Spatial and temporal recharge estimation of the basement complex in Nigeria, West Africa

Article *in* Journal of Hydrology Regional Studies · January 2020

DOI: 10.1016/j.ejrh.2019.100658

5 authors, including:

Eniola Damilola Ashaolu
University of Ilorin

Ifatokun Paul Ifabiyi
University of Ilorin

Khodayar Abdollahi
Shahrekord University

Okke Batelaan
Flinders University

Journal of Hydrology: Regional Studies 27 (2020) 100658

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Spatial and temporal recharge estimation of the basement complex in Nigeria, West Africa

Eniola Damilola Ashaolu[a,*], Jacob Funso Olorunfemi[a], Ifatokun Paul Ifabiyi[a], Khodayar Abdollahi[b], Okke Batelaan[c]

[a] Department of Geography and Environmental Management, Faculty of Social Sciences, University of Ilorin, PMB 1515, Ilorin, Nigeria
[b] Faculty of Earth Science, Shahrekord University, Rahbar Blvd., P.O. Box 115, Shahrekord, Chaharmahal, Iran
[c] National Centre for Groundwater Research and Training, College of Science and Engineering, Flinders University, GPO Box 2100, Adelaide, SA 5001, Australia

ARTICLE INFO

Keywords:
Groundwater
Recharge
WetSpass-M
Groundwater management
Osun basin

ABSTRACT

Study region: Osun Drainage Basin, Nigeria.
Study focus: Estimating spatial and temporal patterns of recharge is important for sustainable groundwater resources management. This is especially true for data poor regions, such as the Basement Complex in Nigeria, which has shallow aquifers, a proliferation of wells and no efficient groundwater monitoring network. This study evaluates the performance of a spatially distributed monthly water balance model (WetSpass-M) in estimating groundwater recharge. The WetSpass-M model has moderate data demands, which allows for comprehensive assessment of recharge.
New hydrological insights for the region: 27 % of the rainfall in Osun drainage basin becomes recharge, while the remaining is lost through evapotranspiration (43 %), surface runoff (21 %) and interception (9 %). September is the month with highest recharge, ranging between 0 and 73 mm in the north and 129 up to 213 mm in the south and northeast of the basin. The study revealed the significance of the applied water balance model in understanding the spatial and temporal status of recharge. Therefore, the spatial and temporal patterns of recharge should be taken into consideration in preparing a sustainable groundwater resources management plan for the Osun drainage basin. Artificial recharge might be adopted to store storm water runoff during wet periods to improve the groundwater supply in dry months. Also, monthly groundwater withdrawals should be regulated in relation to spatial and temporal recharge patterns.

1. Introduction

Groundwater recharge estimation is a well-established research area (Omorinbola, 1986; Lerner et al., 1990; Beekman et al., 1996; Finch, 1998; Arnold et al., 2000; Finch, 2001; Armbruster and Leibundgut, 2001; de Vries and Simmers, 2002; Lerner, 2002; Edmunds et al., 2002; Batelaan et al., 2003; Sophocleous, 2004; Goni et al., 2005; Adelana et al., 2006; Batelaan and De Smedt, 2007; Nolan et al., 2007; Hamza et al., 2007; Jyrkama and Sykes, 2007; Mileham et al., 2008; Milewski et al., 2009; Healy, 2010; Pan et al., 2011; Teklebirhan et al., 2012; Tesfamichael et al., 2013; Zomlot et al., 2015; Abdollahi et al., 2017), however, the paucity of data and limited research capacity in developing countries such as Nigeria means that there is a lack of understanding recharge variability

* Corresponding author.
E-mail address: damash007@yahoo.com (E.D. Ashaolu).

https://doi.org/10.1016/j.ejrh.2019.100658
Received 4 February 2019; Received in revised form 9 December 2019; Accepted 12 December 2019
Available online 27 December 2019

for large parts of the developing world. This can be attributed to the complex nature of groundwater resources and its interaction with the ecosystem, and to what Taylor and Tindimugaya (2012) called the limited hydrological knowledge base, human and institutional capacity in the tropical regions of the world.

Researchers in Nigeria have strived to estimate groundwater recharge of locations and drainage basins across the country using different methods. Some of these methods include: tracers/isotopes (Adanu, 1991; Edmunds et al., 2002; Goni et al., 2005; Sani et al., 2012); empirical relationships (Omorinbola, 1982, 1986; Carter, 1994; Carter and Alkali, 1996; Adeleke et al., 2015; Ashaolu, 2016a); soil moisture balance and water table fluctuation (Adindu et al., 2013; Oke et al., 2014); and hydrograph separation method (Ifabiyi, 2004; Idowu and Martins, 2007). Other scholars also adopted a combination of two or more methods (Adelana et al., 2006) or different empirical equations (Oke et al., 2015), with the intention of comparing the results. Also, previous studies (FMWR, 2014a; Oke et al., 2015) on groundwater recharge in southwestern Nigeria lumped "Ogun" and "Osun" drainage basins together as a unit of investigation and reported a single mean annual recharge for the two basins.

The methods highlighted above, have restricted spatial and temporal capability; and assessed recharge on an annual or seasonal time scale, thereby neglecting important smaller time scale (monthly) recharge variability. Neither did these studies examine the interconnectivity between groundwater and surface water resources, despite their intrinsic role in the hydrological cycle. It has been stressed that groundwater resources do not exist in isolation but are connected to surface water resources and the terrestrial ecosystems (UNESCO, 2008); hence, both should be conceptualized as a combined resource (Winter et al., 1998). Adopting an integrated system approach that recognizes groundwater system as part of the hydrologic cycle is paramount when examining groundwater availability and long-term aquifer sustainability (Healy et al., 2007; UNESCO, 2008). Bredehoeft (2011) also suggested that a holistic approach is needed in assessing the relationships between groundwater and surface water, because groundwater cannot be managed independently from surface water without considering their interdependencies. These issues call for a need to employ an integrated approach for groundwater recharge estimation.

Owing to the complexities in direct assessment of the water budget, hydrologists and water resources engineers have widely adopted hydrological models to enable its comprehension (Ashaolu, 2017). There are several recharge estimation models, such as SWAT (Arnold et al., 2000); SVAT (Armbruster and Leibundgut, 2001); and DREAM (Manfreda et al., 2005) that are data intensive and based on complex hydrological process calculations, thereby reducing their application in developing countries where hourly or daily climatic data are scarce (Abdollahi et al., 2017). The WetSpass model (Batelaan and De Smedt, 2001, 2007) estimate groundwater recharge on seasonal and annual basis, which limited its application in the Basement Complex rocks terrain, where intra-seasonal recharge processes are important and hence a smaller time step for the recharge estimation is required for sustainable groundwater management.

Thus, the general scientific aim of this research is to evaluate the performance of the WetSpass-M model for its capability to estimate regional, spatially and temporally (monthly) variable groundwater recharge, under conditions of limited data availability as is typical in tropical continental climate regions and Basement Complex rocks terrain. The choice for the WetSpass-M model is based on the premise that it offers an efficient approach for basins where there is sparse monitoring and lack of data on hydrological processes (Abdollahi et al., 2017). Studies in different parts of the world, have adopted WetSpass models in assessing the water balance, which yielded satisfying results (Batelaan and De Smedt, 2001, 2007; De Smedt and Batelaan, 2003; Dams et al., 2007; Pan et al., 2011; Teklebirhan et al., 2012; Tesfamicheal et al., 2013; Al Kuisi and El-Naqa, 2013; Zomlot et al., 2015, 2017; Melki et al., 2017; Mustafa et al., 2017; Abdollahi et al., 2017). The last three references applied WetSpass-M, while only the Bangladesh study area of Mustapha et al. (2017) has a similar climate. Albeit this study did not focus on the WetSpass-M performance and has very different hydrogeological conditions. Groundwater occurrence in the Basement Complex rocks aquifer in any environment is defined by the presence of a shallow water table and significant amount of natural recharge is mainly from rainfall (Sekhar et al., 1994; Nyagwambo, 2006) and the groundwater residence time is about three to six months (Nyagwambo, 2006). As there is a high temporal rainfall variability (Ashaolu, 2018) in Nigeria, estimating only annual and seasonal recharge in the Basement Complex aquifer will not be sufficient for understanding intra- and inter-annual variability of the groundwater resource.

This study focuses on Osun drainage basin, which is one of the two major drainage basins in southwestern Nigeria. The Basement Complex rocks underlie about 93 % of this basin. It constitutes a poor aquifer, although sizeable amount of groundwater is found in areas with deeply weathered regolith (Ashaolu, 2016a; Ashaolu and Adebayo, 2014; Taylor and Howard, 2000; Azeez, 1972). In addition, increasing population, put at 12 million in 2018, is putting pressure on water resources development within the Osun drainage basin. It has been argued that long-term water resource planning requires both spatial and temporal information on groundwater recharge to properly manage not only water use and exploitation, but also land use allocation and development (Jyrkama and Sykes, 2006). Hence, this study will help in the long-term sustainable groundwater resources management in the study area.

2. Study area

The Osun drainage basin is located between latitudes 6°25´58.79˝ and 8°21´3.6˝ N and longitudes 3°47´34.8˝ and 5°10´55.2˝ E in south western Nigeria. It extends over 9,259 km^2. The Osun drainage system rises in Oke-Mesi ridge, about 5 km North of Effon Alaiye and flows North through the Itawure gap to latitude 7°53˝ before turning westwards via Osogbo, Ede and southwards to flow into Lagos lagoon about 8 km east of Epe (Fig. 1) (Ogun-Oshun River Basin Development Authority [OORBDA], 1982; Oke et al., 2013; Ashaolu, 2016b). The basin climate is influenced by the movement of the Inter-tropical Convergence Zone (ITCZ), the quasi-stationary boundary that distinguishes the sub-tropical continental air mass over the Sahara and the equatorial maritime air mas over the Atlantic Ocean. The sub-tropical continental air mass is marked by the dry north-easterly winds known as Harmattan, while

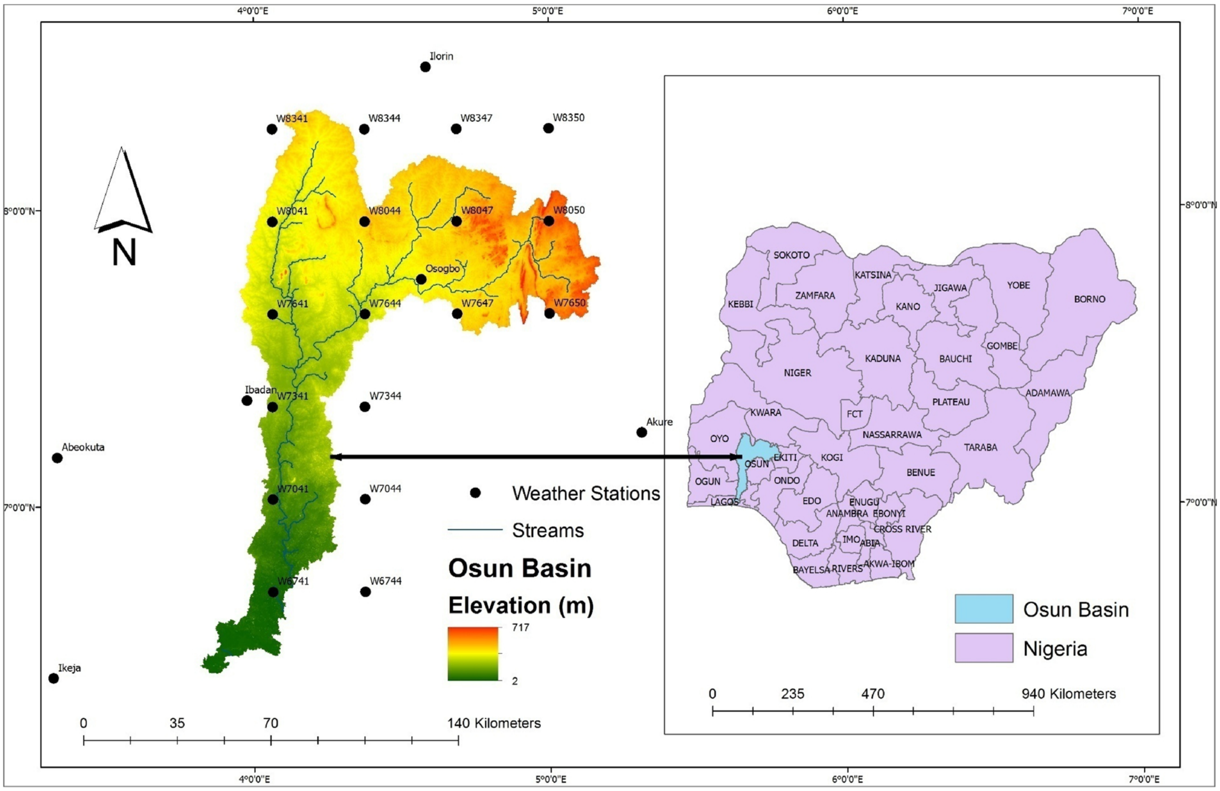

Fig. 1. Location and position of Osun drainage basin, Nigeria.
Source: Modified from Ashaolu (2016b).

equatorial air mass is marked with the rain-bearing south-westerly winds from the Gulf of Guinea (OORBDA, 1982). The basin experiences two types of seasons, dry and rainy (wet) season. The dry season is a period of minimal rainfall, when the northeast trade wind dominates. The rainy season starts by the end of April when the basin is under the influence of the southwest trade wind, which is a rain bearing wind (Ifabiyi, 2005). The switch from the rainy season to the dry season is abrupt, while the onset of the rain after the dry season is gradual (OORBDA, 1982).

The salient feature of the rainfall pattern is its seasonal distribution (Fig. 2). The rainy season begins earlier in the south around March and continues until the end of October or early November. In the north around Ogbomosho, the rain begins in late April or early May and end in mid-October, giving six months of rainfall. Dry days are frequent and regular in late July and early August, which was termed the "little dry season". The mean (1976–2015) wet season rainfall varies from 1020 mm to 1520 mm in the south of the basin to less than 1020 mm in the north. On the other hand, the mean dry season rainfall varies from 127 to 178 mm in the north, while it varies from 178 to 254 mm in the south (OORBDA, 1982). Meanwhile, the mean annual (1976–2015) rainfall amount for Osun drainage basin estimated from the records of the 24 weather stations is 1620 mm. The rainfall amount between 1976 and 2015 exhibits a non-significant decreasing trend in Osun drainage basin using Mann Kendall trend analysis (Fig. 3, Table 1).

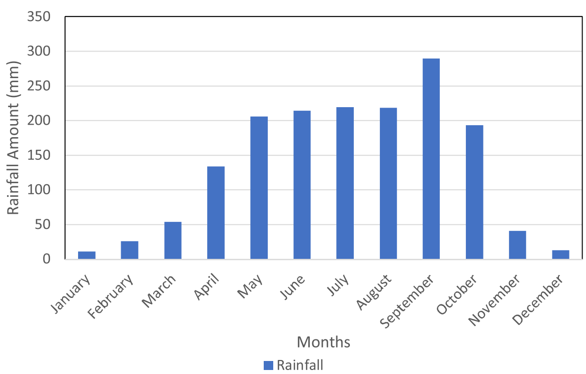

Fig. 2. Mean monthly rainfall amount in Osun drainage basin (1976–2015).

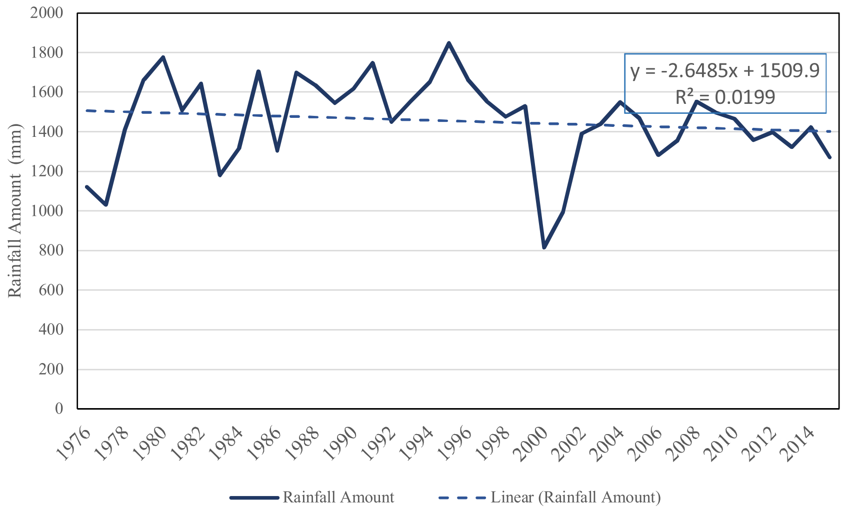

Fig. 3. Temporal trend in rainfall in Osun drainage basin (1976–2015).

Table 1
Trend in climatic variables in Osun drainage basin, Nigeria (1976–2015).

Methods	SN	Weather Variables	S	Z (normalized test statistic)	Q (Sen slope estimate)	Trend Significance	Nature of Trend
Man–Kendal	1	Rainfall Amount	−150.00	−1.74	−5.874	Not Significant	Negative
	2	PET	308.000	3.58	3.37	Significant	Positive
	3	Minimum Temperature	234.00	2.71	0.013	Significant	Positive
	4	Maximum Temperature	266.00	3.09	0.032	Significant	Positive
	5	Relative Humidity	−164.00	−1.90	−0.058	Not Significant	Negative
	6	Wind Speed	110.00	1.27	0.003	Not Significant	Positive

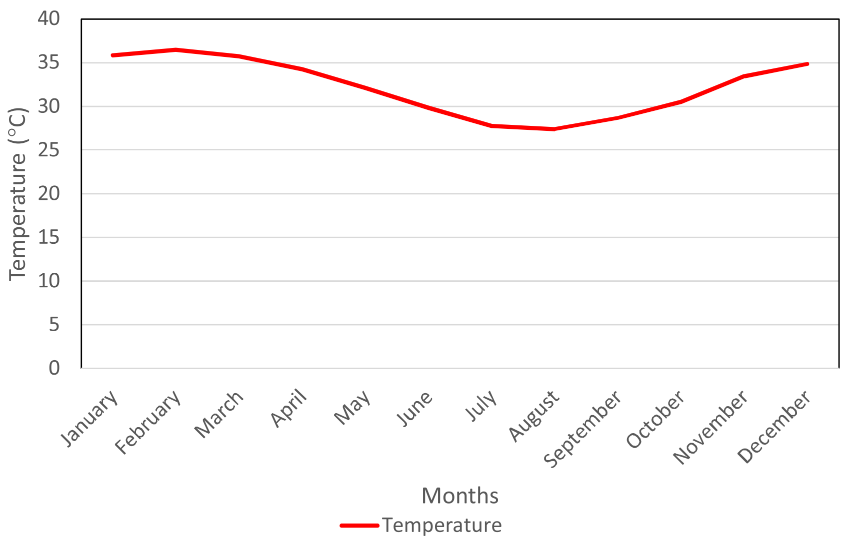

Fig. 4. Mean monthly temperature in Osun drainage basin (1976–2015).

The months of February and March are the hottest in the basin and temperatures are high over the entire basin during this period (Fig. 4). There is also variation in temperature from the south to the north, where it is higher. The lowest mean (1976–2015) minimum temperature in the north is usually in December during Harmattans, while it is usually recorded in July during the rainy season in the southern part of the basin (OORBDA, 1982). The mean annual (1976–2015) temperature is about 30 °C, which can vary depending on the location and time of the year (Ifabiyi, 2005). The temperature in the study area revealed a significant increasing trend over the period of 1976–2015 (Fig. 5, Table 1). In general, relative humidity decreases northwards in the basin. The mean annual humidity varies from 75 % in the south to 55 % in the north (OORBDA, 1982).

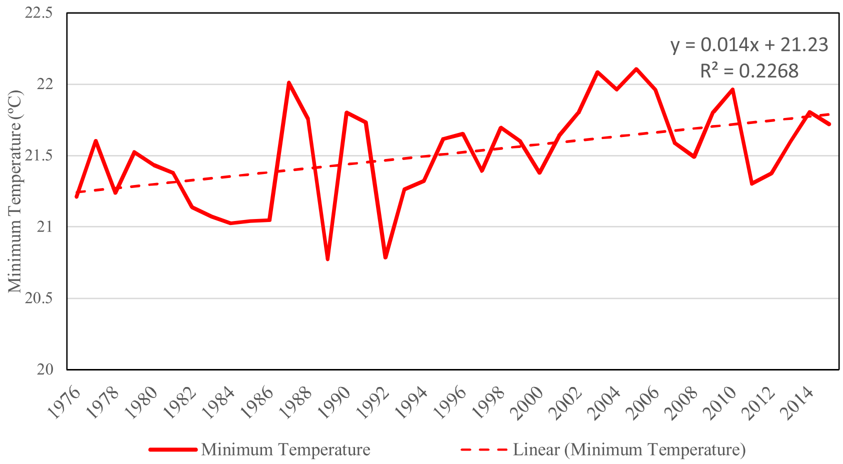

Fig. 5. Temperature trend in Osun drainage basin (1976–2015).

The basin is underlain by two types of rocks, which are the Basement Complex rocks (9259 km^2 or about 93 %) and the sedimentary deposits (668 km^2 or about 7 %) (Fig. 6) (OORBDA, 1982; Oke et al., 2013; Ashaolu, 2016b). The Basement Complex consists mainly of folded gneiss, schist and quartzite complexes, which belong to the older intrusive series with outcrops visible in many places (Oke et al., 2013). The age of the Basement Complex rocks of the study area belong to two eras: the Archean age (2500ma-2750 ± 25Ma) and the Early Proterozoic age (2000Ma–2500Ma) (Ajibade et al., 1987; Rahman, 1988). Sedimentary rocks of cretaceous and later deposits are found in the southern sections of the Osun basin (Oke et al., 2013). The soils belong to the highly ferruginous tropical red soils associated with Basement Complex rocks. Four soil types were identified in the basin on basis of their texture (Fig. 7). These are clay (29 %), sandy clay loam (51 %), sandy loam (16 %) and loamy sand soil (4 %) (Ashaolu, 2016b).

The population distribution pattern of the basin is quite uneven. The urban population in the basin is larger than the rural population. Besides, available records from different investigations and surveys confirmed a migration of population from the rural areas to the cities. Based on the 1963 population census of western Nigeria, the estimated population of the basin made by Ogun-Oshun River Basin Development Authority in 1980 was 4.2 Million and this was used as the basis of estimation for year 2015 at an annual rate of 3 % to be about 12 Million (Ashaolu, 2018).

3. Material and methods

3.1. Data

The data used in this study include climatic data such as rainfall amount (mm), number of rainy days, temperature (ºC), sunshine hour, relative humidity (%) and wind speed (m/s) collected from the Nigeria Meteorological Agency (NIMET). Also, Climate Forecast System Reanalysis (CFSR) data on precipitation, relative humidity, wind speed and solar by the National Centers for Environmental Prediction (NCEP) were downloaded from https://globalweather.tamu.edu/ website. The CFSR provides a high resolution global reanalysis (a best estimate of the observed state of the atmosphere) of past weather at a horizontal resolution of 0.5°. The available 24 weathers stations used in this study are those that fall within and close to the drainage basin (Fig. 1). The data on all the climatic variables spanned 40 years (1976–2015). The trend in the climatic variables determined by Mann-Kendall trend statistics is presented in Table 1. However, some of the stations like Abeokuta and the CFSR stations did not have data to cover the period 1976–2015. Therefore, the missing years records were filled with data from other stations. To achieve this, data from Abeokuta station (1981–2015) was correlated with data from other ground stations for the same period of 1981-2015. The station with the highest coefficient of correlation with Abeokuta was used to fill the period 1976–1980 that have no record in Abeokuta station. A similar approach was adopted for the period 1976–1978 and 2015 that has no record in the CFRS data. Table S1 shows the summary of the climatic stations with their respective locations and years of record. The potential evapotranspiration was estimated using FAO Penman-Monteith method (Allen et al., 1998). This method was selected because it is physically based, clearly incorporates both physiological and aerodynamic parameters as well as regarded as the most reliable predictor of PET rates under all climatic conditions (Jensen et al., 1990). The ETo calculator version 3.2 of FAO was used to compute PET in this study (Raes, 2012).

The classified land use/land cover maps of the study area for 2000 and 2015 by Ashaolu et al. (2019) were used in this study. The classification adopted seven land use/land cover classes: bare surfaces, built up area, crops/shrubs, forest, rock outcrops, water bodies and wetland. The classes fall under four main category of land use/land cover (vegetated cover, bares soil, open water and impervious surfaces) as used by WetSpass-M for runoff parameterization. Table 2 shows that in the Osun drainage area in 2000 crops/shrubs, bare surfaces and forest covered 42 %, 27 % and 21 %, respectively of the total basin. In 2015, these coverages changed to 32 %, 31 % and 22 % for respectively crops/shrubs, bare surface and forest, while built up area accounted for 10.7 % in 2015.

A soil map of the study area was extracted from the harmonized world soil database version 1.2 (2012) prepared by the Food and

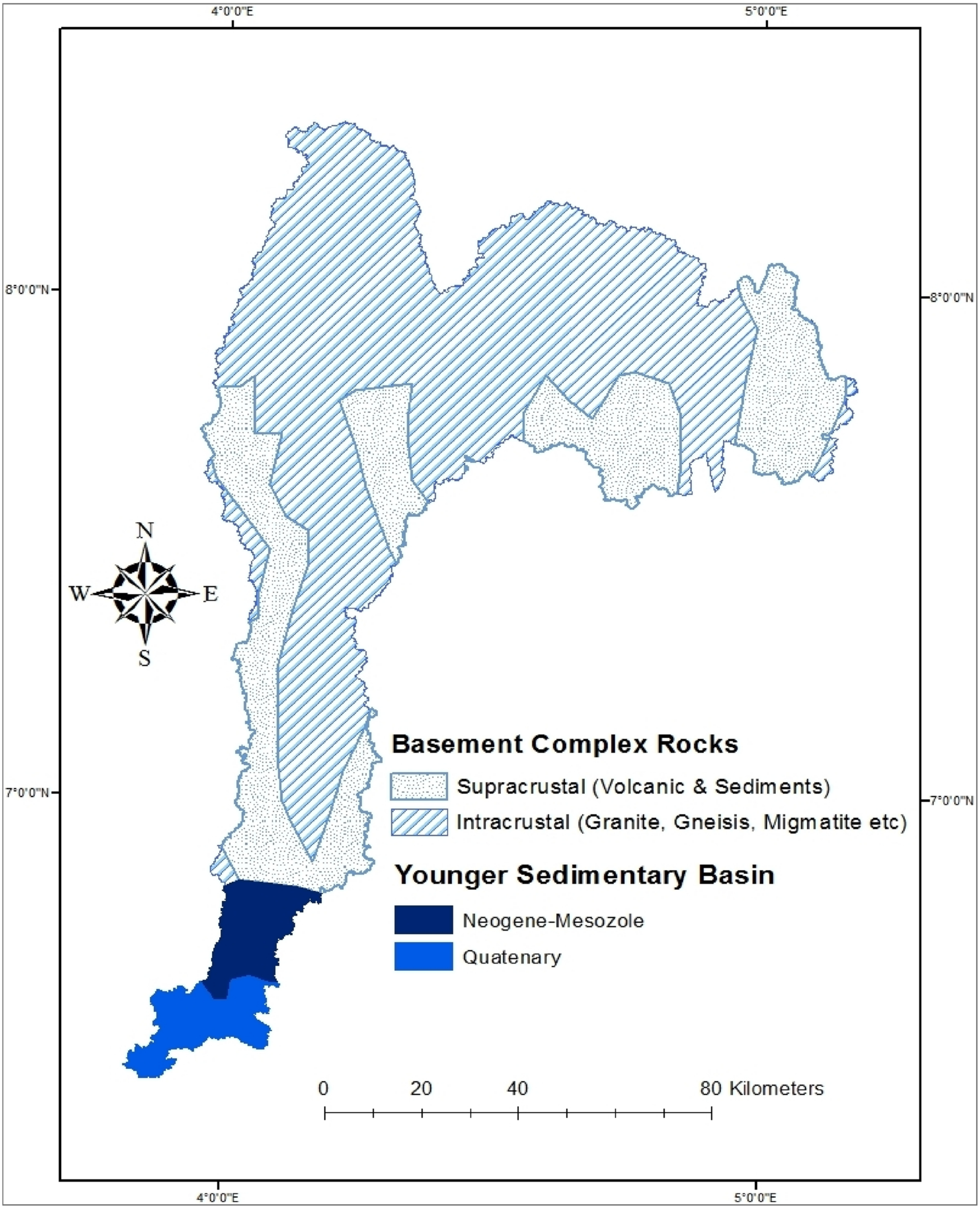

Fig. 6. Simplified geology of Osun drainage basin.

Agriculture Organization of the United Nations (FAO). Digital Elevation Model (DEM) with 30 m resolution of the study area was obtained from the Shuttle Radar Topography Mission (STRM) of the National Aeronautics and Space Administration (NASA). The slope and aspect maps of the study area were processed from the DEM using ArcGIS. Due to the dearth of data on the depth to groundwater in the study area, the mean depth to groundwater for the study area was adopted from the water level for the study area

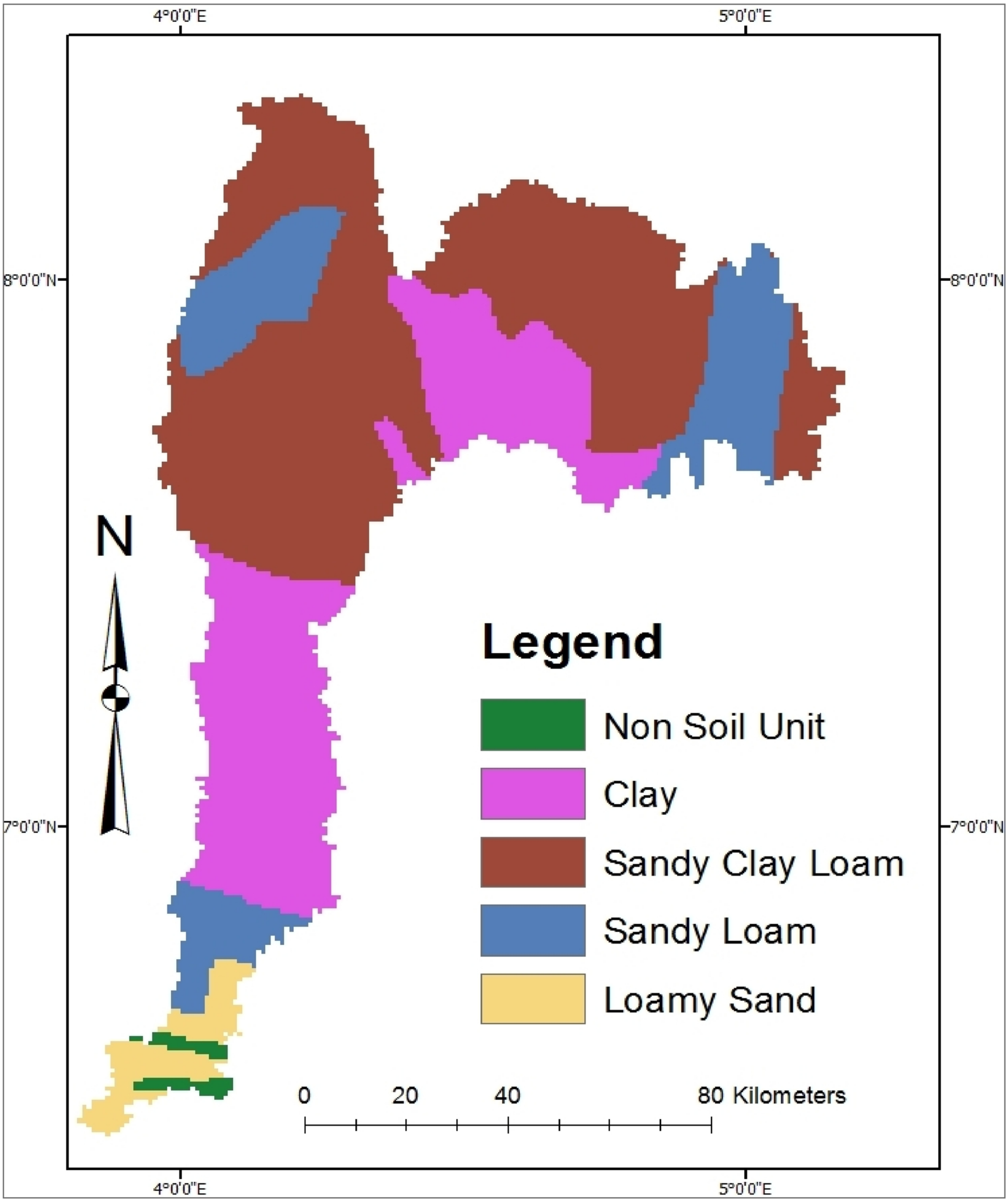

Fig. 7. The soil texture map of Osun drainage basin.

reported in the Federal Ministry of Water Resources (FMWR), 2014a,2014b national water resource master plan report of Nigeria. A 10 m depth to water was adopted for 93 % of the basin underlain by the Basement Complex rocks and 50 m for the remaining 7 % underlain by the sedimentary basin in the south. The available few records from borehole logs, show that depth to groundwater in the basin is more than 2 m. The adoption of a mean depth to groundwater does not influence the WetSpass-M simulation results if the depth to groundwater in an area of investigation is more than the root depth (Tilahun and Merkel, 2009; Tesfamicheal et al., 2013). Stream discharge data available at Apoje gauging station for the period 1980 until January 2000 were collected from Ogun-Oshun

Table 2
Land use/land cover classification of Osun drainage basin for 2000 and 2015.
Source: Ashaolu et al., 2019

Land Use/Land Cover Types		2000		2015	
		Area (Km^2)	%	Area (Km^2)	%
1	Bare Surfaces	2709.57	27.30	3087.31	31.10
2	Built Up Areas	459.18	4.63	1063.91	10.72
3	Crops/Shrubs	4163.35	41.94	3114.86	31.38
4	Forest	2059.21	20.75	2154.87	21.71
5	Rock Outcrops	342.35	3.45	420.09	4.23
6	Water Bodies	61.64	0.62	61.59	0.62
7	Wetland	130.93	1.32	23.59	0.24
	Total	9926.22	100.00	9926.22	100.00

River Basin Development Authority. The hydrograph separation method was used to separate the runoff data into surface runoff, interflow and baseflow using the semi logarithm method (Watson and Burnett, 1995; Ifabiyi, 2004). The baseflow computed is used as an approximation of long-term recharge in the study area, hence, it is likely to be less than the amount of water that actually recharges the aquifer in Osun drainage basin.

3.2. WetSpass/WetSpass-M water balance modelling

The WetSpass-M model is described in S1. The model requires two types of input data, GIS grid maps and parameters tables (Batelaan and De Smedt, 2001). The grid maps include slope, land use/land cover, soil texture, depth to groundwater and monthly climatic maps of rainfall amount, temperature, potential evapotranspiration and wind speed (Abdollahi et al., 2017). All the input maps were converted into ascii grid format. The monthly climatic parameters used in the model are available in all the 24 stations within and close to the basin. Mean monthly values of rainfall amount, temperature, potential evapotranspiration and wind speed for the period 1976–2015 were calculated from the available data in each station. The mean monthly spatial digital maps of the parameters were determined by spatial interpolation of the values obtained in the stations, using the universal Kriging interpolation module in ArcGIS 10.4. WetSpass-M uses the USGS soil texture classes. Therefore, the percentages of coarse, medium and fine particle size fractions in the top soil was used to extract the soil texture map of the study area from Harmonised World Soil Database (HWSD). The types of soil based on the texture are clay, sandy clay loam, sandy loam and loamy sand (Fig. 7).

Land use, number of rainy days and soil characteristic was specified as parameters tables in the model (Batelaan and De Smedt, 2001; Tesfamichael et al., 2013; Abdollahi et al., 2017). These tables were connected to the maps as attribute tables. The land use attribute table include parameters related to land use type; such as rooting depth, leaf area index, vegetation height, Manning coefficient among many others. The soil parameter table contains soil parameters for each textural soil class such as field capacity, wilting point, permeability etc. The runoff attribute is considered to be universal, because a certain combination of slope, land use, and soil type will produce a certain fraction of runoff independent of location (Tesfamichael et al., 2013). For the sake of matrix calculation, all input maps into WetSpass-M must have uniform grid cell size, i.e. the same spatial resolution. However, the data used in this study have different spatial resolutions, which necessitated the need for resampling. Therefore, all the secondary data (LULC, soil map and DEM) and the generated weather maps were resampled into 15 m resolution. The nearest neighbor resampling method was adopted to resample the year 2000 and 2015 land use/land cover maps; and soil map because they are discrete data with distinct boundaries, while bilinear technique was adopted in resampling the DEM because of its continuous nature.

The land use/land cover maps of the year 2000 (Fig. 8) and 2015 (Fig. 9) were selected as the LULC data input. The simulation was first run using the LULC map of the year 2000, the mean monthly record of climatic variables for the period 1980–1999 was used as the weather input, as well as the soil and DEM of the study area for the first simulation. The output of this simulation (runoff and recharge) were used in the calibration and validation of the model, because runoff data in the study area spanned between 1980–1999 and was not available beyond January 2000. The model was calibrated manually using the following parameters: soil moisture alfa coefficient (α), LPa calibration parameter (–) which reduces the potential evapotranspiration depending on the soil moisture (default is 0.65), interception parameter (a), and runoff delay factor (x) which were optimized according to the goodness of fit between the simulated runoff and the runoff from observed discharge at Apoje station. The calibration started with the soil moisture alfa coefficient (Abdollahi et al., 2017). The coefficient of determination (R^2) and the Nash-Sutcliffe model efficiency (NSE) were used for validation using the simulated and observed mean monthly discharge data of 1980–1999 at Apoje gauge station. The Nash-Sutcliffe model efficiency is defined as:

$$E = 1 - \frac{\sum_{t=1}^{T} (Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T} (Q_o^t - \overline{Q_o})^2} \tag{1}$$

Where E is the Nash-Sutcliffe efficiency coefficient, $\overline{Q_o}$ is the mean of observed discharge, $Q_m$is modeled discharge, and Q_o^t is the observed discharge at time t. The result can range -∞ to 1, the closer the model efficiency is to 1, the more accurate the predicted model result.

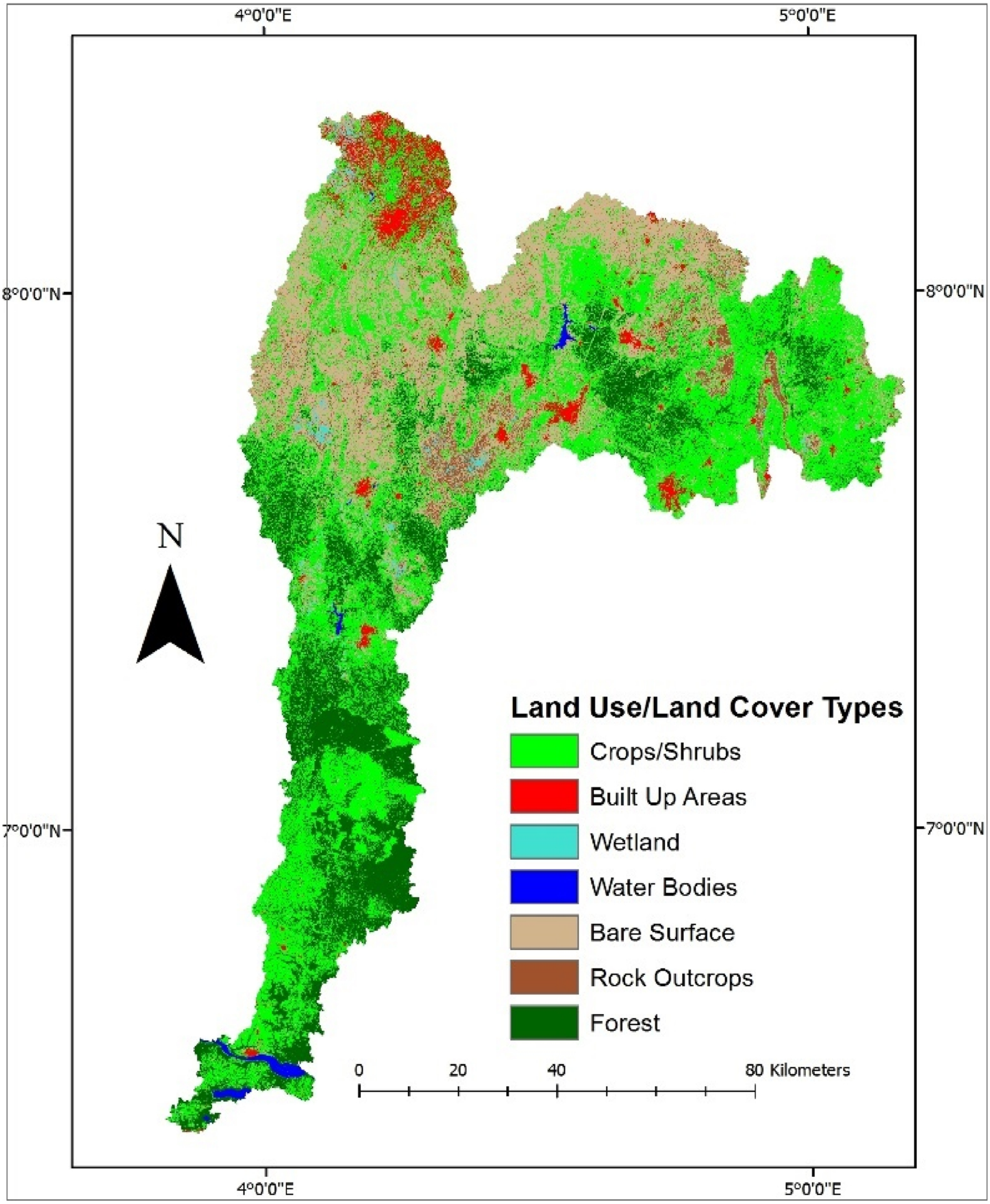

Fig. 8. The year 2000 LULC map of Osun drainage basin.

In addition, the hydrograph separation method was employed to estimate groundwater recharge using the runoff data from the Apoje gauge station.

After the validation of the model for the study area, the LULC of the year 2015 was adopted for simulating the mean monthly water budget for the period 1976–2015. A 10 m and 50 m mean depth to groundwater for the Basement Complex rocks and Sedimentary basin, respectively was prepared with an output cell size of 15 m, while the processing extent was also set to

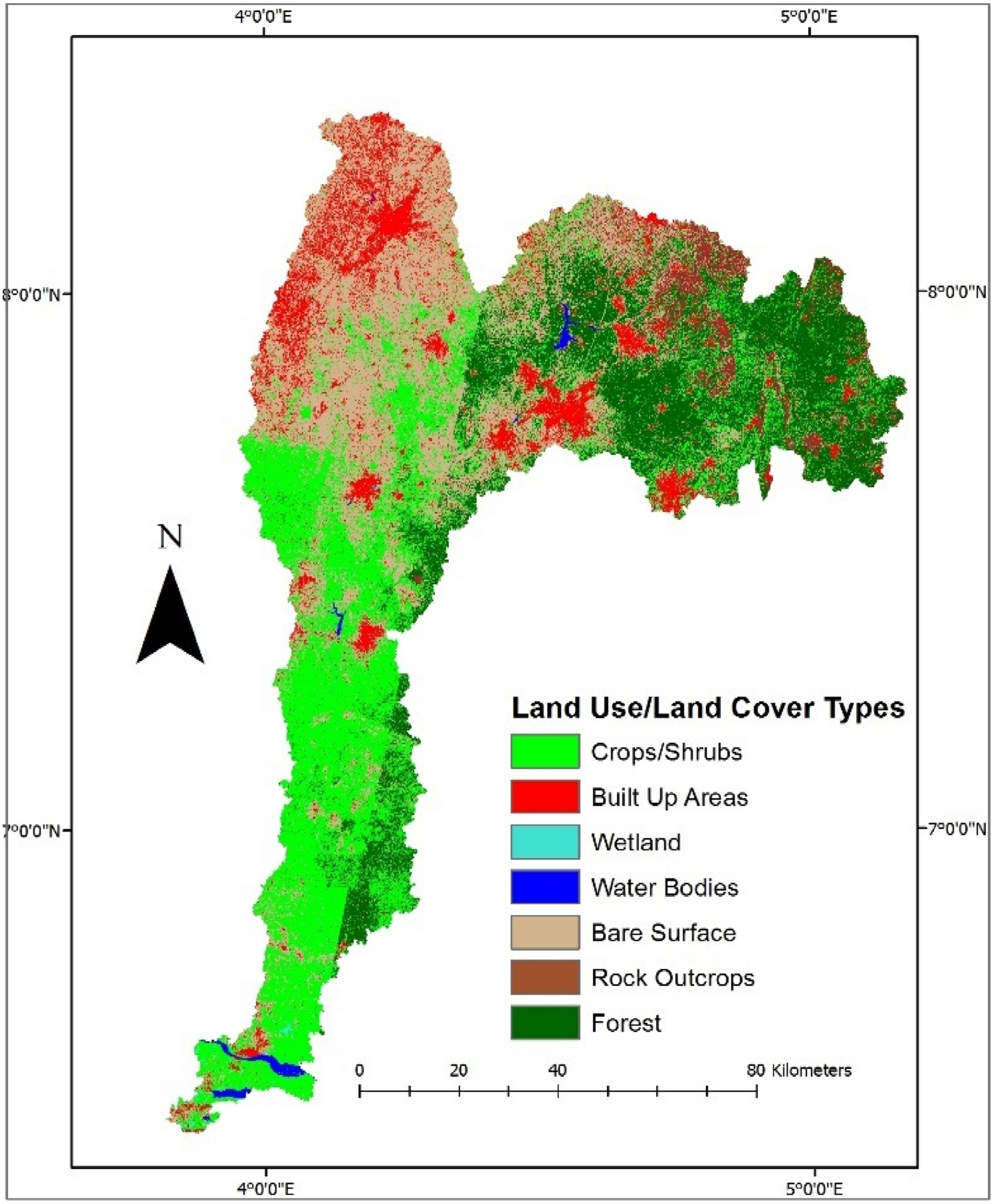

Fig. 9. The year 2015 LULC map of Osun drainage basin.

9977 × 14043 to have the same column and row; and pixel size as the other variables. The DEM of the study area was used to produce the slope map in ArcGIS.

The prepared input data were inputted into the model to begin the simulation of the mean monthly water budget of Osun drainage basin for the period 1976 - 2015. The outputs include several mean monthly spatio-temporal hydrologic outputs, but the mean interception, actual evapotranspiration, runoff and recharge are the main concern of this study.

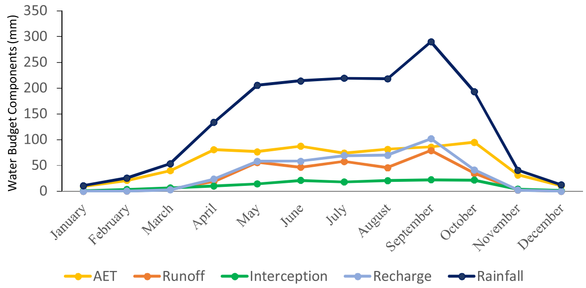

Fig. 10. Mean monthly water balance for Osun drainage basin (1976–2015).

4. Results

4.1. Water budget components in Osun drainage basin

The mean monthly water budget and the ratio of rainfall amount to each of the water balance components are presented in Figs. 10 and 11, respectively. The results of each components of the water balance are presented in section 4.1.1 - 4.4.4.

4.1.1. Interception rate

The monthly mean interception in Osun drainage basin for the period 1976–2015 ranges from 1 mm in January to 23 mm in September, while the mean annual interception is 146 mm. This accounted for 9 % of the mean annual rainfall amount (1620 mm) from 1976 to 2015 (Table 3). The spatial distribution of the mean monthly interception in the Osun drainage basin showed that high interception rates (3 − 47 mm) are found in the forested areas in Awaiye, Apomu, Alagutan, Apoje, Ijebu Ife, Akata and Epe, etc. in the middle of the basin down to the southern part. Low interception rate (0 − 3 mm) is found in Alawere, Ikoyi, Ogbomosho, Aba Epo, Arowomole, Tafun, Iyalode and other places in the northwest zone of the basin (Fig. 12).

4.1.2. Surface runoff

The estimated mean monthly surface runoff ranges from 0 mm to 79 mm, with a mean annual value of 348 mm/year. The highest mean rainfall amount occurred in September, resulting in 27 % becoming surface runoff. The lowest surface runoff (0 mm) occurred in December, January and February and they coincide with the months that have the lowest mean monthly rainfall amount (Table 3). The mean monthly spatial pattern of surface runoff in the basin show that the highest surface runoff (209 − 430 mm) is observed in Apomu, Alaguntan, Apoje, Iganmeji and Akata, etc. located in the central part towards the southern part of the basin for most of the months. Also, high surface runoff was found in some months in the built-up areas such as Osogbo, Ilesha, Ede, etc. and on rock outcrops, especially in the northeastern zone (Fig. 12). The simulated result of runoff was compared to the observed stream discharge in Apoje gauge station located in the southern part of the study area in order to validate the results of the model (Fig. 13). The comparison suggests that WetSpass-M estimated lower and higher run-offs in dry and wet months, respectively. The mean annual surface runoff for different combinations of LULC and soil classes show that the largest surface runoff (1925 mm) occurred on clay soils with water body LULC, while the lowest value (104 mm) is on loamy sand soil in forest area (Table 4). The higher standard deviation values of the surface runoff for different LULC types indicate that surface runoff is less influenced by LULC type compared to the soil types in the study area.

4.1.3. Actual evapotranspiration

The mean monthly AET in the basin ranges from 10 mm in January to 85 mm in October (Table 3). The annual mean AET in the

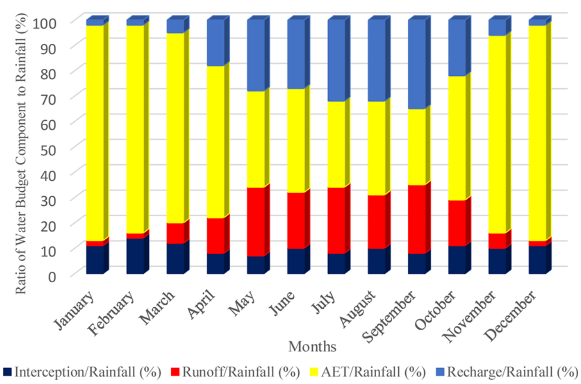

Fig. 11. Ratio of rainfall to water budget components in Osun drainage basin (1976–2015).

Table 3
Mean monthly water budget and ratio of rainfall amount to water budget components, 1976–2015.

	Months	Rainfall (mm)	Interception (mm)	Runoff (mm)	AET (mm)	Recharge (mm)	Interception/ Rainfall (%)	Runoff/ Rainfall (%)	AET/ Rainfall (%)	Recharge/ Rainfall (%)
1	January	11	1	0	10	0	11	0	86	0
2	February	26	4	0	21	1	14	0	82	2
3	March	54	7	4	40	3	12	8	75	5
4	April	134	10	19	81	24	8	14	61	18
5	May	206	16	56	77	58	7	27	37	28
6	June	214	21	47	88	59	10	22	41	27
7	July	219	18	58	74	69	8	26	34	32
8	August	218	21	46	82	70	10	21	37	32
9	September	290	23	79	86	102	8	27	30	35
10	October	193	22	35	95	42	11	18	49	22
11	November	41	4	3	32	2	10	6	78	6
12	December	13	1	0	11	0	11	0	86	0
Mean Annual		1620	146	348	696	430	9	21	43	27

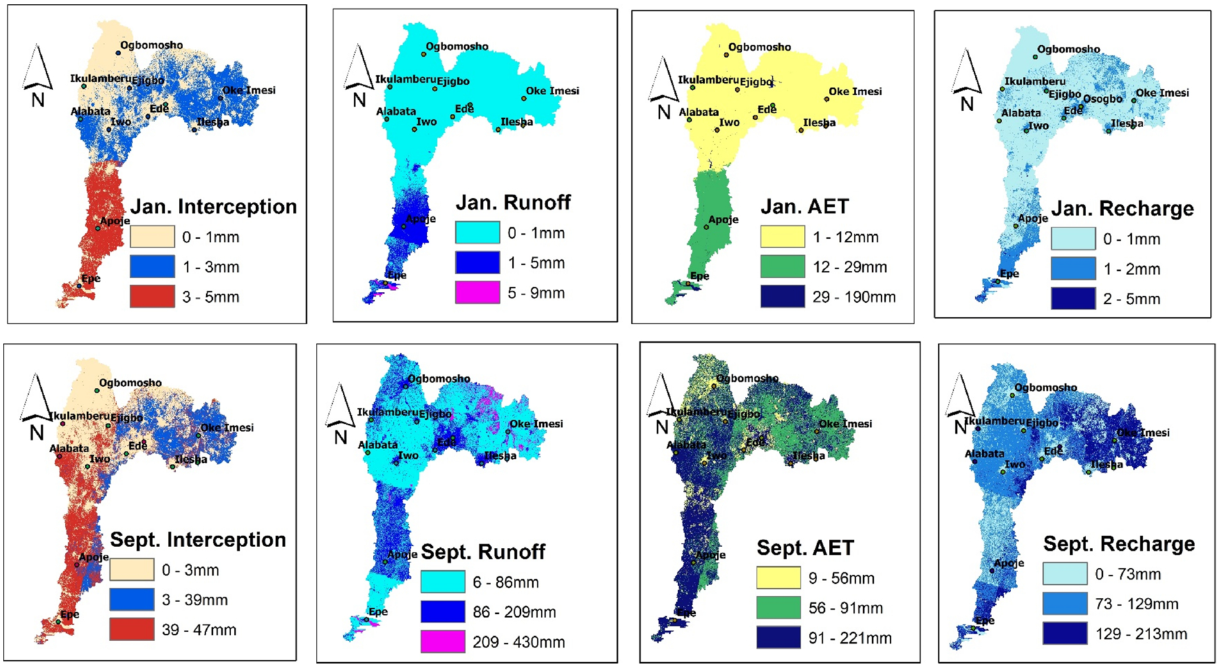

Fig. 12. Spatial pattern of mean monthly water budget in Osun drainage basin.

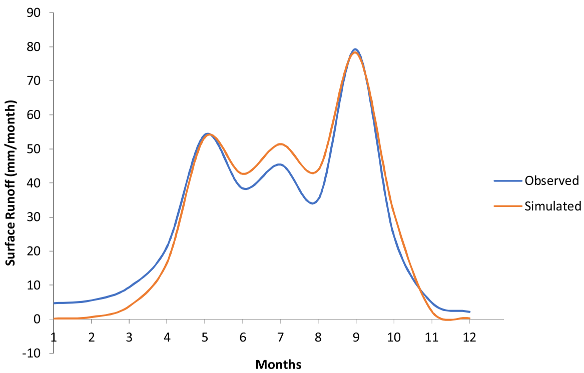

Fig. 13. Observed surface runoff versus simulated surface runoff for the Osun drainage basin for 199.

Table 4
Mean annual runoff (mm/yr) for different combinations of LULC and soil texture.

	Clay	Loamy Sand	Sandy Clay Loam	Sandy Loam	Mean	Standard Deviation
Bare Surface	486	146	184	161	244	162
Built Up	992	608	864	585	762	199
Forest Area	308	104	137	141	172	92
Rock Outcrops	1284	1564	1228	1299	1344	150
Crops/Shrubs	438	190	187	239	263	119
Waterbody	1925	1109	1361	–	1465	418
Wetland	583	471	424	552	507	73
Mean	859	599	626	496		
Standard Deviation	582	552	521	438		

basin is 696 mm/year. AET is the largest component of the water budget in Osun basin, constituting 43 % of the annual rainfall amount. The percentage of AET to rainfall in the basin is highest for the months of January (86 %) and December (86 %), which are the months with lowest amount of rainfall. The spatial distribution of mean monthly AET in the Osun basin showed that open water bodies have high evapotranspiration rate especially during the dry months (November - March). For example, the AET rate from the open water in January is between 29 − 190 mm. The majority part of the basin experience high AET in wet months, where majority of the basin in September recorded AET that ranges between 91 − 221 mm.

4.1.4. Groundwater recharge

The estimated monthly distribution of groundwater recharge in Osun drainage basin is presented in Table 3. The mean monthly groundwater recharge varies from 0 mm in January to 102 mm in September. The highest mean rainfall amount occurred in September, of which 35 % recharges the groundwater system, while 2 % of rainfall in January becomes groundwater recharge (Table 3). The estimated mean annual recharge in the basin was 430 mm. This is 27 % of the mean annual rainfall recorded in the basin for the period of study. The results of the estimated recharge from baseflow separation and the WetSpass-M simulated recharge is presented in Table 5. The correlation coefficient of the mean monthly recharge estimated from baseflow separation method and predicted by WetSpass-M is 0.97, which suggests a good agreement between the recharge estimation from the baseflow separation method and the WetSpass-M model.

The mean monthly spatial distribution patterns of groundwater recharge in Osun drainage basin is presented in Fig. 12. Akata, Epe, Eluju, Iberekodo located in the southern part of the basin have high recharge (2 − 5 mm) in January. This pattern is peculiar to all the five dry months (November-March) in the study area. Arowomole, Oko, Ejigbo, Ifon, etc. found in the northern part of the basin have lower groundwater recharge for the same dry months. Meanwhile, high recharge (129 − 213 mm) is observed in September in the northeastern part in Oke Imesi, Efon Alaye, etc. as well as in some southern parts of the basin in Epe and Ibeju Lekki. All the wet months in the study area have similar recharge pattern to the month of September.

Table 6 shows the mean monthly groundwater recharge for different combinations of LULC and soil classes for September, which is the month with highest groundwater recharge. The highest recharge occurs on loamy sand soil with forest (181 mm), bare surface (152 mm), crops/shrubs (133 mm) LULC, while the lowest values are on clay soil in built up (6 mm) and wetland (32 mm) areas. The higher standard deviation values of the recharge for different LULC types (Table 6) indicate that recharge is less influenced by LULC type than by soil types.

5. Discussion

Groundwater recharge is one of the components of the hydrological cycle, and this study conceptualized it as the residual of the

Table 5
Comparison of the mean monthly recharge (mm) estimated from baseflow separation and simulated by WetSpass-M.

		Estimated Recharge from Baseflow Separation (mm)	WetSpass simulated Recharge (mm)
1	January	2	0
2	February	2	1
3	March	5	2
4	April	12	24
5	May	49	58
6	June	32	59
7	July	57	69
8	August	48	70
9	September	96	102
10	October	28	42
11	November	4	2
12	December	1	0
Mean Annual		337	430

Table 6
Mean recharge (mm) for different combinations of LULC and soil texture for September.

	Clay	Loamy Sand	Sandy Clay Loam	Sandy Loam	Mean	Std. dev
Bare Surface	118	152	115	112	124	18
Built Up	6	47	51	46	38	21
Forest Area	122	181	158	164	156	25
Rock Outcrops	–	–	–	–	–	–
Crops/Shrubs	73	133	100	116	105	26
Wetland	32	62	43	52	47	13
Mean	70	115	93	98		
Std. dev	51	58	47	49		

hydrological cycle. In other words, it was conceptualized as the residual water that enters the groundwater system, after inflow from rainfall and outflow through surface runoff/stream discharge and actual evapotranspiration was estimated. The direct measurement of these various components of the hydrological cycle is usually difficult because of the complex nature of the environmental system. Therefore, it often requires the modelling of similar, but simpler structures to improve its understanding. The groundwater recharge in Osun drainage basin varies over space and time because of the various environmental factors such as climate, slope, soil type, LULC etc. controlling the amount of direct recharge.

The estimation of groundwater recharge with the adoption of a spatially distributed water balance model has provided a new hydrological insight for the Osun drainage basin, in the Basement Complex rocks of Nigeria. This new insight, particularly on groundwater recharge will assist the stakeholders and Government agencies in the area to develop and use the groundwater of this region in a way that is more sustainable, without resulting to unacceptable environmental, economic or social consequences (Ashaolu, 2018; Alley et al., 1999). It is usually better to understand and discuss the various components of the water balance of the region, because of their interconnectivity. Hence, besides groundwater recharge, which is the focus of this research, the other three important components (interception, AET & surface runoff) of the water balance were discussed as well.

The average monthly water balance viz: interception, surface runoff, AET and groundwater recharge for the period 1974–2015 revealed that most of the water balance components follow the temporal pattern of rainfall amount in the basin (Fig. 10). This implies that rainfall variability and the number of dry and wet episodes in the basin determines the rate and pattern of the water balance components, especially the groundwater resources that depends mainly on rainfall in this type of environment. For example, the month of September that has the highest mean monthly rainfall amount (290 mm) also has the highest recharge (102 mm) and runoff (79 mm). This is in agreement with an earlier study in Lake Chad, where most of the mean seasonal water budget components follow the change in seasonal rainfall amounts (Babama'aji, 2013). The observed mean monthly hydrological feedbacks in Osun drainage basin shows that most of the rainfall is lost to evapotranspiration (43 %), especially in the dry months of November to March (Fig. 11).

Despite the huge percentage (43 %) of rainfall amount being lost to AET, more water is able to infiltrate into the soil and percolate to recharge the groundwater system in the wet months, particularly in September, which coincides with the month of highest rainfall in the basin. As expected, there is more surface runoff in the wet months compared to the dry months. The percentage of runoff from rainfall, however varies from month to month depending on the rainfall amount, rainfall intensity and the antecedent soil moisture. Interception is the least (9 %) important component of the hydrological budget in Osun drainage basin.

The small percentage in the mean annual interception can be attributed to the fact that the original rainforest of the basin has been lost over time. In fact, forest area coverage as of 2015, was only 22 % of the total basin area. Interception is the first component of the hydrological budget that respond to rainfall in an environment (Muzylo et al., 2009), and it is a function in WetSpass-M of rainfall amount and intensity, wind speed and Leaf Area Index (LAI) (Babama'aji, 2013). Interception rate is shown to be high in the wet months compared to the dry months. Thus, the rainfall-interception ratio indicated that the interception percentage depends largely on the amount of rainfall received in any particular month.

The result is similar to the earlier observation by Babama'aji (2013) that the Lake Chad basin exhibited higher interception in the mixed forest area found in the southern part of the basin than in the open vegetation found in the west-central part. The study by van Dijk et al. (2011), also revealed that interception was higher in areas of tall forests compared to those of lower vegetation such as grassland or agricultural crops. The northwest zone of the basin is characterized by lower vegetation such as grassland or agricultural crops, which is responsible for the lower interception rate observed. The zone also received lower rainfall amount compared to other parts of the basin. Le Maitre et al. (1999) reported that vegetation cover alters rate of recharge by directly disturbing the passage of rainfall from the atmosphere to the land surface and to the water table by deflecting part of the rainfall. However, the section of the basin with lower vegetation are also areas of lower recharge and rainfall. Meanwhile, the southern part of the basin with high vegetation also recorded high rainfall amount and high recharge rate. Therefore, the intensity and duration of rainfall, windspeed can be said to be responsible for this pattern.

The high surface runoff in September can be attributed to the antecedent soil moisture of the preceding months. This might not be unconnected to the fact that soil has become completely saturated with rainfall of the previous months, thereby making infiltration low or nonexistent. The low runoff in the dry months particularly January (0 mm) is because soil matrix is expectedly dry during this period, hence, the little rainfall received was quickly absorbed, thereby resulting in little or no surface runoff. It was discovered that about 22 % of total annual rainfall amount became surface runoff in the basin during the period under investigation. This result is higher than what was found in the semi-arid, arid and temperate environment in earlier studies (Tesfamicheal et al., 2013; Teklebirhan et al., 2012; Al Kuisi and El-Naqa, 2013; Dams et al., 2007). For example, in the arid Jafr basin, Jordan, Al Kuisi and El-Naqa (2013) observed that as low as 5 % of the total annual rainfall became surface runoff. The differences in the results obtained in arid environment compared to the tropical environment where Osun drainage basin is located is attributed to the extreme dryness of the arid zone.

The highest surface runoff in the central part and towards the southern part of the basin is expected as surface runoff is usually high in areas towards and close to the mouth of a drainage basin. High surface runoff of the built up areas like Osogbo, Ilesha and on rock outcrops in the northeastern zone indicated that interaction between rainfall and surface runoff varies from place to place within the basin. The high runoff observed around Alaguntan, Apoje and other areas in the central part toward the southern part of the basin can be associated with the presence of clay soil, which has low permeability. The low permeability of clay soil enhanced surface runoff in this part of the basin. Similar results, observed by Babama'aji (2013) in the Lake Chad basin, was also attributed to the low permeability nature of clay soil. Al Kuisi and El-Naqa (2013) also attributed the high surface runoff in Jafr basin, Jordan to silt clay soil, which have low permeability.

In most of the northern and the northwestern part of the basin, there is less surface runoff, especially during the dry months (Fig. 12). The pattern observed is also associated with the high composition of sandy clay loam and sandy loam soils found in this part of the basin. This may be connected to the fact that infiltration rate on these soils hinder high surface runoff. It is important to point out that regardless of the LULC types, areas with clay soil, sandy clay loam tend to generate high amount of surface runoff, while places with loamy sand and sandy loam soils generate lower surface runoff. The results of the different combinations of LULC and soil classes revealed that surface runoff pattern in the basin, is highly controlled by the effect of soil types, rather than the effect of land use/land cover type or slope. High surface runoff has been attributed to soil texture, rather than land use/land cover types in some earlier studies (Teklebirhan et al., 2012; Tesfamicheal et al., 2013; Babama'aji, 2013; Al Kuisi and El-Naqa, 2013).

The comparison of the simulated surface runoff and observed stream discharge suggests that WetSpass-M estimated lower and higher run-offs in dry and wet months, respectively. This may be as a result of the same LULC used for all the months, without given consideration to the variation in land cover from one month to another. Especially, when we know that grasses and low vegetation often influence the rate of runoff between wet and dry months. The Pearson Moment correlation coefficient of 0.98 exists between the observed and simulated surface runoff, while the Nash-Sutcliffe coefficient is 0.89. The results of these two coefficients showed good agreements, which indicate that the WetSpass-M model is an efficient tool that can be used to predict surface runoff in the Osun drainage basin.

The results of AET in Osun basin are in agreement with previous studies (Tesfamicheal et al., 2013; Al Kuisi and El-Naqa, 2013; Teklebirhan et al., 2012) elsewhere that suggested that evapotranspiration is the major process by which water loss from a drainage basin occurred. However, this can further be related to the climate, especially rainfall amount, temperature; and vegetation of such basin. These studies revealed that basins in the arid and semi-arid region loose higher percentage of rainfall amount received to evapotranspiration compared to basins in the tropics. For example, Tesfamicheal et al. (2013) found that 76 % of precipitation was lost to evapotranspiration annually in Geba, basin, Ethiopia, while it is as high as 81 % in Illala catchment, Ethiopia (Teklebirhan et al., 2012). A very large percentage of 95 % of the annual rainfall is lost to evapotranspiration in both the Jaffr basin, Jordan (Al Kuisi and El-Naqa, 2013) and the Lake Chad basin (Babama'aji, 2013).

The percentage of AET to rainfall in the basin is highest for the months of January and December, which are the months with lowest amount of rainfall. The sparse rainfall and few number of rainy days in these two months, as well as high evaporative power of the atmosphere in these dry months is responsible for this observation. However, in terms of absolute AET, the highest (95 mm) AET occurs in October, while lowest (10 mm) is in January. The observed pattern of high AET on water bodies can be attributed to the fact that evaporation mostly takes place on open water surfaces of streams and lakes in dry months, because there is little rainfall during this time of the year. Generally, larger percentage of evaporation takes place on open water surfaces compared to other land classes even during the wet period. This result is consistent with the findings of Babama'aji (2013) in Lake Chad basin and Pan et al. (2011) in Guishui River Basin, China. In general, Ikoyi, Aba Epo, Ejigbo, Oko, Inisha, Okuku, Igbajo, Ijero, etc, located in the northern part of the Osun drainage basin have low evapotranspiration due to the low rainfall amount and the relatively low percentage area covered with forest. The southern part of the basin on the other hand, found in areas such as Alaguntan, Ijebu Ife, Apoje, Kure, Apomu and others have high evapotranspiration as a result of high rainfall amount and large areas with tall trees.

The Wetspass-M model predicted higher groundwater recharge in the wet months of April to October, while more recharge was estimated by the hydrograph baseflow separation method in the dry months of November to March compared to the WetSpass-M prediction. The estimated mean annual groundwater recharge was 337 mm from the hydrography separation method and 430 mm from the WetSpass-M model. The difference in the mean annual recharge from the two methods is partly caused by the fact that the discharge data used in baseflow separation covered a period of 20 years (1980–1999), while the climatic parameters used in WetSpass-M model covered a period of 40 years (1976–2015). Another reason might also be because baseflow discharge is not always directly equated to recharge for reasons such as pumpage, evapotranspiration, and underflow to deep aquifers which may also be significant in some cases (Scanlon et al., 2002).

As stated earlier that some previous studies (FMWR, 2014a; Oke et al., 2015) on groundwater recharge in southwestern Nigeria lumped "Ogun" and "Osun" drainage basins together as a unit of investigation and reported mean annual recharge for the two basins as one. Thus, the result of WetSpass-M model for Osun is compared with the result of "Ogun-Osun" basin of these earlier studies. The result of WetSpass-M is higher than the values given by Oke et al. (2015) that adopted three empirical methods, and FMWR (2014a) that an employed rainfall-runoff model for the lumped Ogun-Osun River basin. The mean annual groundwater recharge estimated by the three methods by Oke et al. (2015) range from 232 mm to 205 mm, or about 16–18% of mean annual rainfall amount, while

FMWR (2014a) recharge estimate was 236 mm/year. The reasons for the differences might be due to the scale of the study area, because the recharge values by the two studies were for both Ogun and Osun drainage basins. The other reason might be due to definitions. The generated recharge map by WetSpass-M is the spatial distributed map of potential recharge, which is similar to infiltration.

The percentage of rainfall that recharges the aquifer in the Osun drainage basin is higher than what was reported in studies in dry environment (Adelana et al., 2006; Teklebirhan et al., 2012; Tesfamicheal et al., 2013; Al Kuisi and El-Naqa, 2013; Babama'aji, 2013) and relatively lower to what was reported in temperate environment (Dams et al., 2008). Most recharge occurred between April and October, which coincides with the rainy season in the study area. This indicated the relevance of rainfall to groundwater recharge in the Basement Complex aquifer. The months with the highest rainfall amount are those with higher recharge to the groundwater system.

The high recharge estimated for Akata, Epe, Eluju, Iberekodo located in the southern part of the basin have high recharge in the five dry months of November to March, might be due to the fact that the southern part of the basin receives early rainfall. Also, Arowomole, Oko, Ejigbo, Ifon, etc. found in the northern part of the basin have lower groundwater recharge for the same dry months, this is as a consequences of late rainfall onset and early cessation in the northern part of the basin. This explains why there are drying up of shallow wells in the dry months when there is little or no rainfall in the basin, especially in the northern part. During the dry period, private owned shallow wells and some public hand pump wells usually fail, oftentimes, their operators keep them under lock after the first trip of water fetching in the morning. This is usually done in order for the aquifer to recover a reasonable yield for households to fetch later in the evenings. In the same vein, the recharge to groundwater system is easily noticeable in shallow wells after individual rainfall event in wet months. During these months, wells and hand pump wells are hardly seen under locks because the groundwater level is usually high.

The high recharge to aquifer in Oke Imesi, Efon Alaye etc. in the northeastern part and Epe, Ibeju Lekki among many other areas in the southern parts of the basin during wet months can be attributed to the presence of permeable soils of the sandy loam and loam sand type found in high proportion in these areas coupled with the LULC types in such areas. Most of the built-up area have a reasonable monthly mean recharge rate of between 68–87 mm/month during the wet months. This may be due to the nature of the built-up area, where the ratio of bare lands is high compared to impervious structures such as building, roads and paved surfaces in the basin. This result is at variant with what De Smedt and Batelaan (2003) reported in Belgium, where relatively low recharge was observed in built-up area. The reasons for the relatively low recharge in their study can be associated with high level of paved surfaces in built-up areas in their study area compared to the relatively low level of pavement obtainable in developing countries like Nigeria.

In spite of this general recharge pattern observed, local variation in recharge rate among settlements occur from one month to another. For example, in April, while recharge ranges between 0 − 21 mm in Ogbomosho and Ikulamberu in the northwestern part, it is 21–36 mm in Osogbo and Ilesha in the northeastern part of the basin. Both Osogbo and Ilesha received higher rainfall than Ogbomosho and Ikulamberu in the northwest. In addition, the number of rainy days in each of these settlements are also different and could be responsible for such variation. In fact, most areas like Ogbomosho, Ikulamberu, Osogbo, IbokunImesi Ile, Ara Moko and Igede that have low recharge are located in the northern part of the basin. The low recharge in the northern part corroborates the study on groundwater potential and yield by Akinwumiju (2015) in those settlements that fall within Osun and Ekiti States in the basin. Thus, the recharge to the groundwater system in any area determines to a large extent the groundwater reserve and potential of such location, especially on the Basement complex terrain.

Meanwhile, high recharge rate was found in the north-eastern part of the basin, especially in the settlements and areas located on the uplands, of Oke Imesi, Efon Alaye, Igbajo, Iwaraja, Ijebujesa and Ijeda. The recharge rates in the month of September in these locations ranged between 129 − 213 mm. High recharge rates in this part are attributed in part to high rainfall amount received due to orographic effect of the uplands. The recharge rate to groundwater system therefore determines the groundwater potential and yield of the aquifers, especially in a Basement Complex where we have shallow aquifers. This may be the reason why Akinwumiju (2015) ranked these places in the northeastern part of the basin as areas with high groundwater potential and groundwater yield in the basin. Although, it can be argued that the aquifer type determines groundwater potential, but the argument is more favourable in sedimentary basins with a long-term storage capability, rather than in the Basement Complex aquifer that relies on present day recharge. The Basement complex aquifer relying on the present-day recharge becomes more visible in the dry months with little or no rainfall, when some shallow wells completely dry up. The shallowness of this type of aquifer makes its storage capability respond to the vagaries of the climatic conditions more sharply.

In addition, the mean monthly groundwater recharge for different combinations of LULC and soil classes for September, in the basin revealed that the largest amount of recharge occurs on loamy sand soils with forest, bare surface, crops/shrubs LULC, while the lowest values are on clay soil in built up and wetland areas. The higher standard deviation values of the recharge for different LULC types (Table 4) indicate that recharge is more influenced by LULC type than by soil types. This is at variant with the results of Babama'aji (2013) who reported that recharge in the Lake Chad basin was dependent on the soil type.

6. Conclusion

A spatially distributed monthly water balance model was applied to evaluate the water balance of Osun drainage basin, Nigeria with emphasis on groundwater recharge. About 93 % of this basin is underlain by the Basement Complex aquifer, which makes the groundwater occurrence in most parts of the basin to be shallow. Most of the inhabitants of this basin depend on groundwater for their water use, a result of the erratic nature of public water supply, which is often sourced from the surface water. In this study, the major components of water balance such as actual evapotranspiration, interception, surface runoff and groundwater recharge were simulated to have holistic understanding of the water budget of the study area, with emphases on groundwater recharge. The results of water balance analysis indicate that about 27 % of the total rainfall in Osun drainage basin resulted in groundwater recharge, while the remaining were lost through evapotranspiration (43 %), surface runoff (21 %) and interception (9 %). September is the month with the highest groundwater recharge rate that ranges between 0–73 mm in the north and 129–213 mm in the south and some part of northeast of the basin.

A reasonable amount of groundwater recharge was found in most of the built-up areas, which suggest that there are more bare surfaces within the urban and rural settlements in the basin that allows infiltration and percolation of rainwater. Groundwater resources might be vulnerable to contamination especially in areas with high recharge rates in built up areas and crops/shrubs LULC types based on the nature of waste dumping and fertilizer application. This is because of the shallow aquifer in majority of the basin that makes it relatively easy for contaminants to infiltrate into the deep zones as part of the recharge process.

This study estimated the spatial and temporal pattern of groundwater recharge on a monthly time scale in a basin where the available groundwater resources depend on present day recharge. The monthly spatial and temporal status of the groundwater resources in the basin should be taken into consideration in preparing sustainable groundwater resources management plan for the Osun drainage basin. In addition, efforts should be geared towards improving meteorological and hydrological data collection in the basin on a smaller time scale, such as daily, which can be used to estimate daily recharge and improve groundwater management decisions.

Author declaration

We hereby affirm that the results/ findings in this paper are based on the original research work that have not been published or under consideration of publishing in article form/ or book anywhere else, and the manuscript does not contain any duplication of previously published data arising from the same work. We agree to the condition that this manuscript will not be submitted for publication until we receive the final decision, based on peer-review. The authors declare there is no conflict of interest in the submitted manuscript

Authors statement

The research conceptualization, data curation, formal analysis, investigation, funding acquisition and writing of the original draft was by Eniola Damilola Ashaolu

The supervision and validation were by J. F. Olorunfemi and I. P. Ifabiyi

Software for the research was provided by Khodayar Abdollahi

Reviewing and editing by Okke Batelaan and Khodayar Abdollahi

Acknowledgements

The authors acknowledged National Centre for Environmental Prediction (NCEP), Food and Agricultural Organization of the United Nations (FAO), National Aeronautics and Space Administration (NASA), United State Geological Survey (USGS), the Nigeria Meteorological Agency (NIMET), and Ogun-Oshun River Basin Development Authority (OORBDA) for the data used in this research. This work is part of the Ph.D. thesis of the principal author, Ashaolu (2018).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2019.100658.

References

Abdollahi, K., Bashir, I., Verbeiren, B., Harouna, M.R., Van Griensven, A., Huysmans, M., Batelaan, O., 2017. A distributed monthly water balance model: formulation and application on Black Volta Basin. Environ. Earth Sci. 76, 1–18.

Adanu, E.A., 1991. Source and recharge of groundwater in the Basement terrain in the Zaria- Kaduna area, Nigeria: applying stable isotopes. J. Afr. Earth Sci. 13 (2), 229–234.

Adelana, S.M.A., Olasheinde, P.I., Vrbka, P., 2006. A quantitative estimation of groundwater recharge in part of the Sokoto Basin, Nigeria. J. Environ. Hydrol. 14 (5), 1–16.

Adeleke, O.O., Makinde, V., Eruola, A.O., Dada, O.F., Akintayo, O.O., Aluko, T.J., 2015. Estimation of groundwater recharges in Odeda Local Government Area, Ogun State, Nigeria using empirical formulae. Challenges 6, 271–281.

Adindu, R., Igboekwe, M., Isu, J.O., Igbokwe, K.K., 2013. Estimation of groundwater recharge at Umudike watershed, Abia State-Nigeria. Eur. J. Appl. Eng. Sci. Res. 2 (3), 38–43.

Ajibade, A.C., Woaks, M., Rahman, M.A., 1987. Proterozoic crustal development in Pan- African regime of Nigeria. In: In: Croner, A. (Ed.), Proterozoic Lithospheric Evolution Geodynamics, vol. 17 259-231.

Akinwumiju, A.S., 2015. GIS-based Integrated Approach to Groundwater Potential Assessment of Osun Drainage Basin, Southwestern Nigeria (Ph.D. Thesis). Institute of Ecology and Environmental Studies, Obafemi Awolowo University, Ile-Ife, Nigeria.

Al Kuisi, M.A., El-Naqa, A., 2013. GIS based spatial groundwater recharge estimation in the Jafr Basin, Jordan- application of WetSpass models for arid regions. Revista Mexicana De Ciencias Geologicass 30 (1), 96–109.

Allen, R., Pereira, L.A., Raes, D., Smith, M., 1998. Crop evapotranspiration. FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy.

Alley, W.M., Reilly, T.E., Franke, O.L., 1999. Sustainability of groundwater resources. US Geol. Survey Circular 1186.

Armbruster, V., Leibundgut, C., 2001. Determination of spatially and temporally highly detailed groundwater recharge in porous aquifers by a SVAT model. Phys. Chem. Earth Part B 26 (7-8), 607–611.

Arnold, J.G., Muttiah, R.S., Srinivasan, R., Allen, P.M., 2000. Regional estimation of baseflow and groundwater recharge in the upper Mississippi River basin. J. Hydrol. 227, 21–40.

Ashaolu, E.D., 2016a. Influence of climate on groundwater recharge: clues for sustainable groundwater development in basement complex aquifers of Oshogbo, Nigeria. In: Tilakasiri, S.L. (Ed.), Water, Land and People in Climate Change. Stamford Lake, Pannipitiya, Sri Lanka, pp. 109–128.

Ashaolu, E.D., 2016b. The Osun drainage basin in the western lithoral hydrological zone of Nigeria: a morphometric study. GEOGRAFIA 12 (8), 71–88.

Ashaolu, E.D., 2017. Water resources management: a geographer's viewpoint. In: Tilakasiri, S.L. (Ed.), Geography in Development: Issues and Perspectives. Stamford Lake, Pannipitiya, Sri Lanka, pp. 151–171.

Ashaolu, E.D., 2018. Effect of Climate and Land use/land Cover Change on Groundwater Recharge on Groundwater Recharge in Osun Drainage Basin, Nigeria. Ph.D. Thesis. University of Ilorin, Ilorin, Nigeria.

Ashaolu, E.D., Adebayo, M.O., 2014. Characterizing groundwater level and flow pattern in shallow overburden aquifer: a study of Ilara-Mokin and its environs, Southwestern, Nigeria. Momona Ethiop. J. Sci. 6 (2), 55 74.

Ashaolu, E.D., Olorunfemi, J.F., Ifabiyi, I.P., 2019. Assessing the spatio-temporal pattern of land use and land cover changes in Osun drainage basin, Nigeria. J. Environ. Geogr. 12 (1–2), 41–50.

Azeez, L.O., 1972. Rural water supply in the basement complex of Western state, Nigeria. IASH Bull. 17 (1), 97–110.

Babama'aji, R.A., 2013. Impacts of Precipitation, Land Use Land Cover and Soil Type on the Water Balance of Lake Chad Basin. PhD Thesis. University of Missouri-Kansas City.

Batelaan, O., De Smedt, F., 2007. GIS based recharge estimation by coupling surface- subsurface water balances. J. Hydrol. 337, 337–355.

Batelaan, O., De Smedt, F., 2001. WetSpass: a flexible, GIS based, distributed recharge methodology for regional groundwater modeling. In: Gehrels, H., Peters, J., Hoehn, E., Jensen, K., Leibundgut, C., Griffioen, J., Webb, B., Zaadnoordijk, W.-J. (Eds.), Impact of Human Activity on Groundwater Dynamics. IAHS Publication, pp. 11–17 269.

Batelaan, O., De Smedt, F., Triest, L., 2003. Regional groundwater discharge: phreatophyte mapping, groundwater modelling and impact analysis of land use change. J. Hydrol. 275, 86–108.

Beekman, H.E., Gieske, A., Selaolo, E.T., 1996. GRES: groundwater recharge studies in Botswana 1987-1996. J. Earth Sci. 3, 1–17.

Bredehoeft, J., 2011. Hydrologic trade-offs in conjunctive use management. Ground Water 49 (4), 468–475.

Carter, R.C., 1994. The groundwater hydrology of the Manga grasslands, northeast Nigeria: importance to agricultural development strategy for the area. Q. J. Eng. Geol. Hydrogeol. 27, S73–S83.

Carter, R.C., Alkali, A.G., 1996. Shallow groundwater in the northeast arid zone of Nigeria. Q. J. Eng. Geol. Hydrogeol. 29, 341–355.

Dams, J., Woldeamlak, S.T., Batelaan, O., 2008. Predicting land-use change and its impact on the groundwater system of the Kleine Nete catchment, Belgium. Hydrol. Earth Syst. Sci. 12, 1369–1385.

De Smedt, F., Batelaan, O., 2003. Investigation of the human impact on regional groundwater systems. In: Tiezzi, E., Brebbia, C.A., Uso, J.L. (Eds.), Ecosystems and Sustainable Development. Advances in Ecological Sciences 19. WIT Press, Wessex, UK.

de Vries, J.J., Simmers, I., 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeol. J. 10 (1), 5–17.

Edmunds, W.M., Fellman, E., Goni, I., Prudhomme, C., 2002. Spatial and temporal distribution of groundwater recharge in northern Nigeria. Hydrogeol. J. 10, 205–215.

Federal Ministry of Water Resources, 2014a. The Project for Review and Update of Nigeria National Water Resources Master Plan. Official Dissemination Version Vol. 6 prepared by Japan International Cooperation Agency (JICA).

Federal Ministry of Water Resources, 2014b. The Project for Review and Update of Nigeria National Water Resources Master Plan. Summary Report Vol. 2 prepared by Japan International Cooperation Agency (JICA).

Finch, J.W., 1998. Estimating direct groundwater recharge using a simple water balance model-sensitivity to land surface parameters. J. Hydrol. 211, 112–125.

Finch, J.W., 2001. Estimating change in direct groundwater recharge using a spatially distributed soil water balance model. Q. J. Eng. Geol. Hydrogeol. 34, 71–83.

Goni, I.B., Travi, Y., Edmunds, W.M., 2005. Estimating groundwater recharge from modelling unsaturated zone chloride profiles in the Nigerian sector of the Chad basin. J. Min. Geol. 14 (1), 123–130.

Hamza, M.H., Added, A., Rodríguez, R., Abdeljaoued, S., Ben, M.A., 2007. A GIS-based DRASTIC vulnerability and net recharge reassessment in an aquifer of a semi-arid region (Metline-ras jebel-raf raf aquifer, northern Tunisia). J. Environ. Manage. 84, 12–19.

Healy, R.W., Winter, T.C., LaBaugh, J.W., Frankie, O.L., 2007. Water budget: foundations for effective water resources and environmental management. US Geol. Surv. Circular 1308 90p.

Healy, R.W., 2010. Estimating Groundwater Recharge. Cambridge University Press, Cambridge.

Idowu, O.A., Martins, O., 2007. Hydrograph analysis for groundwater recharge in the phreatic Basement aquifer of the Opeki River basin, southwestern Nigeria. ASSET 6 (2), 132–141.

Ifabiyi, I.P., 2005. Construction versus yield of deep wells in the regolith aquifer of Osun River basin, Nigeria. Water Resour. 16, 1–16.

Ifabiyi, I.P., 2004. The Response of Runoff and Its Components to Basin Parameters in the Upper Kaduna Catchment of Nigeria. PhD Thesis. University of Ilorin, Nigeria.

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evaporation and Irrigation Water Requirements. American Society of Civil Engineers, New York.

Jyrkama, M.I., Sykes, J.F., 2006. The impacts of climate change on groundwater. In: Delleur, J.W. (Ed.), The Handbook of Groundwater Engineering, 2nd ed. CRC Press, USA, pp. 1320.

Jyrkama, M.I., Sykes, J.F., 2007. The impact of climate change on spatially varying groundwater recharge in the Grand River watershed (Ontario). J. Hydrol. 338, 237–250.

Le Maitre, D.C., Scott, D.F., Colvin, C., 1999. A review of information on interactions between vegetation and groundwater. Water South Africa 25, 137–152.

Lerner, D.N., 2002. Identifying and quantifying urban recharge: a review. Hydrogeol. J. 10, 143–152.

Lerner, D.N., Issar, A.S., Simmers, I. (Eds.), 1990. Groundwater Recharge: A Guide to Understanding and Estimating Natural Recharge. Heise, Hannover.

Manfreda, S., Fiorentino, M., Iacobellis, V., 2005. DREAM: a distributed model for runoff, evapotranspiration, and antecedent soil moisture simulation. Adv. Geosci. 2, 31–39.

Melki, A., Abdollahi, K., Fatahi, R., Abida, H., 2017. Groundwater recharge estimation under semi-arid climate: Case of northern Gafsa watershed, Tunisia. J. Afr. Earth Sci. 132, 37–46.

Mileham, L., Taylor, R., Thompson, J., Todd, M., Tindimugaya, C., 2008. Impact of rainfall distribution on the parameterisation of a soil-moisture balance model of groundwater recharge in equatorial Africa. J. Hydrol. 359, 46–58.

Milewski, A., Sultan, M., Yan, E., Becker, R., Abdeldayem, A., Soliman, F., Gelil, K.A., 2009. A remote sensing solution for estimating runoff and recharge in arid environments. J. Hydrol. 373, 1–14.

Mustafa, S.M.T., Abdollahi, K., Verbeiren, B., Huysmans, M., 2017. Identification of the influencing factors on groundwater drought and depletion in north-western Bangladesh. Hydrogeol. J. 25 (5), 1357–1375.

Muzylo, A., Llorens, P., Valente, F., Keizer, J.J., Domingo, F., Gash, J.H.C., 2009. A review of rainfall interception modeling. J. Hydrol. 370, 191–206.

Nolan, B.T., Healy, R.W., Taber, P.E., Perkins, K., Hitt, K.J., Wolock, D.M., 2007. Factors influencing groundwater recharge in the eastern United States. J. Hydrol. 332, 187–205.

Nyagwambo, N.L., 2006. Groundwater Recharge Estimation and Water Resources Assessment in a Tropical Crystalline Basement Aquifer. Ph.D. Dissertation. Delft University of Technology, Delft, Netherlands.

Oke, M.O., Martins, O., Idowu, O., Aiyelokun, O., 2013. Comparative analysis of empirical formulae used in groundwater recharge in Ogun-Oshun River basins. J. Sci. Res. Rep. 2 (2), 692–710.

Oke, M.O., Martins, O., Idowu, O.A., 2014. Determination of rainfall-recharge relationship in River Ona basin using soil moisture balance and water fluctuation methods. Int. J. Water Resour. Environ. Eng. 6 (1), 1–11.

Oke, M.O., Martins, O., Idowu, O.A., Aiyelokun, O., 2015. Comparative analysis of groundwater recharge estimation value obtained using empirical methods in Ogun and Oshun River basins. Ife J. Sci. 17 (1), 53–63.

Omorinbola, E.O., 1986. Empirical equations of groundwater recharge patterns. Hydrol. Sci. J. 31 (1), 1–11.

Omorinbola, E.O., 1982. Systematic decline of groundwater level in the regolith of the Nigerian basement complex due to human activities. Proceedings of Exeter Symposium (Improvement of Methods of Long Term Prediction of Variations in Groundwater Resources and Regimes Due to Human Activity). July 1982, IAHS Publication, no. 36.

OORBDA, 1982. Ogun-Oshun river basin development authority. Osun River Basin Feasibility Study Vol.7 May, 1982.

Pan, Y., Gong, H., Zhou, D., Li, X., Nakagoshi, N., 2011. Impact of land use change on groundwater recharge in Guishui River basin, China. Chin. Geogr. Sci. 21 (6), 734–743.

Raes, D., 2012. Reference Manual, ET*O* Calculator, Version 3.2. Food and Agriculture Organization of the United Nations Land and Water Division, Rome, Italy.

Rahman, M.A., 1988. Recent advances in the study of the basement complex of Nigeria. Symposium on the Geology of Nigeria. Obafemi Awolowo University, Ile-Ife, Nigeria.

Sani, M.G., Nasiru, R., Sadiq, U., 2012. Mean-residence time of groundwater in the Basement Complex terrain of Kano metropolis (Nigeria) estimated from tritium radioisotope. IOSR J. Appl. Phys. 2 (5), 36–41.

Scanlon, B.R., Healy, R.W., Cook, P.G., 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10, 18–39.

Sekhar, M., Kumar, M.S.M., Sridharan, K., 1994. A leaky aquifer model for hard rock aquifers. Hydrogeol. J. 2 (3), 32–39.

Sophocleous, M.A., 2004. Groundwater recharge. In: Luis, S., Stefan, W., Eduardo, J.U. (Eds.), Groundwater. Encyclopedia of Life Support Systems (EOLSS), developed under the Auspices of the UNESCO, EOLSS Publishers, Oxford, UK.

Taylor, R., Howard, K., 2000. A Tectono-geomorphic model of the hydrogeology of deeply weathered Crystalline Rock: evidence from Uganda. Hydrogeol. J. 8 (3), 279–294.

Taylor, R.G., Tindimugaya, C., 2012. The impacts of climate change and rapid development on weathered crystalline rock aquifer systems in the humid tropics of Sub-saharan Africa: evidence from south-western Uganda. In: Triedel, H., Bordes, Martin-, J. L, Gurdak, J.J. (Eds.), Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations. CRC Press/Balkema, Taylor and Francis Group, London, UK.

Teklebirhan, A., Dessie, N., Tesfamichael, G., 2012. Groundwater recharge, evapotranspiration and surface runoff estimation using WetSpass modeling method in Illala catchment, northern Ethiopia. Momona Ethiop. J. Sci. 4 (2), 96–110.

Tesfamichael, G., De Smedt, F., Walraevens, K., Gebresilassie, S., Hussien, A., Hagos, M., Gebrehiwot, K., 2013. Application of a spatially distributed water balance model for assessing surface water and groundwater resources in the Geba basin, Tigray, Ethiopia. J. Hydrol. 499, 110–123.

Tilahun, K., Merkel, B.J., 2009. Estimation of groundwater recharge using a GIS-based distributed water balance model in Dire Dawa, Ethiopia. Hydrogeol. J. 17, 1443–1457.

UNESCO, 2008. Groundwater Resources Assessment under the Pressure of Humanity and Climate Change - GRAPHIC. A Framework Document, GRAPHICS Series No. 2.

van Dijk, A.I.J.M., Peña Arancibia, J.L., Bruijnzeel, L.A., 2011. Top-down analysis of collated streamflow data from heterogeneous catchments leads to underestimation of land cover influence. Hydrol. Earth Syst. Sci. Discuss. 8, 4121–4150.

Watson, I., Burnett, A.D., 1995. Hydrology, an Environmental Approach. CRC Press Inc 702 pp.

Winter, T.C., Harvey, J.W., Franke, O.L., Alley, W.M., 1998. Groundwater and Surface Water: a Single Resource. U.S. Geological Survey Circular 1139. Denver Colorado.

Zomlot, Z., Verbeiren, B., Huysmans, M., Batelaan, O., 2015. Spatial distribution of groundwater recharge and base flow: assessment of controlling factors. J. Hydrol. Reg. Stud. 4, 349–368.

Zomlot, Z., Verbeiren, B., Huysmans, M., Batelaan, O., 2017. Trajectory analysis of land use and land cover maps to improve spatial–temporal patterns, and impact assessment on groundwater recharge. J. Hydrol. 554, 558–569.