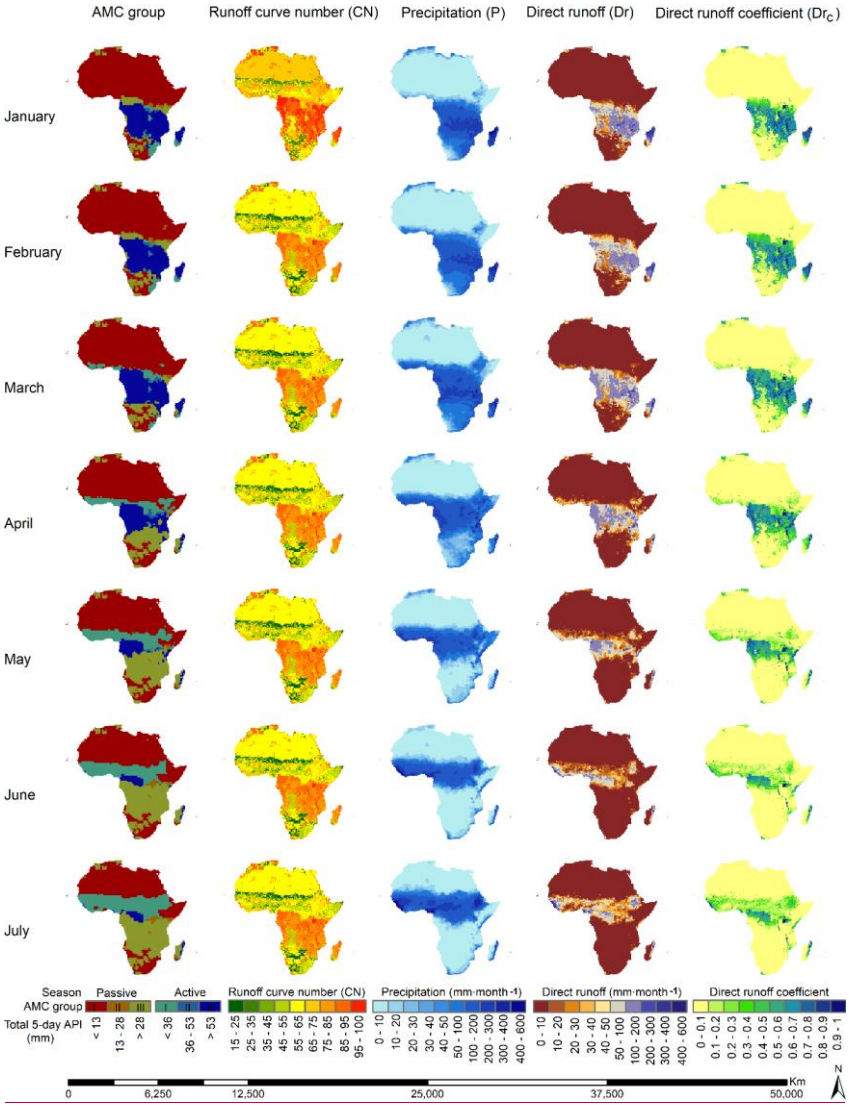
where, i is the number of antecedent days, P_t is the precipitation amount during day t, and k is a decay constant. It has been revealed that k factor is not critical, its values range from 0.85 to 0.90 over most of the eastern and central portions of the United States where it was well tested (Kohler and Linsley, 1951), and this study used a value of 0.90 that is recommended for the basins without a measured k decay constant (Abdi et al., 2017;Viessman Jr and Knapp, 1977;Heggen, 2001). The NRCS-CN method was modified by different researchers depending on the climatic condition of their study area. The most frequently modified parameter was the initial abstraction coefficient (λ), arguing that the assumption of the λ = 0.2 in the original SCS-CN method seems to be high and suggested that λ with values between 0.01 and 0.05 are more realistic and recommended a value of λ = 0.05 (5% of the storage is assumed as the initial abstraction instead of 20%) because it involves either both lower CN values and small rainfall amount (Yuan et al., 2014;Beck et al., 2009;Shi et al., 2009;Hawkins, 1993;Ponce and Hawkins, 1996;Woodward et al., 2003;Lim et al., 2006). Based on these recent studies, our study used an adjusted SCS-CN equation with a value of λ = 0.05 as demonstrated by Hawkins (1993) with the equations (5), (6) and (7).

$$Dr = \begin{cases} 0 & \text{for } P \leq 0.05 * S \\ \frac{(P - 0.05 * S_{0.05})^2}{P + 0.95 * S_{0.05}} & \text{for } P > 0.05 * S \end{cases} \quad (5)$$

$$S_{0.05} = 1.33 * {S_{0.20}}^{1.15} \quad (6)$$

$$S_{0.20} = \frac{2400}{CN} - 254 \quad (7)$$

where, Dr = the direct runoff (mm), P = rainfall (mm) (Figure 6), S is the maximum potential soil water retention (mm), and CN is the curve number (dimensionless). $I_a = 0.05 * S$ is the initial abstraction (all losses before runoff begins). Dr_c = the direct runoff coefficient (dimensionless) (Figure 6). S is related to the soil and land cover conditions of the watershed through the CN which has a range of 0 to 100 values.


AMC group
Runoff curve number (CN)
Precipitation (P)
Direct runoff (Dr)
Direct runoff coefficient (Drc)
January
February
March
April
May
June
July
Season
Passive
Active
AMC group
Total 5-day API (mm)
< 13
13 - 28
> 28
< 36
36 - 53
> 53
Runoff curve number (CN)
15 - 25
25 - 35
35 - 45
45 - 55
55 - 65
65 - 75
75 - 85
85 - 95
95 - 100
Precipitation (mm·month-1)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 600
Direct runoff (mm·month-1)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 600
Direct runoff coefficient
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
0
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12,500
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37,500
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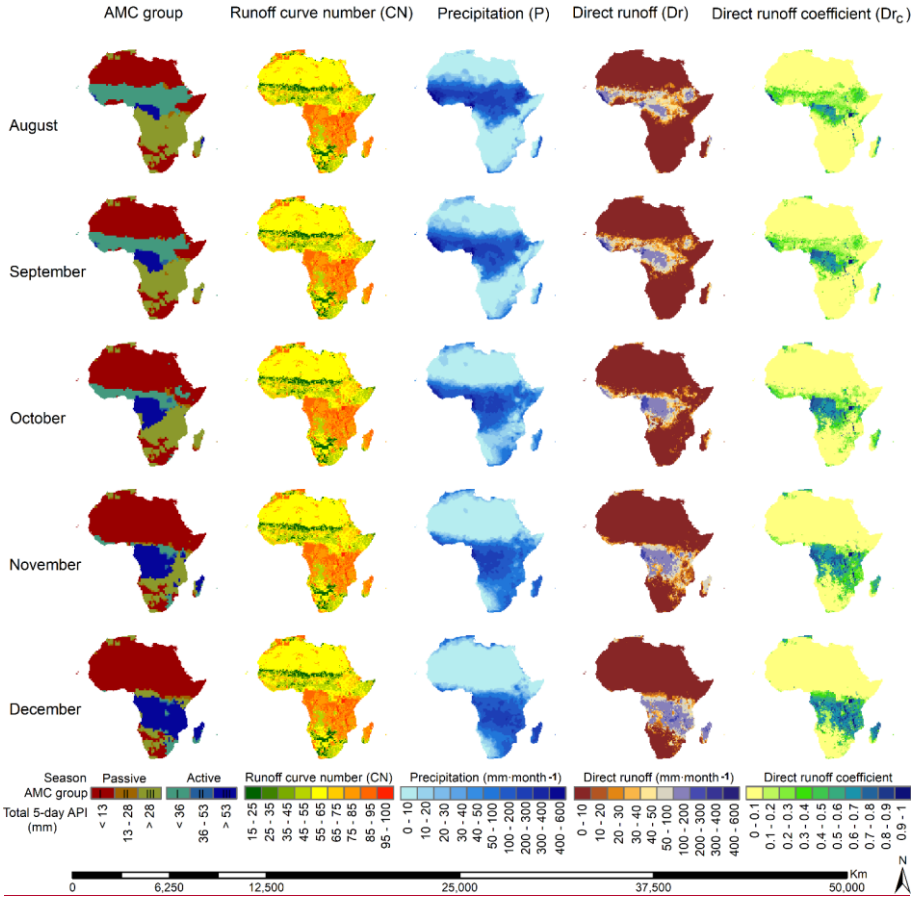

Figure 6. Maps of the runoff curve number (CN) adjusted according to antecedent soil moisture condition (AMC), precipitation (P), direct runoff depths (Dr) and direct runoff coefficients (Dr_c).

2.2.2.2 Downscaling process of the runoff discharges

Equations (8), (9), (10), (11), (12), (13), and (14) express the process used to downscale the observed runoff coefficients and runoff depths from basin scaled to 0.5° grid spatial resolution (Figure 7) based on the direct runoff distributions within different grids of each gauged catchment. This approach provides google results since the mean of observed gridded runoff coefficients and runoff depths equals to the catchment's average observed runoff coefficients and runoff depths, respectively.

$$Drv_g = 0.001 * Dr_g * G \quad (8)$$

$$Drv_b = 0.001 * Dr_b * A \quad (9)$$

$$\emptyset = \frac{Drv_g * 100}{Drv_b} \quad (10)$$

$$Orv_b = 0.001 * Or_b * A \quad (11)$$

$$Orv_g = \frac{Orv_b * \emptyset}{100} \quad (12)$$

$$Or_g = \frac{Orv_g}{G} * 1000 \quad (13)$$

$$Orc_g = \frac{Or_g}{P_g} \quad (14)$$

where, ($\emptyset$) is the percent contribution of each grid's direct runoff volume (Drv_g) in $m^3 \cdot month^{-1}$ to its corresponding basin's direct runoff discharge (Drv_b) in $m^3 \cdot month^{-1}$, Dr_g is the grid's direct runoff depth ($mm \cdot month^{-1}$), Dr_b is the basin's average direct runoff depth ($mm \cdot month^{-1}$), G is the size of a grid in m^2, 0.001 and 1000 are the numbers for unities conversion, A is the drainage area of basin in m^2. Orv_b is the basin' s observed runoff discharge ($m^3 \cdot month^{-1}$), Or_b is the basin's observed runoff depth ($mm \cdot month^{-1}$), Or_g is the grid's observed runoff depth ($mm \cdot month^{-1}$), Orc_g is the grid's observed runoff coefficient (dimensionless), P_g is the grid's precipitation intensity ($mm \cdot month^{-1}$).

2.2.2.3 Application of inter-gauged and ungauged basin parameter transfer approach

Overlay (intersect) is one of useful geospatial overlay methods that stacks several different types of dataset with the same georeferencing system on top of each other in order to assess the relationship between features of each location. Overlay method has been used in different applications such as relationship analysis between rainfall distribution and elevation, examination of environmental sensitivity based on slope, surface drainage, soil erosion and other environmental parameters (Zhu, 2016). This method was applied to the present study in order to establish a unique zonal feature dataset that combines together a set of important physical-climate variables which control the runoff (AMC, CN, TWSC, T, and TWI and slope). Each intersection of these variables falls within gauged and ungauged grids at the same time, here immediately ungauged grids receive an average of observed runoff coefficient locating within the same intersection. This operation was achieved using the "Zonal Statistics as Table Tool" available in the Spatial Analyst *Tools* of the ArcMap v.10.5" where, hydrologic similarity's zonal feature dataset were considered as "Input raster or feature zone data", and downscaled observed runoff as "Input value raster".

The hydrological similarity analysis involved AMC (Figure 6) based on its potential capability to separate the drying and wetting areas, whilst CN (Figure 6) helps to recognize the effect of land use and soil characteristics in runoff generation process. According to the water balance budget, during the rainy seasons water soaks into pervious ground and once filled in

soil porosities starts to flow into rivers and lakes resulting in an increased level of underground water (acquirers) and surface water reservoirs (rivers, lakes and oceans); in impervious surface rainwater flow forward immediately into surface water reservoirs. Accumulation of water infiltrations improves soil moisture condition and boosts the rate of runoff depths while, a declining water storage phenomenon leads to lower amount of runoff discharge (Edwards et al., 2015). Apart from the natural cause of water storage change fluctuations (i.e.: rainfall and evapotranspiration), human activities (i.e.: water storage for hydropower generation and its release, irrigation, water consumption, etc.) also affect the change of water storage and as well river discharge volume. However, the change of water storage is generally controlled by climate and seasons patterns more than human factors (Edwards et al., 2015).

In order to incorporate the effect of water storage change in hydrologic similarity analysis, this study used the long-term monthly terrestrial water storage change (Figure 7) computed from the Center for Space Research (CSR) Gravity Recovery and Climate Experiment (GRACE) RL05 mascon solutions available at 1^{o} resolution for the period starting from April 2002 to June 2016. The Gravity Recovery and Climate Experiment (GRACE) mission was launched in March 2002 under the NASA Earth System Science Pathfinder (ESSP) Program. GRACE is jointly implemented by the US National Aeronautics and Space Administration (NASA) and German Aerospace Center (DLR) (Save et al., 2016).

The land-surface temperature also plays a big role in water balance where, hot regions are often characterized by higher evapotranspiration rates compared to cold or temperate regions. The long-term monthly land-surface temperature (Figure 7) used in this study was calculated from the 4.01 release of the CRU TS (Climatic Research Unit Timeseries) dataset spanning a period of 116 years (1901 – 2016) (Harris et al., 2014). This dataset was developed, subsequently updated, improved and maintained with support from a number of funders, principally by the UK's Natural Environment Research Council (NERC) and the US Department of Energy. Long-term support is currently provided by the UK National Centre for Atmospheric Science (NCAS), a NERC collaborative center (Harris et al., 2014).

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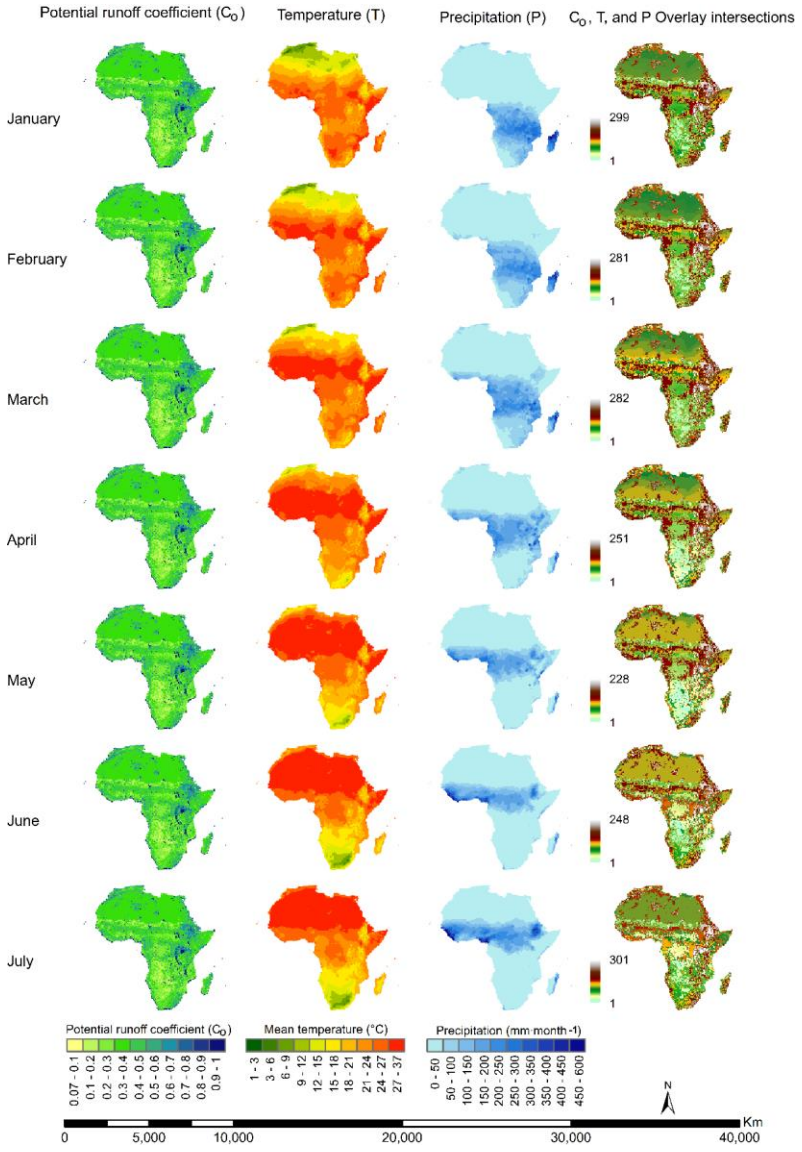

Potential runoff coefficient (C_o)
Temperature (T)
Precipitation (P)
C_o, T, and P Overlay intersections
January
February
March
April
May
June
July
299
281
282
251
228
248
301
1
Potential runoff coefficient (C_o)
0.07 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
Mean temperature (°C)
1 - 3
3 - 6
6 - 9
9 - 12
12 - 15
15 - 18
18 - 21
21 - 24
24 - 27
27 - 37
Precipitation (mm month-1)
0 - 50
50 - 100
100 - 150
150 - 200
200 - 250
250 - 300
300 - 350
350 - 400
400 - 450
450 - 600
N
Km
0
5,000
10,000
20,000
30,000
40,000

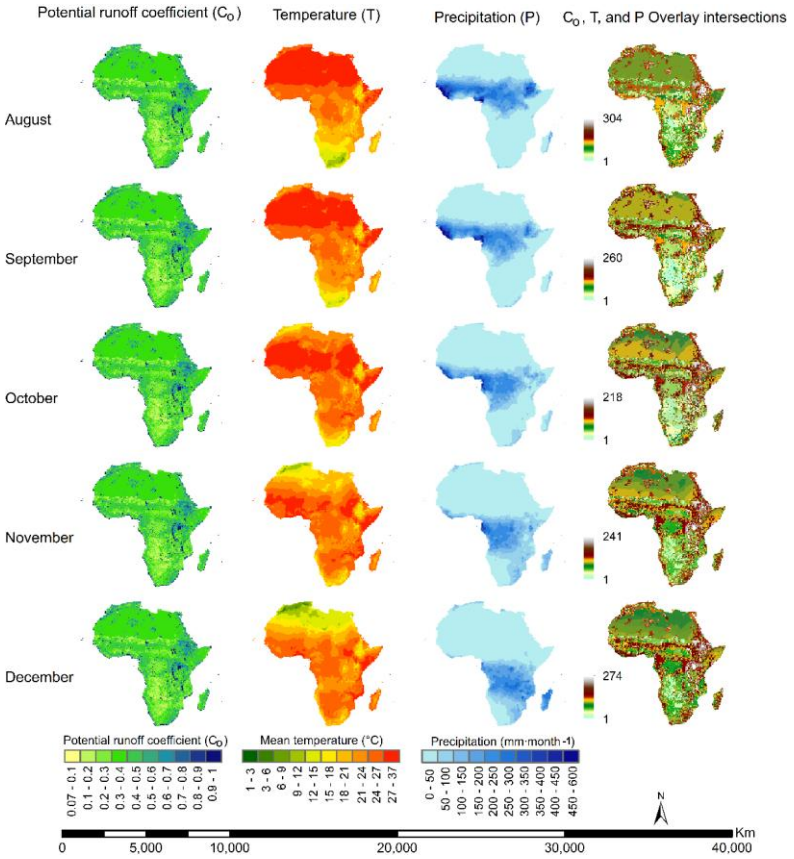


Figure 6. Maps for runoff controlling factors: potential runoff coefficient (C_o), surface temperature (T) and precipitation (P) utilized to establish the C_o, T and P overlay intersections for the interpolation guidance of the observed runoff coefficient (R_c).

~~2.2.3 Estimation of runoff and annual evapotranspiration~~

~~The long-term runoff depth was estimated using Eq. (4).~~

$$R = R_c \times P \quad (4)$$

~~where, R is a runoff depth (mm·month^{-1}), R_c is a runoff coefficient (dimensionless), and P is the precipitation intensity (mm·month^{-1}). The long-term annual R_c is the average of all monthly long-term R_c for the period starting from 1901 to 2017.~~

~~The current study estimated the long-term annual mean evapotranspiration according to the principle of water budget expressed by Eq. (5) referring to the concept water balance, where ground water changes is approximately zero on the long-term annual period basis due to the patterns of wet and dry seasons of the year (Edwards et al., 2015).~~

$$E_T = P - R \quad (5)$$

~~where, E_T is a long-term mean evapotranspiration in mm·yr^{-1}, P is a long-term mean precipitation in mm·yr^{-1}, and R is a long-term mean runoff depth in mm·yr^{-1}. Thus, the evapotranspiration coefficient (ET_c) can be expressed as the ratio of evapotranspiration to precipitation intensity received within the same basin and the identical period (Yang et al., 2018) as presented by Eq. (6).~~

$$ET_c = \frac{E_T}{P} \quad (6)$$

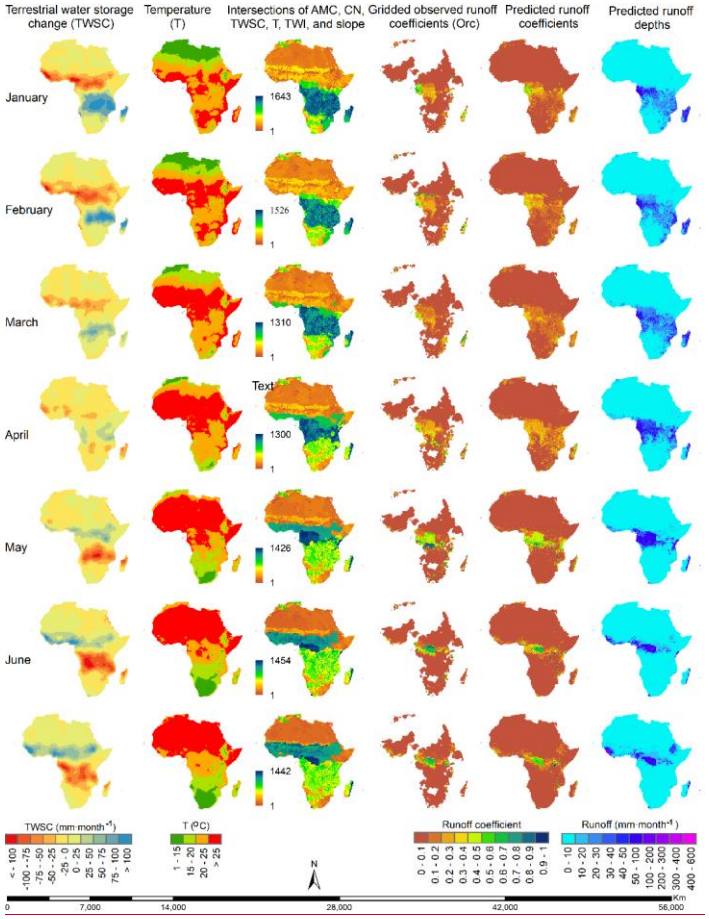
The topography also acts on water flow movement and infiltration; where higher runoff depths are mostly found in regions with steep slopes more than areas with flat and gentle slopes (Ogden et al., 2011). Sometimes, digital elevation model (DEM) is used directly as a parameter that represents the impact of the surface shapes and feature on the hydrological process (Xiao et al., 2017). The dataset of topographic wetness index (TWI) that is also called the Compound Topographic Index (CTI) was developed by Beven and Kirkby (1979) within the runoff model TOPMODEL due to the effect of topography on soil moisture (BEVEN and Kirkby, 1979). TWI (Eq. 15, 16 and 17) that combines local upslope contributing area and slope is commonly used to quantify topographic control on hydrological processes. Higher TWI values represent drainage depressions which are often wet and associated with greater runoff depths compared to crests and ridges relatively with the lower TWI values and dry surfaces that suck a lot of water amount before the beginning of water flow process (Liu et al., 2015;Sörensen et al., 2006;Xiao et al., 2017). TWI and slope parameters (Figure 7) derived from the HydroSHEDS datasets at 15 arc-second resolution (Lehner et al., 2008) were incorporated in the hydrologic similarity analysis of this study in order to separate areas with different topographic features.

$$TWI = \ln\left(\frac{\alpha}{tan\ \beta}\right) \quad (15)$$

$$\alpha = (f + 1) * G \quad (16)$$

$$\beta = (m * (\pi/2)/90 \quad (17)$$

where, α is the upslope area draining through a certain point per unit contour length and β is the slope in radians, f is the flow accumulation calculated from the flow direction that is generated in DEM (meter unity), G is the cell size in m^2, m is the slope in degrees, π is pi equals to 3.141592.



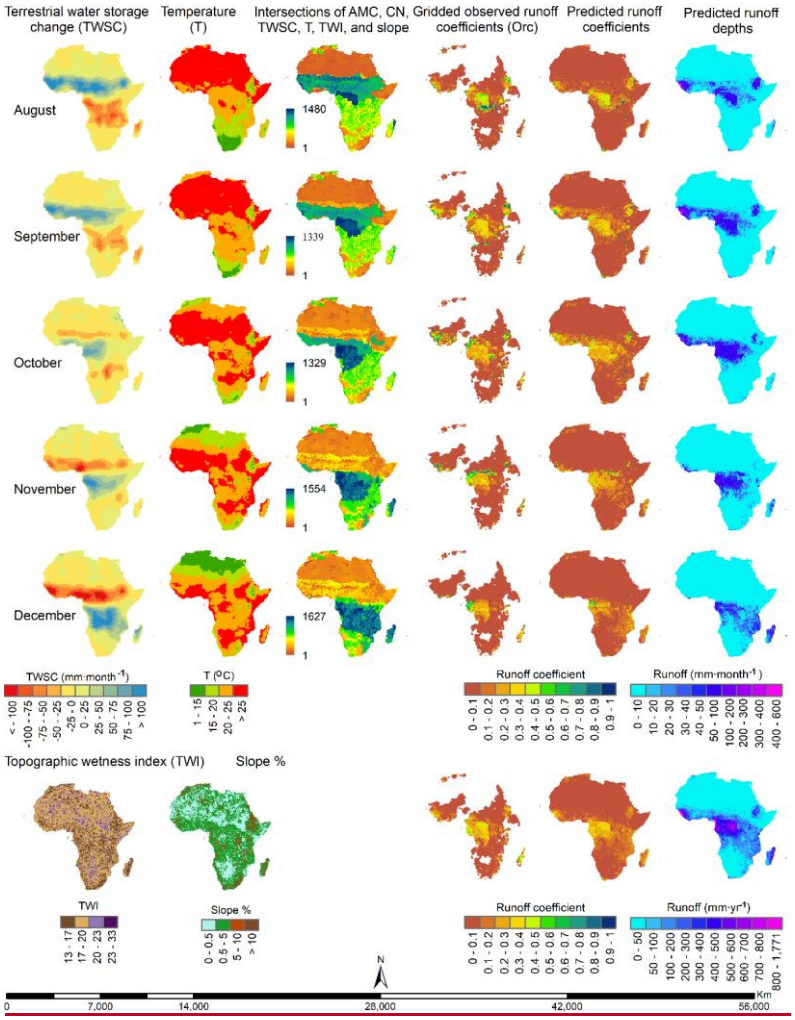


Figure 7. Estimated runoff coefficients and runoff depths based on gridded observed runoff coefficients transferred using inter-gauged and ungauged parameter transfer approach, according to hydrological similarity feature dataset resulted from an overlay (intersect) of the runoff controlling factors (AMC, CN (Figure 6), TWSC, T, TWI, and slope).

3 Results

Figure ~~7~~8 presents the final resultant maps obtained by means of the methods above-described in sections 2.2.1 and 2.2.2. Gridded long-term ~~mean~~ monthly and annual mean runoff ~~coefficient,~~coefficients (RC), precipitation~~,~~ (P), and runoff depths (R) were developed at 0.5° spatial resolution ~~for the period starting from~~ (1901 to ~~2017~~2016) and utilized to ~~produce the~~generate zonal statistics at the continental level~~,~~ (Figure 9 and 10), within 25 major basins ~~and~~(Figure 11), 55 countries of Africa~~.~~ (Figure 12) and as well latitudinal profile (Figure 14 and Table 4).

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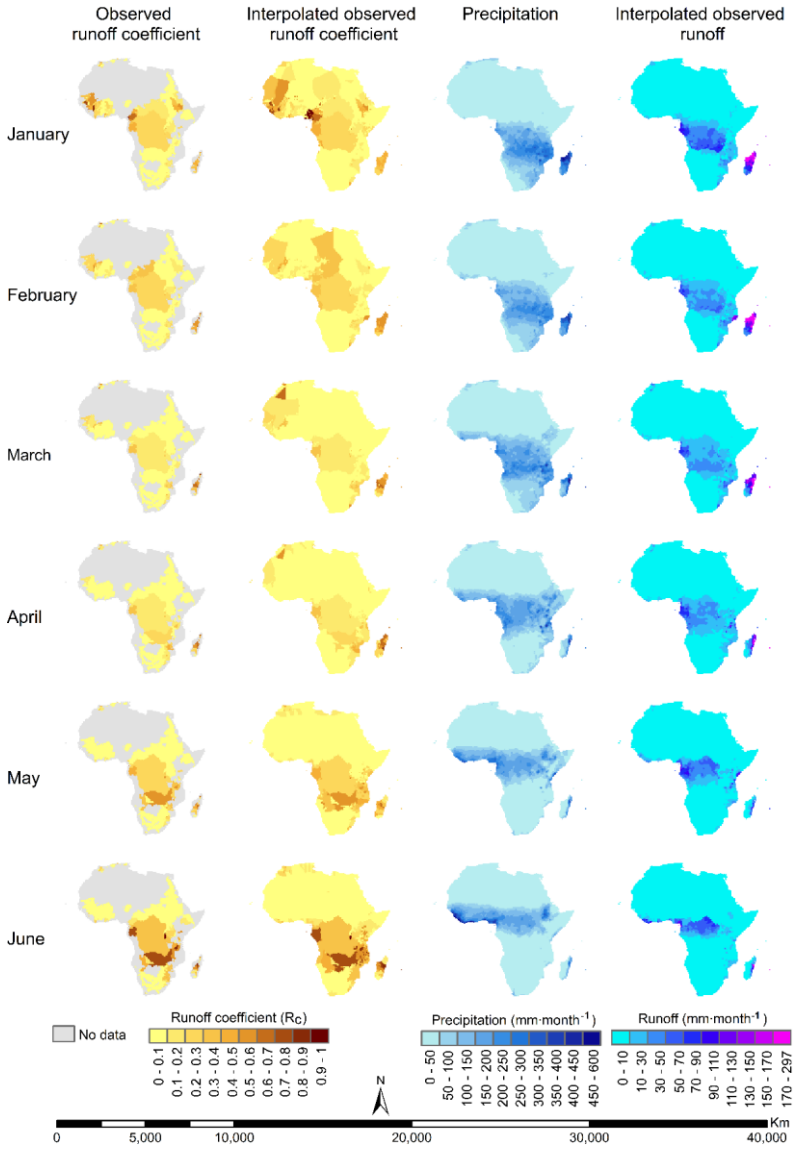
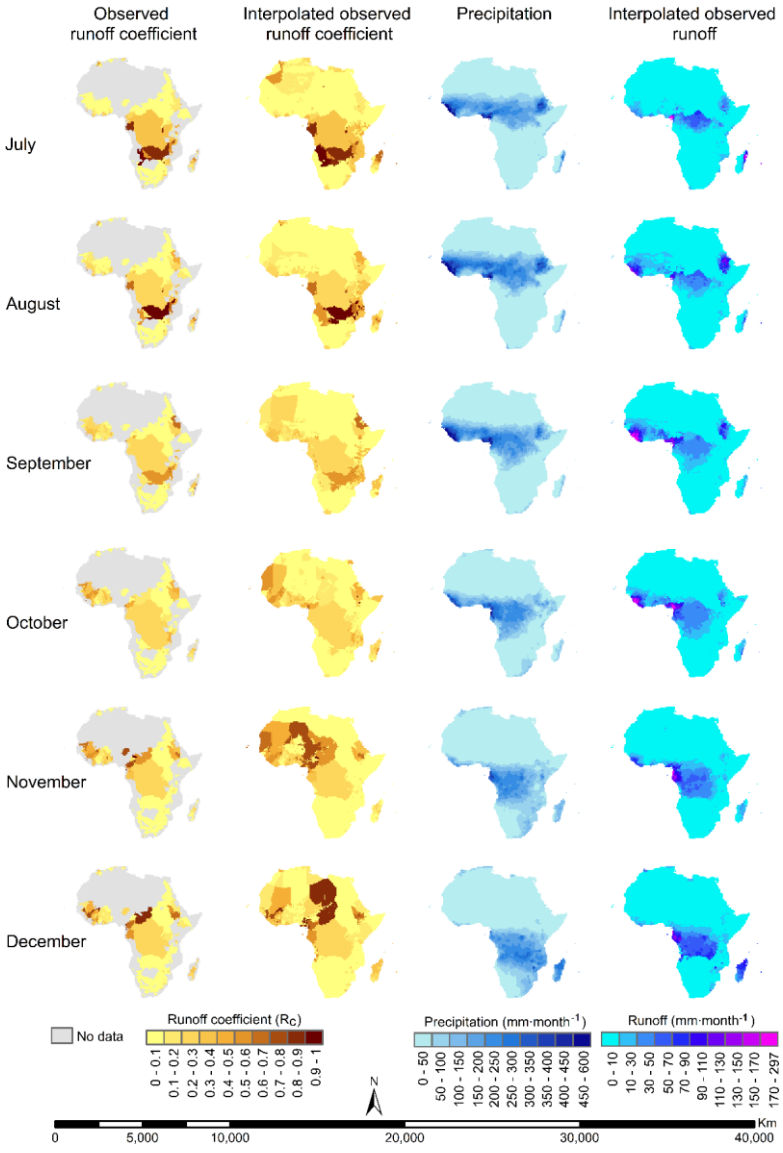
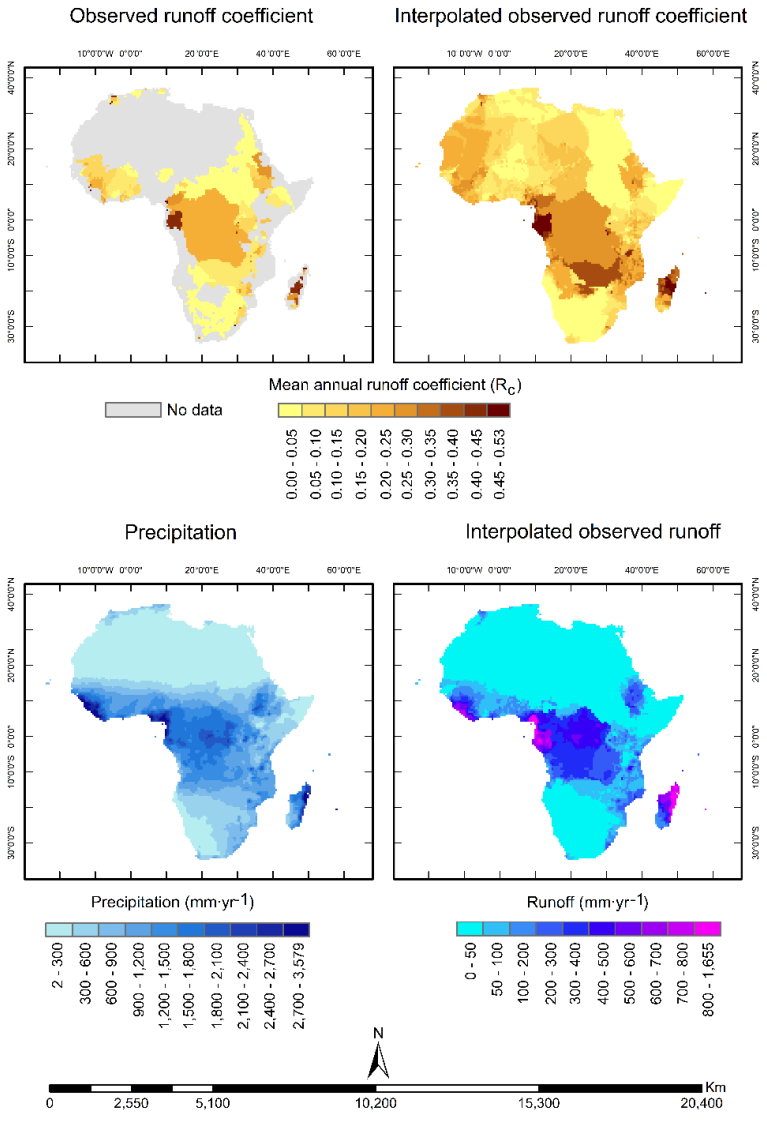
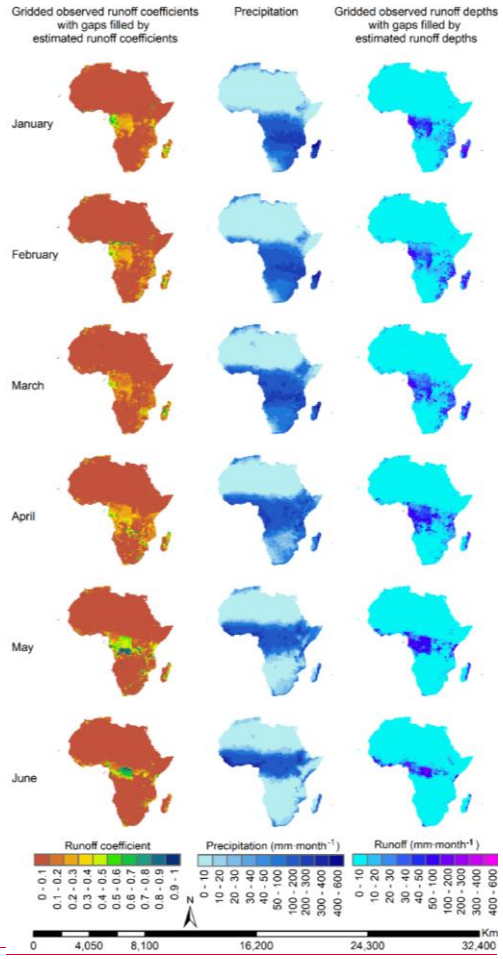
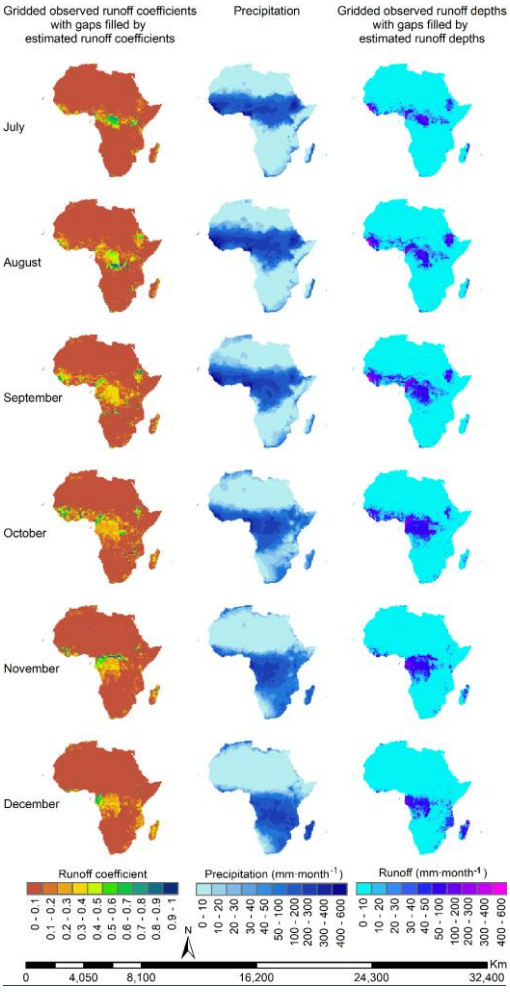

Observed runoff coefficient
Interpolated observed runoff coefficient
Precipitation
Interpolated observed runoff
January
February
March
April
May
June
No data
Runoff coefficient (Rc)
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
Precipitation (mm·month-1)
0 - 50
50 - 100
100 - 150
150 - 200
200 - 250
250 - 300
300 - 350
350 - 400
400 - 450
450 - 600
Runoff (mm·month-1)
0 - 10
10 - 30
30 - 50
50 - 70
70 - 90
90 - 110
110 - 130
130 - 150
150 - 170
170 - 297
N
0
5,000
10,000
20,000
30,000
40,000
Km


Observed runoff coefficient
Interpolated observed runoff coefficient
Precipitation
Interpolated observed runoff
July
August
September
October
November
December
No data
Runoff coefficient (Rc)
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
Precipitation (mm·month-1)
0 - 50
50 - 100
100 - 150
150 - 200
200 - 250
250 - 300
300 - 350
350 - 400
400 - 450
450 - 600
Runoff (mm·month-1)
0 - 10
10 - 30
30 - 50
50 - 70
70 - 90
90 - 110
110 - 130
130 - 150
150 - 170
170 - 297
N
0
5,000
10,000
20,000
30,000
40,000
Km


Observed runoff coefficient
Interpolated observed runoff coefficient
10°0'0"W 0°0'0" 20°0'0"E 40°0'0"E 60°0'0"E
40°0'0"N
20°0'0"N
10°0'0"S 0°0'0"
30°0'0"S
Mean annual runoff coefficient (R_c)
No data
0.00 - 0.05
0.05 - 0.10
0.10 - 0.15
0.15 - 0.20
0.20 - 0.25
0.25 - 0.30
0.30 - 0.35
0.35 - 0.40
0.40 - 0.45
0.45 - 0.53
Precipitation
Interpolated observed runoff
Precipitation (mm·yr-1)
2 - 300
300 - 600
600 - 900
900 - 1,200
1,200 - 1,500
1,500 - 1,800
1,800 - 2,100
2,100 - 2,400
2,400 - 2,700
2,700 - 3,579
Runoff (mm·yr-1)
0 - 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
700 - 800
800 - 1,655
N
0
2,550
5,100
10,200
15,300
20,400
Km


Gridded observed runoff coefficients with gaps filled by estimated runoff coefficients
Precipitation
Gridded observed runoff depths with gaps filled by estimated runoff depths
January
February
March
April
May
June
Runoff coefficient
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
Precipitation (mm·month-1)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 600
Runoff (mm·month-1)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 600
N
Km
0
4,050
8,100
16,200
24,300
32,400

~~Figure 7.~~


Gridded observed runoff coefficients with gaps filled by estimated runoff coefficients
Precipitation
Gridded observed runoff depths with gaps filled by estimated runoff depths
July
August
September
October
November
December
Runoff coefficient
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
Precipitation (mm·month-1)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 600
Runoff (mm·month-1)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 600
N
Km
0
4,050
8,100
16,200
24,300
32,400

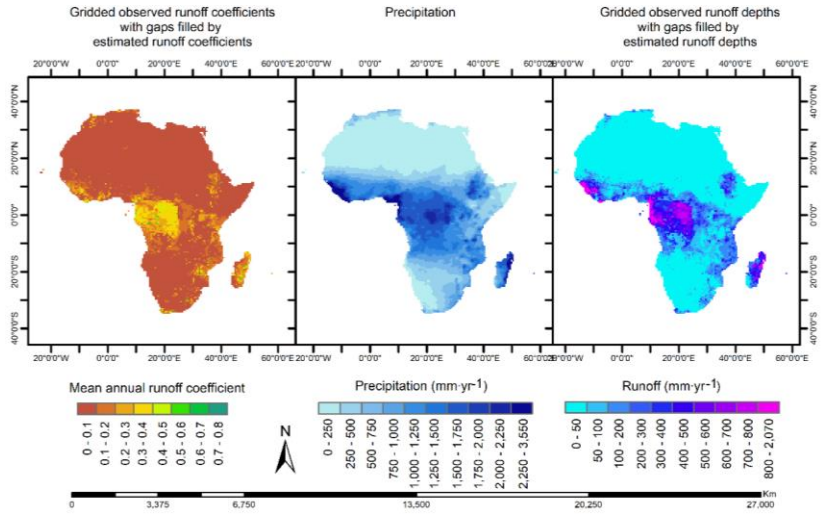
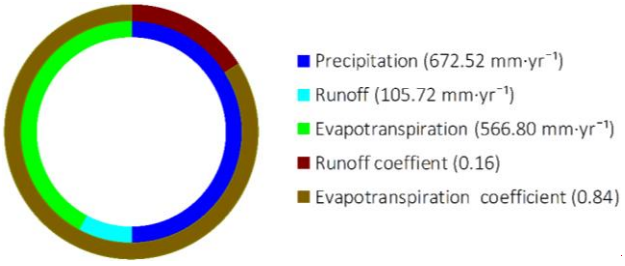


Figure 8. Maps of long-term mean monthly and annual runoff ~~coefficient~~coefficients, precipitation and runoff depths (1901 – ~~2017~~2016).

3.1 Precipitation-runoff relationship over the continent of Africa

~~The zonal~~Zonal statistical analysis at continental level ~~indicates~~revealed that the runoff (~~105.72~~94.9 mm·yr^{-1}) counts ~~16~~14% of the long-term mean precipitation (~~672.52~~671.88 mm·yr^{-1}) and evapotranspiration (~~566.80~~576.98 mm·yr^{-1}) comprises the remaining ~~84%~~86% of total long-term average rainfall amount (Figure ~~8~~9).



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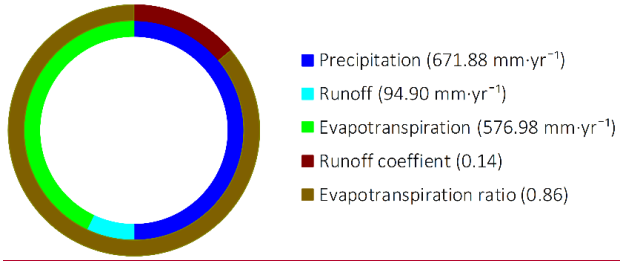
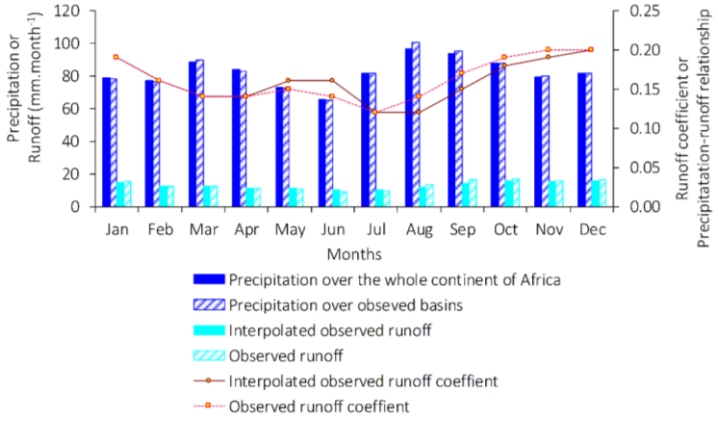


Figure 9. ~~Figure 8.~~ Long-term average annual water balance of Africa (1901 – ~~2017~~2016).

Assessment of the long-term monthly rainfall-runoff relationship revealed that the continent of Africa ~~had~~experienced the highest and lowest long-term mean precipitation intensities of 70.~~33~~47 mm·month^{-1} and 44.~~15~~13 mm·month^{-1} in August and June, respectively. The greatest and smallest long-term mean runoff depths of 11.~~16~~20 mm·month^{-1} and 5.~~64~~19 mm·month^{-1} are observed in ~~October~~September and June, respectively. ~~The~~ Figure 10 illustrates that the greatest rainfall-runoff correlation is ~~noticed~~recorded in October with ~~a~~the R_c = 0.~~2. While,~~19, while the lowest R_c = 0.~~1 are recorded~~11 is observed in July whenever P = 57.36 mm·month^{-1} and R = 6.~~3~~23 mm·month^{-1} (~~Fig. 9). The long-term monthly mean observed runoff and runoff coefficient had better agreements with interpolated observed ones. Some minor mismatches observed in May, June, August, September, October and November are due to different mean precipitation estimates from two distinct zones (monitored area and whole continent) (Figure 9~~Figure 10).



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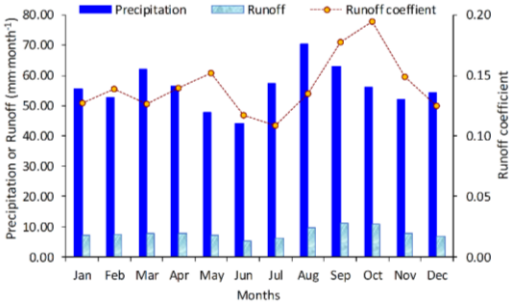

Figure ~~9.~~10. Long-term monthly precipitation-runoff relationship over the African continent (1901 – ~~2017~~2016).

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3.2 Precipitation-runoff relationship within 25 major African basins

Figure ~~10~~11 compares the long-term mean monthly and annual precipitation, ~~interpolated observed~~ runoff~~,~~ ~~interpolated observed~~ depths, runoff ~~coefficient~~coefficients and long-term mean annual evapotranspiration within 25 major African basins (1901 – ~~2017).~~

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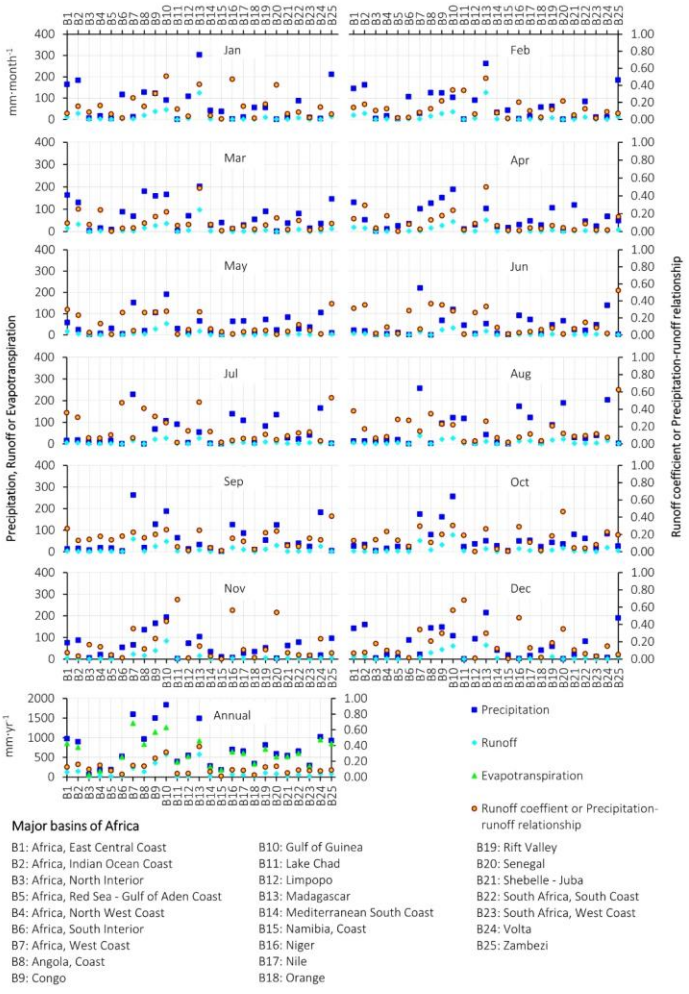

Figure 9. Precipitation-runoff relationship within 25 major basins of Africa (1901 – 2017).

2016). Top eightseven tropical basins out of 25 major African basins that comprised the highest runoff depths > 100 mm·yr^{-1} are: Madagascar (575.42 mm·yr^{-1}), Gulf of Guinea (573.65594.35 mm·yr^{-1}), Madagascar (330.59 mm·yr^{-1}), Congo (355.02302.28 mm·yr^{-1}), Africa-West Coast (227.68278.76 mm·yr^{-1}), Africa-East Central Coast (159.20 mm·yr^{-1}), Africa-

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Indian Ocean Coast (~~143.89 mm·yr^{-1}), Angola-Coast (132.34 mm·yr^{-1}), Africa-East Central Coast (122.88~~147.63 mm·yr^{-1}), and ~~Rift Valley (101.95~~Angola-Coast (111.32 mm·yr^{-1}). ~~These~~Apart from the Volta and Zambezi basins that also have ~~the~~a relatively high precipitation of 1,028.56 and 917.16 mm·yr^{-1}, the above-mentioned basins also comprised of highest long-term annual rainfall intensities among others, ranging from ~~811.88~~873.71 mm·yr^{-1} to 1,~~594.88~~854.64 mm·yr^{-1}, and are amongst ~~the top ten~~ basins with the strongest correlation between rainfall and runoff compared to others with a mean runoff coefficient ranging from 0.~~13~~12 to 0.~~39~~32. The basins with weak precipitation-runoff relationship indicates higher E_T ~~proportions~~ratios. Figure ~~10~~11 also illustrates the details about monthly precipitation-runoff relationship within 25 major basins of Africa.

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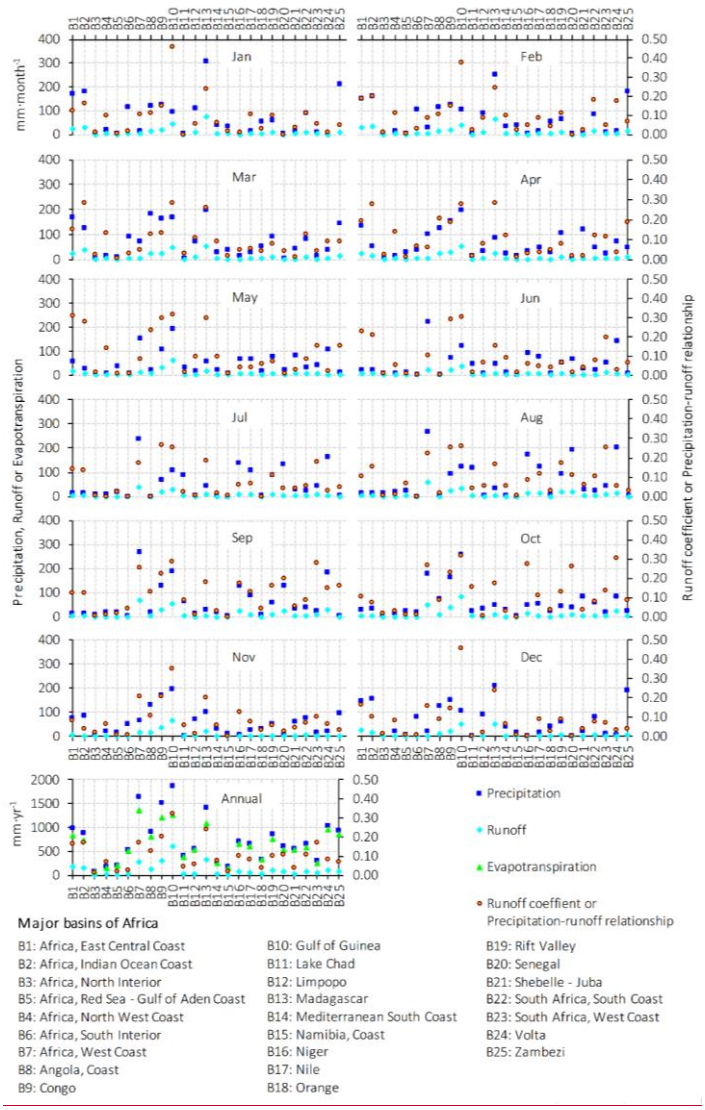

Figure 11. Precipitation-runoff relationship within 25 major basins of Africa (1901 – 2016).

3.3 Precipitation-runoff relationship within 55 African countries

Figure ~~11~~12 correlates the long-term mean monthly and annual ~~precipitation (~~P~~), interpolated observed runoff (~~, R~~), interpolated observed runoff coefficient (~~R_c~~) and RC~~, and long-term mean annual evapotranspiration (E_T)~~ during 1901 – ~~2017~~2016 in 55 countries of Africa. P ranges from ~~21.38~~16.54 mm·yr^{-1} to 2,~~820.92~~788.90 mm·yr^{-1}; R ranges from ~~1.06~~0.11 mm·yr^{-1} to ~~1,410.68~~889.78 mm·yr^{-1}, in Egypt and ~~Mauritius~~Sierra Leone, respectively; Rc ranges from 0.~~01~~004 in ~~Gambia~~Western Sahara to 0.~~5 Mauritius; E_T ranges from 20.32 mm·yr^{-1}~~387 in ~~Egypt to 2,099.14 mm·yr^{-1} in Sierra Leone.~~Gabon. It should be noticed that, with ~~the~~ highest runoff depths > ~~300~~200 mm·yr^{-1}, ~~The top 12 countries, including Mauritius~~Sierra Leone, Equatorial Guinea, Gabon, ~~Sierra Leone,~~ Guinea-Bissau, Republic of Congo, Cameroon, Liberia, Comoros, Seychelles, Democratic Republic of the Congo, Madagascar, São Tomé and Príncipe, ~~Republic of Congo, Cameroon, D. R. Congo, Seychelles, and Guinea-Bissau~~Mauritius, Burundi, Guinea, and Rwanda are ranked among the top ~~20~~16 out of 50 countries that experiences ~~the greatest~~a relatively strongest rainfall-runoff correlation with runoff coefficients range from 0.~~17~~18 to 0.~~50~~32. For comparative illustration of the long-term average monthly precipitation, runoff and runoff ~~coefficient~~coefficients between 55 countries of Africa, see Figure ~~11~~12.

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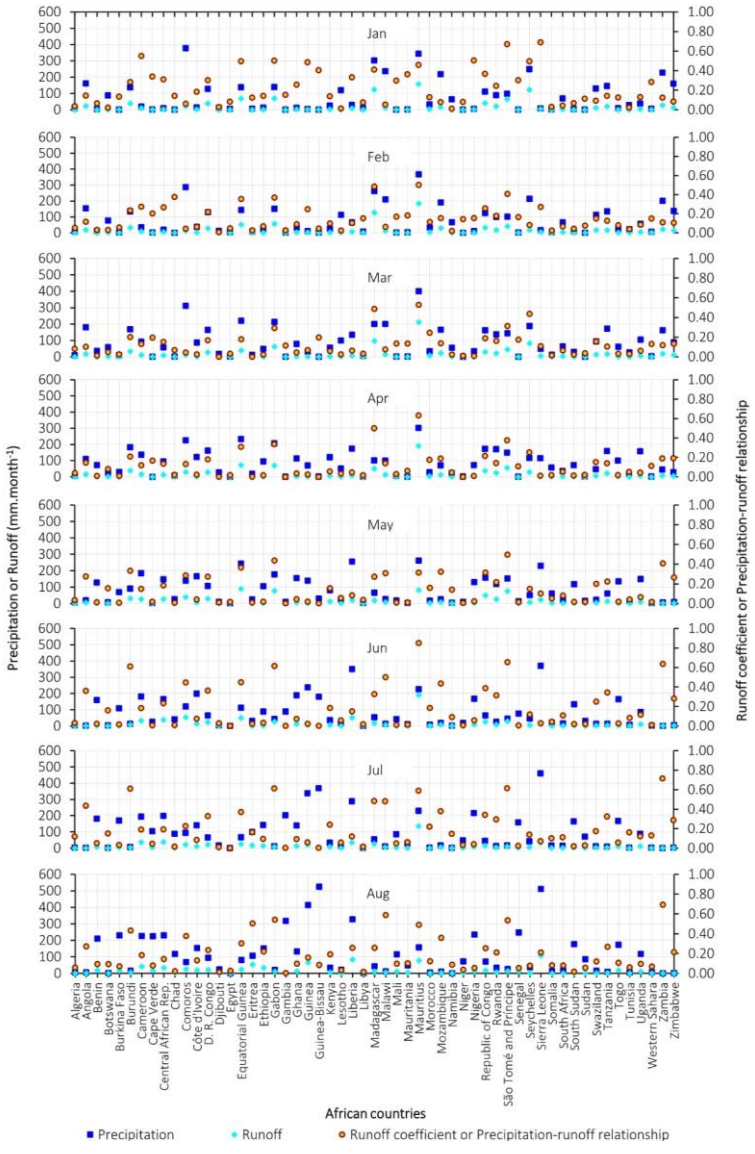
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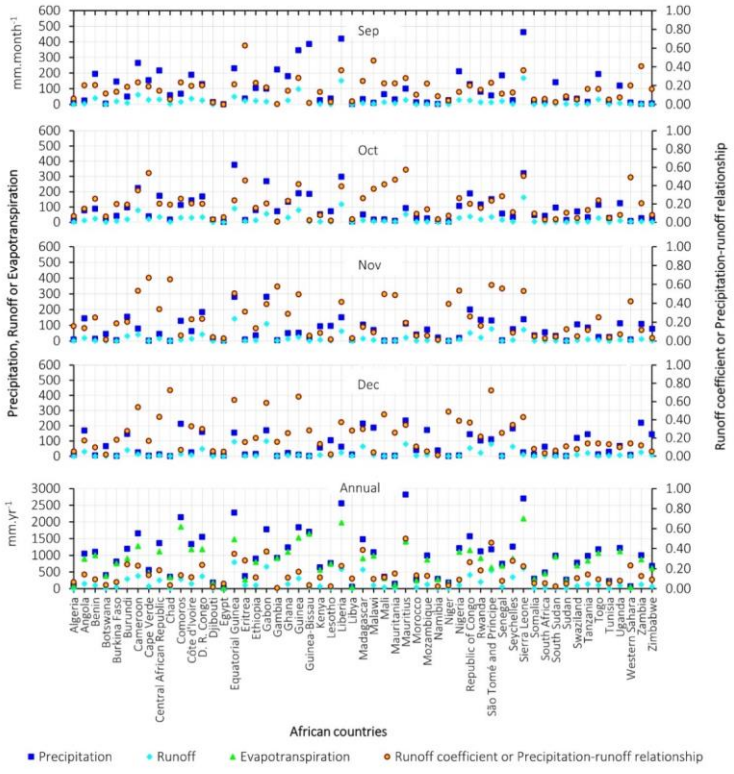
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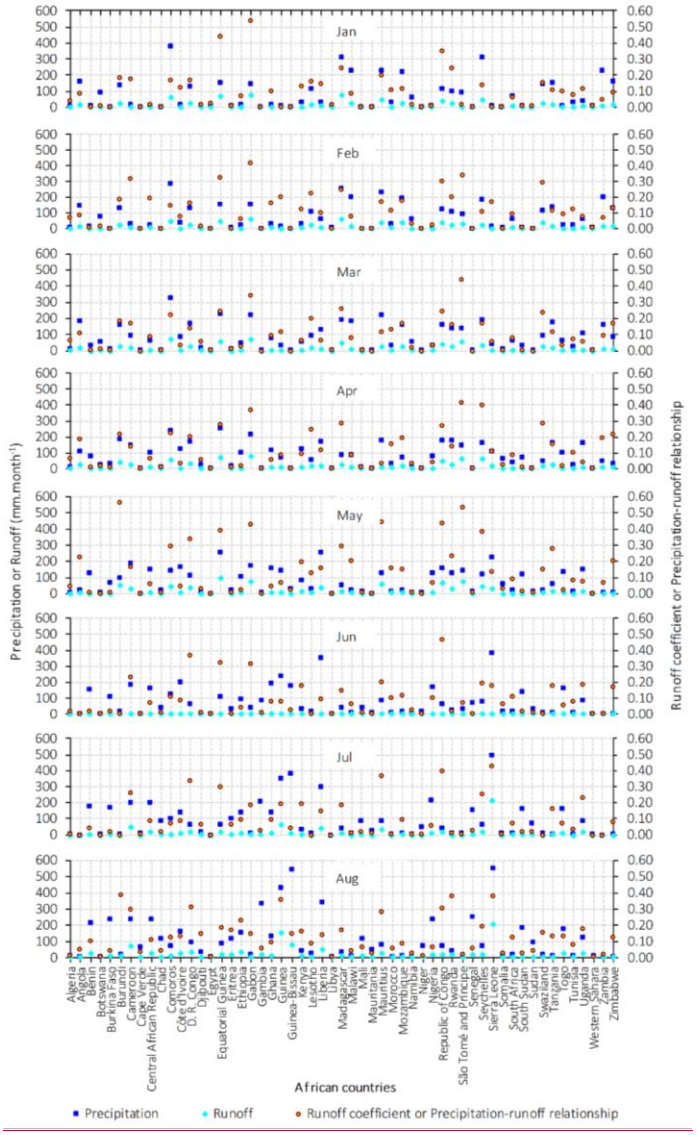
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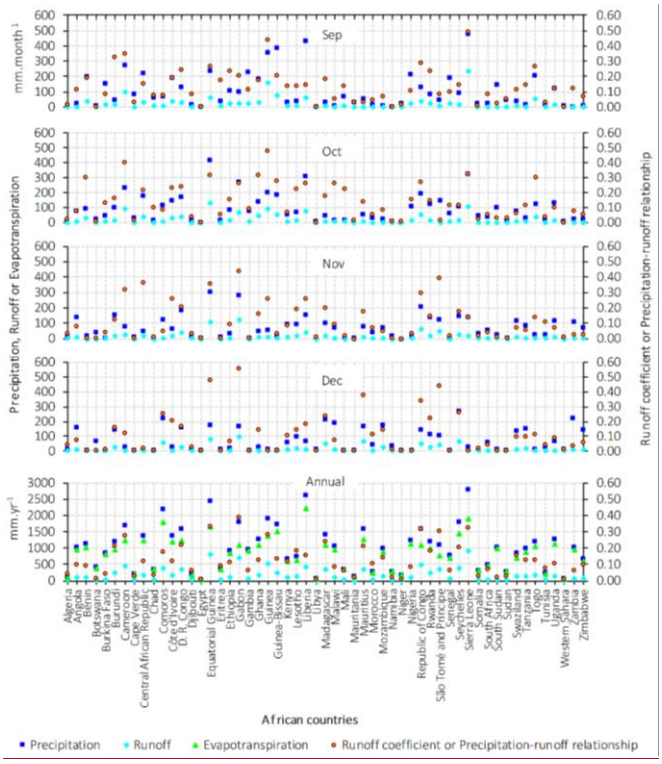

Figure 12. Precipitation-runoff relationship within 55 countries of Africa (1901 – ~~2017~~2016).

4 Discussions

~~Streamflow~~The streamflow and rain gauging stations are known as a trustable source of reliable data for different hydrological studies (Urroz et al., 2001). ~~The GRDC river discharges and GPCC precipitation datasets have outreaching accuracy for spatial analysis of the precipitation-runoff relationship rather than relying solely on the runoff model-based estimates which are likely associated with huge uncertainties caused by non-error-free data and sometimes un-well-constructed models~~, but the GRDC river discharge data are available with temporal and spatial gaps mostly in low income regions including African countries (Figure 13). Obviously, trends in hydrological process are mainly associated with historical climate changes, land-cover change, reservoir storage changes, hydropower releases, and irrigation abstractions which are known to be the primary changing factors affecting the amount of rainwater flow over time (Fekete et al., 2002a). Except, the precipitation datasets

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available for the since the beginning of 20st century, even before, the other above-mentioned changing runoff controllers are available for the recent decades (i.e.: GRACE data for water storage change analysis were collected since 2002 and good quality land cover maps are available since 1990s). Lack of these data for the earlier decades constrained us to predict the past runoff process. Again, if the earlier runoff discharges are excluded from the long-term runoff calculations, spatial gaps would be increased and bring more challenge for validation.

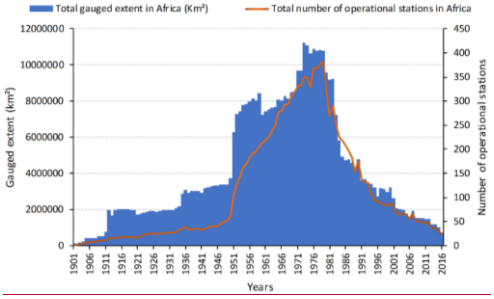

Figure 13. Historical gauged extent and number of operational stations in Africa (1901 – 2016).

A 75.64% of the total observed extent comprise the river discharges with a record of more than 20 years (Figure 3). The scarcity of runoff discharge data is common limitation in runoff prediction at a large extent such as continental scale, but they can provide reasonable results that represent the real world phenomenon (Loucks et al., 2005). ~~The~~Pre-analysis of the historical changes in annual runoff discharges suggested a linear trend varies between 10% and 40% among the stations which drain the catchments covered by a small extent (8.44% total gauged area). Indeed, a large proportion (91.56%) of the total African gauged area, including the catchments recorded in earlier to recent decades has stations that experienced a minor variance ranging from 0% to 10% which is not a major problem in long-term bases analysis of runoff estimation.

Actually, runoff-related studies are often conducted at a drainage basin scale, but, hydrological studies at the grid and country scales are very useful at national level since each government has own policies for water resource management. Utilization of average basin estimates directly at a country level or any other non-catchment locality seems to be unrealistic. This is the reason why this study highlighted the process of downscaling the basin' observed runoff discharges based on grids' direct runoff contributions to their corresponding basins which helps to include the effect of major runoff controlling factors (i.e.: land cover types, soil characteristics, moisture conditions and precipitation intensities) within different grids sharing the same catchment according to the Natural Resources Conservation Service (NRCS) runoff curve number (CN) method. Even though, the runoff generation process is governed by several environmental factors, but they don't have the same sensitivity and it is still too complicated to incorporate all of them in existing runoff models and methods. In this study, additional factors to those ones utilized in NRCS-CN were considered in fact that there is a considerable dissimilarity of hydrological conditions between separate catchments rather than the grids connected each other within the same catchment. It should be noticed that,

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the integration of NRCS-CN in downscaling the runoff discharges do not alter the quantity of observed runoff at a catchment scale, but it redistributes catchment' discharged runoff volumes to their grids according to their respective climate and physical conditions. Some runoff controlling factors such as temperature, topography, etc., are not amongst inputs of the NRCS-CN-based direct runoff prediction, but they also have minor sensitivity a catchment or grid scale with coarse resolution. Runoff discharges were downscaled at 0.5° grid spatial resolution to allow their application at country analysis and facilitate their utilization on estimation over ungauged regions. Gridded observed runoff coefficients were transferred to ungauged areas using inter-gauged and ungauged parameter transfer approach. This is a Geo-spatial analysis technique acceptable for hydrological predictions in ungauged basins (PUB) (Bárdossy, 2007;Blöschl, 2006). This method assumes that two separate catchments can have a similar hydrological process when they have the same range of climatic and physical conditions. Once one of these catchments is observed it can be a source of data to unobserved one. Hydrologic similarity conditions were investigated using the runoff controlling factors selected based on their potential impact highlighted in previous studies. Thus, the efficiency analysis of the approach used to predict the data for filling the gaps suggested that the estimated and observed runoff coefficients have the goodness of fit (R^2) ranging from 0.56 to 0.67 for the long-term monthly Rc and 0.78 for the annual mean Rc (Figure 14). These results are within permissible validity limits since an $R^2 > 0.5$ is considered acceptable for calibration and validation in hydrological modelling (Santhi et al., 2001;Van Liew et al., 2003).

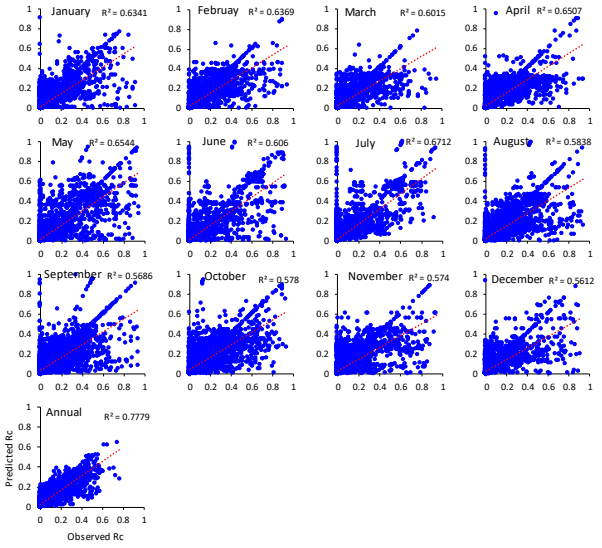

Figure 14. Scatter plots with a best - fit line indicating the efficiency of predicted runoff coefficients vs. gridded observed runoff coefficients over the gauged regions of Africa (Figure 7).

It can be concluded that inter-gauged and ungauged basin parameter transfer based on hydrologic similarity is an alternative approach for gaps filling in runoff prediction and it can even perform much better if the input observed runoff discharges do not have a lot of temporal gaps.

Furthermore, the study conducted by the University of New Hampshire-Global Runoff Data Centre (UNH-GRDC): "high-resolution fields of global runoff combining observed river discharge and simulated water balances" that has been considered as reference to validate the runoff-related hydrological studies since the beginning of 21st century ~~(Fekete et al., 2002; Hong et al., 2007) was compared with the current study based on the latitudinal zones at 1° interval scale (Figure 12). This analysis indicates that the long-term mean~~(Fekete et al., 2002b;Hong et al., 2007) was compared with the current study based on the latitudinal zones at 1° interval scale (Figure 15). This analysis indicates that the long-term annual mean rainfall (1920 – 1980) version 2.01 ~~(Willmott et al., 1998; Fekete et al., 2002)~~(Willmott_C_J_et_al1998, 1998;Fekete et al., 2002b) that was utilized to simulate the UNH/GRDC composite runoff ~~(Fekete et al., 2002) is roughly matching with the long-term (1901 – 2017) mean annual GPCC precipitation estimated in the current study (Figure 12).~~(Fekete et al., 2002b) is roughly matching with the long-term (1901 – 2016) mean annual GPCC precipitation estimated in the current study (Figure 15). Our comparative analysis also shows better agreements over the northern hemisphere between 36°N and 14°N, in the southern hemisphere between 17°S and 34°S latitudes, and in the equatorial zone laying between 4°N and 8°S. Major differences are between 14°N and 4°N in the northern hemisphere and in the southern hemisphere between 8°S and 17°S latitudes. These differences are possibly due to the UNH/GRDC method that assigned the same runoff depths in observed and unobserved basins that led to overestimation of the runoff in drylands of Australia and Africa ~~(Fekete et al., 2002). It should be noted that the interpolation method of observed runoff coefficient under consideration of environmental characteristics (land use and cover types, slope, soil texture classes, surface temperature and precipitation) has improved of both runoff coefficient and runoff over unobserved African regions rather than assuming similar runoff depths to different catchments with different environmental characteristics.~~ and gridded runoff depth that was estimated by considering rainfall factor alone (Fekete et al., 2002). The latitudinal profile analysis revealed that on the 2°S latitude is the runoff hotspot region of Africa with higher mean R depth (387.65 mm·yr^{-1}) and P (1,422.77 mm·yr^{-1}), and a relatively strongest P-R correlation with Rc of 0.27, followed by the 1°S latitude zone with the R of 383.87 mm·yr^{-1}, P of 1,504.47 mm·yr^{-1}, and Rc of 0.26, and as well equatorial zone at 0° latitude with a mean R of 379.99 mm·yr^{-1}, P of 1,490.18 mm·yr^{-1}, and Rc of 0.25.

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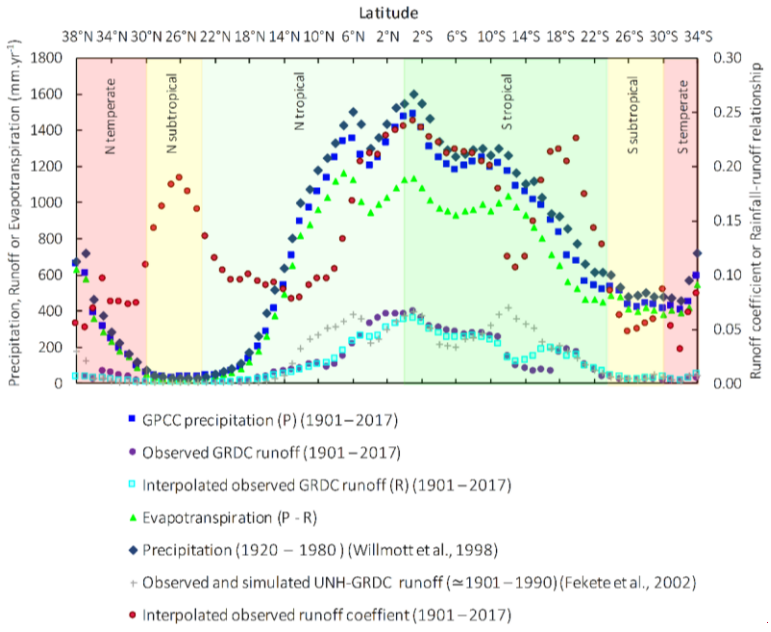
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GPCC precipitation (P) (1901–2017)
Observed GRDC runoff (1901–2017)
Interpolated observed GRDC runoff (R) (1901–2017)
Evapotranspiration (P - R)
Precipitation (1920 – 1980) (Willmott et al., 1998)
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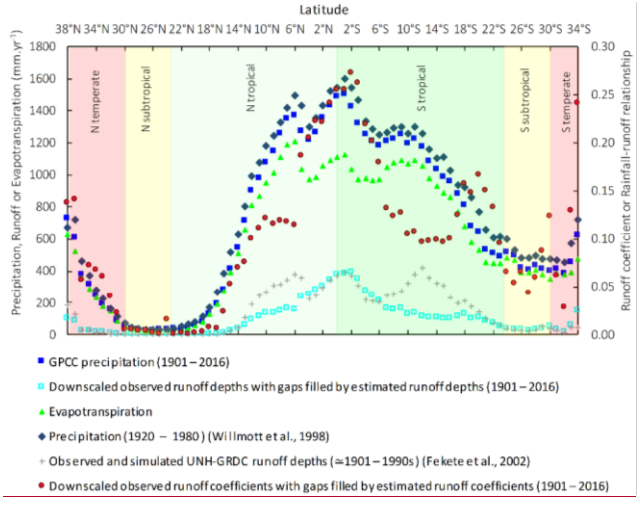
Interpolated observed runoff coeffient (1901–2017)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GPCC precipitation (1901–2016)
Downscaled observed runoff depths with gaps filled by estimated runoff depths (1901–2016)
Evapotranspiration
Precipitation (1920 – 1980) (Willmott et al., 1998)
Observed and simulated UNH-GRDC runoff depths (≃1901–1990s) (Fekete et al., 2002)
Downscaled observed runoff coefficients with gaps filled by estimated runoff coefficients (1901–2016)

Figure 15. Comparison of the precipitation-runoff relationship between the UNH-GRDC (Fekete et al., 2002) and the present study.

The latitudinal profile analysis revealed that 1°S latitude is the most hotspot region of Africa for both high mean annual rainfall intensity (1,486 mm·yr^{-1}), and runoff depth (357.26 mm·yr^{-1}), followed by the equatorial zone at 0° latitude with a mean annual rainfall intensity of 1,466.46 mm·yr^{-1}, runoff depth of 346.66 mm·yr^{-1}, highest runoff coefficient value of 0.24 for both 1°S and equatorial zone (0° latitude). These latitudinal zones also comprised of the highest evapotranspiration rates ranging between 1,119.8 mm·yr^{-1} and 1,157.24 mm·yr^{-1}. This might be one of the remarkable proofs showing good estimates of the present study based on the well-known distribution of precipitation across different latitudinal climatic zones (Peel et al., 2007).

. Comparison of the precipitation-runoff relationship between the UNH-GRDC (Fekete et al., 2002b) and the present study.

Based on the following six latitudinal climate zones: northern (N) tropical (0°Equator ≤ latitude ≤ 23.4°N), southern (S) tropical (23.4°S ≤ latitude < 0°Equator), N subtropicalsubtropics (23.4°N ≤ latitude ≤ 30°N), S subtropicalsubtropics (23.4°S ≤ latitude ≤ 30°S), N temperate (30°N < latitude ≤ 72°N), and S temperate (30°S < latitude ≤ 72°S),) (Peel et al., 2007), the long-term annual mean of the water balance's variables, including precipitation (P), evapotranspiration (E_T), interpolated observed runoff (R) and their corresponding interpolated observed runoff coefficientcoefficients (R_C) for the period of 117116 years (1901 – 20172016) were estimated and presented in Table 24 to provide tangible statistics corresponding to Figure 1215.

Table 4. Long-term annual water balance and runoff coefficientcoefficients within the African latitudinal climatic zones (1901 – 20172016).

Latitudinal climatic zones	% area Africa	P (mm·yr^{-1})	E_T (mm·yr^{-1})	R (mm·yr^{-1})	R_C
Tropical	**75**	**835836.36**	**699713.70**	**136122.66**	**0.1615**
N tropical	48	703708.94	607615.72	9693.22	0.1413
S tropical	26	1,076070.13	865893.45	211176.68	0.2017
Subtropics	**17**	**156146.23**	**143138.03**	**138.20**	**0.0806**
N subtropical	13	3728.35	3128.22	60.13	0.1600
S subtropical	5	468455.27	437425.91	3129.36	0.0706
Temperate zones	**8**	**261257.34**	**243236.94**	**1820.40**	**0.0708**
N temperate	6	210207.51	195193.79	1513.72	0.07
S temperate	2	432423.94	406381.21	2642.73	0.0610

Because of the Saharan desert located in northern Africa, the northern tropical and temperate zones have lower mean annual precipitation and runoff compared to southern tropical and temperate zones. Compared to the tropical zone, subtropics and temperate zones of Africa had low rainfall and runoff amounts (Figure 12 and Table 2), which expose them to water scarcity problem and less rainfall-runoff related disasters. The problem of insufficient water resource in drylands and semi-humid regions can be managed through the use of groundwater, minimization of water losses, establishment of dams, inter-basins water transfer, wastewater reuse, and surface water desalination instead of relying on unmodernized water supply technologies that are no longer meeting the water demand for our contemporary development associated with fast population

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~~growth~~Compared to the tropical zone, subtropical and temperate zones of Africa have low rainfall and runoff amounts (Figure 15 and Table 4), which may expose them to the water scarcity (Maliva and Missimer, 2012). The countries and basins located in the tropical zone ~~comprises high~~are often prone to a higher precipitation intensity which ~~produces~~produce huge runoff volumes enough for underground and surface water replenishment~~. While, excessive surface waterflow induces significant damages which require adequate strategies by promoting practical~~, however, some time causing stormwater ~~management systems (e.g.: forestation, different types of terraces and dams, etc.) that have potential ability to curb the movement and effects of surface water runoffs~~-related disasters (Ponette-González et al., 2015; Karamage et al., 2017b).

5 Conclusions

~~The present study investigated the spatial relationship between precipitation and runoff using the runoff coefficient as the measurement indicator, estimated from the long-term monthly runoff calculated based on the Global Runoff Data Centre (GRDC)'s streamflow records and Global Precipitation Climatology Centre (GPCC) rainfall data for a temporal period of 117 years (1901 – 2017) within monitored basins covering ≃ 41.4% of the total African continent. The interpolation method of observed runoff coefficient directed by the ancillary data (potential runoff coefficient, land surface temperature, and precipitation) that affect the runoff generation process has improved the estimation of runoff coefficient and runoff depths in ungauged basins. Thus, this study provides insightful hydrological information on the precipitation-runoff relationship at three spatial scales, including the whole continent, 25 major basins and 55 African countries which could raise the awareness to a wide range of relevant stakeholders. This study also suggested that the problem of water scarcity in drylands and semi-humid region can be handled through the use of groundwater, minimization of water losses, establishment of dams, inter-basins water transfer, wastewater reuse, and water desalination technologies. The tropical stormwater runoffs require suitable water management programs such as for example forestation, establishment of different types of terraces and dams, etc. in order to minimize the waterflow related disasters.~~

This study has highlighted step by step how the Natural Resources Conservation Service (NRCS) runoff curve number (CN) can be a prominent proxy for the basin's river discharge downscaling at a grid scale which can be reasonably utilized on non-catchment regional studies. This approach helped us to produce gridded long-term monthly runoff depths and coefficients datasets used to analyze the spatial relationship between precipitation and runoff over all 55 countries and 25 major drainage basins covering the whole continent of Africa. The Global Runoff Data Centre (GRDC)'s streamflow records available for 535 catchments covering ≃ 47.43% of the total African continent became a source of information for predicting the P-R correlation over ungauged regions based on the inter-gauged and ungauged parameter transfer approach and spatial hydrologic similarity analysis assed using the key runoff controlling factors including antecedent moisture condition (AMC), NRCS-CN, terrestrial water storage, temperature, topographic wetness index (TWI), and slope. Both higher runoff depths and strong P-R correlation were observed in the tropical humid regions due to their intensive precipitation more than in subtropical and temperate zones. This study suggests the need for rehabilitation awareness of operational stream gauging stations and

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establishment of new ones where they are necessary to make sure streamflow are regularly and widely recorded in different catchments of Africa to provide sufficient update data required for accurate water resource planning.

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