

Effect of Climate and Land Use/Land Cover Change on Groundwater Recharge in Osun Drainage Basin, Nigeria

By

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CERTIFICATION

We the undersigned, certify that by Mr. ASHAOLU Eniola Damilola carried out this research in partial fulfillment of the requirements for the award of Doctor of Philosophy (Ph.D.) in the Department of Geography and Environmental Management, Faculty of Social Sciences, University of Ilorin, Ilorin, Nigeria.

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DEDICATION

To my unborn children, their mother and the generations to come. This sacrifice is for you.

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I thank God for the gift of life, the strength and purpose bestowed on me. This is indeed, a triumph of sheer determination and will to succeed against all odds. *If I have seen further than others, it is by standing upon the shoulders of giants.* I became Professor J. F. Olorunfemi supervisee by accident, but who else could I have asked for? His approach to work always keep me on my toes, because he was always asking questions. I am truly blessed to research my Ph.D. thesis under your tutelage. He was relentless in going through my work, even at odd times and giving feedbacks as soon as possible. I sincerely appreciate your time and efforts. Besides being my supervisor, he supported me financially and morally. May God make your life and family better by far.

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ABSTRACT

Sustainable management of groundwater resources on a Basement Complex (BC) aquifer can be better undertaken with the spatio-temporal knowledge of groundwater recharge. Groundwater residence time of BC aquifers is between three to six months. This makes the knowledge of the monthly groundwater recharge with emphasis on influencing factors imperative using the Osun drainage basin as a case study. The objectives of the study were to: (i) determine the spatio-temporal pattern of climate in the basin between 1976 and 2015; (ii) estimate the spatio-temporal pattern of land use/land cover change between 1984-2015; (iii) estimate the mean monthly water budget of the drainage basin; (iv) examine the effect of climate on the basin groundwater recharge; and (v) evaluate the effect of land use/land cover change on groundwater recharge.

Data used for this study include rainfall amount, number of rainy days, temperature, relative humidity, windspeed, sunshine hour and potential evapotranspiration (PET). Others were satellite imageries, Digital Elevation Model (DEM), slope and aspect, soil texture, depth to water, and runoff discharge. The climate data were sourced from the Nigeria Meteorological Agency (NIMET) and National Centre for Environmental Prediction (NCEP), while PET was estimated using FAO Penman-Monteith method. Satellites imageries and DEM were acquired from USGS-EROS satellite image database and National Aeronautics and Space Administration, respectively. Soil map was extracted from the harmonized world soil database of the Food and Agriculture Organization (FAO). Depth to water was adapted from Federal Ministry of Water Resources master plan (2014), while the discharge data at Apoje station were collected from Ogun-Oshun River Basin Development Authority. The data were subjected to remote sensing and GIS analysis, hydrological modelling using WetSpa-M, Z-score, Mann-kendall, Regression and Spearman Ranks statistical analysis.

The findings of study were that:

- i. eighteen dry years were discovered between 1976 and 2015 based on rainfall amount, and seven (39%) of these occurred in the last decade (2006-2015) of record,
- ii. the most significant land use/land cover change occurred in forest and wetland that declined by about 59% and 85%, respectively between 1984 and 2015, while, built-up area increased by 235% during the same period;
- iii. water budget analysis indicated that about 27% of the rainfall received in Osun drainage basin resulted in groundwater recharge, while the remaining were lost through evapotranspiration (43%), surface runoff (21%) and interception (9%);

- iv. rainfall amount accounted for 95% of the variability in groundwater recharge in Osun drainage basin, with highest recharge occurring in September (0 - 212.74mm); and
- v. land use/land cover change accounted only 10% reduction in mean groundwater recharge between 1984 and 2015.

The study concluded that the knowledge of the monthly spatio-temporal status of the groundwater recharge and the influencing factors are important. It is recommended that in preparing sustainable groundwater resources management plan for the basin the spatio-temporal status of groundwater should be considered. Furthermore, the monthly groundwater withdrawal should be regulated by Ogun-Osun River Basin Development Authority and relevant agencies.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Groundwater recharge is an addition of water to the groundwater system at any of its defined boundaries (United Nations Educational Scientific and Cultural Organization [UNESCO], 2008). It usually occurs through natural or artificial processes. For the purposes of this study, groundwater recharge will be taken as the direct groundwater recharge to the groundwater system through rainfall. As a matter of fact, groundwater occurrence in the Basement Complex aquifers is defined by the presence of shallow water table and significant amount of natural recharge is mainly from rainfall (Sekhar, Kumar & Sridharan, 1994; Nyagwambo, 2006). Groundwater is an important component of the hydrological cycle (Green et al., 2011; Triedel, Martin-Bordes, & Gurdak, 2012). It is essential to several hydrological processes that sustain stream discharges, river baseflow, lakes, wetlands, transport dissolved chemicals as well as facilitate weathering (Custodio, 2002). In addition, the importance of groundwater does not end with its eco-hydrological functions, but has its greatest significance in sustaining human life. However, groundwater resource does not exist in isolation, but connected to surface water resource and the terrestrial ecosystems; consequently, the conceptualization of surface and groundwater as a combined resource (UNESCO, 2008).

According to Triedel, et al. (2012), significant amounts of research have focused predominantly on climate change effect on surface water resources, due to their visibility and accessibility. In fact, some writers consider surface water as a resource that is not connected to the groundwater system and treated it in isolation. Although, some primary work focusing on the effect of global change on groundwater started in the 1980's, the year 1990 witnessed a renewed interest in the

subject matter which peaked in 2005 (Green, et al., 2011; Triedel et al., 2012). Taylor and Tindimugaya (2012) opined that an extreme effect of rapid development and climate change is expected on water resources in the tropics. Ironically, it is the part of the world with limited hydrological knowledge base, human and institutional capacity to contrive sustainable adaptive water management strategies. To corroborate this assertion, Nigeria Hydrological Services Agency ([NHSA], 2016) reported that the hydrogeological studies carried out in Nigeria in the seventies and eighties, revealed that some of the groundwater aquifer systems is declining. A condition that has been aggravated by indiscriminate drilling of boreholes/wells, coupled with increasing population, as well as rapid urbanization.

Based on the awareness of aquifer depletion, the Federal Government of Nigeria's policy is to monitor the major aquifers in the sedimentary basin. The policy proposed to have as many as 100 monitoring wells in the national network across the major aquifers (NHSA, 2016). However, only twelve monitoring wells are in existence, with five instrumented and operational. The current policy ignored most of the Basement Complex aquifers which underlain more than 50% of the country. Perhaps this informed Taylor and Tindimugaya (2012) when they concluded that the countries of the tropics have limited hydrological knowledge base, human and institutional capacity to deal with the extreme effect of rapid development as well as climate change on their water resources. In view of this, and the fact that Nigeria is faced with the challenges of limited or sparse ground data to effectively cope with the effect of climate and human interactions on groundwater resource, necessitates the modelling of groundwater resource with emphasis on factors influencing groundwater reserve in the country.

In an attempt to determine groundwater potential, recharge and storage, researchers in Nigeria have strived to quantify groundwater resource of locations and basins across the country using

different methods. One of such methods include tracers/isotope (Adanu, 1991; Edmunds, Fellman, Goni & Prudhomm, 2002; Goni, Travi, & Edmunds, 2005; Sani, Nasiru & Sadiq, 2012). This method though useful for long time scales groundwater estimation and evaluate smaller fluxes, has a major weakness of mass distortion from secondary input such as nuclear testing which have increased the concentration of some of the tracers in the hydrological cycle. Empirical relationship has been adopted by quite a number of others (Omorinbola, 1982; 1986; Carter, 1994; Carter & Alkali, 1996; Adeleke et al., 2015; Ashaolu, 2016a). This method is practically useful in preliminary investigation and in areas of data scarcity, limited technical and financial resources. The major disadvantage though, is that it is derived from other methods of recharge estimation. It can also become obsolete with changes in catchment physiology, if not re-evaluated from time to time. Besides, it usually ignored the processes in the unsaturated zone completely.

Hundreds of peer reviewed articles have been published on groundwater potential and prospecting in Nigeria adopting the geophysical approach, using electrical resistivity method. An approach adopted because of its capability to determine zones of economically viable groundwater potential from zones of poor groundwater potential. The effects of climate and changes in land use/land cover (LULC) on groundwater availability are rarely considered in this approach. Soil moisture balance and water table fluctuation were adopted by few other researchers (Adindu, Igboekwe, Isu, & Igboekwe, 2013; Oke, Martins, & Idowu, 2014). An approach dependent on readily available data on rainfall, runoff and water level. Although easy to apply, its major short coming is that the independent variables are often difficult to measure accurately. This can be source of error in the estimation. Hydrograph separation method was employed by Idowu and Martins (2007), Ifabiyi (2004) which is an integrative measure of

recharge. The weakness of this approach is that problems may arise if recharge to aquifer is deeper than the draining of the observed river or stream.

Some other scholars have adopted the combination of two or more methods and two or more different empirical equations, with the intention of comparing the results. These studies agreed on the desire for a more suitable method. The combination of isotope, water balance and empirical relationship by Adelana, Olasheinde, and Vrbka (2006), as well as the adoption of three empirical relationship (modified Chartuvedi formula, Krishna Rao and Kumar & Seethpathi) by Oke, Martins, Idowu, and Aiyelokun (2015) are examples. The methods highlighted thus far, have limited capability to incorporate all factors affecting groundwater recharge such as climate, land use/land cover, slope in quantifying groundwater resource in a single quest. Besides, some of these methods are labour intensive, expensive and have restricted potentiality to assess groundwater resource on country wide or regional scale.

A notable study that looked at the impact of 8 years (2003-2010) rainfall, land use/land cover (2005 and 2009) and soil type on the water balance of Lake Chad using hydrological modelling with remote sensing and GIS methodology was by Babama'aji (2013). This study not only looked at rainfall alone, a parameter of climate, but also used a record of less than ten years. The analysis was based on annual and seasonal pattern just like most of the previous studies mentioned above. The use of long term annual and seasonal recharge alone may therefore not be suitable for Basement Complex aquifers analysis because of the presence of shallow water table. Also, climate variability, compared to climate change, have greater impact on Basement Complex aquifer systems (Nyagwambo, 2006). It is important to note that majority of Osun drainage basin is underlain by the Basement Complex rock. This makes the recharge to groundwater system to be highly influenced by climatic fluctuation.

Akinwumiju (2015) assessed the groundwater potential of Osun drainage basin, by integrating digital elevation model (DEM), geological map, topographical map, Landsat imageries, hydrological and vertical electrical sounding (VES) data into a Geographic Information System (GIS) environment. Despite the attempt to use remote sensing and GIS methods that can offer regional scale analysis, the inclusion of hydrogeological and geophysical data limited the coverage of the study to the northeastern part of the basin, because there was no comprehensive and adequate hydrogeological and geophysical data for the whole basin. Studies on groundwater recharge in Osun drainage basin estimated recharge on annual basis and combined Ogun and Osun basin together as an entity of investigation (Oke et al., 2015; Federal Ministry of Water Resources [FMWR], 2014a), which resulted into lumped recharge estimation. A study that focused solely on Osun basin, discovered declining groundwater level in some part of the basin (Omorinbola, 1982) and predicted 2070 as the year of aquifer extinction using least-squares regression techniques. The decline in groundwater observed was in part attributed to increased urbanization and clearing of forest areas for farmland. Of recent, studies on LULC in different parts of the basin have suggested changes in LULC all over the basin (Gasu, Nicholas, Bidmus & Dawam, 2016; Mengistu & Salami, 2007; Akinyemi, 2005; Salami, Ekanade & Oyinloye, 1999; Salami, 1995), which will no doubt influence the water balance of the basin. Thus, groundwater recharge over time and space will be influenced by climate because of the shallowness of the aquifer; and the prevailing incidences of LULC change in Osun drainage basin.

Based on the foregoing, the adoption of a method that will accurately estimate groundwater recharge on a short-term scale perhaps monthly with emphasis on the factors affecting recharge, with wider, regional and national coverage becomes imperative. This calls for the adoption of an integrated approach that will model the hydrological cycle using remotely sensed data, in situ

measurement and GIS. Gokmen (2013) had earlier 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 interdependency. The adoption of an integrated hydrological model with the aid of remote sensing and GIS by this present study is a step in that direction. Thus, the present study examined the effect of climate and land use/land cover change on groundwater recharge in Osun drainage basin which is largely underlain by the Basement Complex rocks.

1.2 Statement of Research Problem

About four issues and challenges have been recognized from the background to this study. The first is that surface and groundwater are often treated as different entities. Groundwater system replenishes the surface water during the dry period through baseflow and surface water contributes to the groundwater system during the wet period in form of infiltration and percolation. It is important to note that changes in either surface or groundwater resource will affect the other. Consequently, for efficient water resources management, a meaningful inquest into the effects of climate and land use/land cover should conceptualize the two as a single entity of the hydrological cycle. This approach will assist in the understanding of the change in groundwater storage. The second is that, Nigeria is located in the tropical environment where an extreme effect of rapid development and climate change are expected on water resources, but with inadequate human and institutional capacity to devise sustainable adaptive water management strategies. The apparent limited number (12) and worse still with only five (5) functional monitoring wells available out of the proposed 100 is a pointer to this direction. Even at that, evidence from these monitoring sources confirmed the decline in the major aquifers of the country. Moreover, the Basement Complex aquifer which underlain more than 50% of the

country where Osun drainage basin is located is currently ignored in the proposed monitoring well network.

Thirdly, most of the methods employed previously in understanding the groundwater potential, recharge and storage in the country have restricted capability to cover the entire country or a region in a single inquest. Most of these methods though costlier, time consuming and labour intensive have limited coverage. Often times, these methods do not consider the interconnectivity between groundwater and surface water resource which is an intrinsic part of the hydrological cycle. More importantly, most of the methods looking into groundwater recharge consider annual and seasonal recharge. Estimating only annual and seasonal recharge, for example in the Basement Complex aquifer with groundwater residence time of about three to six months is not sufficient for long term groundwater resource management.

Lastly, previous studies on groundwater potential and recharge in Osun drainage basin was either limited to some part of the basin because of the approach or lumped with Ogun drainage basin as a single entity of investigation. Such studies that are limited to some parts of the basin tend to generalize for the whole basin and this cannot give the true representation of groundwater recharge and potential over time and space in Osun drainage basin. Others that lumped Ogun and Osun basins together as an entity of investigation only gave annual recharge for ‘Ogun-Osun’ drainage basin and not for Osun drainage basin as a unit. Meanwhile, the manifestation of a declining groundwater resource was observed in part of the Osun drainage basin some three decades ago. The decline, attributed to the level of urbanization, number of well per unit area and the clearing of rainforest for commercial scale agriculture, as of that time has witnessed tremendous urbanization with emerging cities such as Osogbo, Ede, Ilesha, Ikirun, Iwo, Ogbomosho, Oke Imesi, etc. expanding in leaps and bounds. With population increase, no doubt,

more wells have been sunk and more vegetation has been cleared to give way for urbanization. The increasing urbanization and high rate of emerging cities will stress the existing groundwater supply, and in addition place supply at a greater risk of reduced recharge. The response of groundwater recharge to climatic variables fluctuation is more visible on the Basement Complex aquifer because of its shallowness than other types of aquifer such as the sedimentary basins. Indeed, climate fluctuation rather than climate change was considered in this study, not only because of groundwater response to it in a Basement Complex aquifer, but also as a consequence of the uncertainty in Global Circulation Models (GCMs) projections.

The above scenario calls for the quantification of the Osun drainage basin groundwater resource, with the adoption of a methodology that will consider groundwater as a resource connected to the surface water. In fact, a method capable of spatio-temporal recharge quantification on a short-term scale, perhaps monthly, with emphasis on factors affecting groundwater recharge such as climate and land use/land cover change becomes relevant at this point in time. The simple question of what is the likely influence of climate and LULC change on the groundwater recharge in the basin over time and space require answer. The issues and challenges identified climax into the following research questions, which served as the focus of this study:

- i. What is the climate pattern over time and space in the study area from 1976-2015?
- ii. How has land use/land cover changed in Osun drainage basin from 1984-2015?
- iii. What is the overall monthly water budget in the study area?
- iv. How is climate affecting groundwater recharge in Osun drainage basin?
- v. What is the effect of land use/land cover change on groundwater recharge in the study area?

1.3 Aim and Objectives of the Study

The aim of this study is to evaluate the effect of climate and land use/land cover change on groundwater recharge in Osun drainage basin, for sustainable groundwater development and management. The specific objectives are to:

- i. determine the spatio-temporal pattern of climate in the basin (1976-2015);
- ii. estimate the spatio-temporal pattern of land use/land cover change (1984-2015);
- iii. estimate the mean monthly water budget (interception, runoff, evapotranspiration and groundwater recharge) of the drainage basin;
- iv. examine the effect of climate on the basin groundwater recharge; and
- v. evaluate the effect of land use/land cover change on groundwater recharge.

1.4 Justification of the Study

The management of groundwater resources can be better undertaken with the spatial and temporal knowledge of groundwater recharge. This requires the adoption of a physically based methodology that can be used to characterize both temporal and spatial effect of changes in climate and land use/land cover. The use of WetSpass-M model which is a spatially distributed model that can simulate monthly distribution of recharge and overall water balance of a region is considered appropriate. This model is best suited for this study, because it is an area where there is no good monitoring network for groundwater resources and has sparse ground data on the hydrological processes of the region. Lerner, Issar, and Simmers (1990); and De Vries and Simmers (2002) had noted earlier that, the combination of a water balance method, local data, remote sensing and GIS technology offers a scope for a better understanding and quantification of regional groundwater recharge.

Indeed, groundwater recharge is influenced by the physical characteristics of the land surface and soil profile and not only by hydrologic processes. Several climate studies have focused on modeling the temporal changes in the hydrologic processes and only a few gave attention to the spatial variability of the physical properties across the study area. This study integrated the spatio-temporal changes in hydrologic processes and spatial variability of physical properties across Osun drainage basin. Singh and Kumar (2010) noted that most of the methods used in groundwater recharge derived changes in groundwater recharge with the assumption that parameters are constant except rainfall and temperature. It is paramount to know the average change in recharge over time, because these changes will not occur equally over a regional drainage basin. 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 & Sykes, 2006). Hence, this study will help in the long term sustainable groundwater resources management in the face of a changing climate, population increase, land use/land cover change and increasing urbanization in Osun drainage basin, Nigeria.

1.5 Significance of the Study

Holistic approach in dealing with groundwater system in terms of its connection to the hydrologic cycle reveals several interdependencies that need to be evaluated when examining groundwater availability and long-term aquifer sustainability. The interdependency can put huge controls on groundwater budget. These controlling factors can be hugely affected by human activities on the land surface and effect of changes in climatic conditions (Healy, Winter, LaBaugh, & Frankie, 2007; UNESCO, 2008). This study will enhance the existing knowledge in the understanding of how groundwater and surface water interact in Osun drainage basin.

Besides, changes in either surface or groundwater resource influences each other. Therefore, understanding their connectivity in Osun drainage basin in relation to climate and land use/land cover changes will assist in conjunctive water use and sustainable water resource management in the basin.

Osun drainage basin is an area naturally characterized by rainforest vegetation. The natural vegetation, has however, been replaced by secondary forest due to many years of human occupation through vegetation clearing and increasing urbanization (Ifabiyi, 2005). The basin has witnessed one of the fastest rate of forest conversion and change in vegetation. This is a consequence of fuel wood production, road construction, clay/sand quarrying, widespread rotational bush farming, as well as high rate of emerging cities. All these changes in land use/land cover will have significant feedback on the water balance of the basin. In addition, existing groundwater supply will be stressed, with increasing risk of reduced groundwater recharge. Consequently, the ability of the groundwater system to meet the increasing water need now, in the future and sustaining the ecosystem will be at greater risk. This study will assist in understanding the rate of land use/land cover change and trend of change over time. The implication of such change on water resources management will be highlighted and it will inform land use allocation and management within the basin. Hence, the preparedness and adaptation for the possible future water crisis in the basin.

Lastly, estimating groundwater recharge on a smaller time scale would appear the most appropriate for sustainable groundwater management on Basement Complex aquifers (Nyagwambo, 2006). Hanson, Newhouse, and Dettinger (2004) and Pool (2005) asserted that the estimation of groundwater resources in modelling and management usually adopt a long-term average annual recharge as the input into the groundwater system. This approach looks

increasingly insufficient not only because it does not consider the full understanding of recharge processes, but also because it does not account for an assessment of how climate and land use/land cover changes could influence groundwater availability. Thus, evaluating monthly water balance of Osun drainage basin will enhance the understanding of how climate and land use/land cover changes influence the groundwater recharge and storage on a small-time scale. This better represents the monthly state of the groundwater reserve of the basin compared to seasonal or annual evaluation hitherto in partial existence.

1.6 Scope of the Study

Groundwater recharge is a function and interaction between various key environmental elements such as climate, soil, vegetation/land use and topography. Thus, any meaningful quest aimed at quantifying recharge should take into account all these environmental elements that affect recharge. In addition, such study should consider groundwater recharge as an intrinsic part of the hydrological cycle by looking at the interdependency between groundwater and surface water. Wetspass-M hydrological model takes into account all of these environmental elements and was adopted for this study. This research took into account these environmental elements (climate, soil, vegetation/land use, slope and topography) as well as the interdependency between surface and groundwater resources in estimating the groundwater recharge in Osun drainage basin, with emphasis on the effect of climate and land use/land cover change on groundwater recharge.

1.7 Limitations of the Study

The limitations of the study include the differences in the spatial resolutions of the input parameters such as Landsat imageries, soil map, DEM that have to be resampled to the same spatial resolution, which might distort some of the maps, especially the soil map that has the lowest resolution of all data sources. Also, there were limited available records on depth to

water, therefore, mean depth to water on the Basement Complex rocks and sedimentary basins in the study area were adapted for the study. Finally, a single LULC map of 1984, 2000 and 2015 was adopted for the groundwater recharge modelling for 1984, 2000 and 2015, respectively. This does not account for the seasonal variation that might occur especially on land cover such as grasses.

1.8 The Study Area

1.8.1 Location, Position and Size

The Osun drainage basin is located between latitudes $6^{\circ}25'58.79''$ and $8^{\circ}21'3.6''$ N and longitudes $3^{\circ}47'34.8''$ and $5^{\circ}10'55.2''$ E in the western lithoral hydrological zone of Nigeria. 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 $7^{\circ}53''$ before turning westwards via Osogbo, Ede and southwards to flow into Lagos lagoon about 8 km east of Epe (Oke, Martins, Idowu & Aiyelokun, 2013; Ashaolu, 2016b; Ogun-Oshun River Basin Development Authority [OORBDA], 1982). The map showing the location and position of the study area with the weather stations is presented in Figure 1.1.

The basin covers about 42 local government areas that spread across the five states of Osun, Ekiti, Oyo, Lagos and Ogun in the southwestern Nigeria as well as some parts of the southern Kwara state. The basin has an area of $9,926.22\text{km}^2$ and length a of 213km that stretches from the hinterland to the coast (Ashaolu, 2016b). The larger part of the basin is located in Osun, Oyo and Ogun States, with the remaining parts in Kwara, Lagos and Ekiti State (OORBDA, 1982). The area and length of the basin are directly related. The larger the basin, the longer the length which will result in high concentration time (lag time). This will influence the rate of runoff, infiltration as well as percolation into the groundwater system of Osun drainage basin.

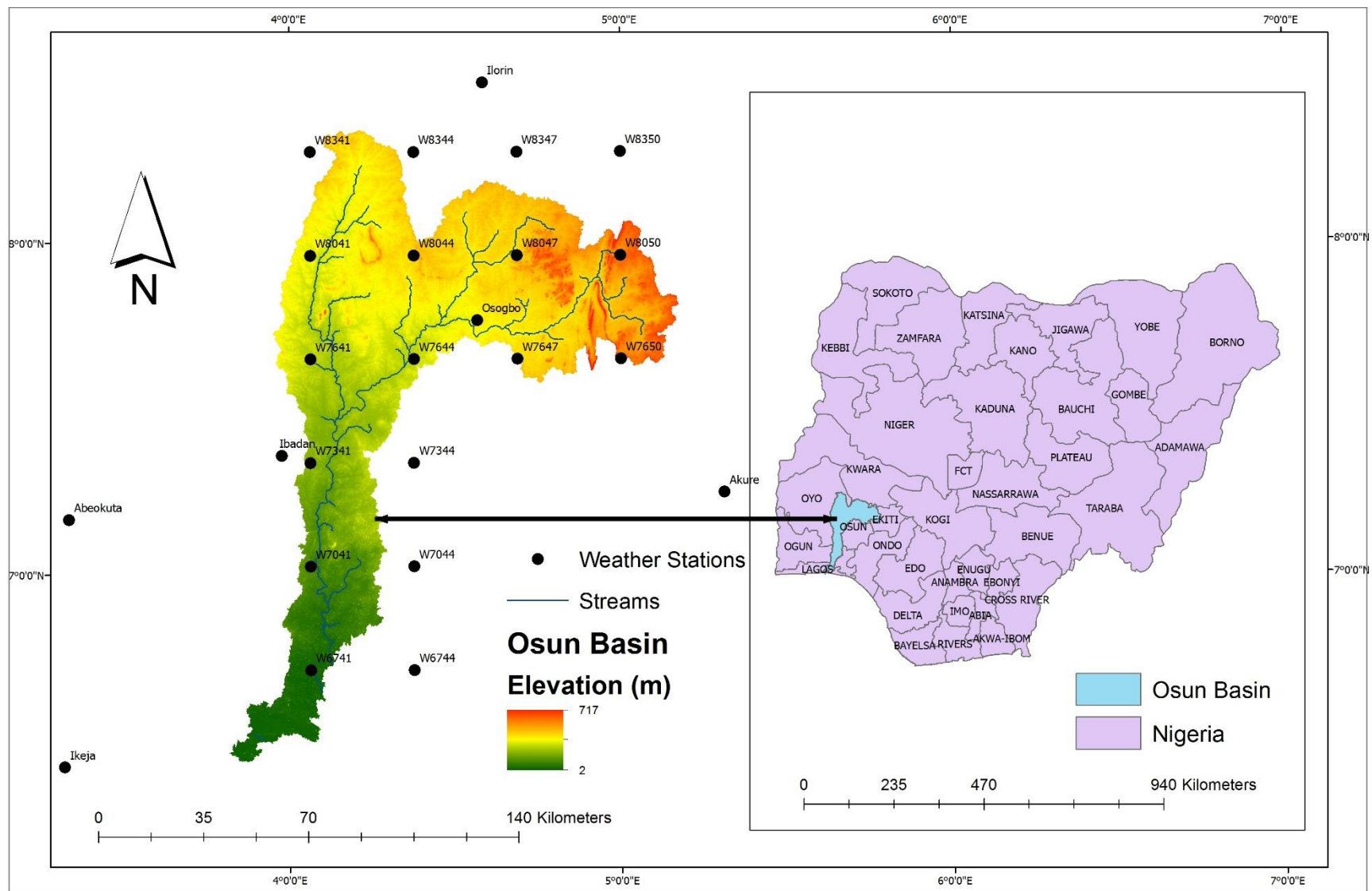


Figure 1.1: Location and Position of Osun Drainage Basin, Nigeria

Source:

Modified

from

Ashaolu

(2016b)

1.8.2 Climate

The basin climate is influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ), the quazi-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 equatorial air mass is marked with the rain-bearing south-westerly winds from the Gulf of Guinea (OORBDA, 1982, p. 4). The climate of the basin can be described as the tropical continental climate of Koppen Aw type humid tropical rainforest climate (Ifabiyi, 2005; Adediji & Ajibade, 2008). 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, p. 4).

The salient feature of the rainfall pattern is its seasonal distribution. 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 wet season rainfall varies from 1,020mm to 1,520mm in the south of the basin and less than 1,020mm in the north. On the other hand, the mean dry season rainfall varies from 127 to 178mm in the north, while it varies from 178 to 254mm in the south (OORBDA, 1982, p. 5). In addition, rainfall the basin is influenced by altitude and the orientation of the coastline relative to the direction of the rain-bearing winds.

Although, the northern plateau averages 300m above sea level, rainfall is lower there than in areas of similar latitude in the northeastern part of the basin around Oke Imesi. This indicates that the fairly steep rise to the plateau and the associated inselbergs have profound influence on rainfall distribution (OORBDA, 1982, p. 4).

The months of February and March are the hottest in the basin and temperatures are high over the entire basin during this period. There is also variation in temperature from the south to the north, where it is higher. The lowest mean 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, p.4). The mean annual temperature is about 30°C, which can vary depending on the location and time of the year (Ifabiyi, 2005, p. 2; Adediji & Ajibade, 2008). 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, p. 4). The pattern of relative humidity is similar to rainfall pattern across the basin. The amount and number of rainy days will influence the amount of water that will be available in this basin, which will eventually percolate to the groundwater system. Since direct recharge of the groundwater system is from rainfall, more recharge is expected in the rainy season months of the basin compared to dry season months that are characterized by little or no rainfall. Also, the degree of temperature, amount of evapotranspiration, wind speed, sunshine hour and relative humidity will also influence the microclimate of the basin, as well as the water balance fluxes, which will affect the groundwater recharge.

1.8.3 Geology

The basin is underlain by two types of rocks which are the Basement Complex rocks and the sedimentary basins (Oke et al., 2013; OORBDA, 1982). The larger percentage of this Basement

Complex rocks are very ancient in age and they showed great variations in grain size and in mineral composition. Sedimentary rocks of cretaceous and latter deposits are found in the southern sections of the Osun basin (Oke et al., 2013, p. 696). This younger sedimentary basin found in the southern part of the basin underlain a total area of 667.72km^2 , which is about 7% of the basin area. The younger sedimentary basins found in the basin are neogene-mesozoic and quaternary close to the coast (Ashaolu, 2016b, p. 79).

The remaining sections are composed of crystalline rocks of the Basement Complex, consisting mainly of folded gneiss, schist and quartzite complexes, which belong to the older intrusive series with outcrops plainly visible in many places (Oke et al., 2013, p. 696). The Basement Complex rocks underlain $9,258.5\text{km}^2$, about 93% of the basin. The rock types are the intracrustal group (e.g. granite, gneiss, migmatite etc) and supracrustal (volcanic and sediments).

The unstable ferromagnesian mineral rocks (schist and amphibolite) is prevalent in the basin, especially in the northern part. This mineral rock types usually weathered into clay under tropical rainforest condition that enhances in situ development of thick impermeable, water discharging kaolinitic layer, which suggest low groundwater potential. In fact, this is an indication that the larger part of the basin is underlain by a poor aquifer system. This type of aquifer can yield reasonable amount of water depending on the degree of interconnection of the voids spaces within the weathered regolith (Akinwumiju, 2015). Local factors such as weathering, presence of faults and fractures provide the medium through which water percolate and made available exploitable quantities of groundwater (Azeez, 1972; Ashaolu, 2016b, p. 78) in this aquifer type. The depth of hand dug wells and boreholes on this type of aquifer are seldom more than 60 m with average static water level varying between 1 to 45 m below the ground surface (Nwaogazie,

1995; Nwankwoala, 2011). The simplified geology map of the study area is presented in Figure 1.2.

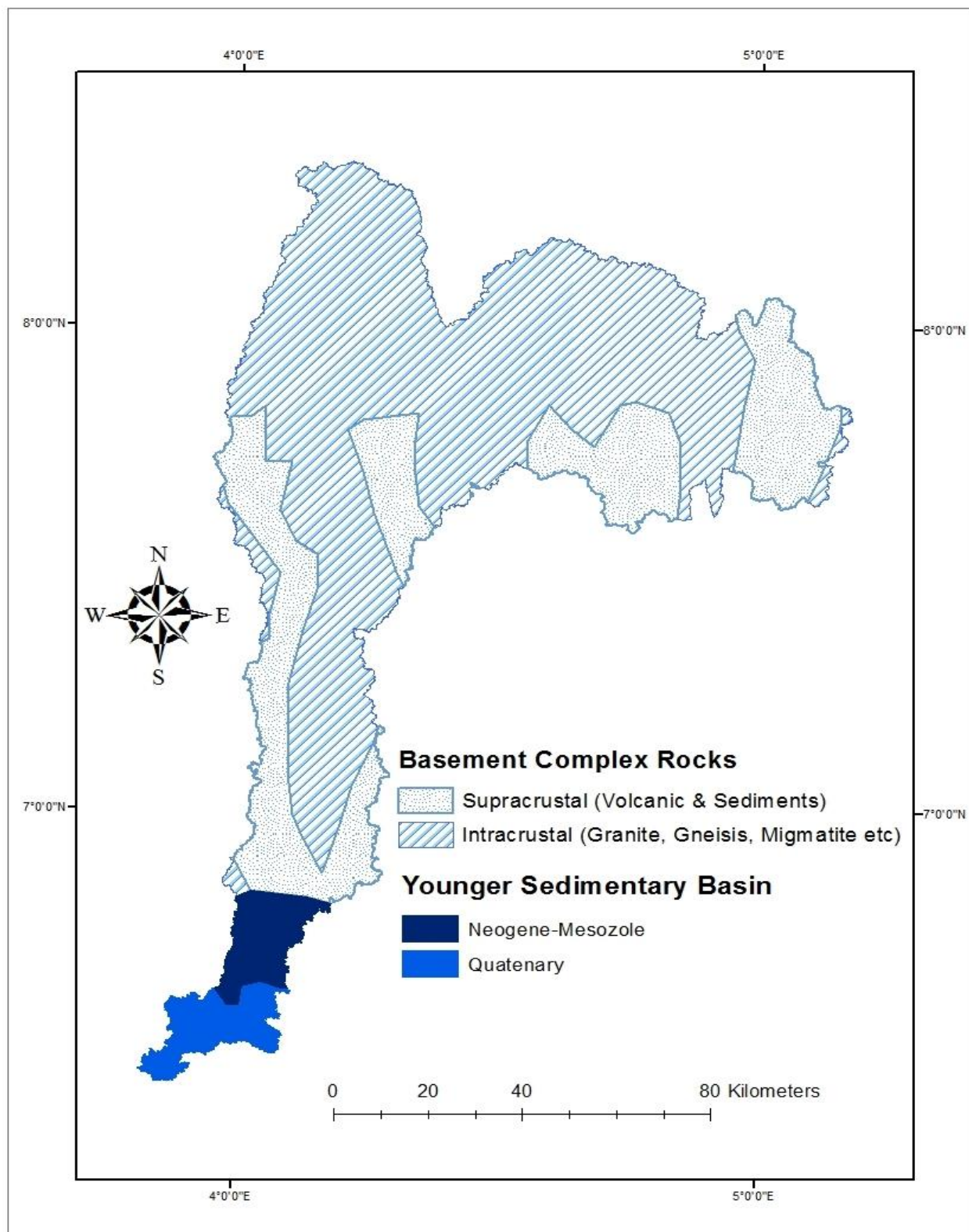


Figure 1.2: Simplified Geology of Osun Drainage Basin, Nigeria
Source: Adapted from Ashaolu (2016b)

The large areas of the lower part of the basin are covered by Recent Deposits that subdivide into the lithoral and lagoonal sediments of the coastal belts and the alluvial sediments of the major rivers. The Coastal Plain Sands consist of soft, very poorly sorted clayey sands, pebble sands, sandy clays and rare thin lignites. The Ilaro Formation underlying the coastal plain sands include both marine and continental deposits. The Ewekoro Formation which consists of limestone of about 30.5m thickness overlain by a shale member of 122m thickness, underlies the Ilaro Formation. The succession of sedimentary rocks is completed by the Abeokuta Formation. The Recent Deposits, Coastal Plain Sands, Ilaro and Abeokuta formations all have good groundwater potential (OORBDA, 1982, p. 6).

1.8.4 Soil

The soils belong to the highly ferruginous tropical red soils associated with Basement Complex rocks. As a result of the dense humid forest cover in the area, the soils are generally deep and of two types, namely, deep clayey soils formed on low smooth hill crests and upper slopes; and the more-sandy hill wash soils on the lower slopes (Ifabiyi, 2005, p. 3). Four soil types were identified in the basin on basis of their texture. These are clay, sandy clay loam, sandy loam and loamy sand soil. Sandy loam and loamy sand covered about 19.78% of the basin with basic infiltration rate of 20.32mm/hour. Also, clay soil covered about 20.34% of the basin with basic infiltration rate of 1.52mm/hour, while 50.89% of the basin is covered by sandy clay loam with basic infiltration rate of 5.08mm/hour (Ashaolu, 2016b, p.76). The soil types will greatly influence the rate of infiltration in Osun drainage basin, although, this is dependent on the antecedent soil moisture content of the basin at a given time. The soil types based on soil texture of the study area is presented in Figure 1.3.

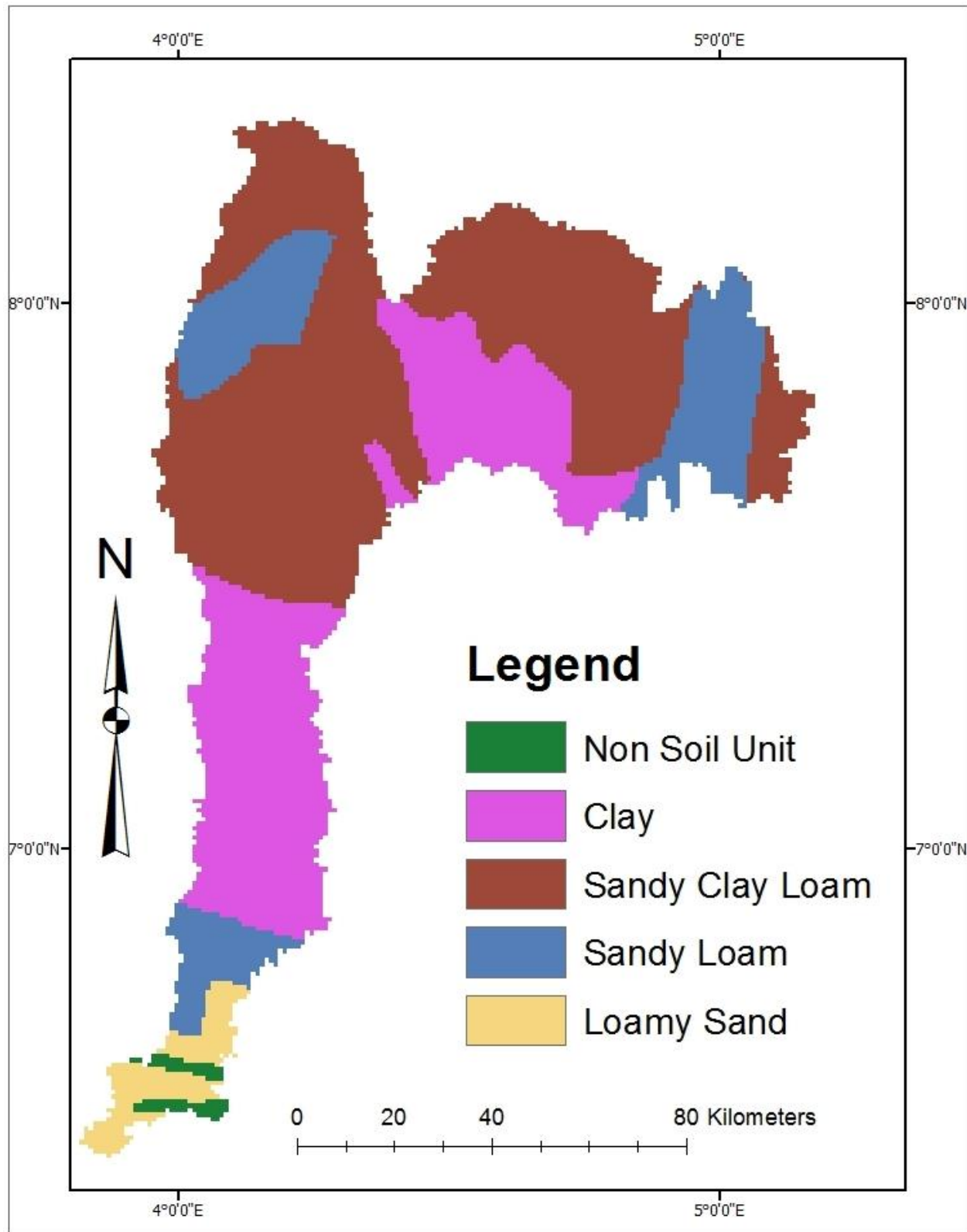


Figure 1.3: The Soil Types of Osun Drainage Basin, Nigeria
Source: Adapted from Ashaolu (2016b, p. 76)

1.8.5 Relief and Drainage System

The relief of the basin is generally undulating and descends from an altitude of about 700 meters in Oke lmesi area to 50 meters and below in areas around Epe and Ibeju Lekki in the southern parts of the basin (Ashaolu, 2016b). Two main relief regions may be identified, the first is the inselberg land scape which is part of the Yoruba highlands, while the second is the coastal plain. The region of inselberg landscape covers more than half of the basin. The northern part is characterized by numerous domed hills and occasional flat-topped ridges. The more prominent hills in this region, are found at Ilesha, Igbajo, Okemesi, Elu and Oba. The total basin relief and relief ratio is 650m and 3.04, respectively. This suggested that the major portion of the basin have gentle slope, hence, low runoff is expected in most part of the basin (Ashaolu, 2016b, p. 85). The implication of gentle slope on groundwater hydrology is that there will less runoff, more infiltration and percolation of the rainwater into the groundwater system. Although, this is dependent on the prevailing climatic and soil moisture conditions at a point in time.

Many Rivers within the basin including the Osun River which is the dominant river, have their source in the northern part of the state. The Osun River is perennial and its volume fluctuates with seasons (Ifabiyi, 2005, p. 3). The river flows through a narrow valley throughout its course across Basement Complex rocks. The tributaries of Osun River that join it at Osogbo include Ajibu River, Elekunkun River, Ogbagba River, Okoko River and Asaba River (Olajire & Imeokparia, 2000). Osun drainage basin is a fourth order drainage basin, with a total number of forty-four streams. The total stream length of the basin is 810.749km and the main stream (Osun River) length is 291.43km (Ashaolu, 2016b, p. 84).

1.8.6 Land Use/Land Cover

The land use pattern within the drainage basin includes land use for residential/settlements, built up areas, bare rocks, soils surfaces, farmlands (annual crops/shrubs and agroforestry/secondary regrowth), vegetation and water bodies. The increasing population density coupled with the long history of agricultural colonization of some parts of the basin has resulted to substantial alteration of the basin's natural environment (Salami, 1995). The basin is covered by secondary forest and the derived savannah mosaic predominates in the northern part. Originally, almost all parts of the basin had a natural lowland tropical rain forest vegetation; but this has however, been replaced by secondary forest regrowth as a result of years of human occupation (Ifabiyi, 2005, p. 2). Salami et al. (1999) also argued that the natural vegetation of so many parts of the basin has been replaced by secondary forest or perennial and annual crops. Hence, the vegetation of the area can be described as derived savannah characterized by gallery of forest along stream sides and tall grasses with scattered perennial trees over land. Some of the reasons for this change in vegetation are fuel wood production, road construction, clay and sand quarrying and traditional farming practices. However, relics of the old rainforest species are still found in some isolated areas (Ifabiyi, 2005, p. 2).

Akinyemi (2005) discovered that the greatest percentage change in land use/land cover of the part of the basin that includes, Ilesha, Ijebu Ijesa, Imesi Ile, Otan Aiyegbaju, Igbajo Efon Alaiye and Oke-Messi among others was recorded on built up areas/roads (88.41%), at an average annual rate of 5.2%, between 1986 and 2002. The study further discovered that Agroforestry/secondary regrowth decreased by 49.06%, bare rocks and soil surfaces increased by 6.6%. The study attributed the change discovered to the expansion of settlements, agricultural land, gold mining activities, fuelwood extraction and intensive biomass burning. In addition, the

increase in bare rock and soil surfaces was linked to the burning of bushes on slopes which is a common practice for easy clearing of land for cultivation. Gasu, et al. (2016) discovered that the urban/built-up areas in Osogbo, one of the major town in the basin have increased by 8135.3 hectares between 1986 and 2012 (27 years), which represents an increase in area coverage of about 415%. They attributed this change to population growth, economic development, education and housing affordability, among others.

In another study conducted by Mengistu and Salami (2007), they reported that a significant conversion of natural vegetation cover to farmland and settlements between 1986 and 2002 in the upper part of the basin. In fact, more natural land area was converted to farmland and settlements/bare surface at the expense of other land cover types. They further stressed that the area covered by Savanna and high forest declined by 71.9 and 8%, respectively. While shrubs/farmlands and settlements/bare surface recorded a net gain of 413.6 and 192.4%, respectively. This suggested that Savanna and high forest diminished at an average rate of 4.5 and 0.5% per annum, respectively, while shrub land/farmland and settlement/bare surface expanded at rates of 25.9 and 120% per annum for the period of 17 years they considered. They therefore, attributed the change in the land use/land cover of the area to the rapid expansion of agricultural land as a result of change in socioeconomic system of the region, as well as expansion of settlements and illegal logging.

Further, the basin is characterized by emergent trees with multiple canopies and lianas. Widespread and persistent practice of rotational bush farming, coupled with the widespread cultivation of cash crops such as cocoa, kolanuts and plantains has led to the destruction of the original vegetation. Most of the fallows vegetation were dominated by the Siam weed, *Chromolaena Odorata*, a rank growth of which protect the ground from direct raindrop impact

(Adediji & Ajibade, 2008, p. 111). The implication of the vegetation type on the hydrology of the basin cannot be overemphasized. This include interception and transpiration which influenced the amount of rainfall that get to the ground surface to infiltrate and percolate to the water table to recharge the aquifer of the basin.

1.8.7 Population

The population of the study area is mainly concentrated in Ede, Ilesha, Oke Imesi, Ogbomosho, Osogbo, Ijebu-jesa, Ejigbo, Iwo, Ifetedo, Ikirun, Ipetu-Jesa, Ila and Ode-Omu (Ifabiyi, 2005, p. 3). The high number of the inhabitants of the basin indicates the need for sustainable management of the groundwater resources of the basin for optimal usage, that will meet the needs of the growing population in view of the challenges of climate change and increasing rate of urbanization within the basin. 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 the constant movement 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 4,281,000. This was used as the basis of estimation for year 2015 at an annual rate of 3.0% (Table 1.1).

Table 1.1: Population Estimates of Osun Drainage Basin

River Basin	1980	1990	2000	2010	2015
<i>Osun</i>	4,281,000	5,753,306	7,731,962	10,391,110	12,046,145

Source: Modified from OORBDA (1982)

1.8.8 Water Supply

The basin has fourteen public water supply schemes located in Esa Odo water Scheme, Ilesha water works, Ede booster stations, Iwo, Eko Ende, Ila Orangun, Mokuro water works, Ifewara water works, Ikeji Ile water works and Ikire. However, potable water supply in more than half of

the drainage basin is supplied by the Ede-Oshogbo water scheme serving several towns and villages. Dams and weirs are found on the major river system within the basin. These include Osun, Erinle, Otin and Ayiba Rivers, Inisa, Okuku and Oyan (Ifabiyi, 2005, p. 3). There is expanded reservoir on Erinle River added to the existing Ede water works at Ede. The expanded reservoir is designed to improve existing water supply system of cities of Osogbo, Ede, Gbongan, Erin-Osun, Ilobu, Ifon and other towns/rural communities located within the Osun drainage basin.

Despite the huge investment on surface water for potable water for all and sundry, majority of the population in this area depend on groundwater (hand dug well or borehole) to meet their domestic water needs because of the erratic and unreliable public water supply from surface water. This is evident in the increasing number of boreholes being sunk within this basin by water agencies and the occurrence of haphazard number of hand dug wells owned by individuals. The rapid spread of borehole and hand dug wells can lead to over abstraction of the groundwater of the basin beyond its natural recharging capacity, hence, groundwater resource depletion.

1.9 Definition of Terms

Climate: is the average atmospheric condition of an environment for a period of time, usually between 30 to 35 years.

Groundwater: is the fresh water stored in the pore spaces of the rocks in the saturated zone beneath the ground surface.

Land use/land cover: land use is the use of landscape by the people either for development, conservation or mixed uses, while land cover is the physical material on the surface of the earth which include grass, trees, bare ground, water, etc.

Recharge: is the soil water in the unsaturated zone that crosses the water table into the saturated zone.

Present day recharge: recharge occurring within a time frame of days or months.

Saturated zone: the zone beneath the water table where the pores and rock fractures are completely filled with water.

Sustainable development: development that meets the needs of the present without putting the needs of the future generation at risks.

Unsaturated zone: zone immediately below the land surface, where the pore spaces are filled with water, air and other gases.

WetSpass: Water and energy transfer between soil, plants and atmosphere under quazi-steady state condition.

1.10 Conclusion

The intrinsic problem of groundwater management in Nigeria was examined in this chapter. Several approaches adopted by earlier studies on groundwater recharge in Nigeria were evaluated. Their weaknesses explored and the need for this present study duly justified. The various socio-physical aspects of the study area were examined viz-a-viz their relationship to groundwater resources.

CHAPTER TWO

CONCEPTUAL FRAMEWORK AND LITERATURE REVIEW

2.0 Introduction

This chapter discussed the conceptual framework and the review of related literature on groundwater recharge. The concept of the hydrological cycle and groundwater sustainability was adopted in this study. Groundwater modelling and the WetSpa-M hydrological model were discussed in this section. The related literature reviewed focused on groundwater recharge and factors affecting it, climate, LULC change and their effect on groundwater recharge from previous studies. Specific attention was paid to groundwater recharge studies in Africa and Nigeria in particular. The gaps in literature especially on groundwater recharge studies in Nigeria were highlighted.

2.1 Conceptual Framework

2.1.1 The Hydrological Cycle and Groundwater Resources

Groundwater recharge is one of the components of the hydrological cycle, and this study conceptualized it as the residual of the 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. 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 endless movement of water in its various stages through the atmosphere, earth, over and through the land, to the ocean and back to the atmosphere is referred to as the hydrological cycle. This process is controlled by the sun, through the stage of changes in water (i.e. evaporation and condensation) that involves storage and release of latent heat. These processes influence the global circulation of the atmosphere, oceans and thus essential in shaping weather and climate. Water gets into the hydrologic cycles as precipitation (rainfall and snow melt) and leaves the system as stream flow/runoff and evapotranspiration (Sophocleous, 2004).

Before rainfall reaches the ground, the vegetation canopy intercepts it, from where it either evaporates or channeled to the ground through stemflow or drips directly to the ground as part of throughfall (Sophocleous, 2004; Jyrkama & Sykes, 2006). The nature of the rainfall intensity and land cover influence the amount of precipitation reaching the ground surface, which may flow overland to streams and tributary channels, ditches and into the subsurface as interflow/lateral subsurface flow, as well as baseflow as it infiltrates into the soil (Sophocleous, 2004).

The infiltrated water into the soil continue to percolate downwards via the vegetative root zone or evaporative zone, from where part of the soil water may be taken up by the plant roots and then transpired through the vegetation canopy. The remaining water in the evaporative zone will continue to percolate deeper into the soil column and eventually become groundwater recharge when it crosses the water table into the saturated zone (Jyrkama & Sykes, 2006, p. 7). It is important to note that, the type of land use/land cover however have a significant impact on infiltration and hence the amount of water that percolates down to the saturated zone. Figure 2.1

shows the visual representation of the endless circulation of water and processes in the hydrological system.

In addition, geology is often seen as the major determinant of groundwater availability in any given environment. In hard rocks environment such as the Osun drainage basin, groundwater occurrence is dependent on the degree of weathered rocks and the level of faults or fractures that can serve as groundwater storage. Despite the relevance of geology, it is arguable that recharge to groundwater is the most significant on a Basement Complex aquifer. This is because this aquifer type is shallow and depends to a large extent on the spatio-temporal variability of groundwater recharge from direct rainfall to replenish the groundwater system.

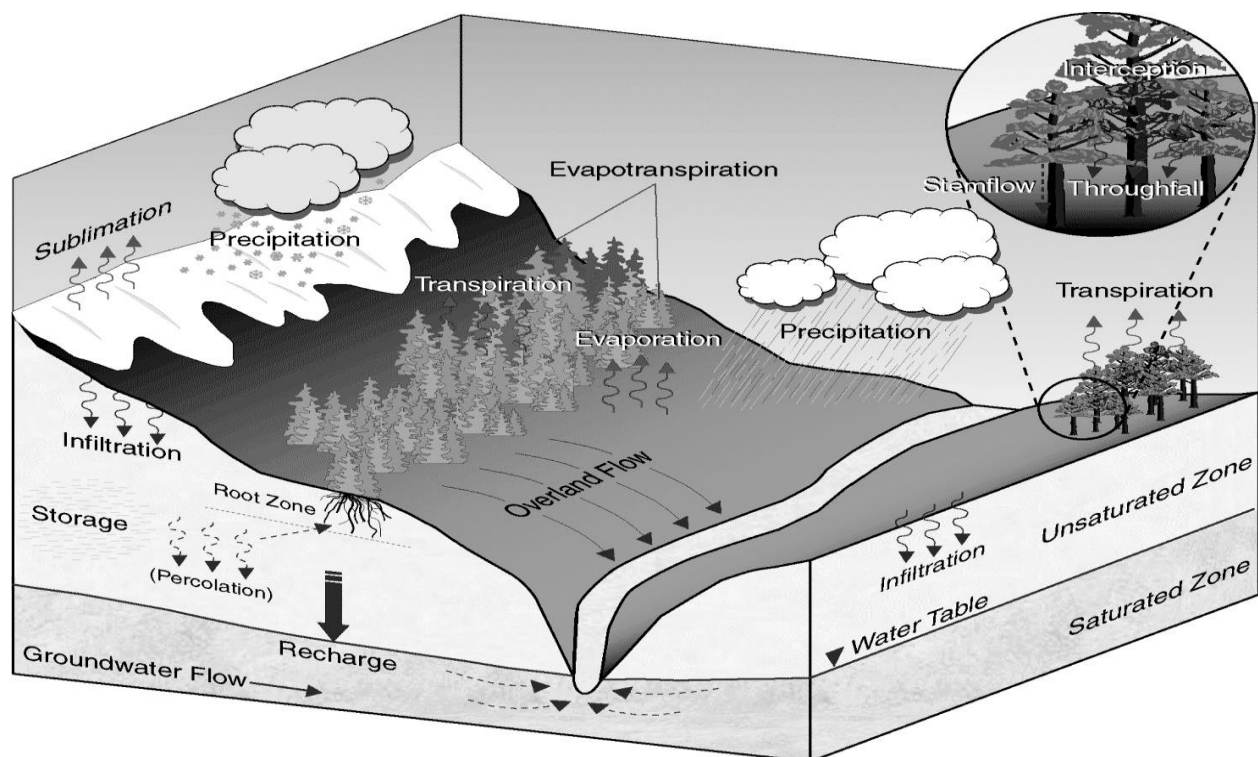


Figure 2.1: The Hydrological Cycle
Source: Adapted from Jyrkama and Sykes (2006, p. 6)

Although weather and climate may be the primary determinants of the quantity of water that infiltrate and percolate to become groundwater recharge in an area, land use/land cover also

plays a significant role. For example, the water balance of an area can be severely altered by urbanization processes. The recharge rate is not only affected in such situation, but the entire climate can also be altered (Lerner et al., 1990). Microclimate may develop that will lead to changes in major climatic elements of the area. Also, an increased impervious area can increase surface runoff considerably, hence decrease the amount of direct groundwater recharge from rainfall. In summary, any changes in climate especially in rainfall amount and actual evapotranspiration, land use/land cover, seasonal changes in vegetation or permanent changes due to urbanization can affect ground water recharge by altering the amount of rainfall, interception, infiltration, surface runoff and evapotranspiration process. All these processes influence the rate, temporal and spatial pattern of recharge to underground water in any given environment.

2.1.2 Concept of Groundwater Sustainability

The groundwater sustainability concept introduced in the 1980s (Custodio, 2002) succeeded the increasingly questionable safe yield (groundwater abstraction that maintains a long-term balance between the amount of annual groundwater withdrawn and annual amount of recharge) approach introduced by Meinzer in the 1920s.

“Sustainable development of a natural resource is the development that meets the needs of the present without compromising the ability of future generations to meet their needs”
(WCED, 1987).

Groundwater sustainability is its development and use in a way that can be maintained for an indefinite term, without resulting to unacceptable environmental, economic or social consequences (Alley, Reilly & Franke, 1999). The view of groundwater sustainability involves four ideas (Kretsinger & Narasimhan, 2005, p. 19), these are:

- i. Surface and groundwater constitute a single resource,
- ii. Groundwater is a finite resource and component of a larger natural resources system. Any actions on one or more components of the system will generally affect the long-term balance of the whole system,
- iii. Groundwater replenishment is greatly influenced by climate variability, as well as natural and enhanced recharge processes. Consequently, groundwater resources development must adapt to the system's varying capacity for renewal,
- iv. Communities need to share and manage groundwater resources so that the natural resources system retains its integrity for the future.

According to Nyagwambo (2006, p. 19) the concept of groundwater sustainability is relatively easy to understand when applied to aquifers of unconsolidated deposits with measurable areal extent depth, and also with meaningful transmissivities and vast storages. This concept however requires the consideration of some points when it is applied to Basement Complex, because of its low storage potential and the resultant thin regolith. A decreasing rate of groundwater recharge on the Basement Complex aquifer will result into falling water level. The energy required to pump water from the longer depth as a result of falling water table will increase. If the decrease exacerbates, it could lead to groundwater exhaustion. The groundwater resources of Basement Complex rocks aquifers largely depend on present day recharge capability (Gustafson & Krasny, 1994). Groundwater management in these types of aquifers may also depend on how accurate seasonal recharge is assessed (Lloyd, 1994). The assessment on a short-term scale such as monthly or daily groundwater recharge capabilities may indeed be necessary. Nyagwambo (2006, p. 20) reported that in Basement Complex aquifers where the storage-to-flux ratio is

relatively low, the accuracy of recharge estimate at smaller time scale becomes paramount for groundwater sustainability.

This means that, on the Basement Complex aquifer, estimating how much groundwater is available at certain period (e.g. monthly) of any particular hydrological year will be crucial to sustainable groundwater management task compared to estimating how much water enter the aquifer yearly. The Osun drainage basin in the western lithoral hydrological zone of Nigeria is underlain by Basement Complex aquifer, and covers 93.28% of the entire basin (Ashaolu, 2016b). This is an indication that the majority of the basin is underlain by a poor aquifer, hence, sustainable groundwater management in the basin will entail estimating how much groundwater is available at a particular time of the hydrological year. This will assist in proper groundwater resources management by controlling the development of groundwater resources that may result in over exploitation and unsustainable groundwater abstraction in the basin.

2.2 Groundwater Modelling

Different methods have been adopted in estimating groundwater recharge over time. They include direct field measurement; empirical methods; water budget approaches; Darcian approaches; isotope/tracer methods; plane of zero flux; base-flow separation; temperature and electromagnetic methods; remote sensing and inverse groundwater modeling. A detailed review of different groundwater recharge estimation methods can be found in Stephens (1996), Scanlon, Healy and Cook (2002), Sophocleous (2004), Jyrkama and Sykes (2006). Each of these methods have their strengths and weaknesses, however, based on the uncertainties associated with direct estimation of recharge in the field, researchers have used groundwater models extensively (Sanford, 2002).

There are two types of groundwater recharge models (coupled and integrated), each with their weaknesses. Despite the many visible shortcomings found in quite a number of these models, they nevertheless provide a more robust and practical way to calculate groundwater recharge compared to the more costly and expensive field methods (Jyrkama & Sykes, 2006, p. 18). Several groundwater recharge estimation models are available and has been used extensively. For example, WetSpa (Wang, Batelaan & De Smedt, 1997); MOGROW (Querner, 1997); TOPOG-IRM (Zhang et al., 1999c); SWAT (Arnold, Muttiah, Srinivasan & Allen, 2000); SWAT and MODFLOW (Sophocleous & Perkins, 2000); WetSpa (Batelaan & De Smedt, 2001); SVAT (Armbruster & Leigbungut, 2001); MIKE-SHE (Graham & Refsgaard, 2001); DREAM (Manfreda, Fiorentino, & Iacobellis, 2005); and WetSpa-M (Abdollahi et al., 2017).

Some of these models, DREAM (Manfreda et al., 2005); SWAT (Arnold et al., 2000); and SVAT (Armbruster & Leigbungut, 2001) are data intensive and require more complex water balance calculations, reducing their application in developing countries where hourly or daily climatic data are scarce (Abdollahi et al., 2017). The WetSpa (Batelaan & De Smedt, 2001) model groundwater recharge on seasonal and annual basis which also limited its application in the Basement Complex rocks terrain, where present day recharge processes are in operation and a small-time scale recharge estimation is needed for sustainable groundwater management. Thus, WetSpa-M hydrological model will be adopted for its capability to estimate groundwater recharge on a monthly time scale. This model incorporates other factors that influence groundwater recharge such as climatic variables, land use/land cover, slope, and soil type, among other. Besides, climatic variables are usually available on a monthly time scale in the study area and Nigeria at large.

2.2.1 WetSpass/WetSpass-M

WetSpass is an acronym for water and energy transfer between soil, plants and atmosphere under quazi-steady state condition (Batelaan & De Smedt, 2001, p. 11). WetSpass was built as a physically based methodology for estimation of the long-term average, spatially varying, water balance components such as surface runoff, actual evapotranspiration and groundwater recharge (Batelaan & De Smedt, 2001, p. 11; 2007). WetSpass model is especially suited for studying long term effects of land use changes and climate on the water regime in a watershed or drainage basin (Batelaan, De Smedt & Triest, 2003; De Smedt & Batelaan; 2003). The model was originally developed and incorporated with GIS Arcview (3.x) as a raster model coded in avenue, the programming languages of Arcview (Al Kuisi & El-Naga, 2013; Abdollahi, Bashir & Batelaan, 2012).

The original WetSpass model simulates all the hydrological processes on a seasonal time scale. The new downscaled model “WetSpass-M” is a raster-based water balance model which partitions precipitation for each pixel partitions into interception, surface runoff, evapotranspiration and groundwater recharge (Figure 2.2). In this new model, coefficients are parameterized base on more universal methods, unlike the previous version with fixed regional values, that is, the model can be applied in any part of the world with accurate results. Distributed land-use, soil texture, groundwater depth, slope and climate data (rainfall, potential evapotranspiration, number of rainy days, wind and temperature) are the required basic input. Four sub-pixel fractions for each land-use class are defined per pixel: vegetated cover, bare soil, open water and impervious surface to address land-use heterogeneity within the pixel (Batelaan & De Smedt 2001, p. 12; Batelaan & De Smedt 2007; Ampe et al. 2012).

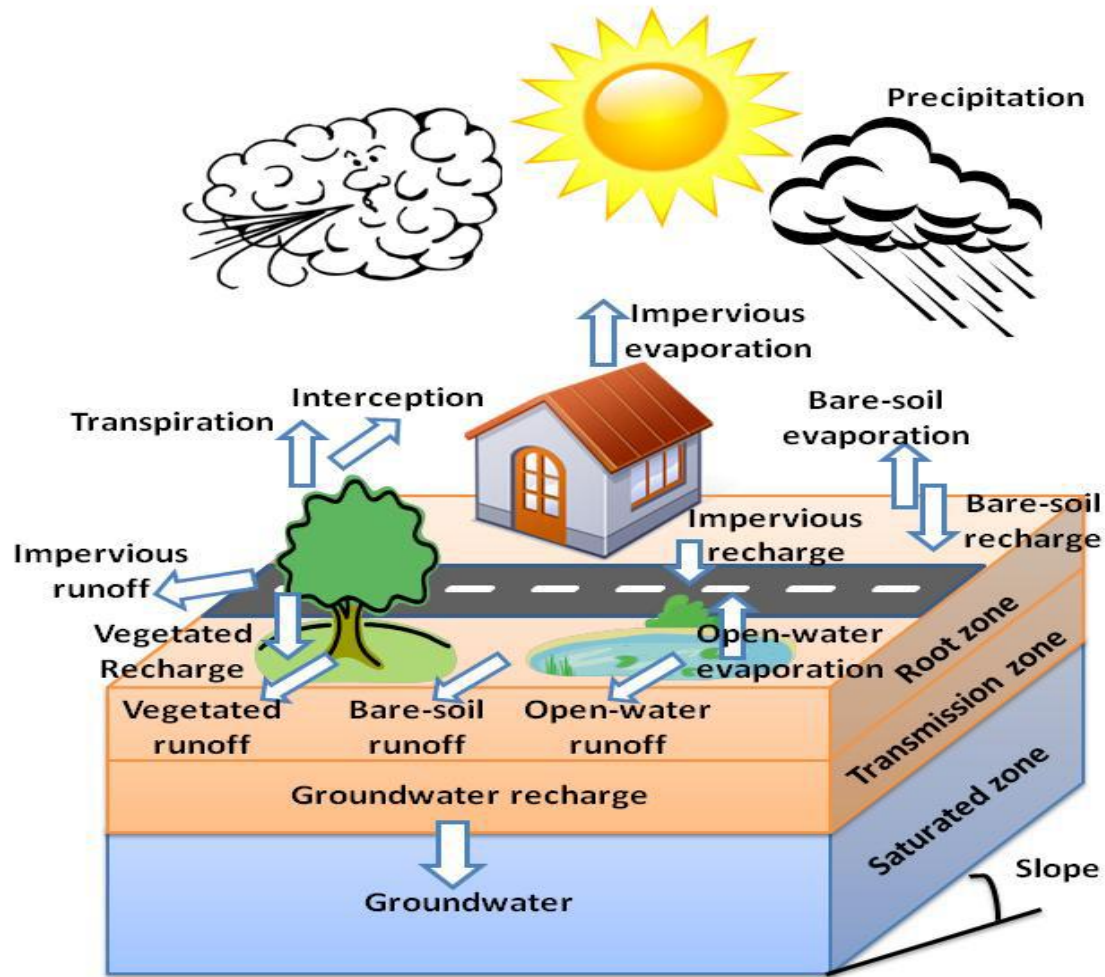


Figure 2.2: Schematic representation of water balance in a non-homogenous land-cover
Source: Adapted from Abdollahi et al., (2017. p. 3)

The implementation of the model consists of four hydrological processes of interception, surface runoff, actual evapotranspiration and recharge. The formulation of the WetSpa-M model by Abdollahi et al., (2017) are detailed in the following sub-sections.

2.2.1.1 Interception

The interception in WetSpa-M is assumed as the fraction of precipitation (rainfall) which is dependent on land-use/land-cover. Seasonal or permanent changes in land-use can modify the Leaf Area Index (LAI), which have effect on interception and evapotranspiration (Abdollahi et al, 2017, p. 3). The total interception estimate is presented in equation 2.1:

$$I_m = P_m I_R \dots\dots\dots (2.1)$$

Where I_m is the interception (mm/month), P_m is monthly precipitation [mm/month] and I_R is interception ratio. Abdollahi et al (2017, p. 3) adopted an interception equation by De Groen and Savenije (2006) to estimate the monthly interception ratio, I_R . The equation is as given in 2.2:

$$I_R = \frac{I_m}{P_m} = 1 - \exp\left(\frac{-I_D dp}{P_m}\right) \dots\dots\dots$$

(2.2) The number of rainy days per month (dp) and the daily interception threshold (I_D) which depends on land-use was adopted from Sutanto, Wenninger, Coenders-Gerrits and Uhlenbrook, 2012 cited in Abdollahi et al (2017, p. 4), this is shown in equation 2.3.

$$I_D = aLAI \left(1 - \frac{1}{1 + \frac{P_m [1 - \exp(-0.463 LAI)]}{aLAI}} \right) \dots\dots\dots (2.3)$$

Where LAI is the leaf area index and a is an interception parameter. Sutanto et al. (2012) found a to be 4.5 mm but the final value can be obtained by calibration (Abdollahi et al., 2017, p. 4). The threshold value I_D is the minimum daily threshold. In other words, if the gross precipitation is below this value, the interception is equal to the daily rainfall and otherwise it is equal to I_D (De Groen, 2002, cited in Abdollahi et al (2017, p. 4).

2.2.1.2 Surface runoff

The amount of surface runoff was estimated using a rational method employed on a monthly time-step using two coefficients (Abdollahi et al., 2017, p. 5), as shown in equations 2.4 and 2.5:

$$SR_m = C_{sr} C_h (P_m - I_m) \dots\dots\dots (2.4)$$

Where SR_m is the monthly surface runoff [mm/month] and C_{sr} actual runoff coefficient [-], C_h is a coefficient [-] representing soil moisture condition (Bahremmand et al. 2007 cited in Abdollahi et al (2017, p. 5):

$$C_h = \left(\frac{\theta_s}{\theta_{sat}} \right)^b \dots\dots\dots (2.5)$$

θ_s is the cell soil moisture content [m³/m³], θ_{sat} is the soil porosity [m³/m³] and b is an exponent [-] representing the effect of rainfall intensity. By including C_h in eq. 2.4, overestimation of surface runoff in areas, like arid and semiarid regions, with low soil moisture and high (potential) evapotranspiration is avoided. Soil moisture data at monthly time-step is scarce C_h value can be approximated between 0 and 1 by integrating evaporative efficiency ratio into the adapted method of Turc (1955) cited in Abdollahi et al (2017, p. 5) at monthly scale (Pistocchi, Bouraoui, & Bittelli, 2008 cited in Abdollahi et al., 2017, p. 5), see equations 2.6 and 2.7.

$$C_h = \frac{P_m}{LP \left(P_m^\alpha + ET_m^\alpha \right)^{\frac{1}{\alpha}}} \quad \text{if } ET_m > P_m \dots\dots\dots (2.6)$$

$$C_h = 1 \quad \text{if } ET_m \leq P_m \dots\dots\dots (2.7)$$

ET_m is potential evapotranspiration [mm/month], LP is a calibration parameter [-] that reduces the potential evapotranspiration depending on the soil moisture. The default is set at 0.65 in WetSpa-M. At a monthly scale, 1.5 was suggested as the value for the exponent α which was the coefficient used for the calibration (Pistocchi et al., 2008 cited in Abdollahi et al., 2017, p. 5).

Surface runoff coefficient comprises of many factors such as surface roughness, infiltration and depression storage. Hence, it is a critical parameter in water balance modelling. The estimation of the potential runoff coefficient per pixel was improved by calculating it from the runoff coefficient for permeable areas (C_{per}) and the runoff coefficient for the impervious part (C_{imp}) in relation to their area. They obtained C_{per} from a weighted sum of land-use, soil, and slope factors, as represented by the 1st, 2nd and 3rd term, respectively in the right-hand side of equation 2.8.

$$C_{per} = w1\left(\frac{0.02}{n}\right) + w2\left(\frac{\theta_w}{1-\theta_w}\right) + w3\left(\frac{S}{10+S}\right) \dots\dots\dots (2.8)$$

Where n is the Manning's roughness coefficient dependent on the land use, θ_w is the volumetric soil water content at wilting point and S is the land surface slope in percentage. See Abdollahi et al., (2017, p. 5) for details. Minimum slope is set at a value of 0.35% (0.2°), to avoid underestimation of the runoff coefficient in flat areas based on the work of Jordan (2007) cited in Abdollahi et al., (2017, p. 5). $w1$, $w2$, and $w3$ are the weights for the three components contributing to C_{per} as shown in equation 2.9.

$$w1 + w2 + w3 = 1 \dots\dots\dots (2.9)$$

The following combination of weights $w1 = 0.4$, $w2 = 0.3$ and $w3 = 0.3$ that best match the runoff coefficients listed in the lookup tables of the original WetSpa model was applied. Roughness of the surface as a land-use factor was considered, which is expressed as the ratio between the Manning's coefficient for open water over that of the corresponding land-use (n). The soil factor is based on the volumetric soil water content at wilting point. The slope factor is parameterized

as a growth-rate relationship because when the slope changed from zero to 47.2 runoff increased proportionally with the slope. Also, rising the percentage of slope from 0.5% to 5% can increase the runoff coefficient from 0.25 to 0.30. See Abdollahi et al., (2017, p. 5) for details on the justification. The weighted potential runoff coefficient (C_{wp}) for a specific pixel was estimated by dividing a pixel into impervious and permeable surfaces, as shown in equation 2.10:

$$C_{wp} = \left(1 - \frac{A_{imp}}{100}\right) C_{per} + \frac{A_{imp}}{100} C_{imp} \quad \dots\dots\dots (2.10)$$

Where C_{imp} is the runoff coefficient of the impervious area, it was obtained using a relation between impervious area and runoff coefficient based on data from Nationwide Urban Runoff Program (NURP US EPA, 1983 cited in Abdollahi et al., 2017, p. 5). A_{imp} is the percentage of impervious surface per pixel. Runoff coefficient varies with the depth of rainfall, thus, coefficient, C_{wp} is adjusted for average daily rainfall in rainy days ($\overline{P_{24}}$ [mm/day/month]) to translate potential to the actual runoff.

$$C_{src} = \frac{C_{wp} \overline{P_{24}}}{C_{wp} \overline{P_{24}} - 5C_{wp} + 5} \quad \dots\dots\dots (2.11)$$

Equation 2.11 was adopted from curve number method correction values for the effect of rainfall on the runoff coefficient (after USDA-NRCS, 1985 cited in Abdollahi et al., 2017, p. 5). The correction for low potential runoff coefficients and rainfall is nearly linear while for higher values this relationship tends to be nonlinear. Due to effect of monthly surface storage, runoff from the current month, contributes to the volumetric runoff of the next month [$m^3 / month$], this is as shown in equation 2.12.

$$Q_{(t)} = xQ_{(t-1)} + 0.001(1-x)ASR_m \dots\dots\dots (2.12)$$

x [-] is delay factor (0-1), $Q_{(t-1)}$ volumetric runoff of the previous month [$m^3 / month$] contributing to the current month, A is area [m^2]. A delay factor of 0 means that during a month with no rainfall there will be no surface runoff. The delay factor is similar to the weighting coefficient in Muskingum method for open channels but ranges between $0 \leq x \leq 1$. Time of concentration and storage in the basin may have an important influence on x . The constant 0.001 is applied for unit conversion.

2.2.1.3 Evapotranspiration

The previous WetSpass estimates evapotranspiration per grid cell by adding up actual evapotranspiration from the vegetated (ET_v), open water (ET_o), bare soil (ET_s) and impervious surface (ET_i) fractions. In a similar way, WetSpass-M uses potential evaporation at a monthly time scale and vegetation coefficients for estimation of actual evapotranspiration. For calculation of the reference transpiration from the potential evapotranspiration (ET_p), a vegetation coefficient is required (Abdollahi et al., 2017, p. 6) which is estimated as shown in equation 2.13:

$$c = \frac{1 + \frac{\gamma}{\Delta}}{1 + \frac{\gamma}{\Delta} \left[1 + \frac{r_c}{r_a} \right]} \dots\dots\dots (2.13)$$

Where γ is the psychrometric constant [kPa/°C], which is the gradient of the first derivative of saturated vapor pressure curve (slope of saturation vapor pressure at the temperature of atmosphere), r_c (bulk) surface resistance [s m⁻¹], and

$$r_a = \frac{1}{K^2 U_a Z_a \left(\ln \left(\frac{Z_a - Z_d}{Z_o} \right) \right)^2} \dots\dots\dots (2.14)$$

Where K is the von Karman constant (0.41), U_a [m/s] is the wind speed at elevation Z_a (m), Z_d is zero displacement elevation [m] and Z_o is the aerodynamic roughness height of surface [m]. For vegetated groundwater discharge areas, the vegetation coefficient is equal to 1. Thus, the reference transpiration (T_{rv}) is as shown in equation 2.15.

$$T_{rv} = cET_p \dots\dots\dots (2.15)$$

In vegetated areas where the groundwater level is below the root zone the actual transpiration is modified as shown in equation 2.16.

$$T_v = (1 - a_1^{w/T_{rv}}) T_{rv} \dots\dots\dots (2.16)$$

Where a_1 is a calibrated parameter (adopted from WetSpass) related to the sand content of the soil type and w is the available water for transpiration, which is defined as shown in equation 2.17.

$$w = p_m + (\theta_{fc} - \theta_{pwp}) R_d \dots\dots\dots (2.17)$$

Where R_d is the rooting depth, $\theta_{fc} - \theta_{pwp}$ is the plant available water content per time step, stated as the difference in water content at field capacity and at permanent wilting point. Summation of interception and actual transpiration gives the actual evapotranspiration for the vegetated area (ET_v). The total actual monthly evapotranspiration per pixel (ET_m [mm/month]) is now as shown in equation 2.18.

$$ET_m = a_v ET_v + a_s ET_s + a_o ET_o + a_i ET_i \dots\dots\dots (2.18)$$

with respectively area fraction and evapotranspiration for vegetated area a_v , ET_v , bare soil a_s , ET_s , open water a_o , ET_o , and impervious surface a_i , ET_i (Batelaan & De Smedt 2001, p. 15; Batelaan & De Smedt 2007, P. 340).

2.2.1.4 Recharge

WetSpass model was developed with the aim of simulating long-term average spatial patterns of groundwater recharge on seasonal basis (Batelaan & De Smedt 2001, p. 11). Just like the earlier WetSpass, WetSpass-M, now estimated monthly recharge (R_m (mm/month)) as the residual term of the monthly water balance as shown in equation 2.19.

$$R_m = P_m - SR_m - ET_m \dots\dots\dots (2.19)$$

Recharge is a rather slow process, thus, monthly base-flow in each cell is estimated based on the storage of the previous month and the groundwater recharge in the considered month:

$$Q_{b(t)} = \beta Q_{b(t-1)} + 0.001 N_m (1 - \beta) \oslash R_m \dots\dots\dots (2.20)$$

Where β is a storage parameter [-] (0 to 1), $Q_{b(t-1)}$ is the base-flow from the previous month [$m^3 / month$], N_m is number of days per month ($\approx 30days$) and $\phi [m^2 / days]$ is the recharge contribution parameter to current base-flow. For pixel area $A [m^2]$ with recession index $k [day]$, ϕ would be (Arnold & Allen 1999) as shown in equation 2.21.

$$\phi = \frac{1.15A}{k} \dots\dots\dots (2.21)$$

2.3 Literature Review

2.3.1 Groundwater Recharge

The deep soil water that migrates past the evaporative and root zones in the vadose zone, which is no longer available to plants are referred to as groundwater recharge by soil scientist (Jyrkama & Sykes, 2006, p. 6.). Precipitation is the driving force for natural groundwater recharge; although, other processes may also lead to groundwater recharge (Jyrkama & Sykes, 2006, p. 6). Lerner et al., (1990) classified groundwater recharge into three different processes:

- i. **Direct Recharge:** is the addition of water to the groundwater system in excess of soil moisture deficits and evapotranspiration by direct vertical percolation of precipitation through the unsaturated zone.
- ii. **Localized Recharge:** is an intermediate form of recharge that occurs from the horizontal surface concentration of water in local joints and depressions.
- iii. **Indirect Recharge:** is the water that flow to the water table through the beds of surface water courses, such as rivers and lakes.

Obuobie (2008) used the classifications of Beekman, Gieske and Selaolo (1996), Lerner et al. (1990) and Lerner, Yang, Barret and Tellam (1999) to classified groundwater recharge as follow:

- i. Direct or indirect on the basis of the origin of the recharging water,
- ii. Piston or preferential flow on the basis of the flow process through the unsaturated zone,
- iii. Point, line or areal recharge on the basis of the area on which it acts, and
- iv. Present-day, short-term or long-term recharge on the basis of the time scale during which it occurs.

The classification of recharge according to (Beekman et al., 1996; Lerner et al., 1999; Lerner et al., 1990) is shown in Table 2.1. Recharge can also be classified as actual, which refers to water that has infiltrated and reaches the water table, or potential, which refers to infiltrated water that may or may not reach the water table because of the unsaturated zone processes or the ability of the saturated zone to accept recharge (Rushton, 1997). It is important to note that a combination of the recharge categories can occur in any area.

Table 2.1 Definitions of Categories of Groundwater Recharge

<i>Sn</i>	<i>Category of recharge</i>	<i>Definition</i>
<i>On the basis of origin of water</i>		
1.	Direct	Water added to the groundwater in excess of soil moisture deficits and evaporation by direct vertical percolation of precipitation through the unsaturated zone
2.	Indirect	Percolation to water table following runoff and localization in joints, as ponding in low lying areas and lakes, or through the beds of surface watercourses
<i>On the basis of flow mechanism through the unsaturated zone</i>		
3.	Piston flow	precipitation stored in the unsaturated zone is displaced downwards by the next infiltration/percolation event without disturbance of the moisture distribution
4.	Preferential flow	Flow via preferred pathways/macro-pores, which are sites (e.g., abandoned root channels, burrows, fissures) or zones (e.g., stream beds) in the unsaturated zone with a relatively high infiltration and/or percolation capacity
<i>On the basis of area on which it acts</i>		
5.	Point recharge	Recharge at a site, with no areal extent
6.	Line recharge	Recharge from a line source e.g., drainage feature or river
7.	Area recharge	Recharge over an area

On the basis of time scale during which recharge occurs		
8.	Present day recharge	Recharge occurring within a time frame of days/months
9.	Short time recharge	Recharge covering a short period in the past or predicted for the near future within a time frame of months/years
10.	Long time recharge	Recharge over a longer period in the past (palaeo-recharge) or predicted for the future (accounting for climate change) within a time frame of tens up to thousands of years

Source: Adapted from Obuobie (2008)

2.3.2 Factors Influencing Groundwater Recharge

Recharge is a function and interplay between various key environmental factors such as climate, soil and geology, vegetation and land use, topography, as well as urbanization. These factors are break down and discussed in subsection 2.3.2.1 to 2.3.2.5:

2.3.2.1 Precipitation

The most significant parameter in groundwater recharge process is precipitation and it is the major driving force in the hydrologic cycle, which provides the water that will ultimately result in recharge of the groundwater system. The influence of climatic factors such as wind and temperature on precipitation result in a very complex and dynamic precipitation distribution pattern. Consequently, determining the amount and rate of precipitation over an area is extremely difficult as a result of high the spatial and temporal variation. Also, the duration, velocity and intensity of storm events can vary widely over an area (Jyrkama & Sykes, 2006, p. 7). Lerner et al. (1990) reported that low intensity rainfall may lead to no recharge as a result of high rate of evapotranspiration, whereas the same amount in a shorter period may be sufficient to saturate the soil and cause recharge. All these assertions are pointing to the fact that spatial and temporal variation, velocity and intensity of storm events make the quest of determining the amount and rate of precipitation over an area difficult.

Accurate measurement of precipitation over an area is also difficult. The instrument commonly used for point measurements (tipping bucket, weighing, capacitance and optical types) measure the accumulation of rainfall in a particular location. These instruments can however be subject to large measurement errors (Habib, Krajewski, & Kruger, 2001; Jyrkama & Sykes, 2006, p. 7), thus providing poor estimates of the spatial distribution of rainfall over a catchment (Jyrkama & Sykes, 2006, p. 7). According to Sophocleous (2004, p. 25), water balance equation is usually adopted to quantify the components of the hydrological cycle in which recharge estimation is usually based. This is because a basic understanding of this water cycling is required in order to understand and estimate aquifer recharge. The water balance equation as presented by Sophocleous (2004, p. 25) is shown in Eq. 2.22

$$P + I = RO + D + ET + S \dots\dots\dots (2.22)$$

Where P is precipitation, I is irrigation, RO is surface runoff, D is deep drainage and recharge, ET is evaporation and S is water stored in the soil. Under non-irrigated conditions, where $I = 0$, the left-hand side of Eq. 2.22 is fixed because it is outside of human control. However, point measurement were provided in most direct measurements of hydrologic variables that are associated to recharge evaluations, and failed to integrate the variables shown in Eq. 2.22 in terms of space and time. Estimating and predicting recharge over space and time, and regionalizing point measurement pose a major challenge in recharge evaluation because recharge varies across the landscape, as a result of the variation in several environmental factors that controls recharge (Sophocleous, 2004, p. 25).

Based on the problem of recharge evaluation reported by Sophocleous (2004, p. 25), most groundwater modelling applications adopted a spatially constant rainfall rates, or they are averaged over time in steady state analyses (Jyrkama & Sykes, 2006, p. 7), Each individual

storm events are seldom accounted for and monthly or annual averages are usually used. However, there is always a spatial variation in rainfall even over short distances; therefore, the spatial variation of rainfall should not be discarded when estimating recharge in a basin or catchment especially over a region.

2.3.2.2 Land Use/Land Cover

The water balance which recharge is a component is also greatly influenced by plant cover and land use practices (Sophocleous, 2004, p. 27). The type and nature of land cover can have a significant influence on infiltration, and thus on groundwater recharge (Jyrkama & Sykes, 2006, p. 8). The studies of Williamson (1990) and Walker, Zhang, Ellis, Hatton and Petheram (2002) in Australia clearly demonstrated the influence of clearing native vegetation and replacing it with shallow-rooted annual crops and pastures on recharge rates. Altering the natural land surface and increasing the number of impervious surfaces as a result of urbanization can also have significant effect on groundwater recharge (Lerner et al., 1990; Lerner, 2002).

Several studies have focused on modelling the effect of land use changes on groundwater recharge. Impacts of urbanization and changes in land use types for sustainable groundwater development was studied in Israel and it was discovered that urban development have negative impact on groundwater quality (Carmon, Shamir & Meiron-Pistiner 1997; Collin & Melloul, 2001). The overall impacts of land use changes on runoff and recharge as a result of wildfires, afforestation, and land abandonment was studied in Spain. It was discovered that the increase in vegetated land cover has negative effect on human water availability in semiarid areas, as a result

of decreased aquifer recharge rates (Bellot, Bonet, Sanchez & Chirino, 2001). The mean annual response of groundwater recharge to land cover changes was estimated by Finch (2001) in the rural catchment of southern England. He observed that changes in land use resulted into changes in the recharge pattern, but there is no significant influence on the overall total recharge in the catchment.

2.3.2.3 Vegetation

The influence of vegetation on hydrologic balance is complex and dependent on factors of crop coefficients, growth stages, rooting depths, soil, water and climatic conditions (Sophocleous, 2004, p. 27). Vegetation alters rate of recharge by directly disturbing the passage of precipitation from the atmosphere to the land surface and to the water table. The vegetation cover deflects part of the falling precipitation, which either evaporates, or is conveyed to the ground through stem-flow, or drops directly to the ground as part of through-fall (Le Maitre, Scott & Colvin, 1999). It is difficult to quantify these processes because they are influenced by different climatic parameters, which include intensity and duration of rainfall, temperature, wind speed, and also the physical characteristics of the individual plants (Larcher, 1983; Jyrkama & Sykes, 2006, p. 8). Despite the difficulty in quantifying these processes, they can still have a significant impact on the recharge process (Taniguchi, Tsujimura & Tanaka, 1996; Finch, 1998; Jyrkama & Sykes, 2006, p. 8).

According to Jyrkama and Sykes (2006, p. 8) the greatest influence of vegetation on recharge is through evaporation and transpiration. These terms are usually combined together with direct

evaporation from the soil and referred to as evapotranspiration. Over time, various methods have been developed to estimate evapotranspiration, which include Penman (1948); Penman-Gridley model (Gridley, 1969); Thornthwaite and Mather (1957); Penman-Monteith (Monteith, 1965); Priestley and Taylor (1972). Also, plant roots play a significant role in the recharge process, as they enable plants to draw water from deep in the vadose zone and even from the saturated zone, which reduces the amount of percolating water that reaches the water table, and also create preferential flow paths and channels that aid water flow through the soil profile (Le Maitre et al., 1999; Jyrkama & Sykes, 2006, p. 9).

Studies have discovered that rooting depth, which depends on soil type, available water, and the type of plant, leaf area index or the ratio of leaf area to ground cover had a significant effect on groundwater recharge rates (Finch, 1998; Zhang, Hume, O'Connel, Mitchell, Milthorpe & Yee, 1999a; Zhang, Dawes, Hatton, Hume, O'Connel & Mitchell, 1999b). Larger leaf areas lead to larger interception of precipitation as well as potentially higher transpiration rates resulting to decreased groundwater recharge (Jyrkama & Sykes, 2006, p. 9). Vegetation has both positive and negative influence on recharge. Vegetation can intercept rainfall and transpires water obtained from the rooted soil profile. It can also enhance infiltration by reducing amount of overland flow and creating surface storing of water that might have runoff. In addition, plant root systems may enhance recharge rates by developing macro-pores and path-ways in the soil profile, and by vertical transfer of water as a result of differences in moisture potentials (Le Maitre et al., 1999; Burgess, Adams, Turner, White & Ong, 2001; Jyrkama & Sykes, 2006, p. 9).

2.2.3.4 Soil Properties

In the unsaturated zone, hydraulic properties of the soils are extremely responsive to moisture content and pressure head distributions (Jyrkama & Sykes, 2006, p. 10). Oftentimes, a little

change in the volumetric water content can lead to a change in the hydraulic conductivity by two or more orders of magnitude (Rushton, 1988). The soils in the unsaturated zone hardly exhibit uniform attributes or characteristics. They often consist of layered sands, silts, and clays, which result in varying moisture distributions. Instability in the wetting front and minute shifts changes in the permeability structure can also result to flow fingering. This fingering process is pronounced by initially dry, layered, coarse-grained systems. However, the antecedent moisture contents dominant in the field in humid climates will generally inhibit its occurrence (Kung, 1990; Selker, Parlange & Steenhuis, 1992; Sililo & Tellam, 2000; Jyrkama & Sykes, 2006, p. 10). Studies have reported that large variability in recharge can take place even across uniform soils as a consequence of topography, leading to depression focused recharge (Freeze & Banner, 1970; Winter, 1983; Jyrkama & Sykes, 2006, p. 10).

2.3.2.5 Urbanization

Urbanization can severely change the water balance of an area, not only is the recharge rate influenced, but the whole climate can also be changed (Lerner et al., 1990; Jyrkama & Sykes, 2006, p. 9). The amount of direct groundwater recharge resulting from precipitation normally reduced as a consequence of impervious surfaces while surface runoff increased significantly (Rose and Peters, 2001). Most often, urban centers import their consumption water from sources outside the centres, thereby increasing the amount of water available in the area. However, a part of this imported water might later become recharge through septic tanks, leaking sewer and water distribution systems, and over-irrigation of lawns and parks (Lerner et al., 1990; Simmers, 1998; Yang, Lerner, Barret & Tellam, 1999; Foster, 2001; Lerner, 2002; Jyrkama & Sykes, 2006, p. 9).

This indirect induced recharge can result in significant recharge rates or balance the loss of precipitation that ought to become recharge but lost to runoff as a result of impervious surfaces (Lerner, 2002; Jyrkama & Sykes, 2006, p. 9). It is important to note, that determining the accurate spatio-temporal distribution pattern of indirect recharge is extremely complicated to consider or estimate in any modeling exercises (Yang et al., 1999; Jyrkama & Sykes, 2006, p. 9). Jyrkama and Sykes (2006, p. 9) further explained that any changes in land cover, seasonal or permanent changes as a result of urbanization, can influence groundwater recharge by changing the interception, infiltration, surface runoff, evaporation, and transpiration processes experienced in urbanized area or environment.

2.3.2 Climate, Land Use/Land Cover and Groundwater Recharge: Global Perspective

UNESCO International Hydrological Programme (IHP) and its Groundwater Resources Assessment under the Pressure of Humanity and Climate change (GRAPHIC), in an attempt to raise the global attention on the interaction of climate and groundwater, supported the compilation of a book edited by Triedel et al. (2012) titled “Climate Change Effects on Groundwater- A Global Synthesis of Findings and Recommendations”. They made a compilation of about 20 case studies on climate and groundwater resources from more than 30 different countries. The studies in the book addressed groundwater resources in different hydrological settings ranging from mountainous to coastal aquifer systems, including unconfined, semi-confined and confined aquifers to unconsolidated to fractured-rock material and different climatic settings/scenarios.

The studies of groundwater under the influence of climate has not received enough consideration in developing countries especially Africa and Nigeria in particular. Few studies have been carried out in this part of the world mainly because of the dynamic nature of groundwater

resources and the dearth of hydrological data and expertise. However, based on the factors that influence groundwater resources, the impacts of climate on groundwater resources cannot be considered alone without considering the influence of human pressure which can be in form of abstraction or land/use land cover changes among others. This approach is believed will give a holistic understanding of the groundwater resources in any part of the world for sustainable development.

Bouraoui, Vachaud, Li, Le Treut, and Chen (1999) developed a general approach to estimate the influence of potential climate changes on groundwater resources. They proposed a general methodology in order to disaggregate outputs of large-scale GCMs models that can be used directly in hydrologic models. The method is applied to a CO₂-doubling scenario through the development of a local weather generator and its impact was examined on groundwater recharge in France. The outcome of their study revealed that recharge would decline in their study area as a result of increase in atmospheric CO₂. Stone, Moomaw, and Davis (2001) adopted a methodology that combined GIS analysis, empirical surface modelling and water balance calculations to examine the groundwater recharge within the hydrographic basins in the Great Basin region of the South West United States.

Croley and Luukonen (2003) adopted a regional scale MODFLOW model of Lansing, Michigan to examine the influence of climate change on groundwater resources of the area. Two separate GCMs were first used to estimate baseflow rates and the recharge in the regional groundwater model was modified on the condition of the differences in the estimated baseflow from the two GCMs. Their results show that the simulated groundwater levels were predicted to increase or decrease as a result of climate change, depending on the GCMs adopted. Allen et al. (2004)

modeled the sensitivity of an aquifer to changes in recharge and river stage consistent in the Grand Forks aquifer, in the south-central British Columbia Canada, using the four climate change scenarios predicted for the area. They computed average annual recharge rates for each of the four scenarios and applied it across the region. Their results suggested that variations in recharge to the aquifer under the different climate-change scenarios, modeled under steady-state conditions, have a much smaller influence in the overall groundwater table configuration.

Brouyere, Carabin, and Dassargues (2004) evaluate the influence of climate change on the water balance of a chalky groundwater basin in Belgium. An integrated hydrological model (MOHISE) was adopted which consider most hydrological processes in a physically consistent way. The model comprised of three sub models, each for soil, surface water and groundwater that were linked through flux boundaries. Monthly changes in precipitation and temperature were computed under three different GCMs scenarios, which was later used to modify the daily historical record to obtain climate change scenarios. Two of the three scenarios revealed a decreasing groundwater levels, while the last model shows no significant change in groundwater level. Holman (2006) reported an integrated approach to evaluate the effect of regional climate and socio-economic change on groundwater recharge of East Anglia, UK. Different factors may influence groundwater recharge in the future. These include change in rainfall and temperature regimes, coastal flooding, urbanization, woodland establishment, and changes in cropping and crop rotations systems. Relevant sources of uncertainty and weakness in recharge assessment were discussed in the context of the results. The doubt and relevance of socio-economic scenarios in investigating the causes of unknown future changes were highlighted. The results of the study indicated that changes to soil properties are occurring in a way such that the soils of the future may not have the same infiltration capacities and properties as existing soils.

Scibek and Allen (2006) assessed the future effect of climate change on groundwater resources by linking climate models and groundwater model in an unconfined aquifer in South central British Columbia, Canada. Climate change scenarios from the Canadian Global Coupled Model 1 (CGCM1) were downscaled to local conditions and inputted to the recharge model. The direct recharge to the aquifer was simulated from infiltration of rainfall. The model comprises of spatially distributed recharge zones, shown in the Hydrologic Evaluation of Landfill Performance (HELP) hydrologic model connected to a geographic information system (GIS). They adopted a three-dimensional transitory groundwater flow model, incorporated in MODFLOW, was used to simulate four climate scenarios (1961–1999 present, 2010–2039, 2040–2069, and 2070–2099) and compare the results to present groundwater levels. The predicted future climate for the area will result in more recharge to the unconfined aquifer from spring to the summer season. Although, the overall impact of recharge on the water balance is minute as a result of major river-aquifer interactions and river water recharge.

Ranjan, Kazamaa, and Sawamoto (2006) examined the effects of climate change particularly salt-water intrusion on fresh groundwater resources in a water resources stressed coastal aquifers. Their investigation adopted the Hadley Centre climate model, HadCM3 with high and low emission scenarios (SRES A2 and B2) for years 2000–2099. There is an increasing long-term trend in all the stressed areas, with an exception of the northern Africa Shara region as shown by the annual fresh groundwater resources loss under the two scenarios adopted. They discovered a poor correlation between the major climatic drivers (precipitation and temperature) and fresh groundwater loss. Conversely, aridity index and fresh groundwater loss revealed a strong inverse relationship. Jyrkama and Sykes (2006) used the hydrologic model HELP3 to generate a physically based and highly detailed recharge boundary condition for groundwater modelling.

The model uses daily rainfall and temperature records in addition to land use/land cover and soil data. Their results provided a spatially distributed daily groundwater recharge rates for the Grand River watershed over a period of 40 years. Further, the results indicated that on average, only one-fifth of the overall rainfall in the watershed contributes to direct groundwater recharge, with an average recharge rate of approximately 200mm/yr.

Woldeamlak, Batelaan, and De Smedt (2007) modeled the impacts of climate change on the groundwater systems in the Grote-Nete catchment, Belgium adopting wet (greenhouse), cold or NATCC (North Atlantic Thermohaline Circulation Change) and dry climate scenarios. Seasonal and annual water balance components as well as groundwater recharge were simulated using the WetSpa model. Also, mean annual groundwater elevations and discharge were simulated using MODFLOW groundwater model. WetSpa results for the wet scenarios revealed that wet winters and drier summers are expected relative to the present situation. MODFLOW results for wet high scenario showed groundwater levels increase by as much as 79 cm. Results obtained for cold scenarios revealed drier winters and wetter summers relative to the present. No recharge was obtained during the summer, which is majorly associated to high evapotranspiration rates and low rainfall.

Hsu, Wang, Cheu, Chen, and Ma (2007) in Pingtung Plain Taiwan, evaluated the response of groundwater system to climate variability using numerical modeling method. This is an area which is experiencing pronounced declination in groundwater quantity and quality as a result of overexploitation. Also, the evidence of climate change leads to the instability of surface-water resources and emphasized the relevance of the groundwater resources in the area. Applying the linear regression model of rainfall to the next two decades, the result revealed a declining water level in the proximal fan. They concluded that suitable water resources management in response

to hydrological effects of the future climatic change are desirable. Fu, Barber and Chen (2007) used ArcGIS Geostatistical Analyst tool to create a method to evaluate the effects of global climate change on regional hydrological regimes, which can be used and expanded to different watersheds. They applied it to Spokane River Watershed and the results show that a 30% rainfall increase leads to a 50% increase of stream flow when the temperature is normal, while there is only a 20–30% increase in stream flow when the average annual air temperature is 1.5°C higher than normal. On the contrary, a 20% rainfall decrease results in approximately 25–30% decrease in stream flow when the temperature is normal, but a 45% decrease in stream flow if the temperature is 1.5°C higher than normal. The study results can be used as reference conditions for long-term watershed water management strategies under global warming scenarios (Singh & Kumar, 2010).

The implications of the future predicted climate change on groundwater recharge resources for the arid and semi-arid south Okanagan region, British Columbia was modelled by Toews (2007). HELP 3.80D hydrology model was used to modeled spatial recharge using the available data on soil and climate of the region. Stochastically-generated climate from three different GCMs were adopted to evaluate the impacts of climate change on recharge. The mean annual recharge estimated was 45 mm/year, which is expected to increase slightly with climate change. Though, crop water demand and growing season will increase which will result to additional strains on water use in the region. The MODFLOW model also used to simulate the future water table which gives an increasing water table in the future which will mainly be influenced by increase in irrigation application.

The effect of LULC on groundwater recharge was studied by Zamlot, Verbeiren, Huysmans and Batelaan (2015) and they discovered that forest land-use type has a positive higher effect on

groundwater recharge in Flanders, Belgium. Albhaisi, Brendonck, and Batelaan (2013) examined the effect of LULC change on groundwater recharge in upper Berg catchment, South Africa using WetSpa hydrological model. They discovered that groundwater recharge on bare LULC class increases significantly from 23% in 1984 to 64.7% in 2008. The influence of LULC change on groundwater recharge was investigated by Dams, Woldeamlak, and Batelaan (2008) in Kleine Nete Catchment, Belgium. They adopted four LULC change between 2000 and 2020. They observed that recharge reduced in urban centres in all the scenarios, which was highest in Scenario A1. Pan, Gong, Zhou, Li, and Nakagoshi (2011) investigated the hydrological processes and recharge ability of various land use types in Guishui River Basin, China, using WetSpa and GIS. They discovered that the annual-lumped groundwater recharge rate decreases in the order of cropland, grassland, urban land, and forest, which has resulted in a decrease of 4×10^6 m³/year of groundwater recharge between 1980 and 2005. They attributed the decrease in groundwater recharge observed to an increase in urban area and rural settlements; and decrease in cropland land use class.

2.3.3 Groundwater Recharge Studies in Africa

Chemical and isotopic tracers was adopted by Sami (1992) in the study of groundwater recharge mechanisms and geochemical processes of a catchment in the Eastern Cape, South Africa. He hypothesized that high rainfall event intermittently disintegrate heap of superficial meteoric salts and leach them into groundwater system. The geochemical variations in the results show that there are variations in volume of recharge, evaporative enrichment and extent of leaching of accumulated surficial salts. Taylor and Howard (1996) estimated groundwater recharge of the Arouca sub-basin in Victoria Nile basin of central Uganda by adopting Soil Moisture Deficit (SMD). The estimated recharge was compared to stable isotope data and groundwater flow

modelling. The groundwater recharge estimated was 200 mm/annum, which was dependent on the number of heavy individual rainfall events but not the total volume of the annual rainfall.

Butterworth et al. (1999a) used rainfall data, groundwater level data and soil moisture data to investigate the relationship between recharge and recession in the superficial weathered aquifers of the Romwe catchment. The results revealed that in a free draining soil profile, groundwater levels responded in short time whenever there was a large rainfall event. They observed minimal annual fluctuations and gradual rise in groundwater levels in zones of thick clay soils. Butterworth, Mugabe, Simmonds and Hodnett (1999b) also examined the pattern of rainfall redistribution in a red clayey soil and a sandy-clay soil. They measured runoff in the sub-catchments of Romwe catchment during the cropping season and the subsequent dry season. Their results revealed that in years of low/evenly distributed rainfall, surface water redistribution is of great relevance to groundwater.

Alemaw and Chaoka (2003) created a GIS hydrological model to estimate water balance component such as surface runoff in Southern Africa using soil moisture deficit principle. Soil and land cover data were used to calculate runoff by adopting the Curve Number (CN) method of USDA-SCS (1985). The effectiveness of a SMD method for the different climate regions (arid, semi-arid, and humid) in South Africa was not accounted for. The model estimated mean annual runoff generated in Southern Africa to be 151 mm/annual. Hamza, Added, Rodríguez, Abdeljaoued and Ben (2007) estimated groundwater recharge in Semi-arid Tunisia to range from 61 to 108 mm/annum by incorporating the equation of Williams and Kissel (1991) into GIS. The method connects groundwater recharge to precipitation within a defined four hydrological soil. Nyagwambo (2006) adopted three methods to examined groundwater recharge in Nuyndo catchment, Zimbabwe. These are the chloride mass balance, daily catchment water balance and

the water table fluctuation methods. The three methods employed in the study gave the same range of annual groundwater recharge, that showed high spatial variability across the catchment. The study concluded that single point measurements of recharge is not a good indicator of regional recharge estimation. The study however proposed a simple model for assessing potential recharge using rainfall characteristics, soil and vegetation properties.

Vouillamoz et al. (2008) examined depth of water table, aquifer transimivity, aquifer total porosity, and specific yield capacity using magnetic resonance sounding (MRS) in semi-arid Niger. The water table fluctuation method was adopted to estimate groundwater recharge and the groundwater recharge was about 2 mm/annum before land clearance 1950s, however, the estimated groundwater recharge rates between 1995 and 2005 was about 23 mm/annum. The study revealed the effect of vegetation on groundwater recharge rate. Mileham et al. (2008) investigated the influence of different rainfall interpolation methods on groundwater recharge estimate in the humid tropics of equatorial Uganda. They estimated runoff as a percentage of daily precipitation above a 10 mm threshold, and calculated potential evapotranspiration from pan evaporation because of the paucity of hydro-meteorological data in the study area. The study estimated a mean annual recharge of 104 mm/annum and mean annual surface runoff of 144 mm/annum for the study area.

Milewski, Taylor, Thompson, Todd, and Tindimugaya. (2009) estimated runoff and groundwater recharge in the arid Sinal Peninsula and the eastern desert of Eygpt using Soil Water and Analysis Tools (SWAT). The study used large rainfall events data sets from remote sensing as input into the SWAT model. Teklebirhan, Dessie, and Tesfamichael (2012) estimated groundwater recharge, evapotranspiration and surface runoff using WetSpass model in Illala catchment, northern Ethiopia. Long term mean hydro-meteorological data and physical

characteristics of the catchment such as land use/land cover, soil type, topography, groundwater level and slope are used as an input to the model. The results of the model revealed that the mean annual groundwater recharge, evapotranspiration and runoff were 66, 440 and 40mm respectively. The study revealed that, recharge accounts for 12% of the precipitation while the rest 81% and 7% becomes evapotranspiration and surface runoff respectively. They concluded that the study area is characterized by low groundwater recharge due to the presence of high evapotranspiration rate associated with high temperature, dry wind, low rainfall and relative humidity. The estimated recharge was however based on annual and seasonal time scale which may not be enough for sustainable management of groundwater resources.

Tesfamichael et al. (2013) used a spatially distributed water balance model (WetSpass) to assessed surface water and groundwater resources in the Geba basin, Tigray, Ethiopia. Relevant input data for the model is prepared in the form of digital maps using remote sensing images, GIS tools, FAO and NASA databases, field reconnaissance and processing of meteorological and hydrological observations. The model produces digital maps of long-term average, seasonal and annual surface runoff, evapotranspiration and groundwater recharge. Results of the model show that 76% of the precipitation in the Geba basin is lost through evapotranspiration, 18% becomes surface runoff and only 6% recharges the groundwater system. The model predictions are verified against river flow observations and are shown to be reliable.

2.3.4 Groundwater Recharge Studies in Nigeria

Adanu (1991) discovered that direct infiltration of rainfall at soil surface was the main source of groundwater recharge in Zaria-Kaduna area of Nigeria using stable isotope tracers. Carter (1994) adopted a steady-state unconfined flow equation to estimate groundwater recharge in the Manga Grasslands, northeast Nigeria. The estimated groundwater recharge was 60mm/annum in the

area. Carter, Morgulis, Dottridge, and Agbo (1994) modelled the groundwater resources of the Manga grassland on the basis of the results of the previous study by Carter (1994). Also, a one-dimensional flow equation was adopted by Carter and Alkali (1996) to estimate groundwater recharge in the northeast arid zone of Nigeria. The estimated groundwater recharge was 0.9 mm/annum, which is a very low recharge rate. Edmunds et al. (2002) adopted a chloride (Cl) mass balance method to estimate groundwater recharge in northern Nigeria at the plot scale. The estimated groundwater recharge ranges from 14-49 mm/annum. The results obtained at the plot scale was extrapolated to give a regional scale recharge of the area.

Goni et al. (2005) modelled six unsaturated zone chloride (Cl⁻) profiles from the Nigerian part of the Chad basin against annual rainfall at the Maiduguri station, which were smoothed using a 5-year moving average. The model estimates recharge rates to range from 10 - 28 mm/annum with an average of 19 mm/annum for the study area. The recharge rates obtained from the model are significant, although lower than those obtained for the same area from Cl-mass balance and piezometric fluctuations. The average rate from the model is considered as the long-term minimum for the region. They concluded that this has implications for groundwater management, as the estimated recharge rate is in excess of demands by the rural communities, where groundwater abstraction is usually through hand-dug wells, and thereby imposing limitation on the quantity to be withdrawn.

Adelana et al. (2006) used three basic methods which include empirical (using three simplified equations), hydrochemical (chloride mass balance) and climatic-hydrological methods, to estimate and compared groundwater recharge from the three methods in part of Sokoto basin. The result of the empirical method shows exaggerated values of recharge compared to the chloride and water balance methods. Their results show recharge around the Wurno and Goronyo

areas is <1 % of annual rainfall while for areas outside this region recharge is 3.2 % of annual rainfall. They attributed the significant variation observed in recharge to local conditions of climate and lithology. They concluded that the chloride mass balance method appears to be most suitable for estimation of recharge in most of the basin, but is still limited by inadequacy of chloride measurements in rainwater in some part of the area.

Idowu and Martins (2007) adopted hydrograph analysis method to estimate groundwater recharge in the phreatic basement aquifer of the Opeki river basin, a sub-basin of the Ogun river basin. The estimation revealed an annual value of between $29.23 \times 10^6 \text{ m}^3$ and $259.09 \times 10^6 \text{ m}^3$, with an average of $134.45 \times 10^6 \text{ m}^3$ (i.e. 137 mm). The study revealed that recharge is between 3 to 20 % of the total annual precipitation, the base flow ranges from 6 - 47 % of the total annual stream flow with a mean annual runoff of 708 mm. The high correlation ($r=0.98$) between baseflow and groundwater recharge revealed the reliance of baseflow on the amount of groundwater recharge. The positive influence of precipitation on baseflow and groundwater recharge, were further explained by correlation coefficients of 0.6 and 0.7 respectively.

Sani et al. (2012) estimated the mean-residence time of groundwater in the Basement Complex aquifer of Kano metropolis, Nigeria using tritium radioisotope. The tritium concentration in groundwater samples collected from 28 selected motorized boreholes was used to estimate the mean-residence time using isotope. The results indicated that groundwater recharge of the area is 'Modern' (water younger than 50 years). However, one borehole showed insignificant tritium of $0.0 \pm 0.2 \text{ TU}$, which implies that only minimal recharge took place in groundwater around this borehole after the early 1950s. They concluded that there is the need for judicious exploitation of this part of the aquifers for sustainability in the area.

Adindu et al. (2013) estimated the groundwater recharge at Umudike watershed for the year 2012 using soil water balance method. They divided the watershed into six (6) zones using the building landmarks (Male Hostel Block, Admin. Block, Female Hostel, science block, poultry/engineering block and P.G Hostel Blocks) as the criteria and discovered that recharge varied from one zone to another. The highest amount of recharge estimated was 12.87cm which occurred in the Male Hostel Block and the lowest was in the Science Block with an estimation of 1.59cm. They argued that no recharge occurred in both Admin and P.G Hostel Blocks. They however concluded that recharge was influenced by infiltration, runoff and the storage capacities of both the surface soils and sub soils of the watershed. The six zones chose for the study were chose arbitrarily, and the results cannot give a true representation of the spatial pattern of recharge within the watershed.

Babama'aji (2013) study the impact of 8 years (2003-2010) rainfall, land use land cover (2005 and 2009) and soil type on the water balance of Lake Chad basin using WetSpass. The analysis of the study was based on annual and season pattern. In the findings, Soil evaporation, transpiration and surface runoff show higher correlations with precipitation. Surface runoff account for about 50 - 70% for the built-up areas, which is 2 to 3 times higher than the runoff from the agricultural land. The annual mean interception in LCB for the period 2003 - 2010 ranges from 0 - 63 mm with the mixed forest intercepting more water than open vegetation such as grass and shrub. Also, the annual mean actual evapotranspiration ranges from 60 - 400 mm, which constitute 90% of the annual precipitation (69 – 430 mm) from 2003 - 2010. The analysis further revealed that the shrub and agricultural land are more sensitive to the change of precipitation for balancing of transpiration and soil evaporation. Agriculture and built-up on sand, loamy sand and sandy loam produce the highest recharge.

Oke et al. (2014) investigated the relationship between rainfall and groundwater recharge within Ona River basin, southwest Nigeria, using soil moisture balance and water table fluctuation. The results obtained from the soil moisture balance by considering the three dominant soil types within the basin (sandy loam, clay and fine sand), suggests that groundwater recharge follows a positive trend as the corresponding rainfalls. The results from water table fluctuation method suggested that recharge ranged from 40.50 to 220.25mm. They concluded that groundwater recharge within the Ona River basin follows a positive trend as rainfall, and it ranges from 2.8 to 24.44% of annual rainfall.

Adeleke et al. (2015) used 32 years climatological data collected from Ogun-Oshun River Basin Development Authority (OORBDA) to estimate groundwater recharge and determined the recharge coefficient using empirical methods in Odeda, Ogun state. The results showed that groundwater recharge was 194.7 mm per year, and the recharge coefficient was 20.2% for the study area. The result also showed that about 11% of rainfall infiltrated the aquifer, 73% was lost to evapotranspiration, and 16% ended up as run-off. Pearson correlation coefficient was used to evaluate the strength of the relationship between meteorological variables. The impact of independent variables (humidity, temperature, rainfall, wind speed, and sunshine hour) on estimated recharge was evaluated using linear regression. The results of the Correlation and linear regression between climatic parameters and the estimated groundwater recharge showed that rainfall has the most significant influence on recharge.

Oke et al. (2015) adopted three empirical formulae (modified Chaturvedi formula, Krishna Rao and Kumar and Seethapathi) to estimate groundwater recharge in Ogun and Osun drainage basins. They compared results from these three empirical formulae using line graph, inter-item correlation and one-way analysis of variance (ANOVA). They obtained correlation coefficients

between 0.99-1.0 which suggested that any of the formula is applicable for groundwater recharge estimation in the basins because of the perfect positive correlations. However, despite the perfect correlations between the three methods, there existed a significant difference in the means of Kumar and Seethapathi formula and the two other (Modified Chaturvedi formula and Krishna Rao formula) methods. Based on the result of the ANOVA, they concluded that although any of the recharge formula can be used for estimations, the Kumar and Seethapathi formula is preferred.

The literature review on groundwater recharge studies in Nigeria revealed that:

- i. most of the groundwater recharge studies were carried out without giving serious attention to factors affecting recharge,
- ii. the focus of most of the researches were on mean annual recharge, while a few looked at seasonal recharge, but none on a small-time scale such as monthly and daily groundwater recharge,
- iii. most study assessed the spatial distribution pattern of groundwater recharge by comparing point based estimation results,
- iv. most of the studies shy away from looking at the effects of climate on groundwater recharge, perhaps because climate and groundwater is a rather recently emerging research area, and
- v. most of the studies employed tracer, empirical equations, water balance approaches and graphical hydrograph separation methods. The application of hydrological model with the aid of GIS and remote sensing techniques in estimating groundwater recharge would offer a better approach to groundwater recharge estimation in Nigeria.

Therefore, the present study employed hydrological modelling with the use of remote sensing and GIS methodology. Factors affecting groundwater recharge such as soil, climate, land use/land cover, slope and topography were considered, with emphasis on climate and land use/land cover change. The spatio-temporal pattern of groundwater recharge was examined on a monthly time scale for sustainable groundwater management.

2.4 Conclusion

The concept of hydrological cycle and groundwater resources was discussed and groundwater recharge was conceived as the residual of the hydrological cycle. The concept of groundwater sustainability and various hydrological models were examined. The detailed processes of WetSpas-M hydrological model adopted for this study are presented, while groundwater recharge and factors affecting it were highlighted. The literature reviewed ranged from studies on groundwater resources and recharge from global perspective to Africa and to Nigeria.

CHAPTER THREE

RESEARCH METHODOLOGY

3.0 Introduction

This chapter consists of the types and sources of data used, sampling framework, data preprocessing, and the data analytical procedures.

3.1 Types of Data Used

The data used in order to achieve the objectives of the study are:

- i. climatic data such as rainfall amount, number of rainy days, temperature, sunshine hour, relative humidity, wind speed at 2m above ground level and potential evapotranspiration,
- ii. Land use/land cover map,
- iii. Soil map,
- iv. Digital Elevation Model (DEM),
- v. Slope angle map,
- vi. Aspect,
- vii. Population,
- viii. Depth to water, and
- ix. Discharge data

3.2 Sources of Data Used

The data used were gathered from the following sources:

- i. climatic data such as rainfall amount, number of rainy days, temperature, sunshine hour, relative humidity and wind speed were 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°.
- ii. potential evapotranspiration was estimated using FAO Penman-Monteith method (Allen, Pereira, Raes, & Smith, 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, Burman & Allen, 1990). The ETo calculator version 3.2 of FAO was used to compute PET in this study. The details of the ETo calculator can be found in the reference manual (Raes, 2012).
- iii. Land use/land cover maps of the study area were acquired from USGS-EROS satellite image database.
- iv. Soil map of the study area was extracted from the harmonized world soil database version 1.2 (2012) prepared by the Food and Agriculture Organization of the United Nations (FAO) and others.

- v. Digital Elevation Model (DEM) 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.
- vi. population data was extracted from the National Bureau of Statistics (NBS), annual abstract of statistics, 2012.
- vii. depth to groundwater was adopted from the static water level for the study area reported in the Federal Ministry of Water Resources (FMWR) 2014 national water resource master plan report.
- viii. discharge data was collected from Ogun-Oshun River Basin Development Authority

3.3 Sampling Framework

- i. The data on all the climatic variables used spanned 40 years (1976-2015), this is because the World Climatic organization (1956) suggested thirty to thirty-five years as the minimum period for averaging climatic variable before variability can be ascertained (WMO, 2007 and WMO, 2009). Although, some of the stations did not have data covering the period 1976-2015, the missing years records were filled with data from other stations. The approach adopted is discussed in subsection 3.4.1 The available 24 weathers stations are those that fall within and close to the drainage basin. Table 3.1 shows the summary of the climatic stations with their respective locations and years of record.
- ii. The Digital Elevation Model with 30 m resolution was selected for the study based on its high resolution and its availability for the study area.
- iii. Due to the paucity of data on the depth to water in the study area, the mean depth to water for the study area was adopted. Based on FMWR (2014) report on depth to water, 10m depth was adopted for the 93.28% of the basin underlain by the Basement Complex rocks

and 50m depth to water for the remaining 6.67% underlain by the sedimentary basin in the south close to the Atlantic Ocean. The same depth to water was used for all the months of estimations. The available few records from borehole logs, shows that depth to water in the basin is above 2 meters. The adoption of mean depth to water is permitted by the WetSpass-M model if the depth to water in a study area is above 2m (Personal communication with WetSpass-M developer, 2015). In fact, studies in arid environment where the depth to water is generally more than 2m, completely ignored the depth to water as part of input parameters (Tefamicheal et al., 2013; Tilahun & Merkel, 2009).

Table 3.1: Summary of the Climatic Stations Data Adopted for the Drainage Basin

SN	Name of Stations	Locations			Years of Record
		Elevations (M)	Latitude (DD)	Longitude (DD)	
1	Abeokuta	104	7.16666	3.33333	1976-2015
2.	Akure	335	7.24666	5.31111	1976-2015
3.	Ibadan	234	7.35944	3.97611	1976-2015
4.	Ikeja	41	6.5775	3.32111	1976-2015
5.	Ilorin	307	8.48333	4.58333	1976-2015
6.	Osogbo	318	7.76666	4.56666	1981-2015
7.	W6741	56	6.71292	4.0625	1979-2014
8.	W6744	68	6.71292	4.375	1979-2014
9.	W7041	82	7.02514	4.0625	1979-2014
10.	W7044	136	7.02514	4.375	1979-2014
11.	W7341	199	7.33737	4.0625	1979-2014
12.	W7344	178	7.33737	4.375	1979-2014
13.	W7641	241	7.64961	4.0625	1979-2014
14.	W7644	245	7.64961	4.375	1979-2014
15.	W7647	430	7.64961	4.6875	1979-2014
16.	W7650	541	7.64961	5.00	1979-2014
17.	W8041	305	7.96184	4.0625	1979-2014
18.	W8044	454	7.96184	4.375	1979-2014
19.	W8047	457	7.96184	4.6875	1979-2014
20.	W8050	581	7.96184	5.0000	1979-2014
21.	W8341	307	8.27406	4.0625	1979-2014
22.	W8344	315	8.274060	4.375	1979-2014
23.	W8347	334	8.274060	4.6875	1979-2014
24.	W8350	436	8.274060	5.000	1979-2014

Source: Author's Compilation, 2016

- iv. The stream discharge data available from Apoje gauging sites at lower southern part of basin is from 1980-2000.
- v. Land use/land cover image of the study area was collected for 3 epochs, to give a total of three land use/land cover images. Table 3.2 show the type, path/row, date and characteristics of the satellite images acquired.

Table 3.2: Satellite Image Characteristics

<i>SN</i>	<i>Image Type</i>	<i>Path/Row</i>	<i>Acquisition Date</i>	<i>Resolution</i>
1.	Landsat 8 OLI/TIRS	191/54	24/12/2015	15 m
		191/55	24/12/2015	
		190/54	17/12/2015	
		190/55	17/12/2015	
2.	Landsat 7 ETM	191/54	06/02/2000	30 m
		191/55	06/02/2000	
		190/54	15/02/2000	
		190/55	15/02/2000	
3.	Landsat 5 TM	191/54	18/12/1984	30 m
		191/55	18/12/1984	
		190/54	11/12/1984	
		190/55	11/12/1984	

Source: Author's Compilation, 2016

3.4 Data Preprocessing

3.4.1 Climate Data Preprocessing

Data from Abeokuta station (1981-2015) was correlated with data from other ground stations for the same period of 1981-2015 so as to have the same number of records. 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. Similar approach was adopted for the period 1976-1978 and 2015

that has no record in the CFRS data. The Kolmogorov-Smirnov test was carried out on the climatic variables to determine that they were normally distributed, and found suitable for the study analysis.

3.4.2 Data Resampling

For the sake of matrix calculation, all input maps into WestSpass-M must have uniform pixel size, that is, the same spatial resolution. However, the data used in the study have different spatial resolution, which necessitated the need for resampling. The 2015 satellite image is the only data with high resolution (15m) besides the generated weather maps. Thus, all the data were resampled into 15m pixel size from their original sizes to have a uniform pixel size. The nearest neighbor resampling method was adopted to resample the satellite images and soil map because they are discrete data with distinct boundaries, while bilinear technique was adopted in resampling the DEM because its continuous nature (Table 3.3).

Table 3.3: Data Spatial Resolution and Methods Adopted in Resampling

	<i>Data</i>	<i>Original Resolution</i>	<i>Resampled Resolution</i>	<i>Resampled Method</i>
1	1984 Satellite Image	30m	15m	Nearest Neighbour
2	2000 Satellite Image	30m	15m	Nearest Neighbour
3	2015 Satellite Image	15m	-	Not Resampled
4	Soil Map	30 arc sec. (1km Approx.)	15m	Nearest Neighbour
5	DEM	30m	15m	Bilinear

Source: Author's Compilation, 2017

3.5 Methods of Data Analysis

The methods of data and statistical analysis employed are those of SPSS, GIS and remote sensing; and hydrological modelling using WetSpass-M software. The objectives and the procedures are as detailed in subsections 3.5.1-3.5.5.

3.5.1 Spatio-temporal Pattern of Climate in Osun Drainage Basin

The following descriptive and inferential statistical methods were employed to handle the climatic data used:

3.5.1.1 Descriptive Statistics: mean, maximum, minimum, standard deviation, and coefficient of variation were used in summarizing the large climatic data.

3.5.1.2 Temporal pattern analysis: the trend in the climatic variables was determined by using simple regression statistics and the non-parametric Mann-Kendall trend test statistics. The details on Mann-kendall trend analysis and its test of significance can be found in Salmi, Määttä, Anttila, Ruoho-Airola, and Amnell (2002), Khambhammettu (2005) and Olofintoye and Sule (2010). The equation is as written in equation 3.1.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{Sgn}(x_j - x_k) \dots\dots\dots (3.1.)$$

Where x_j and x_k are the annual values in years j and k, j>k, respectively.

Also, the equation from the trend analysis was used to predict the climate of the study area up to the year 2025. Anomalies index was used to determine the anomalies in the climatic variables, especially the number of wet and dry episodes in the four decades investigated.

3.5.1.3 Spatial pattern analysis: The climatic data from the 24 stations were interpolated using universal kriging method in ArcGIS 10.4 to determine the spatial distribution pattern of the climatic variables in the basin. The processes extent of the spatial maps was set to 15m so as to have similar spatial resolution with other resampled data. The kriging interpolation method was selected because studies (Chong-yu, Lebing, Tong, Deliang & Singh, 2006; Zhifeng, Qiang & Baoshan, 2011; Tesfamichael et al., 2013) have shown that it yields better results than other

interpolation methods such Inverse Distance Weighted (IDW), Thiessen polygons among many others.

3.5.2 Spatio-temporal Pattern of Land Use/Land Cover Change

The following processes were carried out to determine the spatio-temporal pattern of land use/land cover change of the drainage basin.

3.5.2.1 Image stacking, mosaicking and sub setting: The study area falls within four different satellite scenes. The bands of each of the satellite image scenes of the three periods were first stacked in Erdas Imagine 2014. These four scenes for the years 1984, 2000 and 2015 were mosaic using the MosaicPro algorithm in Erdas Imagine 2014. The resulting images were subset using the study area shapefile to bring out the satellite images of the area of interest (AOI).

3.5.2.2 Image enhancement and rectification: the AOI images were enhanced, resampled and projected. The images were enhanced into natural colour composite to improve the visual interpretation. The three imageries were resampled to equalize the spatial resolution of the datasets because of their varying spatial resolution. All the images were projected to Universal Transverse Mercator projection of WGS84 coordinate system, zone 31N.

3.5.2.3 Land use/land cover classification: the supervised classification method in Erdas Imagine 2014 was adopted, using the maximum likelihood algorithm. The coordinates of some identified features within the basin were recorded and used as training samples for supervised classification of the remotely sensed data. The training sites (signatures) of all images were developed by using the spectral characteristics of known to train the classification algorithm for the land use/land cover mapping of the basin, which represent various land use/land cover of interest.

Seven land use/land cover classes such as bare surfaces, built up area, crops/shrubs, forest, rock outcrops, water bodies and wetland were adopted in this study. These seven classes fall under four main category of land use/land cover (vegetated cover, bares soil, open water and impervious surfaces) recognized by WetSpaa-M hydrological model. This was done to avoid land use heterogeneity within the pixel (Batelaan & De Smedt 2001, p.12; Ampe et al., 2012) and based on the influence such land use/land cover have on water balance of the area.

The land use/land cover maps of the basin for the period 1984, 2000 and 2015 were developed and measured for each land use/land cover types. The percentage change to determine the trend of change is given in equation 3.2.

$$Trend(\% \text{ change}) = \frac{ObservedChange}{SumofChange} \times 100 \dots\dots\dots (3.2)$$

To obtain the annual rate of change for the period of study, the percentage change was divided by 100 and multiplied by the number of study year.

3.5.2.4 LULC change prediction: Modules for Land Use Change Evaluation (MOLUSCE) plugin in QGIS was adopted in simulation of the future LULC change in the basin. The LULC change explanatory variables employed are population, elevation, aspect and slope of the study area. All these variables are ranked between 0 and 1 using the fuzzy membership tool in ArcGIS. Also, the change transition matrix for the predicted 2046 LULC change was computed.

3.5.2.5 Accuracy assessment: 250 points were randomly selected in preparing confusion matrix for accuracy assessment, which is a popularly accepted method in determining the accuracy of LULC classification (Foody 2002). The randomly generated points in the classified 2015 image

was imported into Google Earth image of 14/12/ 2015 to verify the accuracy of the classification. Thereafter, the Kappa coefficient and overall accuracy were calculated to assess the overall accuracy of the LULC classification.

3.5.3 Monthly Water Budget of Osun Drainage Basin

The estimation of the monthly water budget of Osun drainage basin was carried out by adopting spatially distributed hydrological model (WetSpass-M).

3.5.3.1 WetSpass-M model

This model requires two types of input data, these are; GIS grid maps and parameters tables (Batelaan & De Smedt, 2001; p. 15). These grid maps include slope, land use/land cover, soil texture, depth to groundwater and monthly climatic maps of rainfall amount, number of rainy days, temperature, potential evapotranspiration and wind speed (Abdollahi et al., 2017, p. 2). All the input maps were converted into ascii grid format using gdal translate command in QGIS. Also, all the no data values in the grid maps are set as -9999. The model is described in details in section 2.2 under conceptual framework and literature review. The preparation of the input data is discussed in subsection 3.5.3.2

3.5.3.2 WetSpass-M input data preparation

A. GIS Grid Maps

- i. **Climatic Input Data:** 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, number of rainy days/month, temperature, potential evapotranspiration and wind speed were calculated from the available data in each station. From this, the digital maps of the monthly rainfall amount, temperature, potential evapotranspiration and wind speed were determined by spatial interpolation of the values observed in the stations, using the

universal kriging interpolation module of ArcGIS 10.4. This method was employed by Tesfamichael et al. (2013).

- ii. **Soil Data Input:** The soil map of the study area was translated into the USGS soil texture classes using the percentages of coarse, medium and fine particle size fractions in the top soil. This enable us to produce the soil map of the study area that reflect the percentages of each soil types based on their texture within the basin.
- iii. **Land Use/Land Cover Data Input:** the classified 2015 land use/land cover map of the study area was selected as the LULC data input for this objective.
- iv. **The Depth to Groundwater Data Input:** The 10m and 50m mean depth to water for the Basement Complex rocks and Sedimentary basin, respectively in the study area was adopted. This was used to prepared the depth to groundwater in the study area using the create raster image in ArcGIS 10.4. The output cell size was set at 15m, while the processing extent was also set to 9977x14043 to have the same column and row; and pixel size as the other variables
- v. **Digital Elevation Model Data Input:** DEM map of the study area was used to produce the slope angle map of the drainage basin using the ArcGIS tools to reflect the variation in slopes of the study area.

B. Parameters Table

Land-use, number of rainy days and soil characteristic was specified as parameters tables in the WetSpass model (Tesfamichael et al., 2013, p. 115; Batelaan & De Smedt, 2001, p. 15). 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 table contain parameters for runoff for all combinations of land-uses, slope, and soil type (Tesfamichael et al., 2013, p. 115).

Further, the soil type attribute tables, requires no modifications, because parameters in this table are based on the United States Department of Agriculture (USDA) soil classification. The runoff attribute table also requires no modification, because values in this table are considered to be universal, that is, a certain combination of slope, land-use, and soil type will produce a certain fraction of runoff independent of location (Tesfamichael et al., 2013, p. 115). After the input data were prepared, they were inputted into the model to begin the simulation of the monthly water budget. The outputs include several spatio-temporal (monthly and spatial distribution) hydrologic outputs such as interception, actual evapotranspiration, runoff and recharge among many others. See figure 3.1 for the flowchart of WetSpass-M water balance model.

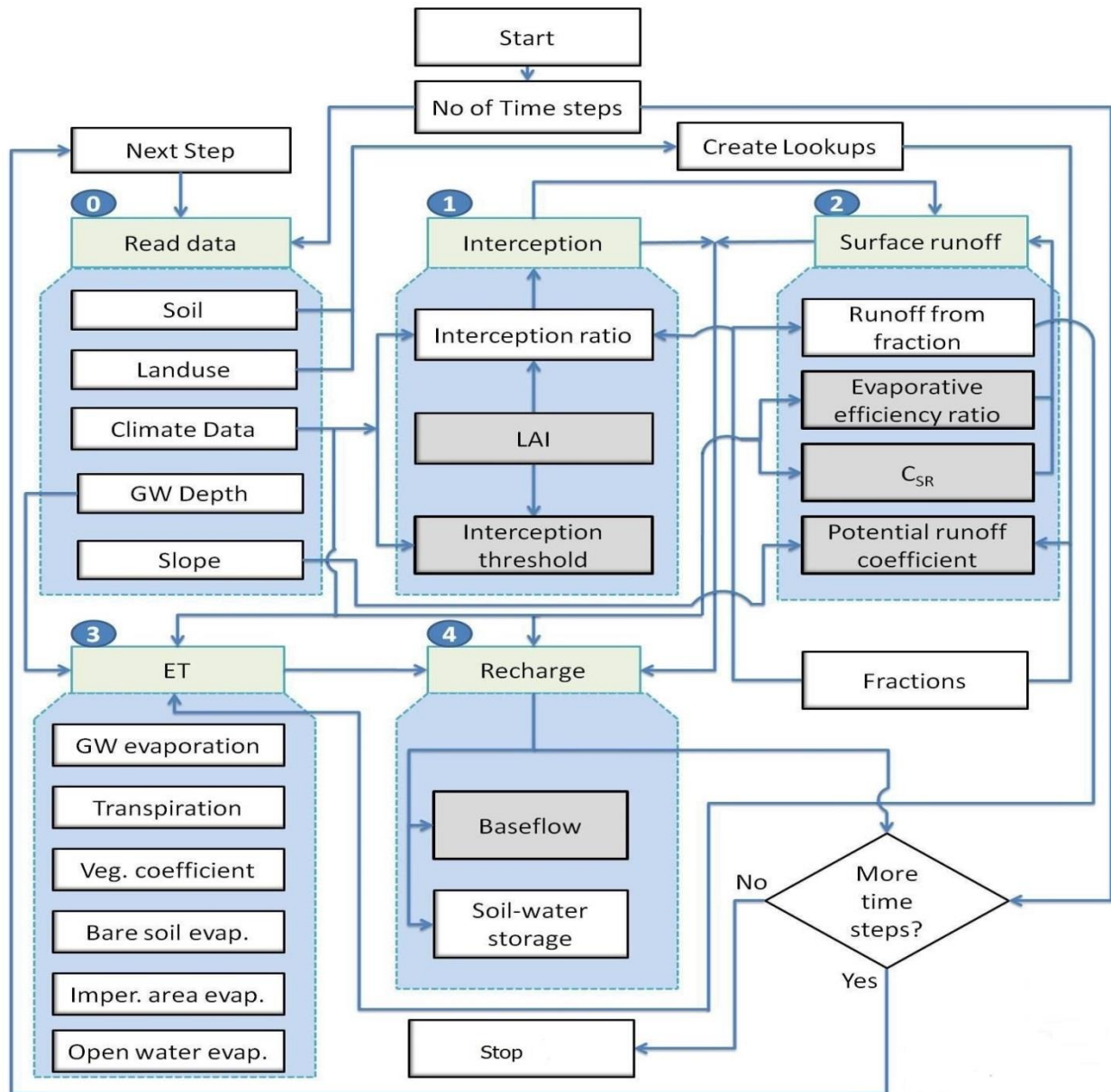


Figure 3.1: Flowchart for Monthly Spatially Distributed Water Balance model, WetSpas-M
Source: Adapted from Abdollahi et al., (2017, p. 8)

3.5.3.3 Model calibration

The model was calibrated manually using the following parameters: soil moisture alfa coefficient (α), LP a 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 alpha coefficient (Abdollahi et al., 2017, p. 11) The coefficient of determination (R^2) and the Nash-Sutcliffe model efficiency (NSE) were used for validation using the simulated and observed discharge data of 1999 at Apoje gauge station. The Nash-Sutcliffe model efficiency equation is presented in equation 3.3.

$$E = 1 - \frac{\sum_{t=1}^T (Q_m^t - Q_o^t)^2}{\sum_{t=1}^T (Q_o^t - \overline{Q_o})^2} \dots\dots\dots (3.3)$$

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 $-\infty$ to 1, The closer the model efficiency is to 1, the more accurate the predicted model result.

3.5.4 Effects of Climate on Groundwater Recharge

3.5.4.1 Statistical Analysis

Statistical techniques of multiple and stepwise multiple regression analysis and Spearman rank correlation were adopted to determine the effect of climate on groundwater recharge, which are presented in equations 3.4 and 3.5, respectively. The estimated recharge results from WetSpa-M was the dependent variable, while the independent variables are the climatic variables.

$$y = a + b_1x_1 + b_2x_2 \dots b_nx_n + e \dots\dots\dots (3.4)$$

Where y = groundwater recharge, $b_1 - b_n$ = partial regression coefficient of the climatic variables

$x_1 - x_n$ = climatic variables (rainfall amount, temperature, sunshine hour, wind speed, relative humidity)

a = intercept

e = error term.

$$p=1-\frac{6\sum d^2}{n(n^2-1)} \dots\dots\dots (3.5)$$

p is Spearman rank correlation, $\sum d^2$ is total number of ranked hydro-climatological variables, and n is the number of cases.

3.5.5 Effects of Land Use/Land Cover Changes on Groundwater Recharge

3.5.5.1 WetSpass-M model

WetSpass-M model was also employed to determine the impacts of land use/land cover on groundwater recharge. Every other input parameters were held constant, while the land use/land cover of the three epochs (1984, 2000 and 2015) were used one after the other to run the model. This enabled the identification of the effects of land use/land cover changes over time on the groundwater recharge of the basin. This approach was adopted by Pan et al. (2011) and Albhaisi et al. (2013) to evaluate the effect of LULC change on groundwater recharge in Guishi River basin in China and Berg catchment in South Africa, respectively. The recharge on each LULC classes for the three periods (1984, 2000 and 2015) were isolated and aggregated in ArcGIS 10.4. The percentage of recharge occurring on each LULC were computed from the overall basin recharge for each period and the result compared.

3.6 Conclusion

This chapter provided the detailed methods and procedures employed in investigating the effect of climate and LULC on groundwater recharge in Osun drainage basin.

CHAPTER FOUR

SPATIO-TEMPORAL PATTERN OF CLIMATE IN OSUN DRAINAGE BASIN

4.0 Introduction

This chapter presents the spatio-temporal analysis of the climate of Osun drainage basin. The general statistical characteristics of the weather parameters are first presented in order to have an overview of the mean climatic condition of the study area. Spatio-temporal pattern of rainfall amount, potential evapotranspiration, minimum and maximum temperature, relative humidity and wind speed were computed and discussed in this chapter. The climate of the study area was forecast for the period 2016 to 2025 and the anomalies for the period 1976 to 2015 highlighted; and discussed.

4.1 Annual Mean of Climatic Variables in the Study Area

The mean annual rainfall amount for Osun drainage basin is 1455.62mm, with CV of 15.10% (Table 4.1). This reinforced the fact that there is homogeneity in mean annual rainfall amount in the study area. Also, the estimated mean rainfall amount (1455.62mm) is within the range of 1,020 to 1,520mm reported by OORBDA (1982, p. 5) for the drainage basin. Mean annual relative humidity in Osun drainage basin was estimated as 76.02%, with CV of 3.13%. This is an indication that there is no high variability in mean annual relative humidity throughout the 40 years under review. The result is close to the 75% recorded in the southern part of the basin in earlier study (OORBDA, 1982, p. 4).

Osun drainage basin estimated mean annual PET is 1613.66mm, with CV of 4.22%. This signifies a lower variability in mean annual PET in the basin. As a result of latitude, it is normal to have a non uniform duration and amount of solar radiation across the basin. Hence, spatial

variation in mean annual PET received across the basin is expected, regardless of the small percentage in the coefficient of variation. Local conditions such as type of vegetation, land use/land cover among many others will greatly influence PET and actual evapotranspiration from one location to another in the drainage basin. Settlements with very high PET, mostly in the northern part of the basin are most likely to have low rainfall amount. This scenario will affect the water balance of the basin, particularly the amount of rainfall that will recharge the groundwater system.

Table 4.1: Mean Climatic Condition in Osun Drainage Basin 1976-2015

SN	Weather Parameters	Min	Max	Mean	STD	CV
1	Rainfall amount (mm)	815.08	1848.45	1455.62	219.73	15.10
2	Relative humidity (%)	70.30	80.62	76.02	2.38	3.13
3	PET (mm)	1486.44	1785.54	1613.66	68.02	4.22
4	Minimum temperature (°C)	20.77	22.11	21.52	0.34	1.60
5	Maximum temperature (°C)	30.42	33.88	32.25	0.83	2.56
6	Wind speed (m/s)	2.05	4.84	2.41	0.43	18.14

Source: Author's Computation, 2017

The estimated mean annual minimum and maximum temperature is 21.51°C, with CV of 1.60% and 32.25°C, with CV of 2.56%, respectively. This is an indication of low variability in mean annual minimum and maximum temperature for the 40 years of record. Despite the small percentage in the coefficient of variation of minimum and maximum temperature over time, characteristics of the environment such as vegetation types, land use/land cover, urban heat island effect in the urbanized areas among many others might significantly affect the spatial distribution pattern of minimum and maximum temperature from one settlement to another in the drainage basin. The mean annual wind speed estimated for Osun drainage basin is 2.41m/s, with CV of 18.14%. This indicated mild variability in mean annual wind speed in the area.

4.2 Spatio-temporal Pattern of Climate in Osun Drainage Basin

The spatio-temporal pattern of climate in Osun drainage basin was presented and discussed in this section. The temporal climate data used for the analysis were derived from the average of the 24 weather stations employed in this study. To ascertain the validity of the outcome, two methods (Mann-Kendall and Regression) were employed to test the temporal trend in the climatic variables. This is for the purpose of comparing the results from the two methods. In addition, the monthly and annual averages from the 24 locations were used to prepared the climate spatial pattern map for the study area adopting universal krigging interpolation method.

4.2.1 Spatio-temporal Pattern of Rainfall Amount in Osun Drainage Basin

Rainfall amount exhibit a negative trend in Osun drainage basin using Mann-Kendall trend statistic (Table 4.2). However, the downward trend is not statistically significant and cannot be attributed to any cause. Therefore, rainfall amount decreasing into the future based on the evidence at hand (1976-2015) cannot be ascertained. Nevertheless, this result may be associated to the fact that decreasing rainfall amount over time were observed in 75% of the weather stations, where the averages were used in this analysis. It is a reflection of the rainfall amount received in most part of the basin.

Table 4.2: Climatic Trend in Osun Drainage Basin (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
Linear Regression	SN	Weather Variables	P-value	Regression equation	Sample correlation	Trend Significance	R ²
	1	Rainfall Amount	.386	Y=1509.9-2.6485X	-.141	Not Significant	1.99%

	2	PET	.001	$Y=1539.2+3.6303X$	.624	Significant	38.9%
	3	Minimum Temperature	.001	$Y=31.54+0.0346X$	.490	Significant	24.02%
	4	Maximum Temperature	.002	$Y=21.23+0.014X$	.476	Significant	22.68%
	5	Relative Humidity	.054	$Y=77.304-0.0625X$	-.307	Not Significant	9.42%
	6	Wind Speed	.263	$Y=2.2787+0.068X$	.181	Not Significant	3.29%

Source: Author's Computation, 2017

The result of the linear regression analysis indicates that there is no statistically significant relationship between rainfall amount and year at 95 % confidence level (Table 4.2). The R-squared statistic reveals that the model, as fitted, explains 1.99 % variability in rainfall amount in the study area. The correlation coefficient of -0.141 reveals a negative relationship between rainfall amount and time (year). This result revealed that rainfall amount is decreasing over time in Osun drainage basin which is not statistically significant and cannot be ascertained to continue into the future. The graph (Figure 4.1) obtained from the plot of rainfall amount against time shows a negative trend line. Although there was yearly fluctuation in rainfall amount, the trend line equation, revealed that the rainfall amount is reducing at a low rate of -2.65mm/ year during 1976 to 2015.

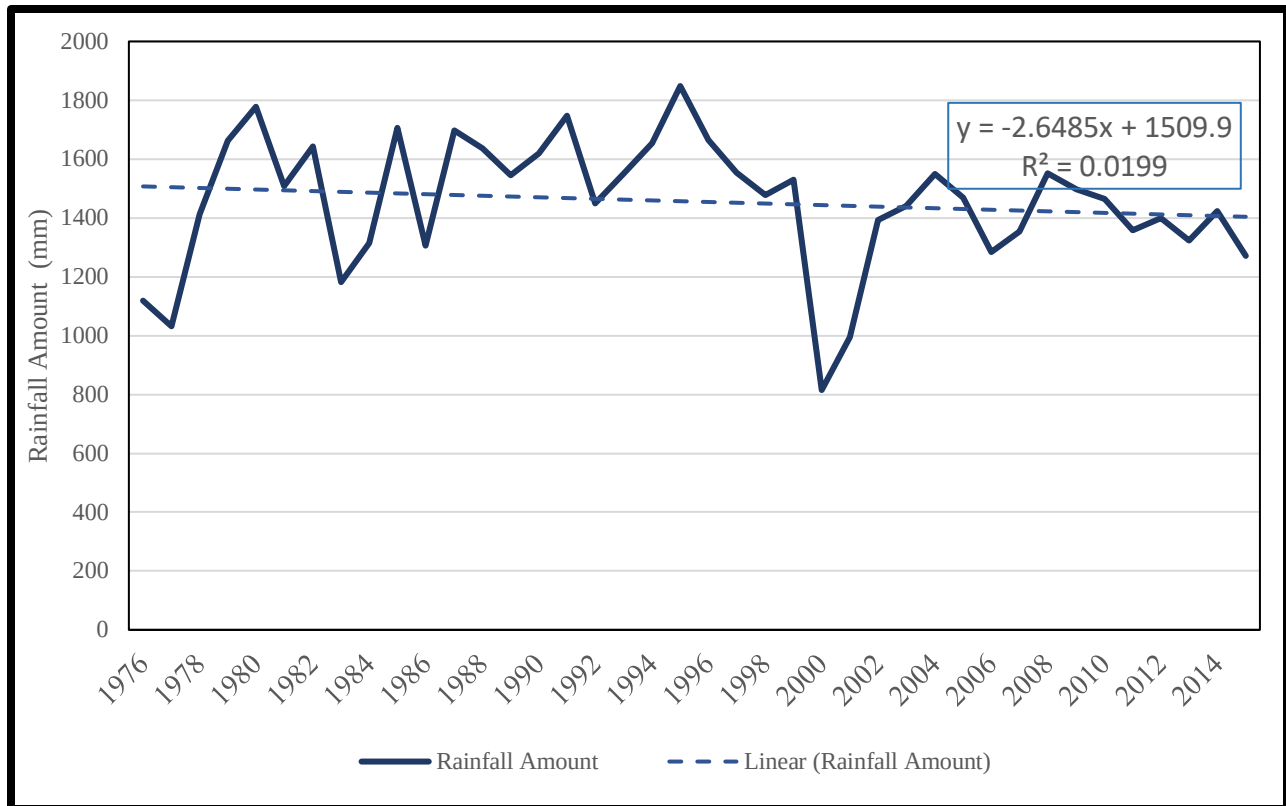


Figure 4.1: Temporal Trend in Rainfall Amount with Time in Osun Drainage Basin (1976-2015)

Source: Author's Computation, 2017

The results of the two methods employed show that the decreasing rainfall amount in the study area is not statistically significant. It might therefore exhibit an upward trend in the future depending on the future climate change. Unreliability and variability in rainfall amount as a consequent of climate change has been reported by Ayoade (2004). Therefore, uncertainty remains in the future direction of rainfall amount in the study area.

The pattern of mean monthly rainfall amount revealed the variation from the coast to the hinterland (Figures 4.2 and 4.3). The highest range of rainfall amount in January (23.95-32.29mm) was recorded in Epe, Iberekedo, Ijebu Ife, and Akata in the south, while the lowest (1.914-5.49mm) was recorded in the northern part in settlements such as Ejigbo, Ikulambaru, Ogbomosho, Arowomole, Iyalode and Aba Epo, etc. (Figures 4.2). This pattern can be attributed to the fact that rainfall starts earlier in the southern part compared to the northern part of the

study area. Monthly rainfall from January to June in the basin followed similar spatial pattern with highest rainfall amount in the south. The computed monthly rainfall amount map is in agreement with the previous study which reported that raining season begins earlier in the south around March, but late in the northern axis in late April or in early May (OORBDA, 1982, p. 5).

The reason why higher rainfall amount is received in the southern part compared to the northern part is because rainfall formation in this region is influenced by movement of the Inter-Tropical Convergence Zone (ITCZ). The pattern of monthly rainfall amount indicates that settlements in the southern part might have water surplus compared to the northern part, which coincidentally receive more hours of solar insolation, hence, higher evaporation. Annual and Monthly rainfall from January to December in the basin followed similar spatial pattern with highest rainfall amount in the south, with the exception of August and September.

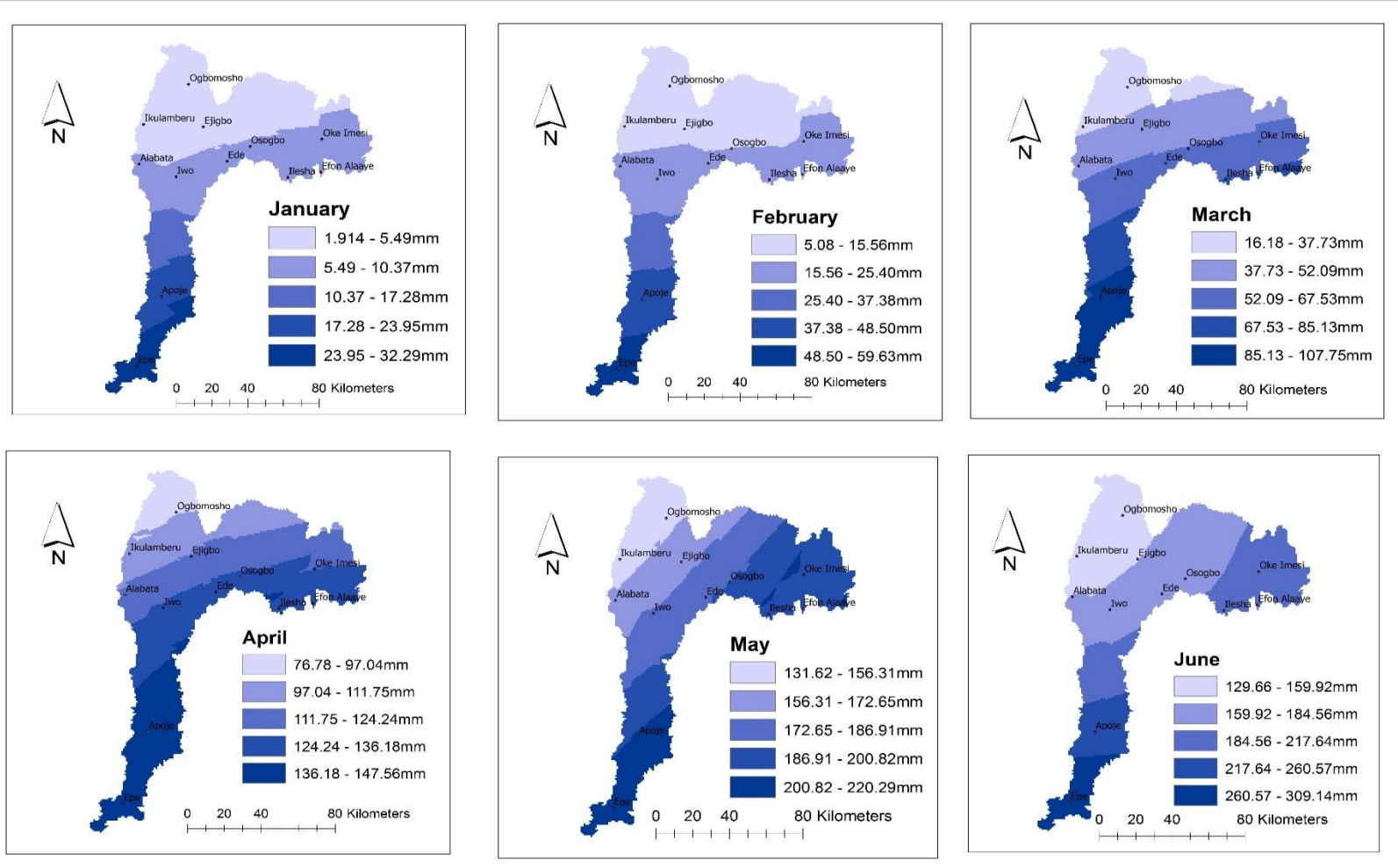


Figure 4.2: Mean Monthly (January-June) Pattern of Rainfall Amount in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

The difference in rainfall amount, particularly in August is as a result of high variability in rainfall amount in this month. The high variability in rainfall amount was a consequence of frequent dry days in the month of August tagged the “the little dry season”, thus the common terminology of August break (OORBDA, 1982, p. 5). Also, September is the month with the highest rainfall amount in the basin and this might be responsible for the pattern observed. For example, in September, the highest range of rainfall amount (219.74-237.47mm) was recorded in the northeastern settlements like Obokun, Oke Imesi and Ijero and southern part in Apoje, while the lowest (219.74-237.47mm) was in Ikoyi. Ikulamberu, Ogbomosho and Alawere in the northwestern part of the drainage basin (Figure 4.3).

The general agreement was that rainfall amount decreases as you move away from the coast towards the hinterland. However, the pattern in August and September indicates that some settlements in the hinterland received more rainfall amount than the ones in the south. The observed variant with the general pattern with other months may be connected with orographic influence around Oke Imesi, on higher elevation. It can thus be inferred that fairly steep rise in plateau above sea level and the associated inselbergs have enhanced effect on rainfall distribution in the basin, especially in August and September (OORBDA, 1982, p. 4). High rainfall amount is usually recorded in the basin between April and October. September and January recorded the highest and lowest rainfall amount, respectively in the study area. Rainfall is the major determinant of groundwater recharge in the Basement Complex environment (Nyagwambo, 2006, p. 4; Sekhar et al., 1994), hence, high recharge to aquifer is expected between April to October, and highest in September which is the month with highest rainfall amount in the basin.

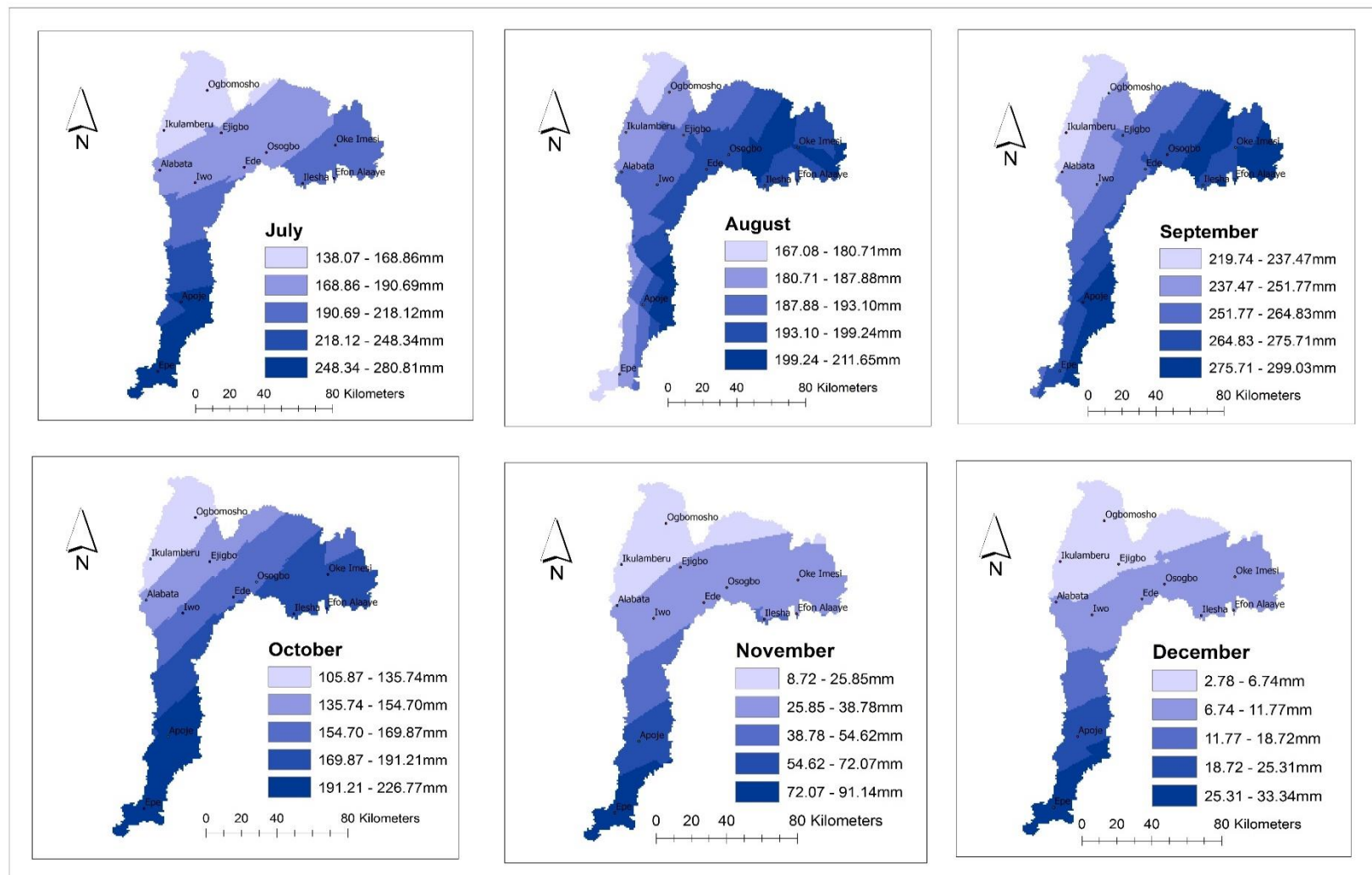


Figure 4.3: Mean Monthly (July-December) Pattern of Rainfall Amount in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

Highest mean annual rainfall amount (1,753.68-1,977.52mm) was in the southeastern part in Iganmeji, Ijebu Ife, Akata, Epe, Eluju, Iberekodo and Apoje, etc, while the lowest (1,010.05-1,237.69mm) was in Alawere, Ikoyi, Ogbomosho, Arowomole, Aba Epo and Ikulamberu in the northwestern axis (Figure 4.4). The observed annual spatial variation in rainfall amount is the function of the position of Inter-Tropical Convergence Zone (ITCZ) which is the boundary between moist maritime air mass from the Atlantic and dry continental air mass from the Sahara Desert (Ayoade. 1974, OORBDA, 1982, p. 3). The onset of rainfall in the basin is associated with the northward advance of the ITCZ, while the cessation is associated with the southward retreat which explains why rainfall begins earlier in the south OORBDA, 1982, p. 4).

Hypothetically, the computed mean annual rainfall amount pattern suggests that water surplus will be experienced in southern part of the basin, which will in turn increase the soil water storage that will enhance groundwater recharge. This will expectedly sustain domestic water usage, river channels during period of low flow and the ecosystem in general. On the other hand, the northwestern part with lower mean annual rainfall amount might have water deficit. This is because there is usually higher rate of evaporation in the northern part as a consequence of longer duration of insolation. Hence, low groundwater recharge is expected in settlements in the north. Also, drying up of streams, especially in the dry season is a common phenomenon in this areas as there is no water surplus in the sub-surface to maintain the river channels during this period of low flow.

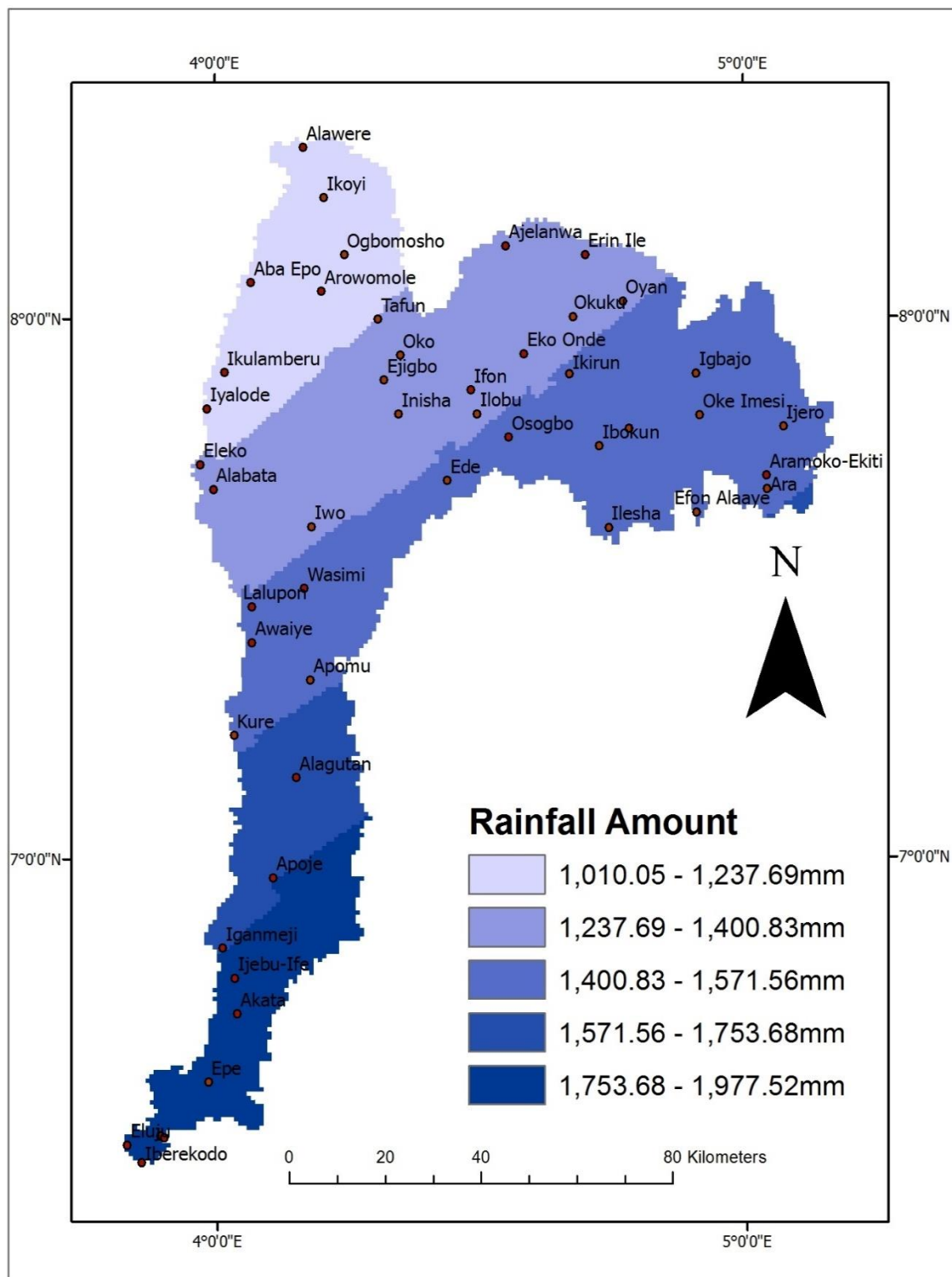


Figure 4.4: Pattern of Annual Rainfall Amount in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

4.2.2 Spatio-temporal Pattern of Potential Evapotranspiration in Osun Drainage Basin

The result of Mann-Kendall trend analysis revealed a statistically significant positive temporal trend in PET for the period of study (Table 4.2). This suggests that the observed increasing trend in the basin might be as a result of some underlying factor(s). These factors may include soil characteristics, wind speed and the physical attribute of the vegetation in the basin. Based on the evidence of record (1976-2015) and the obtained Z value, there is certainty that PET will continue to increase in the future. The graph (Figure 4.5) shows the upward trend in PET over the 40 years of study. From the trend line equation, it can be deduced that PET is increasing at a low rate of 3.63mm/ year during this period.

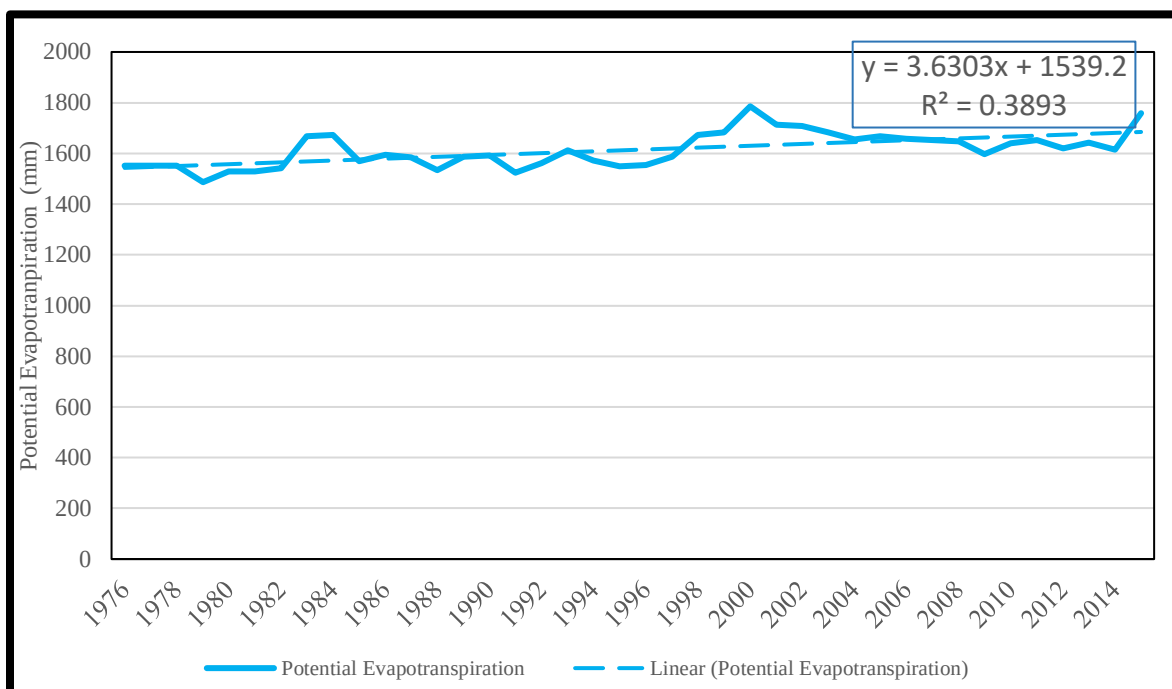


Figure 4.5: Temporal Trend in PET with Time in Osun Drainage Basin (1976-2015)

Source: Author's Computation, 2017

Also, the result of the regression trend analysis indicates a statistically significant relationship between PET and year at 95 % confidence level (Table 4.2). The correlation coefficient of 0.624 reveals a strong positive relationship between PET and time (year). The result means that the upward trend observed will continue into the future. The R-squared statistic reveals that the

model, as fitted, explains 38.9 % variability in PET in the study area. PET is usually equal to actual evapotranspiration at soil field capacity (Egwuonwu, Okafor, Ezeanya, Nzediegwu & Okorafor, 2012). Therefore, actual evaporation is expected to have similar trend to PET in Osun drainage basin.

The extreme northern part recorded highest range of PET in January (180.85-195.26mm) in Ogbomosho, Ikoyi, Alawere, and Aba Epo area, while the lowest (137.85-152.04mm) was in the southern part in Epe, Iberekedo, Akata, and Apoje (Figure 4.6). Figures 4.6 and 4.7 shows that the month of January to December exhibit the same spatial pattern, with the exception of August, September and October. However, the spatial range of PET from the lowest to the highest varies from month to month. The high amount of PET in the northern part of the basin can be attributed to the long hour of insolation. This indicates that settlements in the northern part is likely to experience more dryness compared to the southern settlements. Consequently, there are possibilities of water deficit and surplus in the northern and southern settlements, respectively.

August, September and October revealed a different pattern of lowest PET from what was observed in other months. Lowest amount of PET in these months were in the northeastern part, whereas, lower PET was in the south in the remaining months. For example, Ogbomosho, Ikoyi, Alawere, and Aba Epo, etc. recorded highest range of PET (100.79-106.66mm) like other months in August, but the lowest (85.86-90.76mm) was in Ede, Oshogbo, Ilesha, Efon Alaye and Oke Imesi, etc. (Figure 4.7). This result might be connected to lower amount of relative humidity, temperature, solar radiation and wind speed in these three months in northeast of the basin. Also, the local conditions such as the relief and land use/land cover type coupled with the prevailing atmospheric conditions in the areas might be responsible for different pattern.

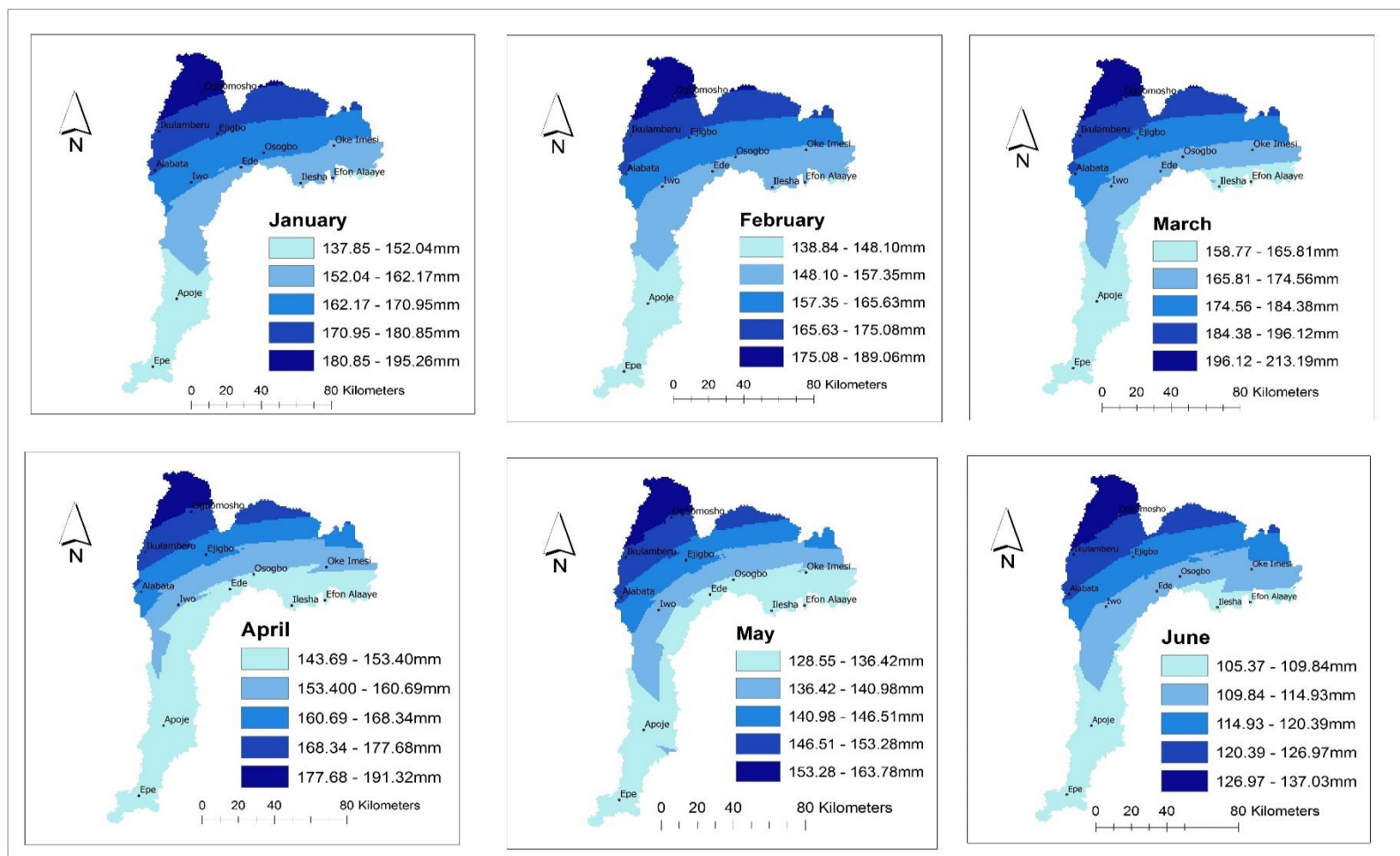


Figure 4.6: Mean Monthly (January-June) Pattern of Potential Evapotranspiration in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

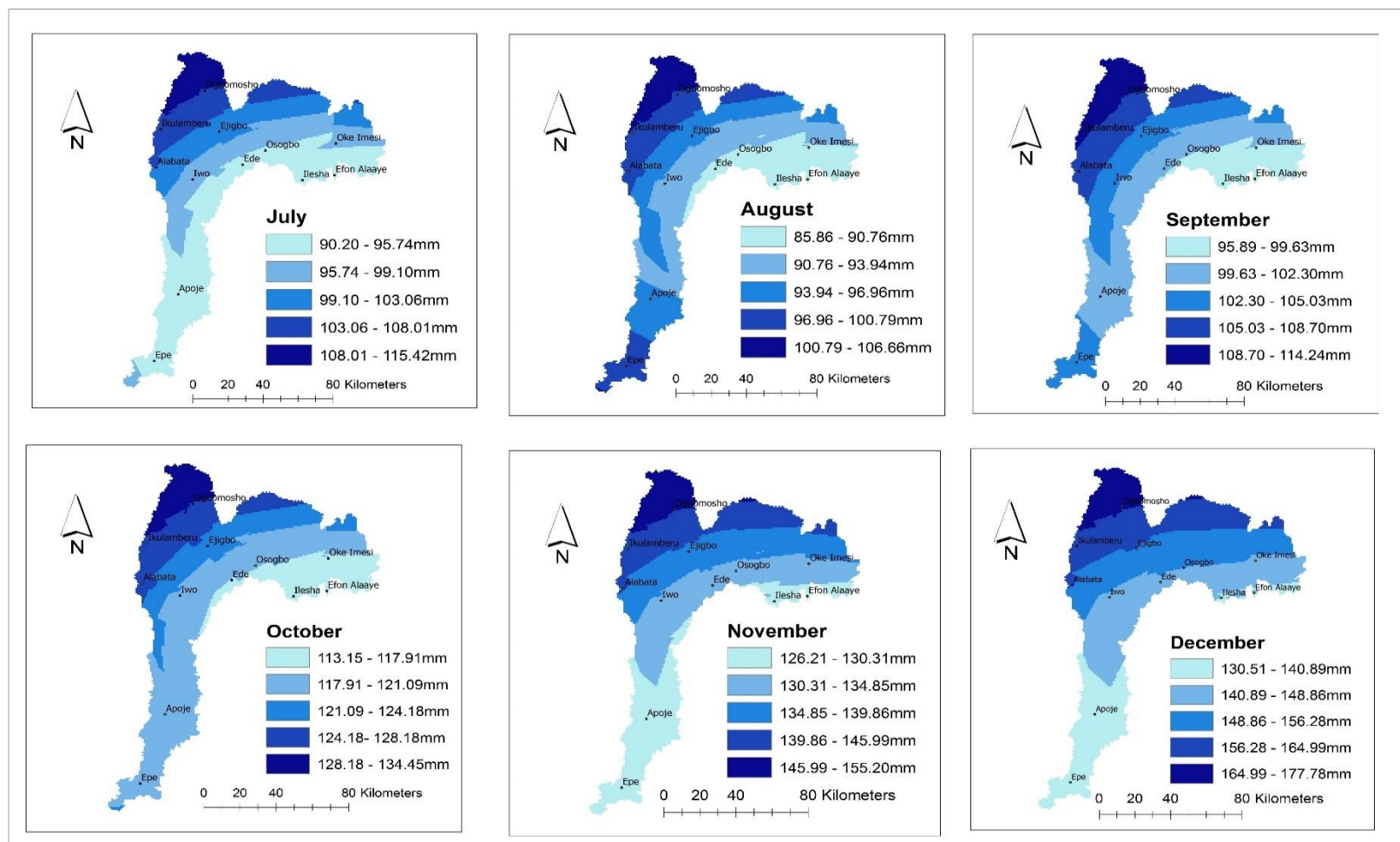


Figure 4.7: Mean Monthly (July-December) Pattern of Potential Evapotranspiration in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

The extreme northern part of the basin recorded the highest mean annual PET (1,765.76-1,893.73mm). This northern area comprises settlements such as Alawere, Ogbomosho, Ikoyi, and Aba Epo (Figure 4.8). The lowest mean annual PET amount (1,490.87-1,552.48mm) was in Eluju, Iberekodo, Epe, Akata, and settlements such as Ilesha, Efon Alaye, Aramoko Ekiti in the eastern part. The observed spatial variation in PET is attributed to the location and position of the settlement. Moreover, it is normal to have non-uniform duration and amount of solar radiation across the basin as a result of latitude. Lower PET observed in the eastern part of the study area in some months may be connected to the physical attributes of the vegetation such as vegetation cover, plant height, leaf area index, soil characteristics as well as land use/land cover types.

The pattern of mean annual PET amount over space suggests that there is high probability that areas like Ogbomosho, Ikoyi and Alawre, etc. might experience water deficit, that will affect the water supply and usage, especially for domestic purposes. High rate of PET will affect surface and groundwater resources, especially in the dry months. This is why some of the perennial streams and hand dug wells dry up in the dry season in the study area. As a matter of fact, drying up of streams and shallow wells is a common phenomenon in the Basement Complex environment where settlements with the highest mean annual PET are located. Water surplus will be experienced in southern part of the basin where low PET was observed, all things being equal. This area is also the area that receives the highest amount of mean annual rainfall amount in Osun drainage basin.

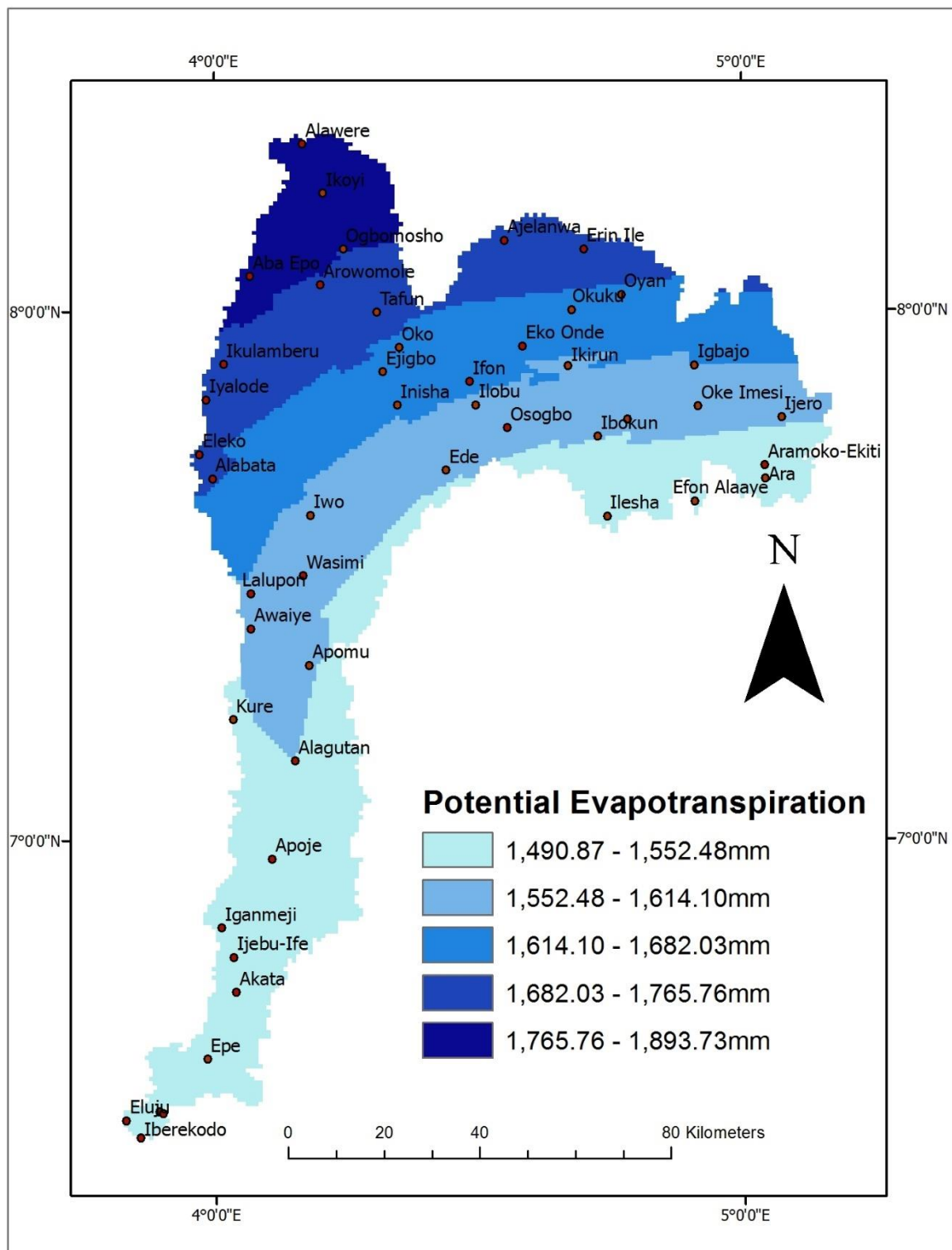


Figure 4.8: Pattern of Annual Potential Evapotranspiration in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

4.2.3 Spatio-temporal Pattern of Minimum Temperature in Osun Drainage Basin

Mann-Kendall statistic showed a statistically significant positive trend in minimum temperature in Osun drainage basin (Table 4.2). This is an indication that the upward trend of minimum temperature in the basin can be ascribed to factor such as the general increase in air temperature around the globe as a result of global warming, especially in the continent of Africa (Christensen et al., 2007). It can therefore be ascertained, based on the evidence at hand (1976-2015) that minimum temperature in the study area will continue to increase in the future. The results of regression trend analysis (Table 4.2) reveals a statistically significant relationship between minimum temperature and year at 95 % confidence level. The correlation coefficient of 0.476 reflects a positive relationship between minimum temperature and time (year) that suggests an increasing scenario will continue into the future. The graph in Figure 4.9 shows a positive trend line, which implies minimum temperature is increasing at a rate of 0.01°C/year over the period.

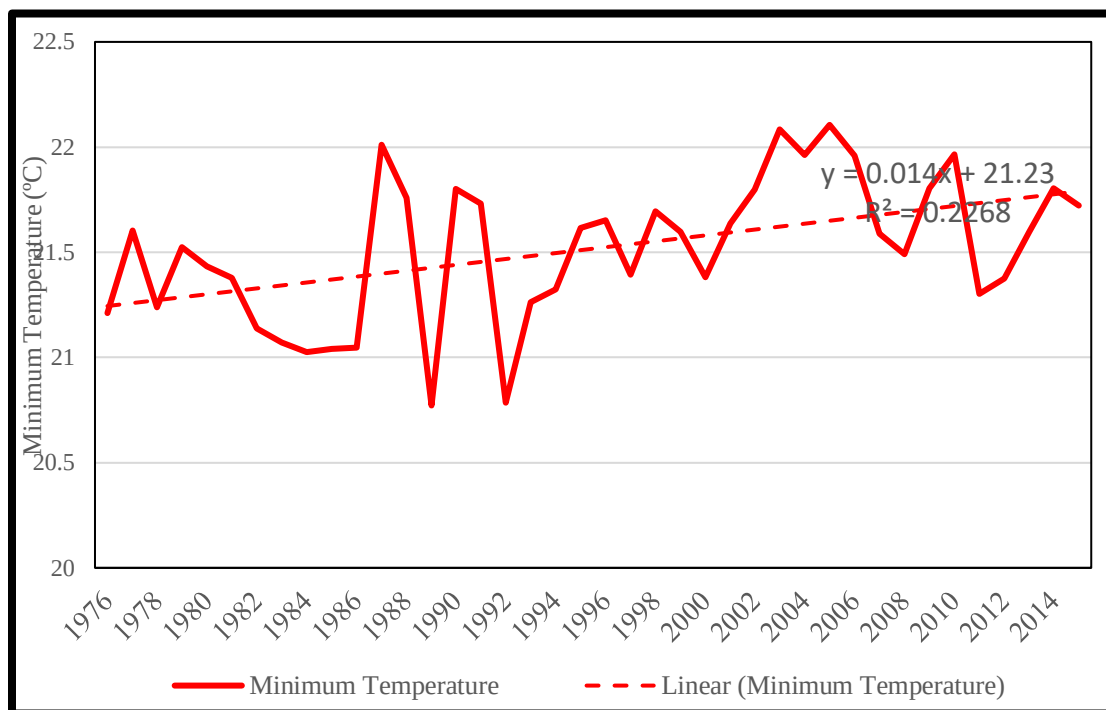


Figure 4.9: Trend in Minimum Temperature with Time in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

The computed spatial map of minimum temperature revealed that settlements in the southern part received higher minimum temperature from January to December (Figures 4.10 & 4.11). The minimum temperature over space varies from 18.20°C in the month of December in the north to 24.85°C in the month of April in the south. The lowest minimum temperature in the north in the month of December was as a result of harmattan season that is usually dominant in the basin at that period of the year. The results corroborated earlier findings in the study area where the lowest minimum temperature was recorded in December during the harmattan season especially in the northern part of the basin (OORBDA, 1982, p. 4).

Also, settlements in the south receiving highest minimum temperature can be attributed to the fact that most of the weather stations in the southern part are located in highly urbanized areas, thus the result may be connected to urban heat island effect compared to most of the stations in the northern part located mainly in rural environment. The range of minimum temperature varies across the basin from one month to another. For example, in April, Epe, Iberekedo, and Eluju in the southern part recorded the highest minimum temperature range (24.15-24.85°C), while the lowest (22.34-22.75°C) was in the north and northeastern settlements like Oyan, Okuku, Osogbo, Ilesha Aramoko Ekiti and Efon Alaye (Figure 4.10). The highest range of minimum temperature (21.13-22.40°C) in December was in Epe, Iberekedo, Eluju and Akata, while the lowest (18.20-18.82°C) was in the northern settlements like Okuku, Ifon and Osogbo (Figure 4.11).

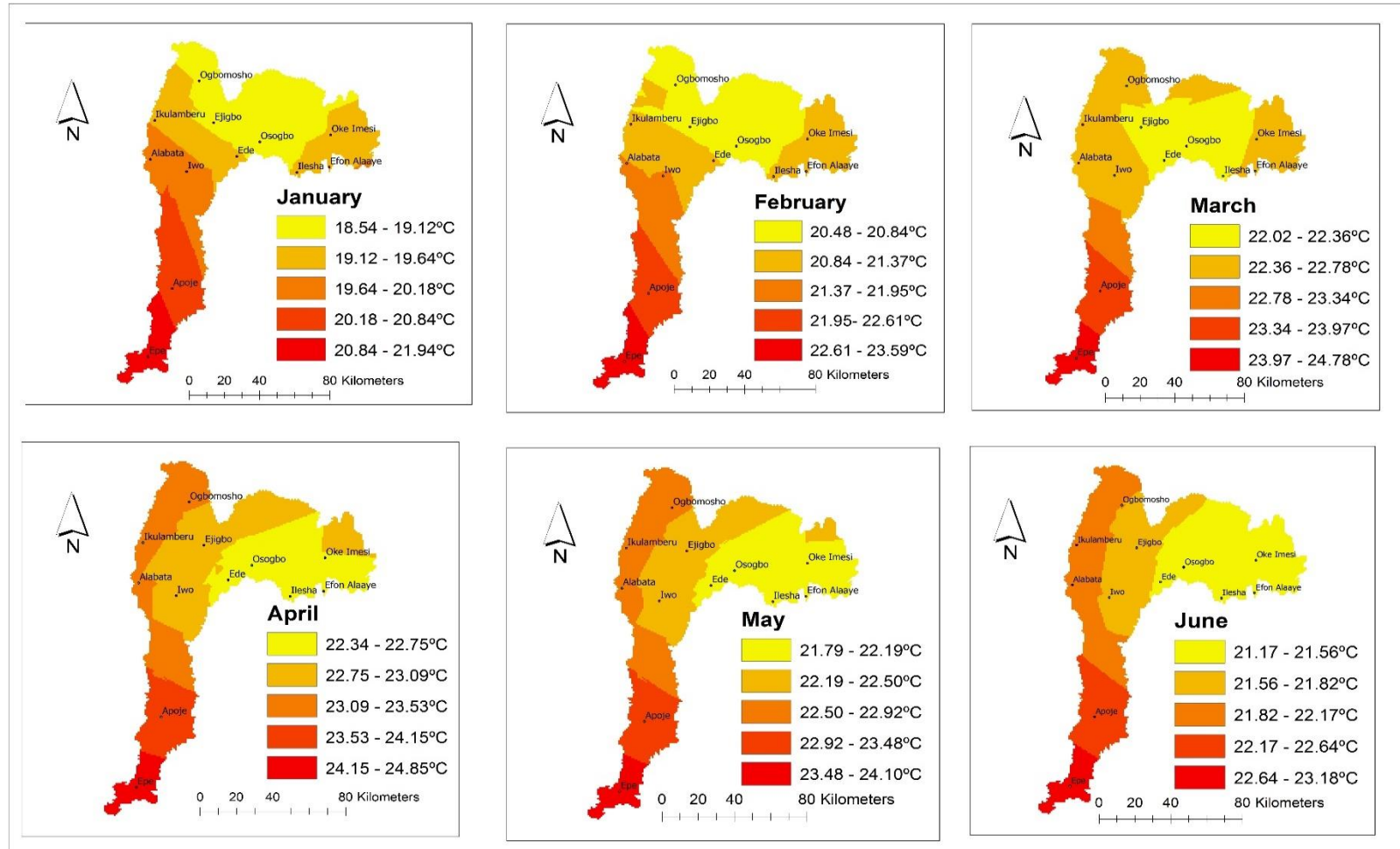


Figure 4.10: Mean Monthly (January-June) Pattern of Minimum Temperature in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

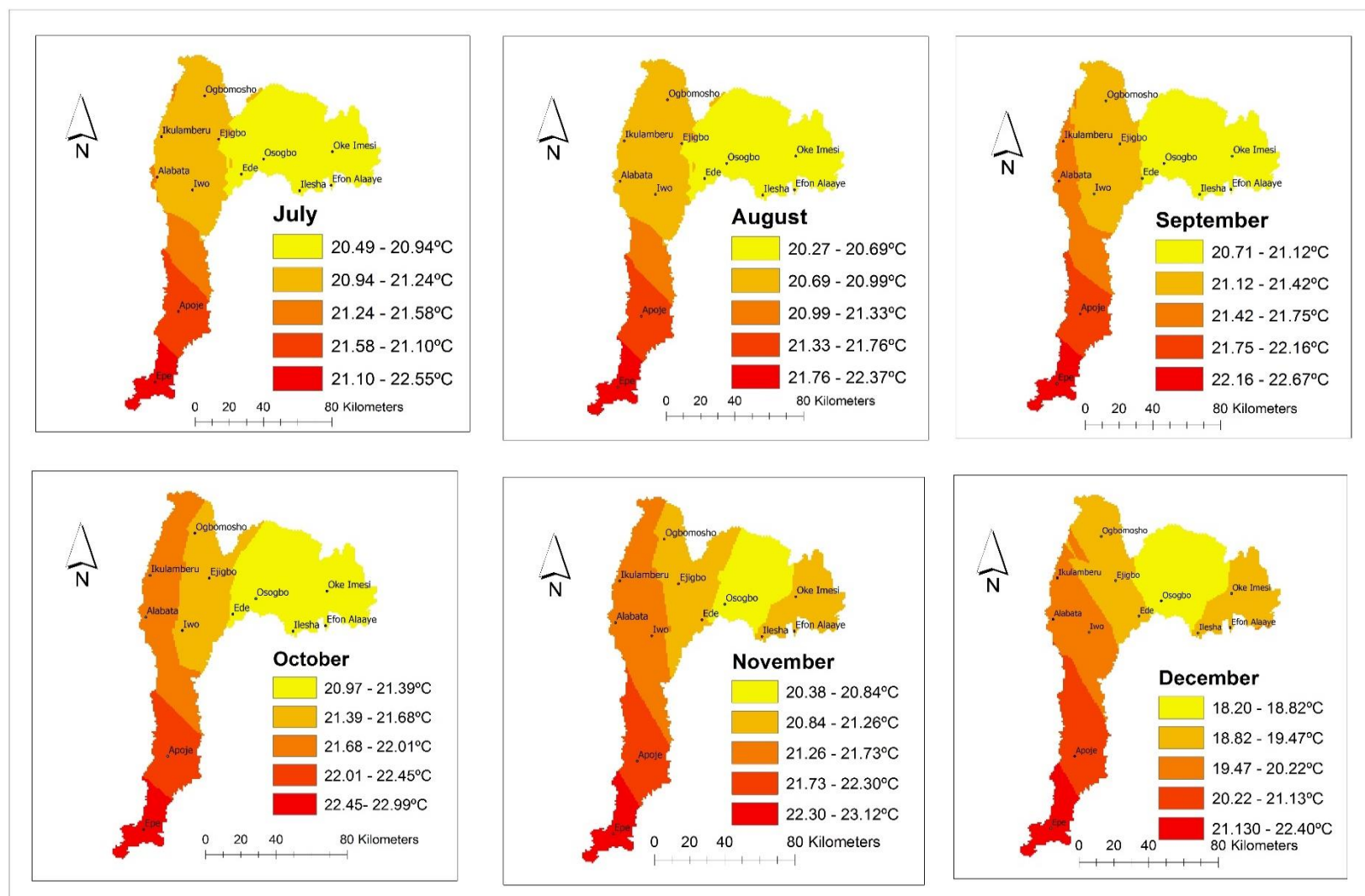


Figure 4.11: Mean Monthly (July-December) Pattern of Minimum Temperature in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

Mean annual minimum temperature range from 20.64°C in the north to 23.21°C in the south of Osun drainage basin. The highest mean annual minimum temperature (22.48-23.21°C) was in the southern part in Ijebu Ife, Akata, Epe, Eluju and Iberekodo, while the lowest (20.64-21.12°C) was in the north and northeastern part of the basin in Ajelanwa, Erinle, Ifon, Inisha, Oshogbo, Ibokun, Efon Alaye, Igbajo and Oke Imesi (Figure 4.12). The observed spatial variation in minimum temperature revealed that the extreme southern part of the study area received higher minimum temperature in the basin. The observed pattern may be attributed to the southern part's closeness to large water bodies, especially the lagoon and Atlantic Ocean which modifies the minimum temperature. This is a result of large water body serving as heat sinks to absorb large amount of solar radiation. This is later radiated back to the surrounding environment and resulted in the high minimum temperature.

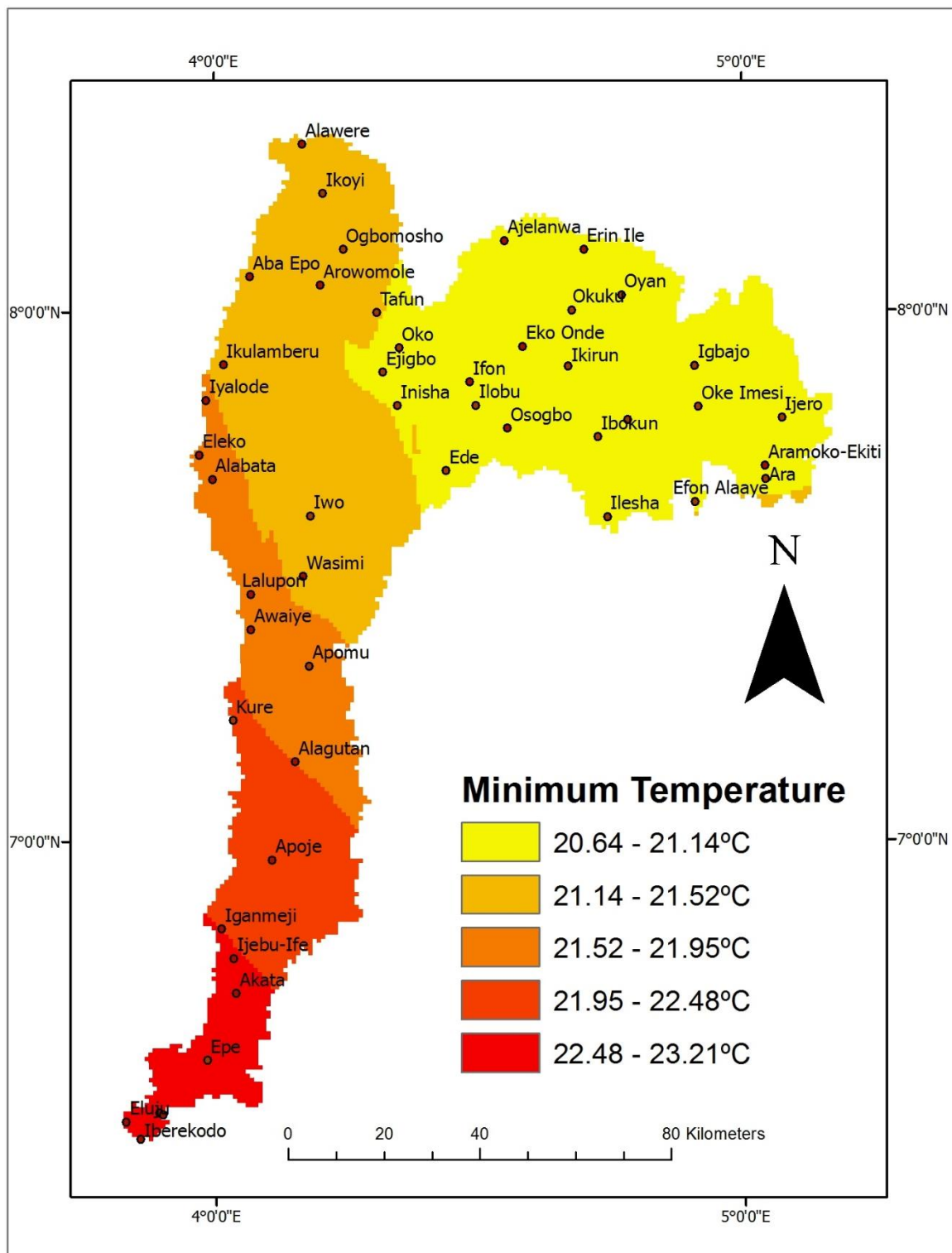


Figure 4.12: Pattern of Annual Minimum Temperature in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

4.2.4 Spatio-temporal Pattern of Maximum Temperature in Osun Drainage Basin

A statistically significant positive trend in maximum temperature was observed from the result of Mann-Kendall and regression trend analysis (Table 4.2). Thus, there is certainty that maximum temperature will continue to increase into the future in the study area. The statistically significant positive relationship between maximum temperature and year at 95 % confidence level also indicates that the trend will continue into the future. The trend line equation, revealed that maximum temperature is increasing at a rate of 0.03°C/ year during the period of study (Figure 4.13). Although there was yearly fluctuation in maximum temperature with about 19 years of above normal temperature during the 40 years of records.

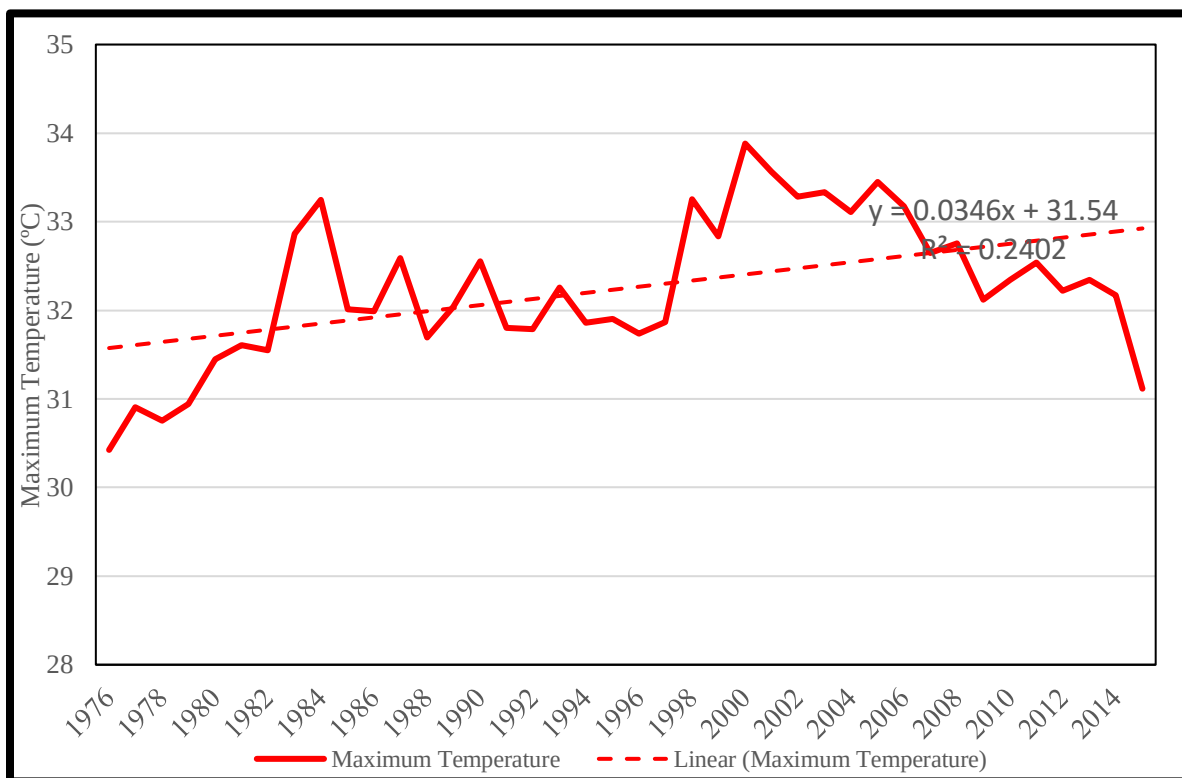


Figure 4.13: Trend in Maximum Temperature with Time in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

The reason for the increasing trend in maximum temperature may be connected to increase in greenhouse gasses concentration such as CO_2 . In addition, this region is experiencing rapid

urbanization and natural vegetation conversion to different land classes. The rain forest is gradually being replaced with secondary forest regrowth, and built up areas. All these factors may contribute to the increasing maximum temperature in the basin. Consequently, increasing temperature coupled with other factors such as increase wind speed and physical characteristics of the vegetation in the basin will definitely increase the rate of actual evapotranspiration. This will in turn affect the water balance of the region, especially the rainfall amount that will recharge the groundwater system.

Mean monthly maximum temperature ranges from 26.52°C in August in the uplands of the northeastern settlements to 38.44°C in March in the extreme north. Ejigbo, Alabata, Ikulamberu, Ogbomosho and Arowomole etc. in the northwestern part have the highest maximum temperature (36.12-36.88°C) in January, while the lowest (32.96-34.05°C) was in Epe, Iberekodo, Eluju and Akata in the south (Figure 4.14). This is an indication that monthly maximum temperature increases northward in Osun drainage basin. A similar pattern was observed from February to December with the exception of August and September. In September, highest maximum range of temperature (29.05 -29.51°C) was in Alawere, Aba Epo, Ikulamberu, and Alabata in the northwest, while the lowest (27.84-28.26°C) was in northeastern settlements like Oshogbo, Ilesha, Aramoko Ekiti, Oke Imesi and Efon Alaye (Figure 4.15). Despite the similar pattern in maximum temperature, February and March are usually the hottest months in the basin (OORBDA, 1982, p. 4). The observed pattern indicates that settlements in the northwestern part received higher maximum temperature in the basin, as a result of usually long hours of insolation. There is often a higher cloud cover in the south that absorbs and reflects incoming solar radiation. This prevents heat to build up, hence, lower maximum temperature in the southern axis of the basin.

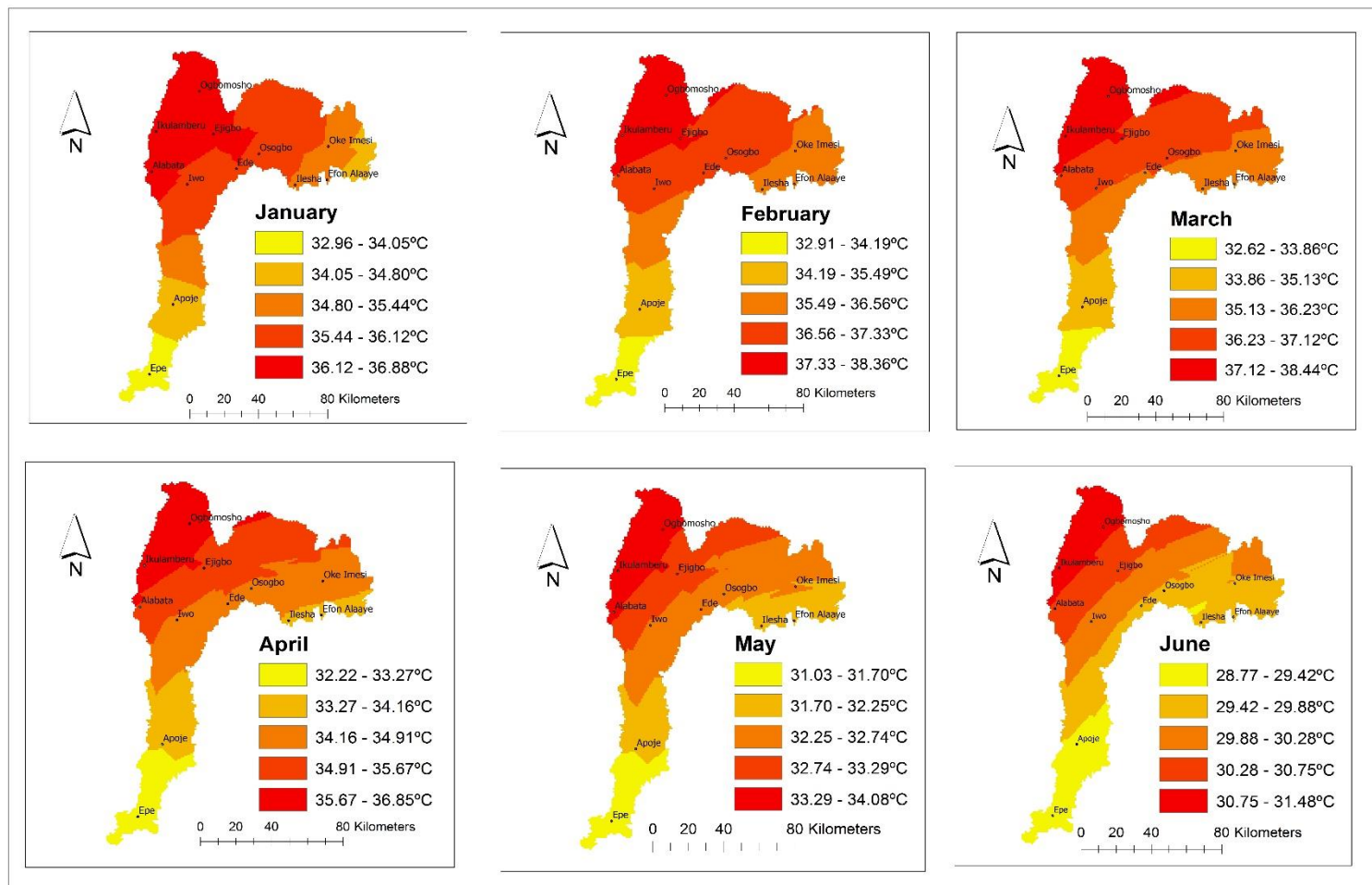


Figure 4.14: Mean Monthly (January-June) Pattern of Maximum Temperature in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

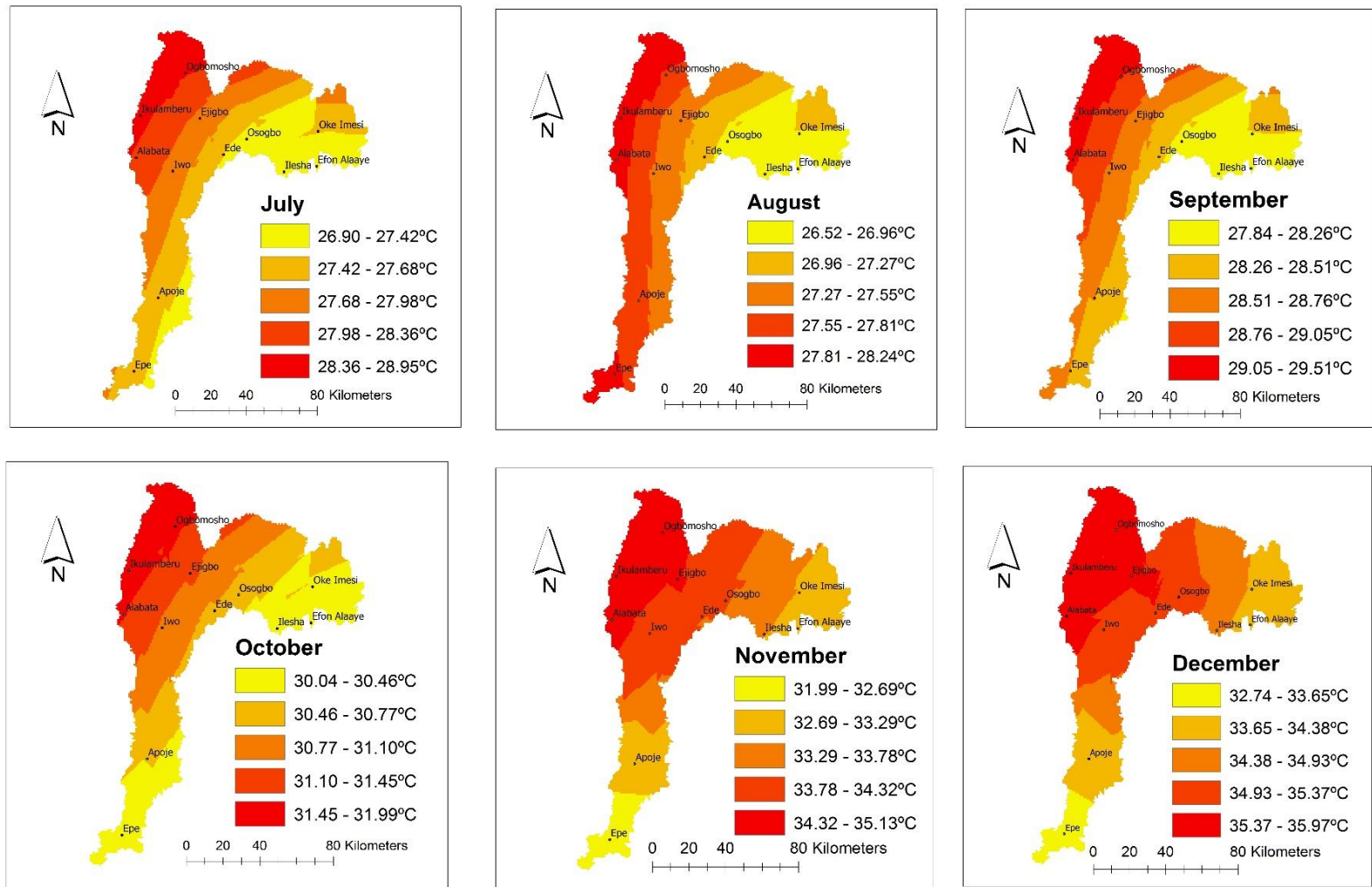


Figure 4.15: Mean Monthly (June-July) Pattern of Maximum Temperature in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

Mean annual maximum temperature range from 30.85°C in the south to 33.82°C in the northwest. Highest range of mean annual maximum temperature (33.04-33.82°C) was in Arowomole, Ogbomosho, Aba Epo, Iyalode, Ikulamberu, Alabata, etc. in northwestern part, while the lowest (30.83-31.54°C) was in Ijebu Ife, Akata, Epe, Eluju, Iganmeji and Iberekodo, etc. in the south (Figure 4.16). The observed spatial variation in maximum temperature revealed that northwestern part of the study area received higher maximum temperature in the basin. The result is in agreement with the early study that revealed northward increase in mean annual temperature in the study area (OORBDA, 1982, p. 4). The pattern observed is as a result of longer duration of insolation in the northern part because the longer the hour of insolation, the higher the air temperature. This is one of the important factors that affect evaporation. Other factors include cloud cover, land use/land cover as well as elevation and aspect. The maximum temperature and the estimated PET in the study area have similar pattern, while the mean annual rainfall amount has an inverse pattern in relation to maximum temperature and PET.

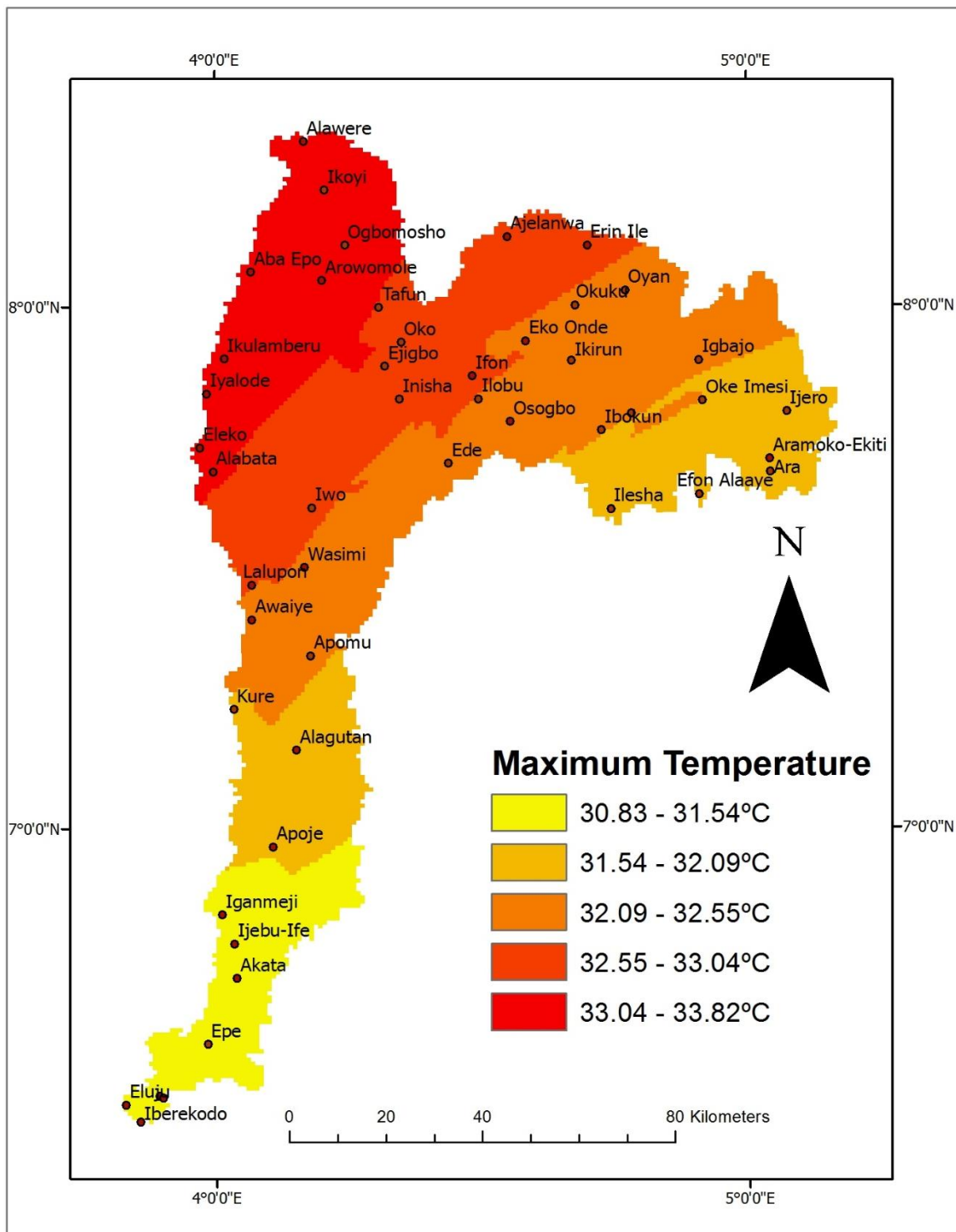


Figure 4.16: Pattern of Annual Maximum Temperature in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

4.2.5 Spatio-temporal Pattern of Relative Humidity in Osun Drainage Basin

A downward trend in relative humidity was obtained from the result of Mann-Kendall statistics and regression trend analysis which are not statistically significant (Table 4.2). Hence, it cannot be associated with a phenomenon and its continuation into the future is uncertain. The regression result shows that there is no statistically significant relationship between relative humidity and year at 95 % confidence level from the regression result. The graph in Figure 4.17 shows a decreasing trend at the rate of -0.06% every year during the period with yearly fluctuations. Although, the results of the two methods employed suggested that the observed decreasing trend might not continue into the future. The present scenario will significantly affect the rainfall amount in the study area. Decreasing rainfall amount was also observed during this period which signifies the significant influence of relative humidity on rainfall.

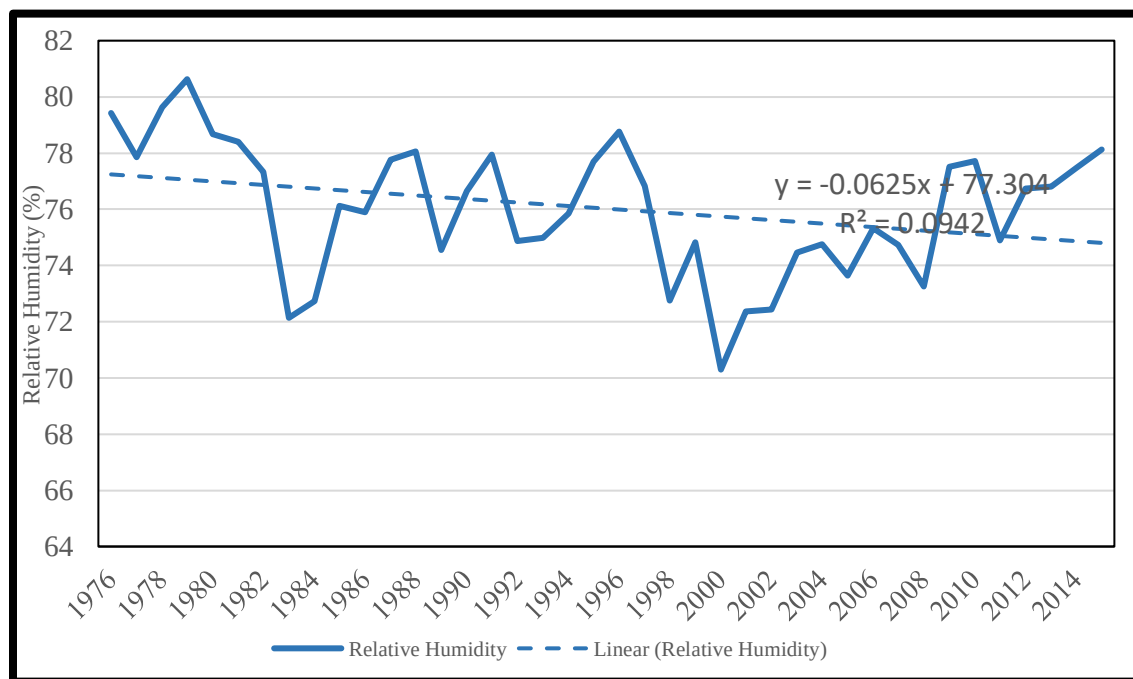


Figure 4.17: Trend in Relative Humidity with Time in Osun Drainage Basin (1976-2015)

Source: Author's Computation, 2017

Mean monthly relative humidity ranges from 43.78% in January in the north to 90.59% in September in the southeastern part and the uplands in the northeastern part. The highest range of

relative humidity in January (70.86-78.31%) was in Epe, Iberekedo, Ijebu Ife, and Akata, while the lowest (43.78-51.23%) was in Ejigbo, Ikulamberu, Ogbomosho, Arowomole, Iyalode and Aba Epo etc. in the northern part (Figure 4.18). The result indicates that settlements in the southern part have higher relative humidity in most of the months with few exceptions in the study area. The computed pattern of monthly relative humidity also agrees with the earlier study which reported that relative humidity decreases northwards in the basin (OORBDA, 1982, p. 4). The months that have slight difference in the pattern of relative humidity are July, August, September and October (Figure 4.19).

For example, highest range of relative humidity in September (89.13-90.59%) was Ede, Osogbo, Ilesha, Efon Alaye and Aramoko Ekiti in the northeastern part, while the lowest (85.50-86.88%) was in Alawere, Ikoyi, Ikulamberu and Aba Epo etc in the northwestern part. The general agreement was that relative humidity decreases as you move away from the coast towards the hinterland. However, the pattern in July, August, September and October revealed that some settlements in the hinterland received high relative humidity. This is attributable to the fact that low air temperature is found in some of the settlements in these months and relative humidity is inversely related to temperature. Mean annual relative humidity range from about 68% in the north to 82% in the south. The mean annual relative humidity has been reported to varies from 75% in the south to 55% in the northern part of the basin (OORBDA, 1982, p. 4). The highest range of mean annual relative humidity (78.70-82.49%) was in the south in Akata, Epe, Alaguntan and Apoje, etc, while northwest recorded the lowest (67.86-71.53%) in Alawere, Ogbomosho and Aba Epo (Figure 4.20). This explains why rainfall begins earlier in the south compared to the north.

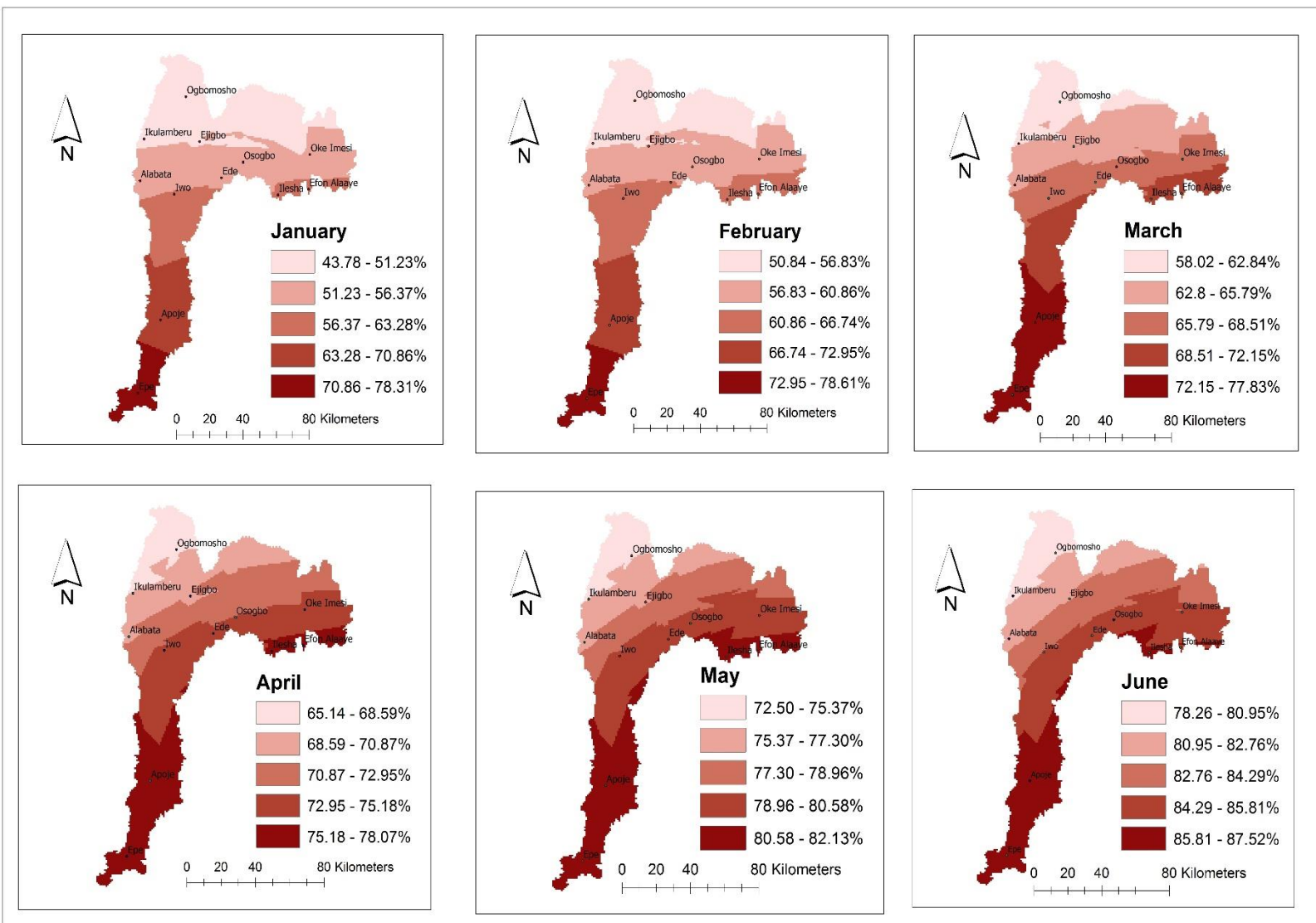


Figure 4.18: Mean Monthly (January-June) Pattern of Relative Humidity in Osun Drainage Basin (1976-2015)

Source: Author's Computation, 2017

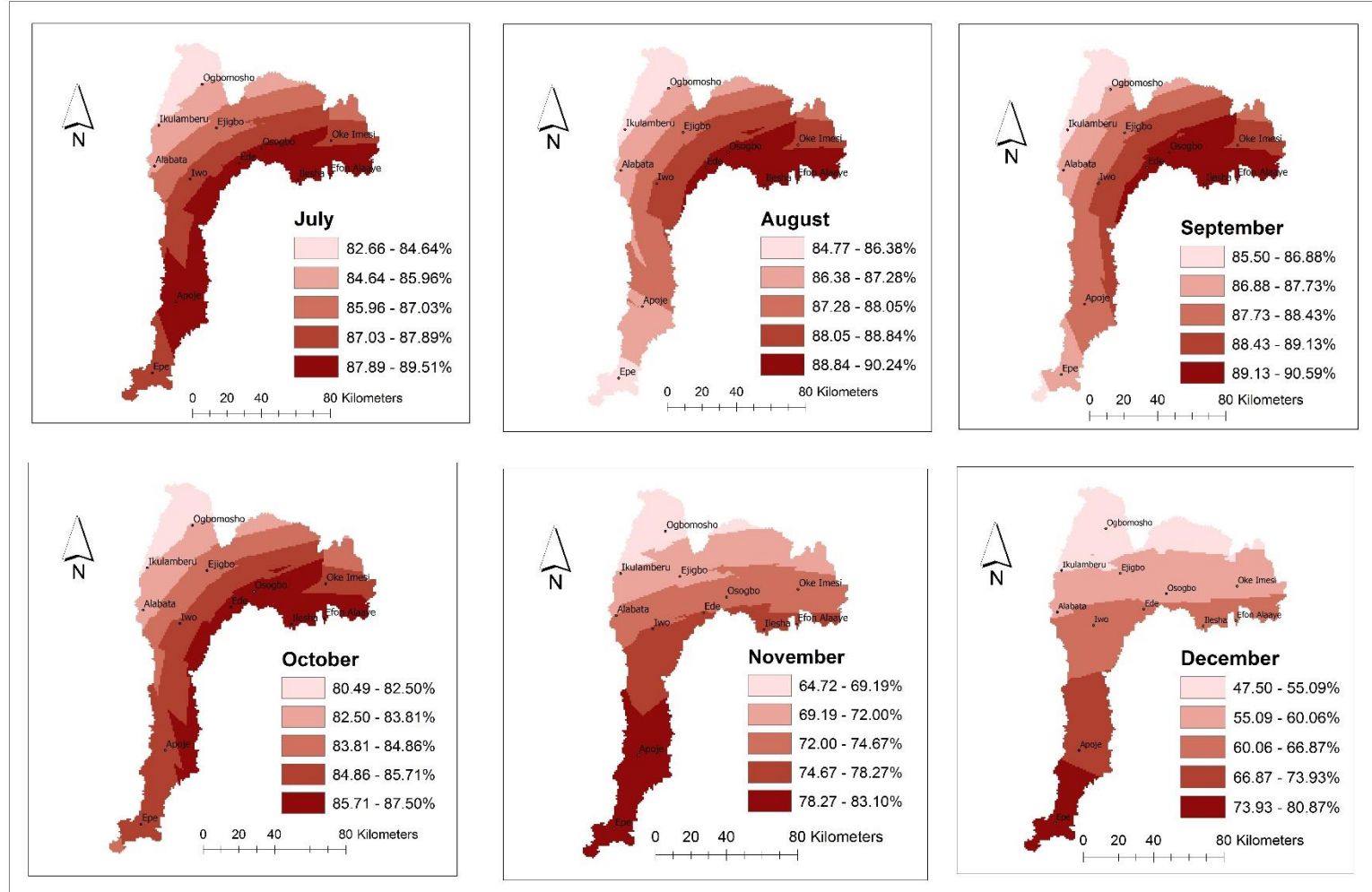


Figure 4.19: Mean Monthly (June-July) Pattern of Relative Humidity in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

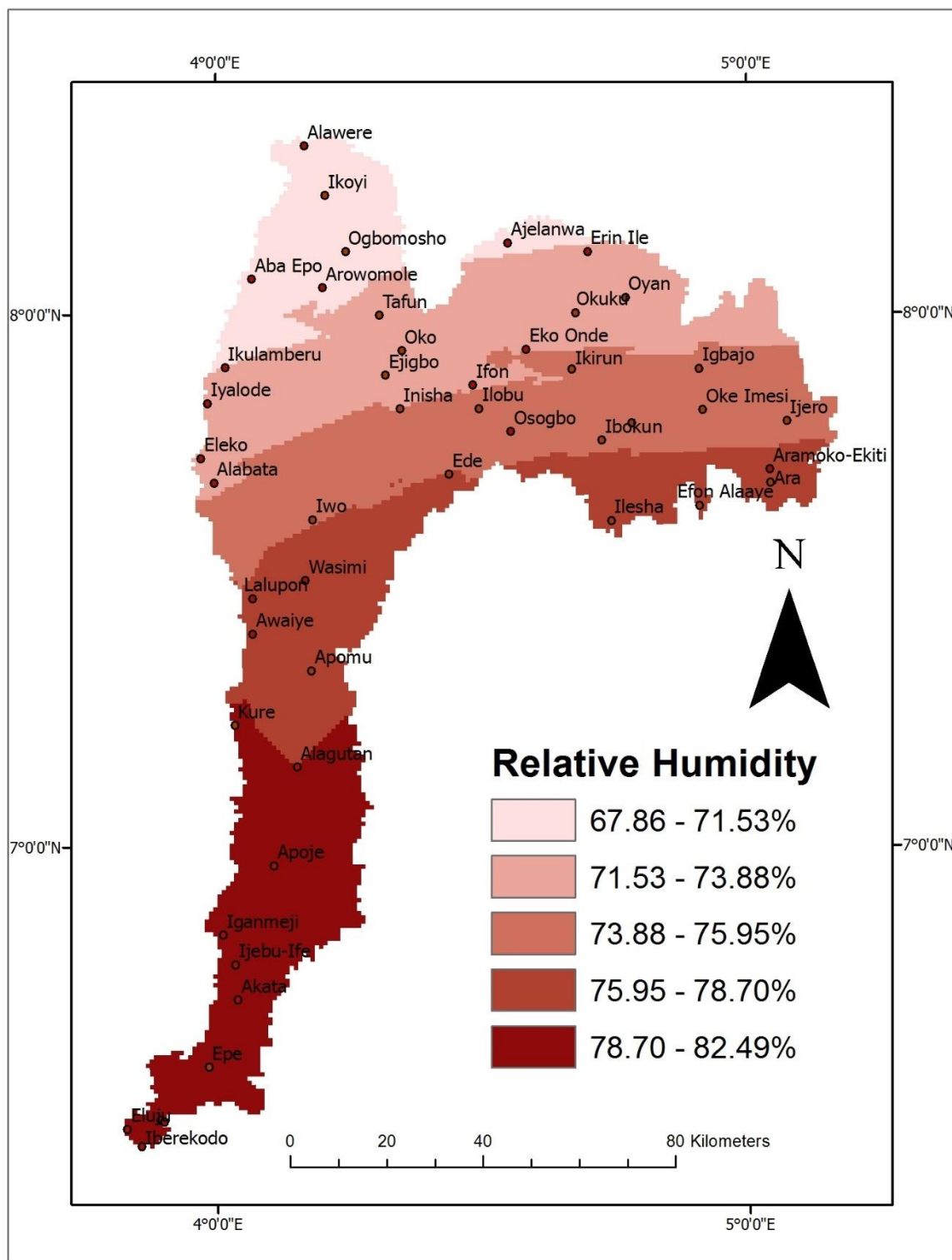


Figure 4.20: Pattern of Annual Relative Humidity in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

4.2.6 Spatio-temporal Pattern of Wind Speed in Osun Drainage Basin

Mann-Kendall trend analysis shows a positive trend in wind speed that is not statistically significant (Table 4.2). This indicates that the positive trend cannot be ascribed to any factor(s). It therefore occurred by chance and cannot be ascertained to continue to increase in the future based on the record at hand (1976-2015). The regression trend analysis also shows that there is no statistically significant relationship between wind speed and year at 95 % confidence level (Table 4.2). The R-squared statistic reveals that the model, as fitted, explains 3.29 % variability in wind speed in the basin. Figure 4.21 shows the positive trend line of wind speed and its trend equation which signifies an increase at a low rate of 0.06 m/s every year during the period of study. There was yearly fluctuation of wind speed and it was discovered that it was below the mean for most of the study period, especially between 1979 to 1998.

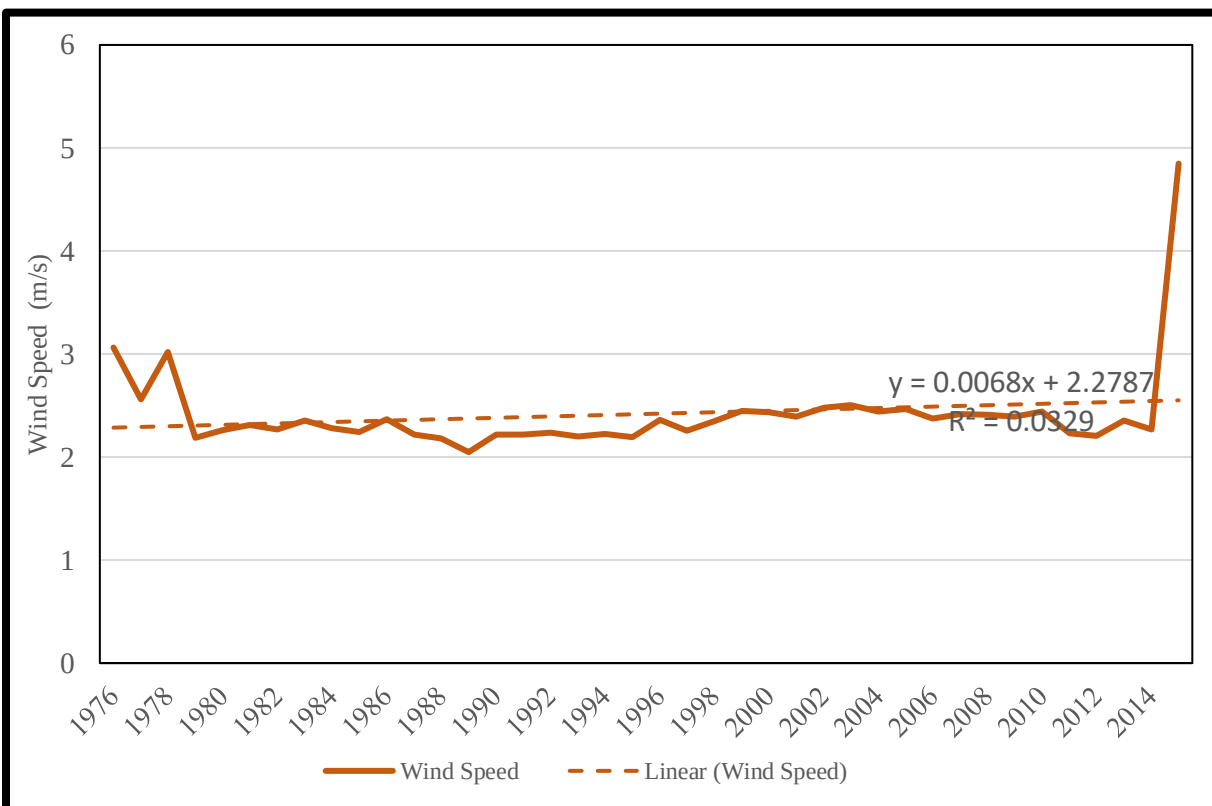


Figure 4.21: Trend in Wind Speed with Time in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

The mean monthly wind speed ranges from 1.4m/s in October towards the south to 3.88m/s in April in the north of Ogbomosho. The pattern of wind speed for all the months indicates that settlements in the north have higher wind speed (Figures 4.22 and 4.23). This signifies that the northern settlements received relatively high wind speed regime compare to other parts of the basin. For example, Ikoyi, Alawere and north of Ogbomosho in extreme northern part recorded the highest range of wind speed (2.36-2.66m/s) in January, while the lowest (1.66-1.90m/s) was in Apoje and Alaguntan towards the south (Figure 4.22). The pattern of the mean monthly wind speed is attributable to low vegetation in the north, where the percentage of tall trees that serve as wind breaker is relatively low in relation to the middle and southern part of the basin.

Mean annual wind speed ranges from 1.72m/s in the south to 30.06m/s in the north. The highest mean annual wind speed of 2.70-3.06m/s was observed around Ikoyi, Alawere, Aba Epo, Ajelanwa and Erin Ile, etc. (Figure 4.24). The lowest (1.71-2.09m/s) was in south around Apoje and Alaguntan as well as in fringe of the southeastern in Obokun and Ilesha. The observed spatial variation in wind speed is attributable to the function of pressure gradient, vegetation and land use/land cover in the basin. Other factors responsible for this variation include latitude which increases from the south to the north as well as changes in vegetation from forest zone in the south to savanna in the north. Wind speed varies from low regime in the south to relatively high-speed regime in the north (Adaramola and Oyewola, 2011). The observed pattern follows the general pattern of wind speed in Nigeria, where high wind speed is usually in the north compared to other location in the south, with few exceptions.

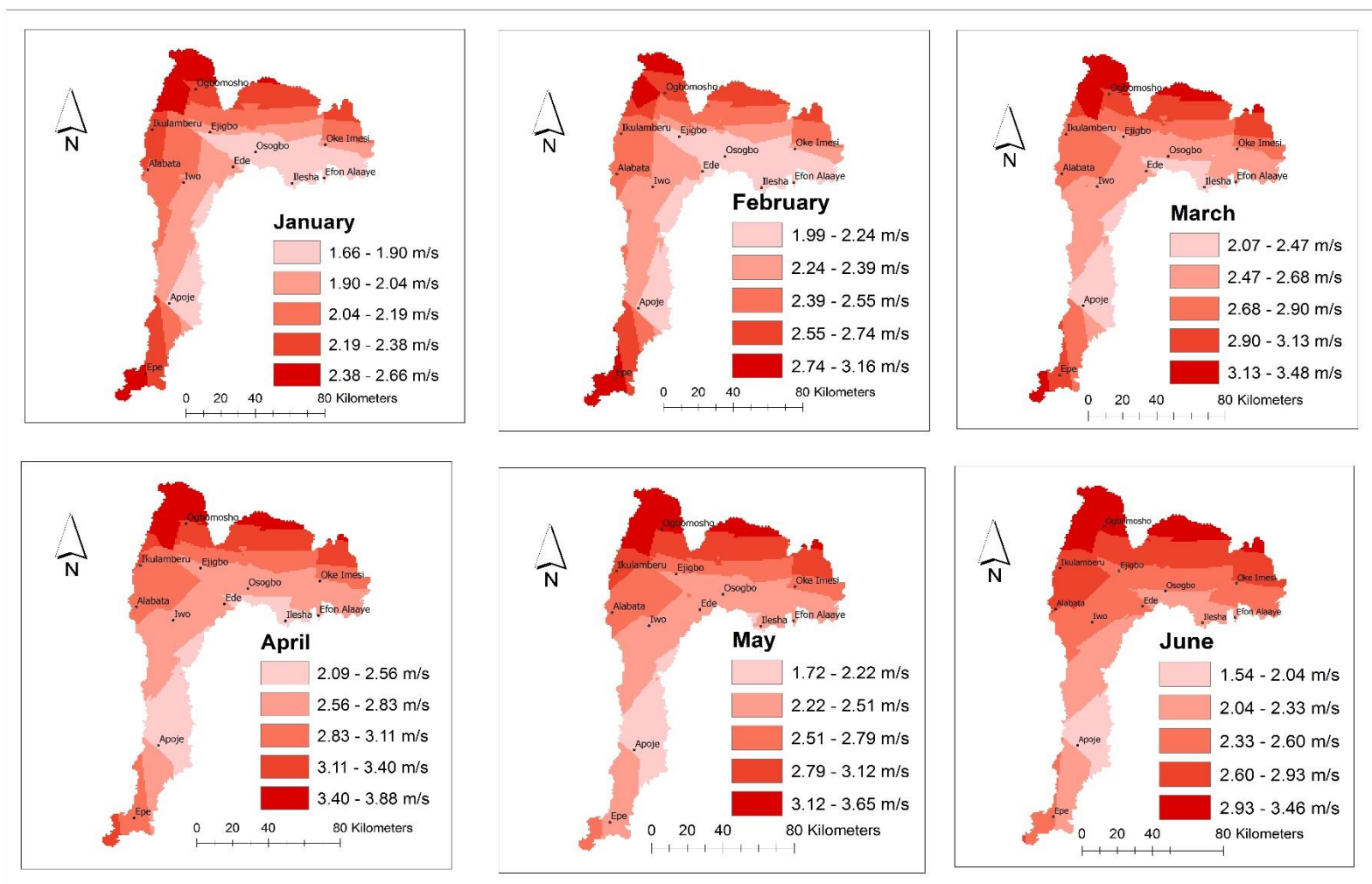


Figure 4.22: Mean Monthly (January-June) Pattern of Wind Speed in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

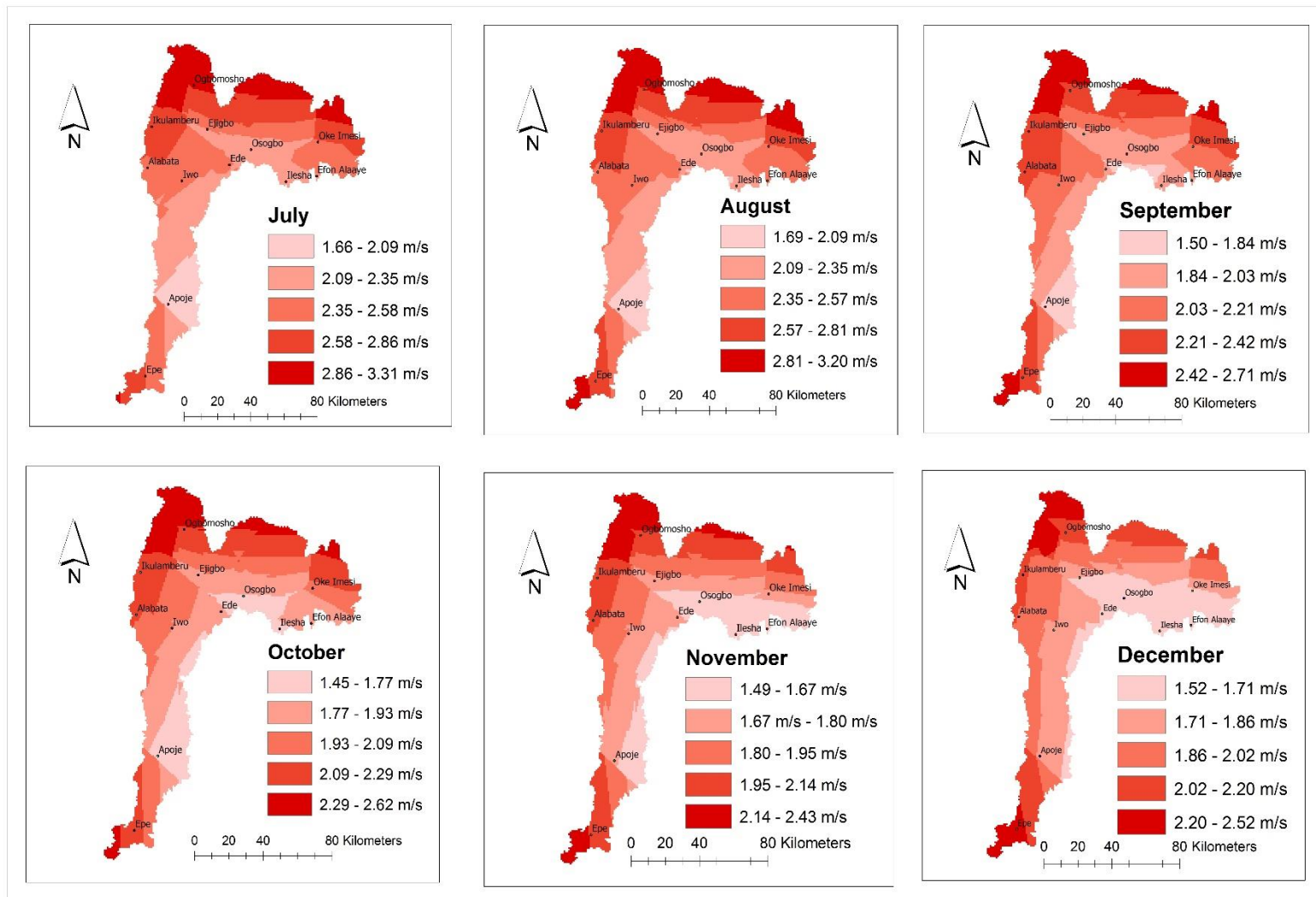


Figure 4.23: Mean Monthly (June-July) Pattern of Wind Speed in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

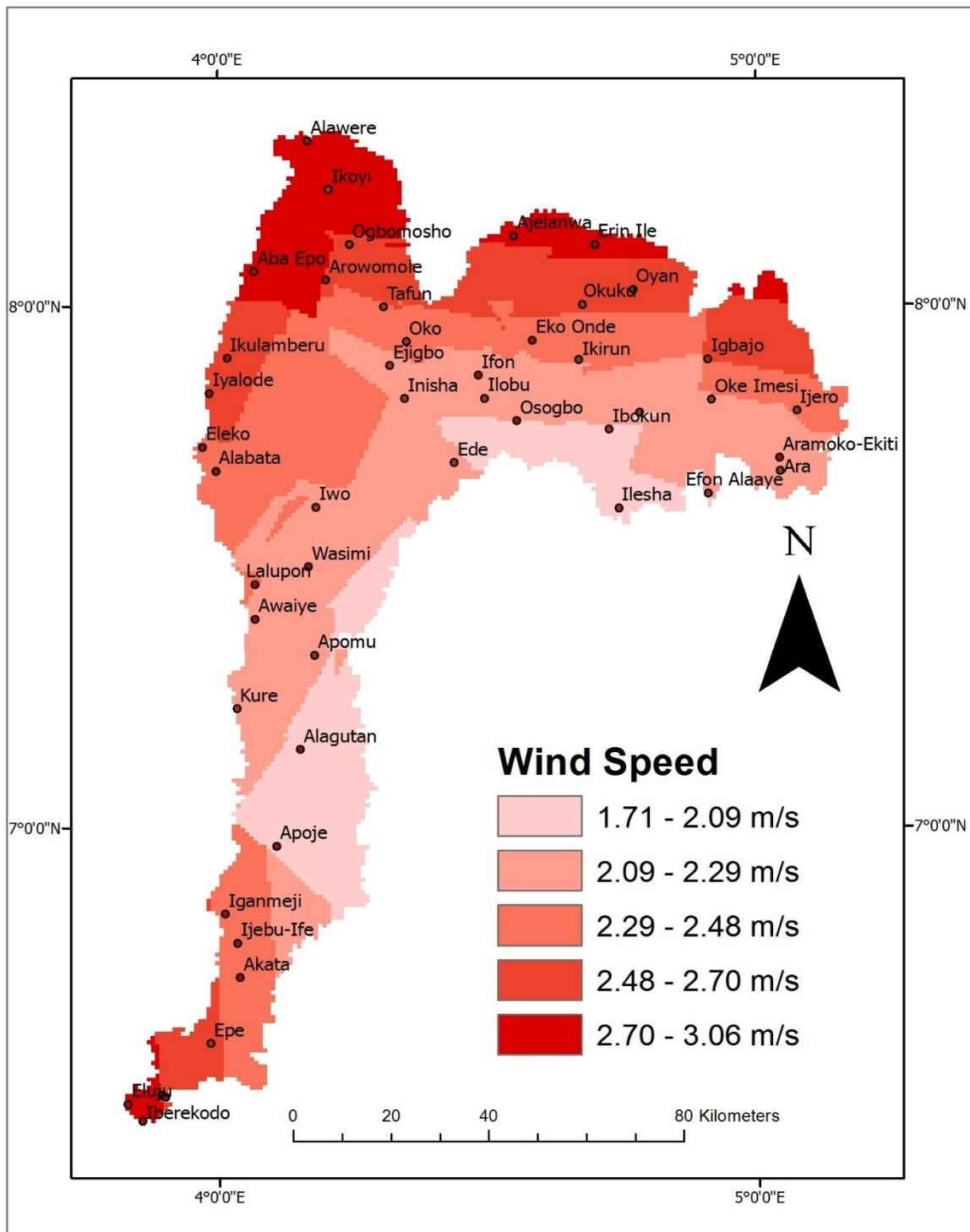


Figure 4.24: Pattern of Annual Wind Speed in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

4.3 Climate Forecast and Anomalies in Osun Drainage Basin

This section present and discusses the climate forecast for the period 2016-2025 from the result of trend analysis (regression) and the anomalies of the climatic variables for the period of study.

4.3.1 Climate Forecast for Osun drainage basin (2016-2025)

The predicted value of annual rainfall (Table 4.3) shows a downward trend from 1401.33mm (2016) to 1377.49mm (2025) in the basin. Based on the predicted results, annual rainfall amount will continue to decrease in the next decade in the study area. However, since the decreasing trend observed prior to this period is not statistically significant, there is likelihood of an increasing trend in the future. Whichever is the case, the trend in rainfall amount will subsequently influence the groundwater recharge in the drainage basin, because rainfall is the major source of direct recharge to aquifer.

Table 4.3: Climate Forecast for the Study Area 2016-2025

SN	Years	Rainfall Amount (mm)	Minimum Temperature (°C)	Maximum Temperature (°C)	Relative Humidity (%)	Wind Speed (m/s)	PET (mm)
1.	2016	1401.33	21.80	32.96	74.74	2.56	1688.08
2.	2017	1398.68	21.82	32.99	74.68	2.56	1691.71
3.	2018	1396.03	21.83	33.03	74.62	2.57	1695.34
4.	2019	1393.38	21.85	33.06	74.55	2.58	1698.97
5.	2020	1390.73	21.86	33.10	74.49	2.59	1702.60
6.	2021	1388.09	21.87	33.13	74.43	2.59	1706.23
7.	2022	1385.44	21.89	33.17	74.37	2.60	1709.86
8.	2023	1382.79	21.90	33.20	74.30	2.61	1713.49
9.	2024	1380.14	21.92	33.24	74.24	2.61	1717.12
10.	2025	1377.49	21.93	33.27	74.18	2.62	1720.75

Source: Author's Computation, 2017

Relative humidity shows a decreasing trend from 74.74% (2016) to 74.18% (2025). However, there might be an upward trend in the near future as the downward trend in the last 40 years that precedes the period 2016-2025 is not statistically significant. Minimum and maximum temperature indicated an upward trend from 21.80°C (2016) to 21.93°C (2025) and 32.66°C

(2016) to 33.27°C (2025), respectively. The positive trend observed in minimum and maximum temperature between 1976-2015 prior to this period are statistically significant, which is an indication that the increase predicted for this period is of higher likelihood and should be expected. This further reinforced the fact that the global temperature is increasing, especially in Nigeria.

The wind speed and PET also show an upward trend from 2.56m/s (2016) to 2.62m/s (2025) and 1688.08mm (2016) to 1720.75mm (2025), respectively. The positive trend in wind speed might be reduced because there is no statistically significant relationship between wind speed and time. Although the increasing trend from record of the last 40 years (1976-2015) was unable to associate such trend to any factor. High rate of forest conversion in the study area will increase wind speed in the future due to the degree of surface roughness. Also, PET in the basin shows the high likelihood of increase in the future based on the level of significance in the period under review.

4.3.2 Climate Anomalies in Osun Drainage Basin (1976-2015)

According to Olaniran (2002), climate anomalies are the deviation above or below the long term established normal climatic condition of an area. Climatic fluctuation is therefore a recurrent deviation from the normal. Hence, Osun drainage basin climate anomalies is the deviation from the long-term climate mean established in the basin.

4.3.2.1 Rainfall anomaly in Osun drainage basin

Standardized Anomalies Index (SAI) was used to establish the dry and wet years in the basin for the period of study (Table 4.4). The forty-year period were divided into four periods of ten years (decade). Thus, the number of dry and wet episodes (years) within each of the ten years' period were identified. The results revealed that from 1976-1985, there existed a five year each of wet and dry periods. Between 1986-1995, there were eight wet periods and two dry periods. In fact, this particular decade has more wet years than the other three (1976-1985, 1996-2005 and 2006-

2015) decades. The period 1996-2005, has six and four periods of wet and dry episodes, respectively.

Table 4.4: Dry and Wet Episodes in Osun Drainage Basin (1976–2015)

Periods	Dry years	Wet years
1976-1985	1976(-1.53), 1977(-1.93), 1978(-0.19), 1983(-1.25), 1984(-1.64),	1979 (0.94), 1980(1.46), 1981(0.23), 1982(0.85), 1985(1.14)
1986-1995	1986(-0.69), 1992(-0.03)	1987(1.10), 1988(0.82), 1989(0.41), 1990(0.75), 1991(1.32), 1993(0.44), 1994(0.89), 1995(1.79)
1996-2005	2000(-2.92), 2001(-2.09), 2002(-0.29), 2003(-0.07)	1996(0.95), 1997(0.45), 1998(0.10), 1999(0.34), 2004(0.43), 2005(0.06)
2006-2015	2006(-0.78), 2007(-0.46), 2011(-0.44), 2012(-0.26), 2013(-0.61), 2014(-0.15), 2015(-0.84)	2008(0.43), 2009(0.19), 2010(0.04)

**Standard Rainfall Anomalies Index are italics in parentheses

Source: Author's Computation, 2017

Lastly, the period 2006-2015 has seven and three periods of dry and wet episodes, respectively.

This shows that about 39% of the total dry period experienced in the basin for the 40 years period under investigation was in the last 10 years. This decade has more dry years than the other three decades. This is an indication that the dryness is becoming pronounced in the basin in recent years compared to what is usually obtainable. This will have significant effect on groundwater resources of the area as natural recharge to aquifer in this type of environment solely depend on rainfall. Figure 4.25 shows the rainfall anomalies in the study area over the period of study.

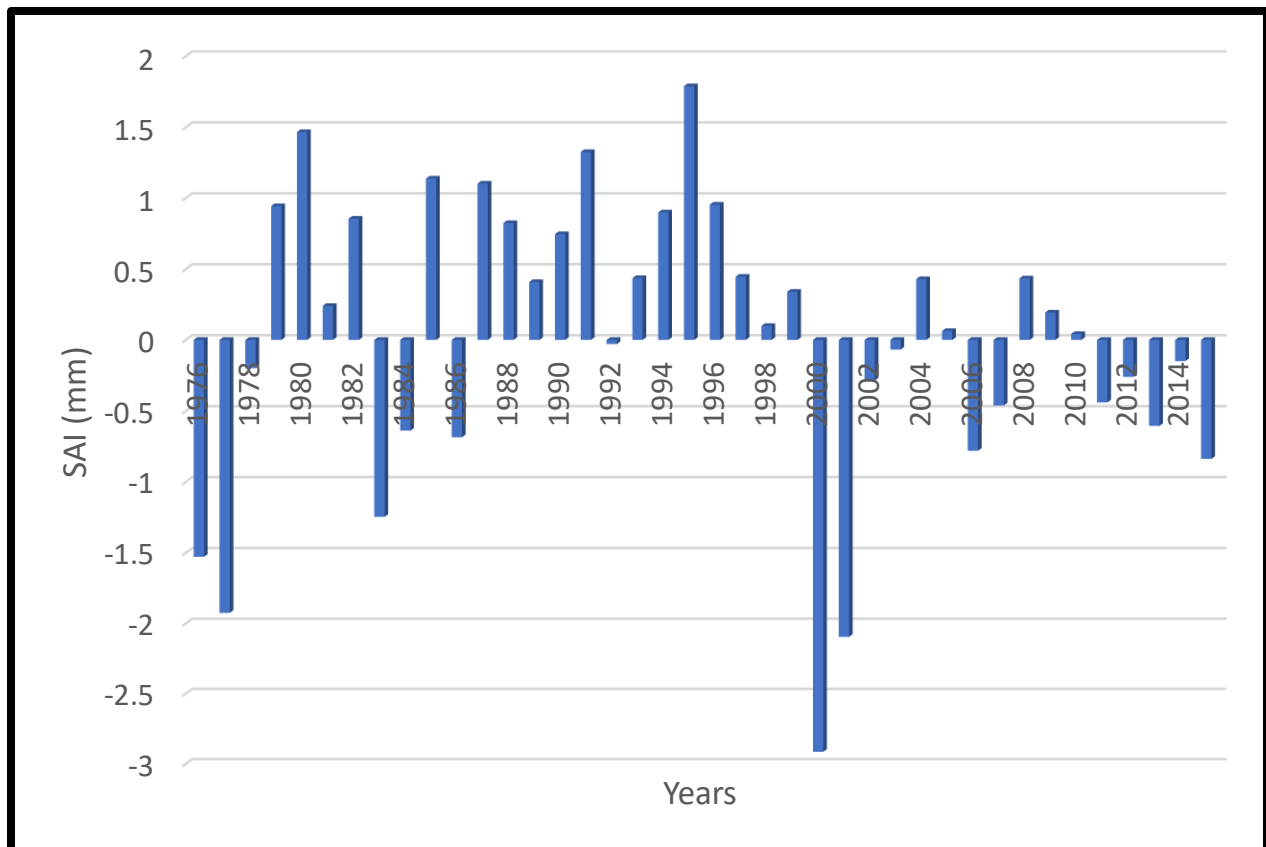


Figure 4.25: Rainfall Anomalies in Osun Drainage Basin (1976-2015)

Source: Author's Computation, 2017

4.3.2.2 Potential evapotranspiration anomaly in Osun drainage basin

Between 1976 to 1985, there existed two years of above normal PET condition and eight years of below normal PET condition (Figure 4.26). The decade 1986 to 1995, has below normal PET in the drainage basin. Thus, there is possibility of water surplus during this period (1986-1995) as it coincided with the decade of eight years of above normal rainfall amount in the study area. The period 1996-2005, has eight years of above normal PET and two years of below normal PET. This indicated that there was abnormal PET for 80% of this decade. Thus, it signaled the beginning of dramatic change in number of years with abnormal PET. Be it as it may, 8 years of abnormal PET in a decade will have a significant effect on the water budget of the basin, particularly the surface and ground water resources because of their interconnectedness. Lastly,

the period 2006-2015 has nine and one periods of above normal and below normal PET, respectively. The results of the last two decades is an indication that PET is becoming higher than the established long-term average in recent years. This period is the period when there were more dry years. Thus, dryness is becoming apparent and this have a significant influence on the water balance of the area.

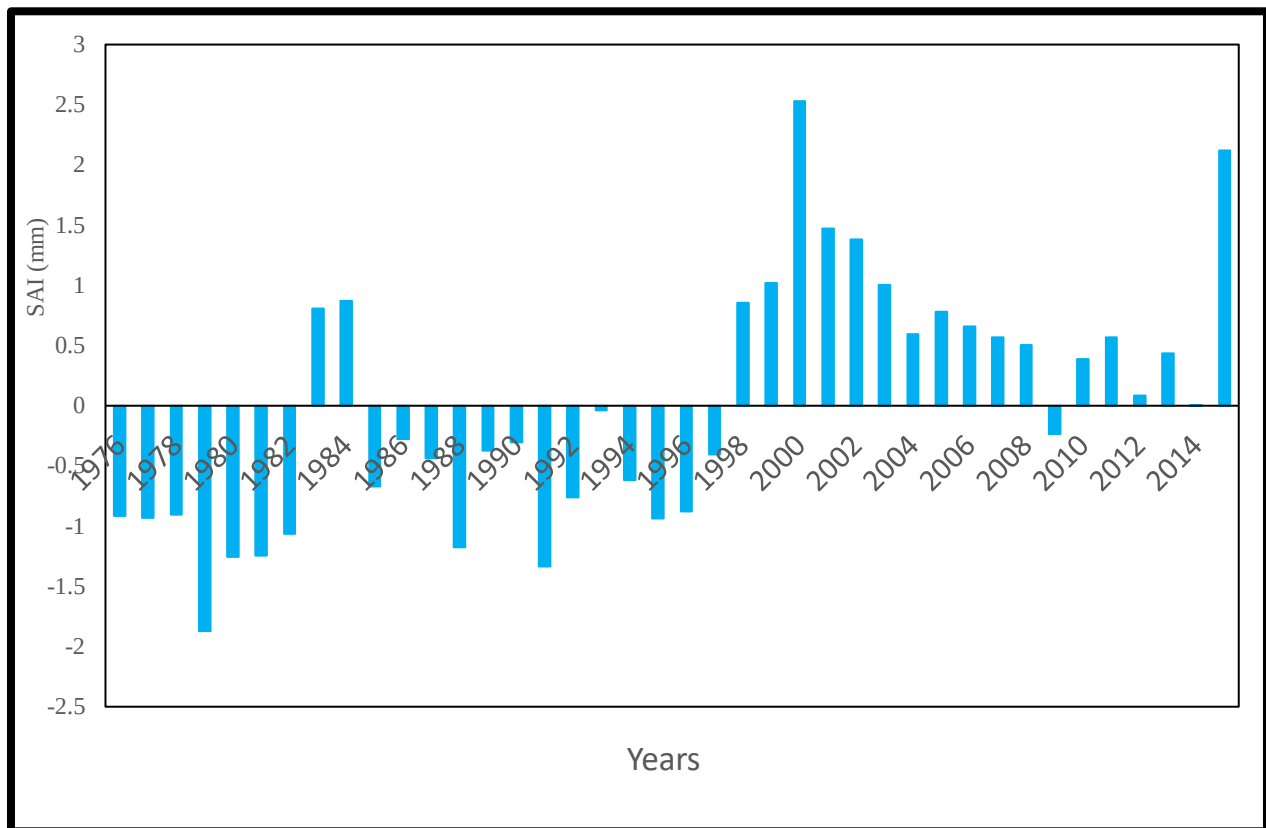


Figure 4.26: Potential Evapotranspiration Anomalies in Osun Drainage Basin (1976-2015)

Source: Author's Computation, 2017

4.3.2.3 Temperature anomaly in Osun drainage basin

Further, temperature anomaly is a deviation from a long-term average temperature recorded. A positive anomaly shows that the observed temperature is hotter than the long-term average value, while a negative anomaly reveals a cooler temperature than the long-term mean. There existed two hotter years and eight cooler years between 1976-1985 (Figure 4.27). Between 1986-1995,

there are two hot years and eight cool years. This indicated that the first 20 years has more cooler years than hotter years. Eight years and two years of hotter and cooler years, respectively were experienced between year 1996-2005.

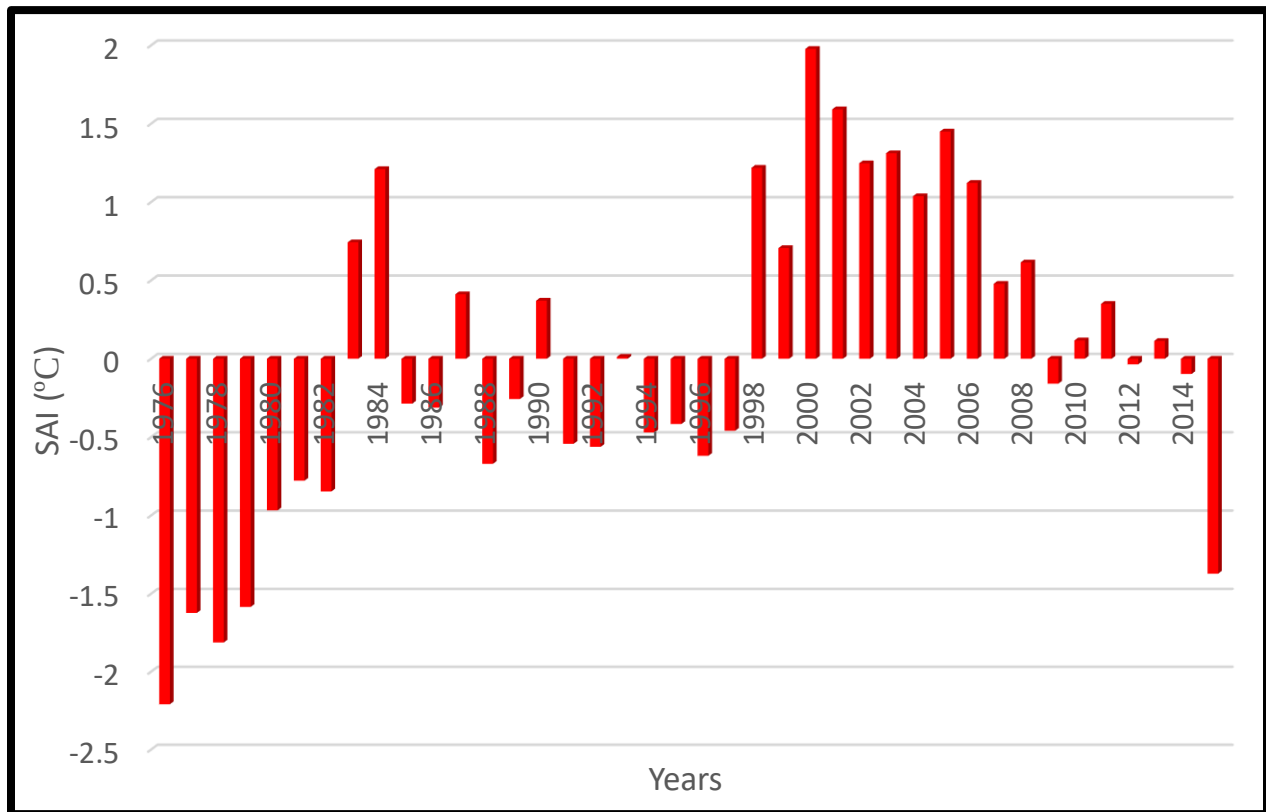


Figure 4.27: Maximum Temperature Anomalies in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

The period 1961-1990 was usually seen as the period of climatic normal. This period is usually use as the baseline to compare recent change in climate (WMO, 2007). This baseline period terminated is 1990, therefore, the eight hotter years from 1998-2006 experienced can be expected and it reflects the assertion that climate of the study area has changed. Also, the period 2006-2015 experienced six and four years of hotter and cooler temperature, respectively. This indicates that about 32% of the hotter years experienced in the basin for the 40 years period under investigation was in the last 10 years. This suggested the basin is becoming hotter over time, especially in the last two decades. The results reflected the increase in global warming as a

result of increase in greenhouse gases such as CO_2 . Early studies on land use/land cover changes in part of the basin have revealed the rate of forest conversion and increase in built up areas (Salami et al., 1999 and Akinyemi, 2005). Therefore, the increasing number of hotter years in the basin may be connected to the fact that trees that serves as carbon sinks has been removed, coupled with the increasing rate of urbanization in the basin.

In the case of minimum temperature, from 1976 to 1985, there existed a year of above normal and nine years of below normal minimum temperature (Figure 4.28). During this period, there is certainty of general cooler minimum temperature in the study area.

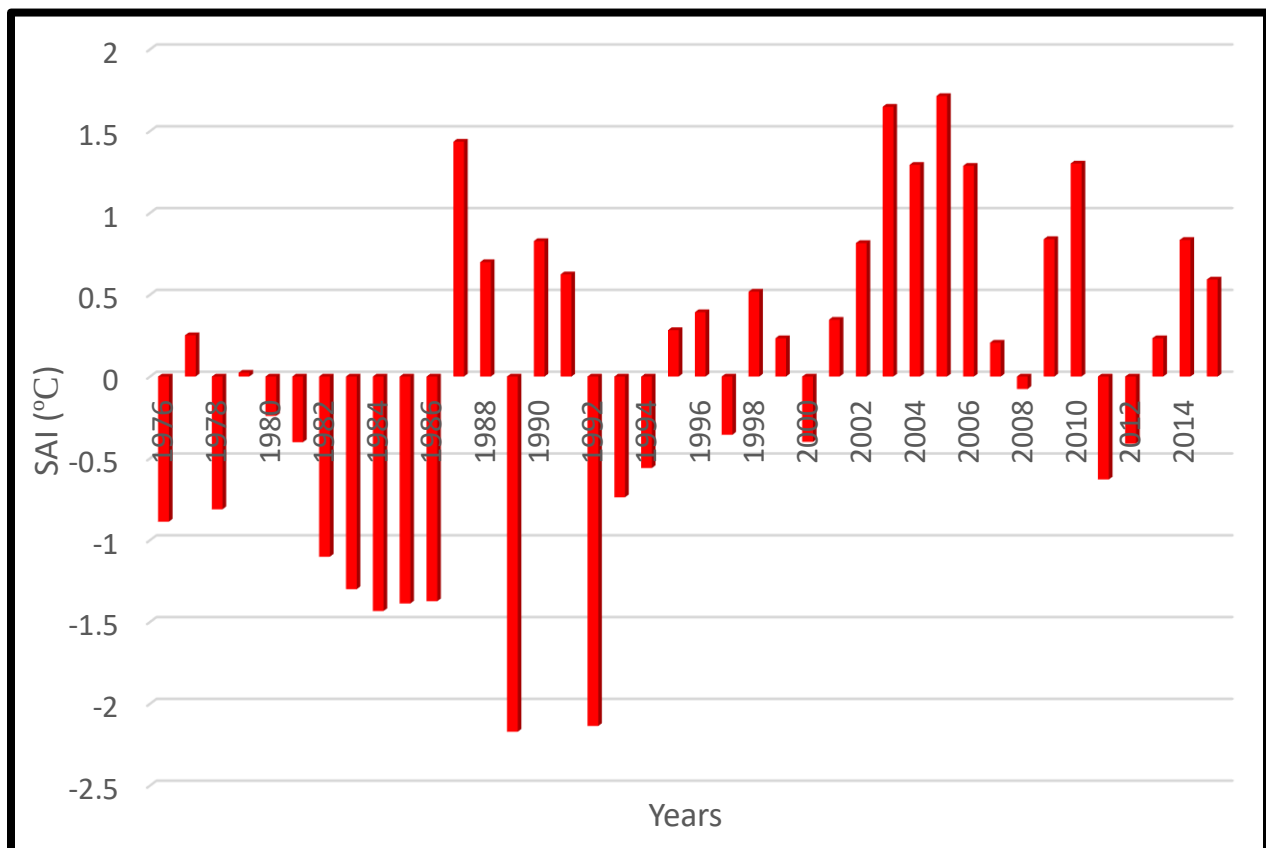


Figure 4.28: Minimum Temperature Anomalies in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

Between 1986 to 1995, there are five years each of above normal and below normal minimum temperature. The period 1996-2005, has eight years of above normal and two years of below

normal minimum temperature. Finally, the period 2006-2015 has seven and three years of hotter and cooler temperature, respectively. The observed minimum temperature anomalies in the last two decades (1996-2015) have similar pattern of PET and rainfall. This might be attributed to the general change in climate all over the world during the last 20 years.

4.3.2.4 Relative humidity anomaly in Osun drainage basin

Eight and two years of above and below normal relative humidity, respectively were identified between 1976-1985 (Figure 4.29). Between 1986-1995, there were five years each of above and below normal relative humidity. There were eight and two years of below and above normal relative humidity, respectively between 1996-2005. Also, the period 2006-2015 experienced six and four years of above and below normal relative humidity, respectively. There existed direct relationship between relative humidity and rainfall, thus these results will influence the rainfall amount in the basin.

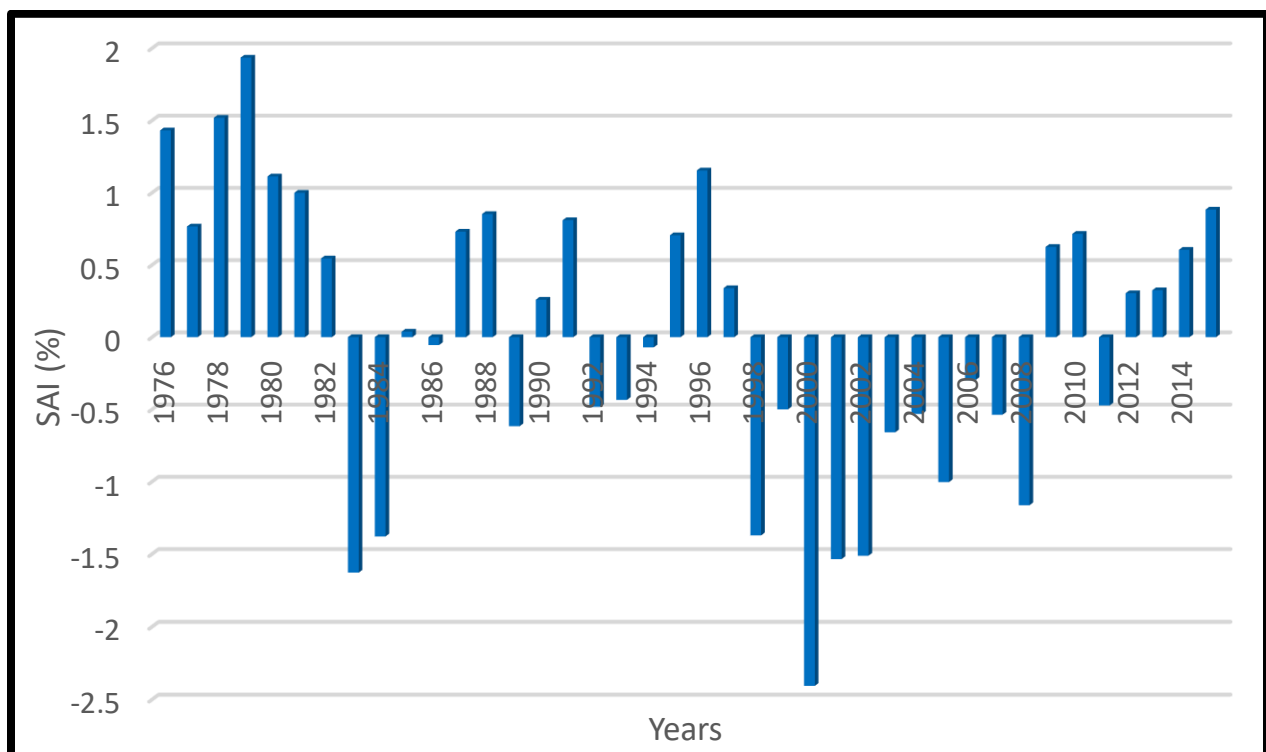


Figure 4.29: Relative Humidity Anomalies in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

4.3.2.5 Wind Speed anomaly in Osun drainage basin

Figure 4.30 shows that from 1976-1985, there existed seven years of below and three years of above normal wind speed. All the years between 1986-1995 experienced below normal wind speed. This is an indication of decreasing wind speed during this period. The period 1996-2005, has five years each of positive and negative. There existed two and eight years of above and below normal wind speed, respectively between 2006-2015. These results indicated a high deviation from the long term mean of that wind speed in this region with 28 years of below normal wind speed.

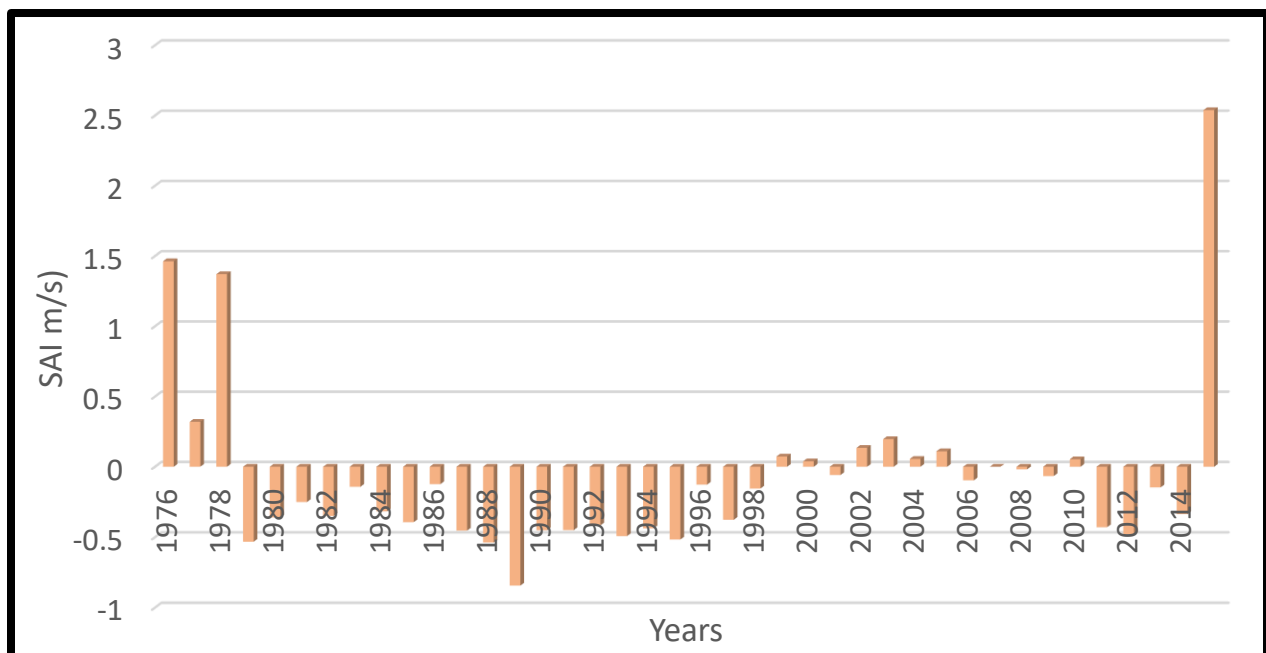


Figure 4.36: Wind Speed Anomalies in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

4.4 Conclusion

The averages of the climatic records from the 24 weather stations were used to compute the climatic condition of Osun drainage basin; and the spatio-temporal pattern identified and

discussed. In addition, the trend line equation was used to predict the future trend in climate from 2016-2025. Finally, climate anomaly for the study area was identified for the period of investigation.

CHAPTER FIVE

SPATIO-TEMPORAL PATTERN OF LAND USE/LAND COVER CHANGE IN OSUN DRAINAGE BASIN: 1984-2015

5.0 Introduction

This chapter examines the spatio-temporal patterns of land use/land cover changes in Osun drainage basin. The land use/land cover classifications for 1984, 2000 and 2015 were carried out; rate of change estimated; and change detection transition matrix computed in order to determine the change in LULC, with a view to identifying the rate of change in land use/land cover in Osun drainage basin.

5.1: Land Use/Land Cover Classification, 1984-2015

The land use/land cover (LULC) maps of Osun drainage basin were generated from Landsat imageries of the study area using Erdas Imagine 2014. The supervised image classification technique was employed by identifying the known features through their spectral signatures which assisted in the classification exercise. The Maximum Likelihood Classification Algorithm was adopted to extract the various land use/land covers of interest from the satellite imageries. These LULCs are bare surfaces, built up areas, crops/shrubs, forest, rock outcrops, water bodies and wetland. For the LULC map of 2015, the Kappa coefficient and overall accuracy were found to be 0.79 and 0.82, respectively. There was no record to check the accuracy of the classifications of 1984 and 2000, therefore the LULC areas that remained unchanged in 1984 and 2000 as at 2015 were identified in the three LULC classification maps. Thus, the same accuracy

was assumed for the three LULC classification. The results of the seven (7) classified LULC for the study area are presented in Table 5.1 and Figures 5.1-5.3.

Table 5.1: Land Use/Land Cover Classification of Osun Drainage Basin, 1984-2015

<i>Land Use/Land Cover Types</i>		1984		2000		2015	
		Area (Km ²)	%	Area (Km ²)	%	Area (Km ²)	%
1	Bare Surfaces	2040.95	20.56	2709.57	27.30	3087.31	31.10
2	Built Up Areas	317.64	3.20	459.18	4.63	1063.91	10.72
3	Crops/Shrubs	1646.14	16.58	4163.35	41.94	3114.86	31.38
4	Forest	5223.61	52.62	2059.21	20.75	2154.87	21.71
5	Rock Outcrops	493.05	4.97	342.35	3.45	420.09	4.23
6	Water Bodies	50.76	0.51	61.64	0.62	61.59	0.62
7	Wetland	154.07	1.55	130.93	1.32	23.59	0.24
	Total	9926.22	100.00	9926.22	100.00	9926.22	100.00

Source: Author's Computation, 2017

In the base year, forest area constituted the most extensive type of land use/land cover of Osun drainage basin. Accordingly, it accounted for about 52.62% of the total drainage basin area in 1984, followed by bare surface and crops/shrubs, occupying 20.56% and 16.58% of the total drainage area, respectively (Table 5.1). About 0.51% of the study area was covered by the water bodies which is the least of the seven (7) land use/land cover classified in 1984. In 2000, crops/shrubs, bare surfaces and forest covered 41.94%, 27.30% and 20.75%, respectively of the total basin area. Also, bare surface, crops/shrubs, forest covered 31.10%, 31.8% and 21.71%, respectively, while built up area accounted for 10.72% of Osun drainage area in 2015.

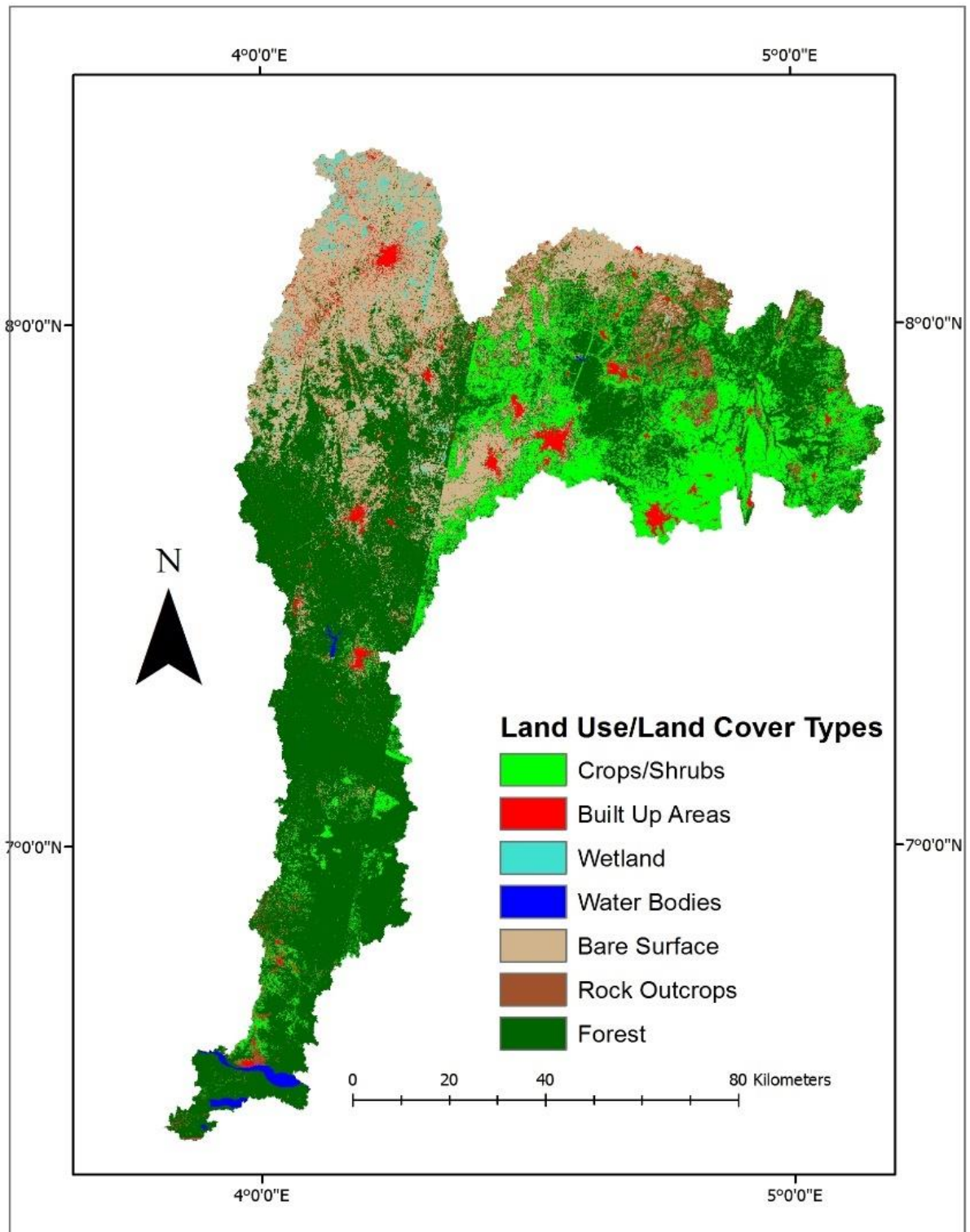


Figure 5.1: The Classified Image of Osun Drainage Basin, 1984
Source: Author's Classification, 2017

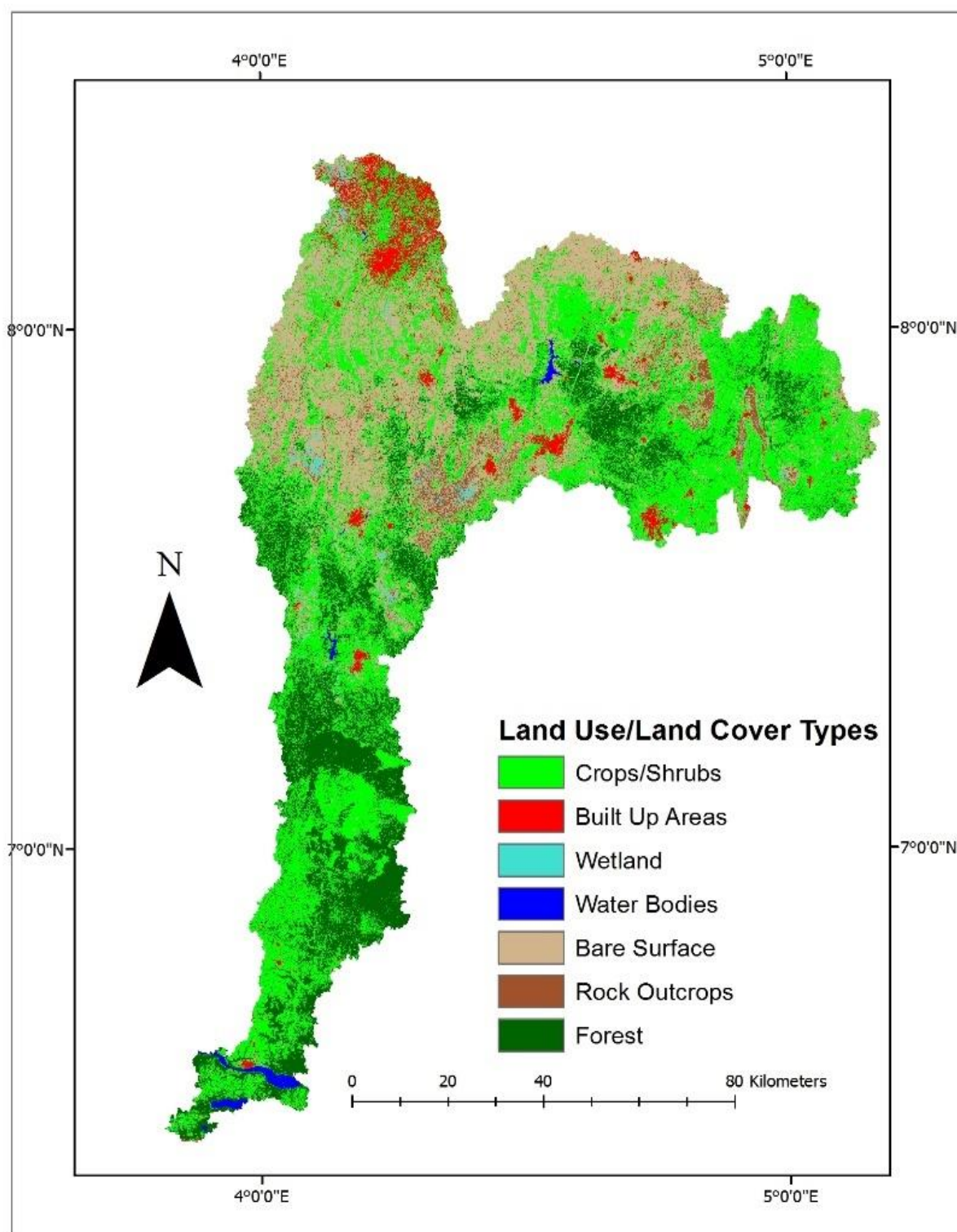


Figure 5.2: The Classified Image of Osun Drainage Basin, 2000
Source: Author's Classification, 2017

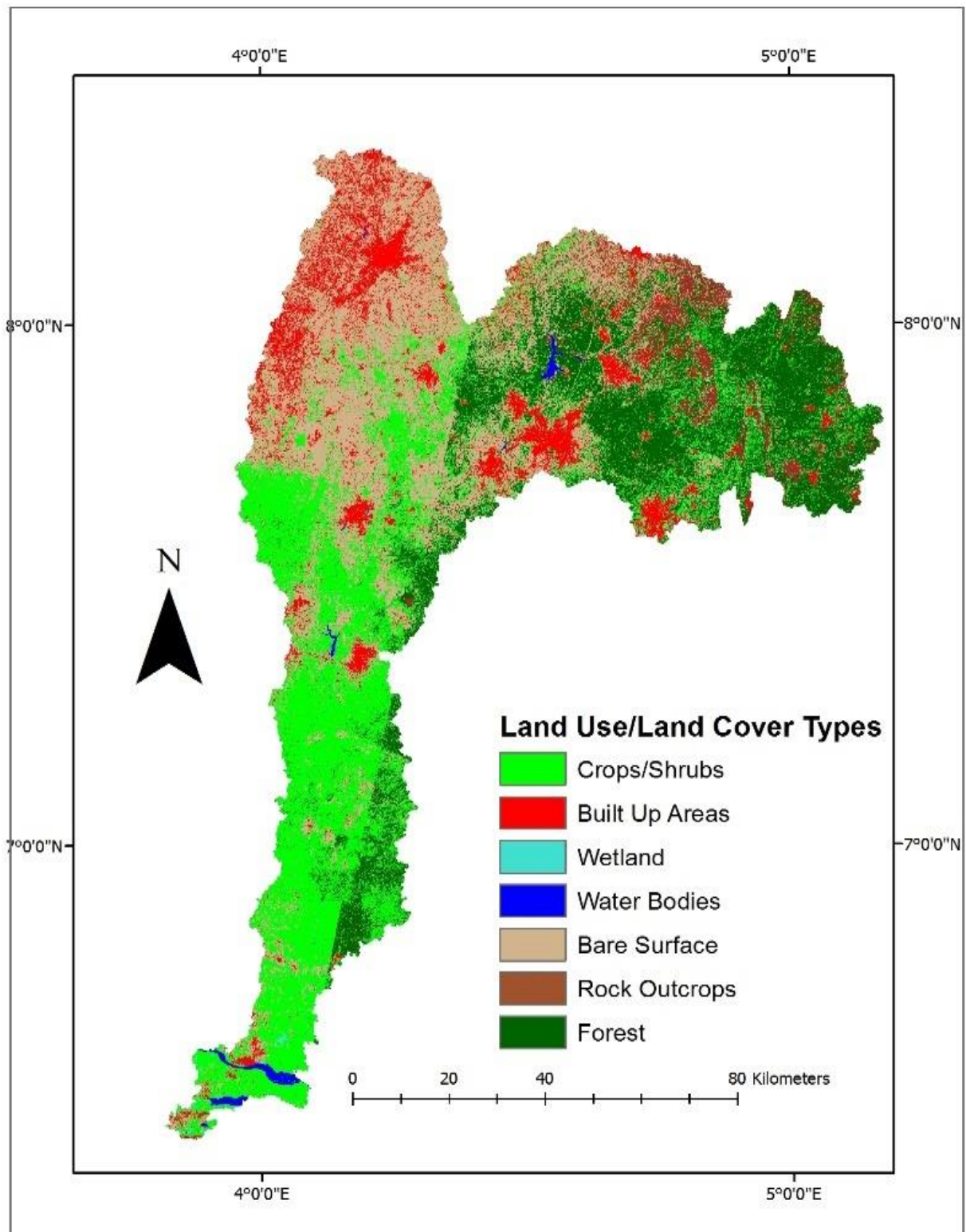


Figure 5.3: The Classified Image of Osun Drainage Basin, 2015
Source: Author's Classification, 2017

5.2: Land Use/Land Cover Change, 1984-2015

The pattern of land use/land cover change presented in Table 5.2 show the rate of change in LULC classes between 1984-2015. To explain the changes of one LULC class to another during the period of study, a change detection matrix was prepared and the results are presented in Tables 5.3.

5.2.1: Land use/land cover change, 1984-2000

Between 1984 and 2000, bare surfaces, built up areas, crops/shrubs and water bodies gained a total land area of 668.62km^2 , 141.54km^2 , 2517.21km^2 and 10.88km^2 , respectively. Crops/shrubs has a remarkable increase of 152.92%. It was also observed that built up area increased with about 44.56% between 1984 and 2000. This can be attributed to the increasing human population within the basin. Akinyemi (2005, p. 4), Mengistu and Salami (2007, p. 103) and Gasu et al (2016, p. 62) similarly reported increases in settlements/built up areas in their studies in the different parts of the basin. This confirms the facts that there is an increasing trend in the size of built up areas in the Osun drainage. The area covered by bare surfaces, built up areas, crops/shrubs and water bodies expanded at an annual average rate of 1.93%, 2.62%, 9.00% and 1.26%, respectively between 1984 and 2000.

In the same period, forest, rock outcrops and wetland lost a total land area of 3164.40km^2 , 150.70km^2 and 23.15km^2 , respectively. The forest area decreased rapidly with a total loss of 60.58% of its initial areal coverage. The sharp decrease in the size of forest between 1984 and 2000, is due to anthropogenic activities. Similar results were observed in some parts of the basin 1986 and 2002 (Akinyemi, 2005, p. 4; Mengistu & Salami, 2007, p. 103). The forest area, rock outcrops and wetland receded at an annual rate of 3.56%, 1.80% and 0.88%, respectively between 1984 and 2000.

Table 5.2: Area and Amount of Change in Land Use/Land Cover Categories in Osun Drainage Basin, 1984-2015

<i>Land Use/Land Cover Types</i>		<i>1984-2000</i>		<i>Average Rate of Change (1984-2000)</i>		<i>2000-2015</i>		<i>Average Rate of Change (2000-2015)</i>		<i>1984-2015</i>		<i>Average Rate of Change (1984-2015)</i>	
		Area (Km ²)	%	Area (Km ²)	%	Area (Km)	%	Area (Km ²)	%	Area (Km)	%	Area (Km ²)	%
1	Bare Surfaces	668.62	32.76	39.33	1.93	377.74	13.94	23.61	0.87	1046.36	51.27	32.70	1.60
2	Built Up Areas	141.54	44.56	8.33	2.62	604.73	131.70	37.80	8.23	746.27	234.94	23.32	7.34
3	Crops/Shrubs	2517.21	152.92	148.07	9.00	-1048.50	-25.18	-65.53	-1.57	1468.72	89.22	45.90	2.79
4	Forest	-3164.40	-60.58	-186.14	-3.56	95.66	4.65	5.98	0.29	-3068.70	-58.75	-95.90	-1.84
5	Rock Outcrops	-150.70	-30.57	-8.86	-1.80	77.74	22.71	4.86	1.42	-72.96	-14.80	-2.28	-0.46
6	Water Bodies	10.88	21.44	0.64	1.26	-0.05	-0.07	0.00	0.00	10.84	21.35	0.34	0.67
7	Wetland	-23.15	-15.02	-1.36	-0.88	-107.34	-81.98	-6.71	-5.12	-130.48	-84.69	-4.08	-2.65

Source: Author's Computation, 2017

Note: The signs + and - indicate increase and decrease, respectively.

5.2.2: Land use/land cover change, 2000-2015

The change detection analysis further revealed that between year 2000 and 2015, bare surfaces, built up area, forest and rock outcrops increased in areal extents (Table 5.2). Built-up areas increased significantly during this period. It indeed increased by 131.70% from its original size of 459.18 km² in 2000 to 1064.91 km² in 2015. This gives an average annual growth rate of 8.23%. A change largely due to increasing population and urbanization. As a matter of fact, the population of the basin that was put at 4,281,000 in 1980 by OORBDA (1982) was estimated to be 12,046,145 in 2015.

The increasing built-up areas can severely change the water balance of the study area, influence the rate of recharge and the microclimate of the area (Lerner et al., 1990; Jyrkama & Sykes, 2006, p. 8). Also, the amount of direct groundwater recharge resulting from rainfall may reduce as a result of the increase in impervious surfaces from built up areas, while surface runoff will increase significantly (Rose & Peters, 2001). Expectedly, crops/shrubs, water bodies and wetland receded at an annual rate of 1.57%, 0.08% and 5.12%, respectively. For example, crops/shrubs lost an area of 1048.50 km², which is about 58% of its basin coverage in 2000. The study of Akinyemi (2005, p. 4) in a small section of the drainage basin, while agreeing with this finding continues up until 2015.

5.2.3: Land use/land cover change, 1984-2015

The greatest percentage change for the 32 years period was recorded on built-up area. The 234.94% increase at an average annual rate of 7.34% is notable (Table 5.2). Built-up area increased significantly from 317.64 km² in 1984 to 1063.91 km² in 2015. The increasing areal extent of the built-up areas confirmed the results of early studies (Akinyemi, 2005, p. 4; Mengistu & Salami, 2007, p. 103; Gasu et al, 2016, p. 62) in some parts of the study area. Also,

crops/shrubs gained about 89.22% with an average annual rate of 2.79%. Crops/shrubs increased by an area of 1468.22km², from 1646.16km² in 1984 to 3114.86km² in 2015. The increase recorded in the percentage area of crops/shrubs conform with the work of Salami et al. (1999) which reported that natural vegetation has largely been replaced by perennial and annual crops in many parts of the basin. The changes in land use/land cover during this 32 years, especially increase in built up and crops/shrubs can be attributed to population growth and settlement expansion, these scenarios had culminated into conversion of natural vegetation to farmland. Other human activities such as fuel wood extraction, sand mining, quarrying and gold mining etc. have all contributed to land use changes.

The most notable decrease in LULC classes in the Osun drainage basin was observed in the forest area and wetland. Forest decreased from a total land area of 5223.61km² (52.62%) in 1984 to 2154.87 km² (21.71%) in 2015. The forest area receded at an annual average rate of 1.84% during the period under investigation. This can be attributed to the years of human occupation and interference with the tropical vegetation of the drainage basin. The long history of agricultural practices and increasing population density in the area would have resulted into substantial modification of the natural vegetation in the study area. Wetland declined from a total land area of 154.07 km² in 1984 to 23.59 km² in 2015. Wetland area receded at an annual average rate of 4.08 km² during this period. This is attributable to wetland being converted to built-up area as there is need for accommodation for the teeming population in the basin. Figure 5.4 shows the percentage change in LULC in Osun Drainage Basin between 1984 and 2015. This shows the areal extent increase or decrease by each LULC in percentages.

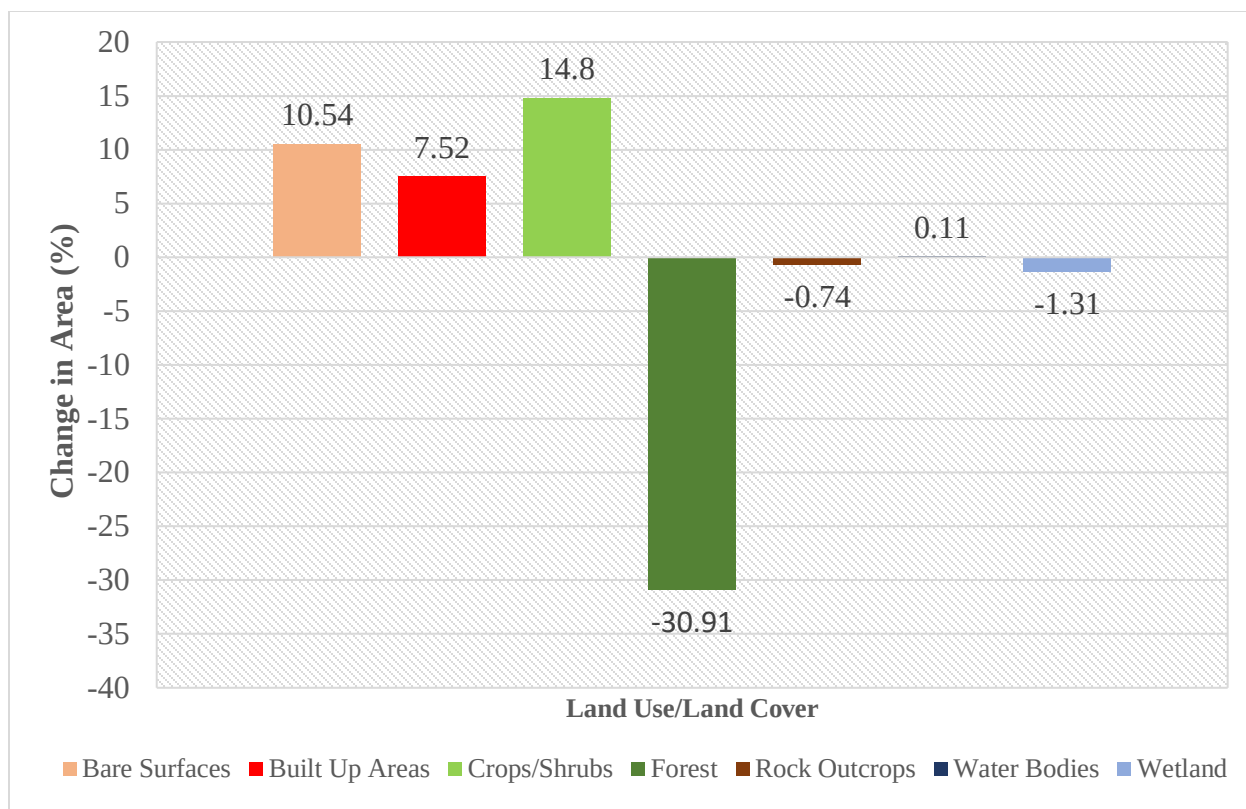


Figure 5.4: Percentage Change in Land Use/Land Cover in Osun Drainage Basin, 1984-2015
Source: Author's Computation, 2017

It is important to note that all man's activities on the surface of the earth leads to some environmental consequences that may be unwholesome to present and future generations. As a matter of fact, man's historical and present decision on land usage influence the use and changes observed in a particular environment. The socio-economic characteristics of the people in the study area has significantly influenced the changes in LULC observed. Most communities in Osun drainage basin earn their living through farming, logging and fuel wood production. The issue of climate change is a major cause of the disappearing natural vegetation in addition to the prevailing human activities. The Sudano-sahelian zone has been reported to be advancing southward of latitude 10° N resulting in loss of forest species and arable lands. All these are responsible for the rapidly changing land use and land cover in the Osun drainage basin (Fasona & Omojola, 2005; Mengistu & Salami, 2007, p. 108).

The implications of the changing LULC include increasing incidences of soil erosion, increasing reservoir sedimentation, soil degradation and unfavourable changes in the hydrological regime. Groundwater recharge is influenced by plant cover and land use practices. Hence, the type and nature of land cover can have a significant influence on infiltration, and on groundwater recharge (Jyrkama & Sykes, 2006, p. 8). Altering the natural land surface as observed in this study will significantly alter the groundwater recharge (Lerner et al., 1990; Lerner, 2002).

The results of the change detection transition matrix between 1984 and 2015 (Table 5.3) revealed that:

- i. about 25% of the area that are bare in 1984 has been converted into built-up area, 4.55% are crops/shrubs, 5.06% are rock outcrops, while 65.43% remained unchanged;

Table 5.3: Land use/land cover Change Transition Matrix in Osun Drainage Basin (1984-2015)

Land use/land cover Categories		Land Use/Land Cover 2015 (Km ²)							
		Bare Surfaces	Built Up Areas	Crops/Shrubs	Forest	Rock Outcrops	Water Bodies	Wetland	Total Area
Land Use/Land Cover 1984 (Km ²)	Bare Surfaces	1333.54 <i>65.43</i>	493.53 24.8	92.93 4.55	15.31 0.75	103.37 5.06	0.80 0.04	1.48 0.07	2040.95 100
	Built Up Areas	3.50 1.10	309.96 <i>97.58</i>	3.25 1.02	0.00 0.00	0.70 0.22	0.06 0.02	0.17 0.05	317.64 100
	Crops/Shrubs	343.56 20.87	108.61 6.60	667.99 <i>40.58</i>	437.51 26.58	81.89 4.97	6.42 0.39	0.16 0.01	1646.14 100
	Forest	1132.32 21.68	41.22 0.79	2282.96 43.70	1649.40 <i>31.58</i>	91.07 1.74	7.17 0.14	19.48 0.37	5223.61 100
	Rock Outcrops	173.21 35.13	66.36 13.46	61.14 12.40	51.45 10.44	139.67 <i>28.33</i>	0.43 0.09	0.78 0.16	493.05 100
	Water Bodies	0.06 0.12	0.56 1.10	3.84 7.56	0.03 0.07	0.12 0.23	45.35 <i>89.35</i>	0.80 1.57	50.76 100
	Wetland	101.12 65.63	43.68 28.35	2.76 1.79	1.16 0.75	3.28 2.13	1.35 0.88	0.72 <i>0.47</i>	154.07 100
	Total Area	3087.31	1063.91	3114.86	2154.87	420.09	61.59	23.59	9926.22

Source: Author's Computation, 2017

Note: Figures in the upper rows indicate areas of particular LULC type that remained unchanged (in bold) or converted to other LULC types in Km².

Figures in italics in the lower rows indicate areas of particular LULC type that remained unchanged (in bold) or converted to other LULC types in percentage.

- ii. about 32% of forest area in 1984 remained unchanged, while it lost 43.70% and 21.68% to crops/shrubs and bare surfaces, respectively;
- iii. rock outcrops lost 35.12% to bare surfaces, 13.46% to built-up areas and 12.40% of its areal extent to crops/shrubs;
- iv. no significant conversion of water bodies to other LULC class, as it maintained 89.35% of its size; and
- v. about 66% of wetland was converted to bare surfaces.

5.3 Predicted Future Land Use/Land Cover Change in Osun Drainage Basin, 2046

Based on the rate of change between 1984 and 2015 in the Osun drainage basin (Table 5.2), the future LULC change was predicted using Modules for Land Use Change Evaluation (MOLUSCE) plugin in QGIS. Population, elevation, slope and aspect were the change driving factors selected in predicting the future change. The results of the expected change by the year 2046 are presented in Table 5.3. The predicted LULC change revealed that by 2046, bare surface will increase slightly by 188.01 km² at an average rate of 0.19% per annum. Thus, bare surface would have increased from 3087.31 km² in 2015 to 3275.32 km² in 2046.

Built-up area from this result would have increased steadily from 1063.91 km² in 2015 to 1658.85 km² by 2046. This is 55.92% increase. The simulated result shows that the increase in built-up area are closely associated with the existing built-up areas. This will be more pronounced in the northwestern part of the study area, especially in the Oyo State portion of the basin, in and around Ogbomosho. The growth that will be experienced in this area is attributable to population increase, that will lead to the expansion of built-up areas. Also, crops/shrubs LULC class will increase slightly from 3114.86 km² in 2015 to 3311.11 km² by 2046, which is an

increase of 6.30%. In other words, crops/shrubs LULC class would grow at an average annual rate of 0.20% over the period. This suggest that farming activities in the basin will increase only slightly. There may be further increase if the effort of the Federal Government of Nigeria to diversify the economy is vigorously pursued.

Table 5.3: Predicted Land Use/Land Cover Change between 2015 and 2046

<i>Land Use/Land Cover Types</i>		<i>2015</i>		<i>2046</i>		<i>2015-2046</i>		<i>Average Rate of Change (2015-2046)</i>	
		Area (Km ²)	%	Area (Km ²)	%	Area (Km ²)	%	Area (Km ²)	%
1	Bare Surface	3087.31	31.1	3275.32	33.00	188.01	6.09	5.88	0.19
2	Built Up Areas	1063.91	10.72	1658.85	16.71	594.94	55.92	18.59	1.75
3	Crops/Shrubs	3114.86	31.38	3311.11	33.36	196.25	6.30	6.13	0.20
4	Forest	2154.87	21.71	1257.18	12.67	-897.69	-41.66	-28.05	-1.30
5	Rock Outcrops	420.09	4.23	359.79	3.62	-60.30	-14.35	-1.88	-0.45
6	Water Bodies	61.59	0.62	59.93	0.60	-1.66	-2.70	-0.05	-0.08
7	Wetland	23.59	0.24	4.04	0.04	-19.55	-82.87	-0.61	-2.59
<i>Total</i>		9926.22	100	9926.22	100.00				

Source: Author's Computation, 2017

Note: The signs + and - indicate increase and decrease, respectively

The future LULC change revealed that between 2015 and 2046, the forest area will continue to decrease. As much as 897.69 km² of forest land may be lost to other uses between this period. Thus, it is expected that forest area will decrease from 2154.86 km² in 2015 to 1257.18 km² by 2046. The 42% reduction in forest area, is worrisome because it reflects the unrelenting activities of wood loggers in the study area. Continuous deforestation of the forest area will certainly have significant impacts on the water budget of the study area, especially groundwater recharge. Based on this study, water bodies LULC will decrease by 2.70%. This is an annual rate of 0.08% decrease during the period. Wetland which is one of the important groundwater recharge

mechanisms in a drainage basin would have decreased in size from 23.59 km² in 2015 to mere 4 km² by 2046. The predicted LULC of 2046 is presented in Figure 5.5.

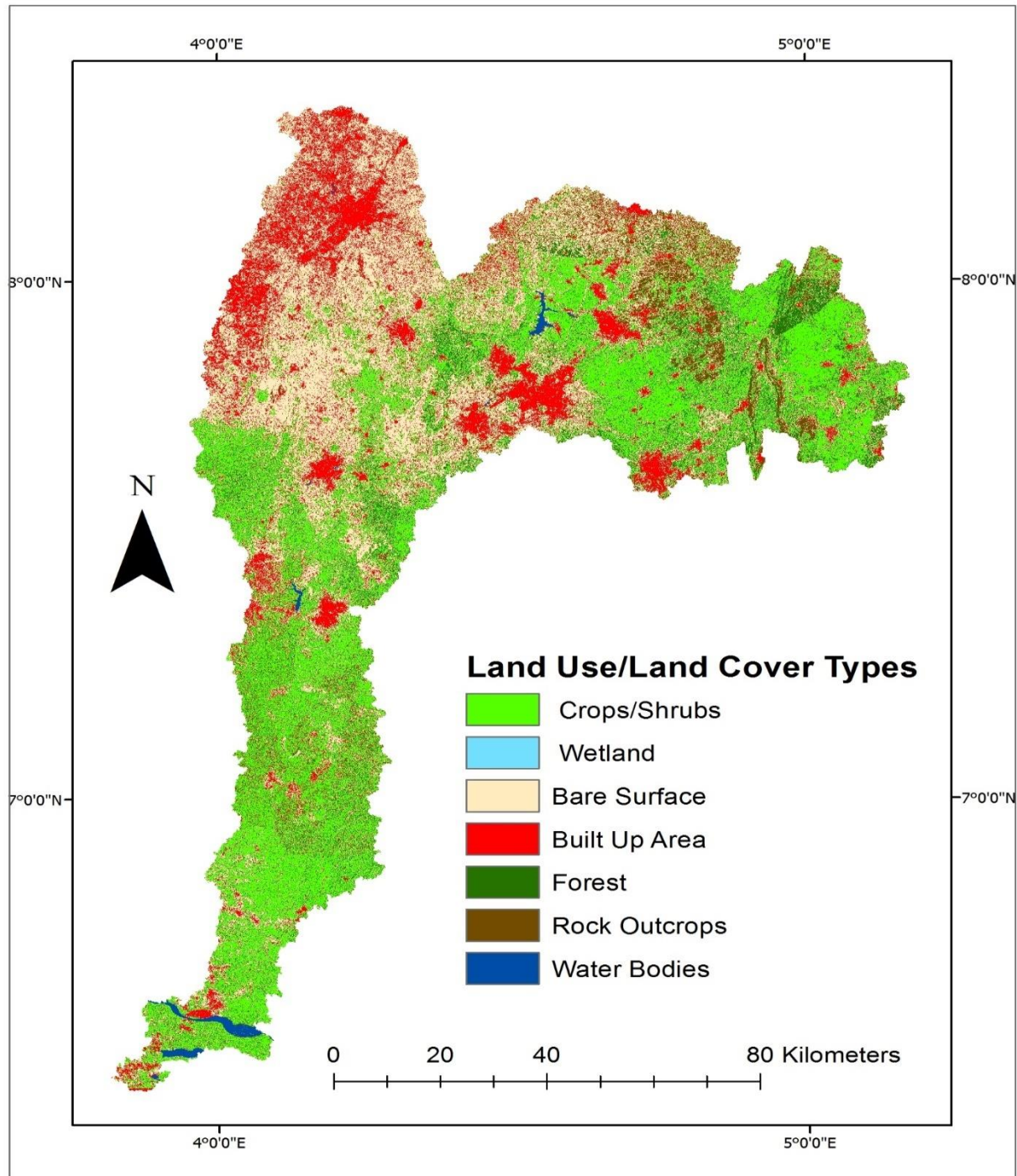


Figure 5.5: Predicted Future Land Use/Land Cover, 2046
Source: Author's Simulation, 2017

In summary, the change detection transition matrix between 2015 and 2046 (Table 5.4) indicates that:

- i. about 16% of the bare surface in 2015 will be converted into built-up area by 2046;
- ii. there will be no significant decrease in built-up areas, rather it will increase from 1063.91 km² to 1658.85 km² ;
- iii. about 34% of wetland would have been converted to built-up area;

Table 5.4: Land Use/Cover Change Transition Matrix in Osun Drainage Basin (2015-2046)

Land Use/Cover Categories		Predicted Land Use/Land Cover 2046 (Km ²)							
		Bare Surfaces	Built Up Areas	Crops/Shrubs	Forest	Rock Outcrops	Water Bodies	Wetland	Total Area
Land Use/Land Cover 2015 (Km ²)	Bare Surfaces	2493.64 <i>80.77</i>	495.55 <i>16.05</i>	24.56 <i>0.80</i>	22.90 <i>0.74</i>	50.49 <i>1.64</i>	0.10 <i>0.00</i>	0.06 <i>0.00</i>	3087.31 <i>100</i>
	Built Up Areas	77.26 <i>7.26</i>	968.01 <i>90.99</i>	12.00 <i>1.13</i>	5.22 <i>0.49</i>	1.20 <i>0.11</i>	0.16 <i>0.02</i>	0.06 <i>0.01</i>	1063.91 <i>100</i>
	Crops/Shrubs	352.85 <i>11.33</i>	107.96 <i>3.47</i>	1911.06 <i>61.35</i>	661.13 <i>21.23</i>	81.57 <i>2.62</i>	0.00 <i>0.00</i>	0.30 <i>0.01</i>	3114.86 <i>100</i>
	Forest	297.69 <i>9.64</i>	24.19 <i>1.12</i>	1348.98 <i>62.60</i>	544.63 <i>25.27</i>	27.99 <i>1.30</i>	0.03 <i>0.00</i>	1.37 <i>0.06</i>	2154.87 <i>100</i>
	Rock Outcrops	130.31 <i>31.02</i>	55.02 <i>13.10</i>	13.49 <i>3.21</i>	22.80 <i>5.43</i>	198.34 <i>47.21</i>	0.12 <i>0.03</i>	0.00 <i>0.00</i>	420.09 <i>100</i>
	Water Bodies	0.75 <i>1.22</i>	0.16 <i>0.26</i>	0.74 <i>1.21</i>	0.09 <i>0.15</i>	0.07 <i>0.11</i>	45.35 <i>96.61</i>	0.80 <i>0.45</i>	61.59 <i>100</i>
	Wetland	12.82 <i>54.35</i>	7.95 <i>33.69</i>	0.28 <i>1.20</i>	0.41 <i>1.74</i>	0.14 <i>0.60</i>	0.01 <i>0.03</i>	1.98 <i>8.39</i>	23.59 <i>100</i>
	Total Area	3275.32	1658.85	3311.11	1257.18	359.79	59.93	4.04	9926.22

Source: Author's Computation, 2017

Note: Figures in the upper rows indicate areas of particular LULC type that remained unchanged (in bold) or lost to other LULC types in Km².

Figures in italics in the lower rows indicate areas of particular LULC type that remained unchanged (in bold) or lost to other LULC types in percentage.

- iv. significant areal extent of about 1349 km² of forest will be converted to crops/shrubs; and
- v. water bodies will remain about 96.61% of its size in 2015 by 2046.

5.4 Conclusion

This chapter is on the seven LULC classification adopted in Osun drainage basin for the year 1984, 2000 and 2015. Land use/land cover change for the period 1984-2015 were examined based on the data generated from satellite imageries. In addition, LULC change transition matrix was computed with a view to determining the percentage change of one land class to another during the period of study. Also, the future LULC change was simulated for the year 2046, to understand the level and direction of change that might be experienced in the future in Osun drainage basin. The results have underscored the increasing human occupation and the high rates of conversion of the natural vegetation into other land use classes.

CHAPTER SIX

MEAN MONTHLY WATER BUDGET IN OSUN DRAINAGE BASIN

6.0 Introduction

This chapter is on the mean monthly water budget of the Osun drainage basin and it focuses on the physical processes of the hydrological cycle, using the physically based spatially distributed WetSpass-M model. The water budget components comprising of interception, runoff, actual evapotranspiration (AET) and recharge were extracted from the results of the WetSpass-M model, presented and discussed.

6.1 Mean Monthly Water Balance : An Overview

The average monthly water balance viz: interception, surface runoff, AET and groundwater recharge for the period 1974 to 2015 revealed that most of the water balance component follow the pattern of rainfall amount in the basin (Figure 6.1). For example, the month of September that has the highest mean monthly rainfall amount also have the highest recharge and runoff.

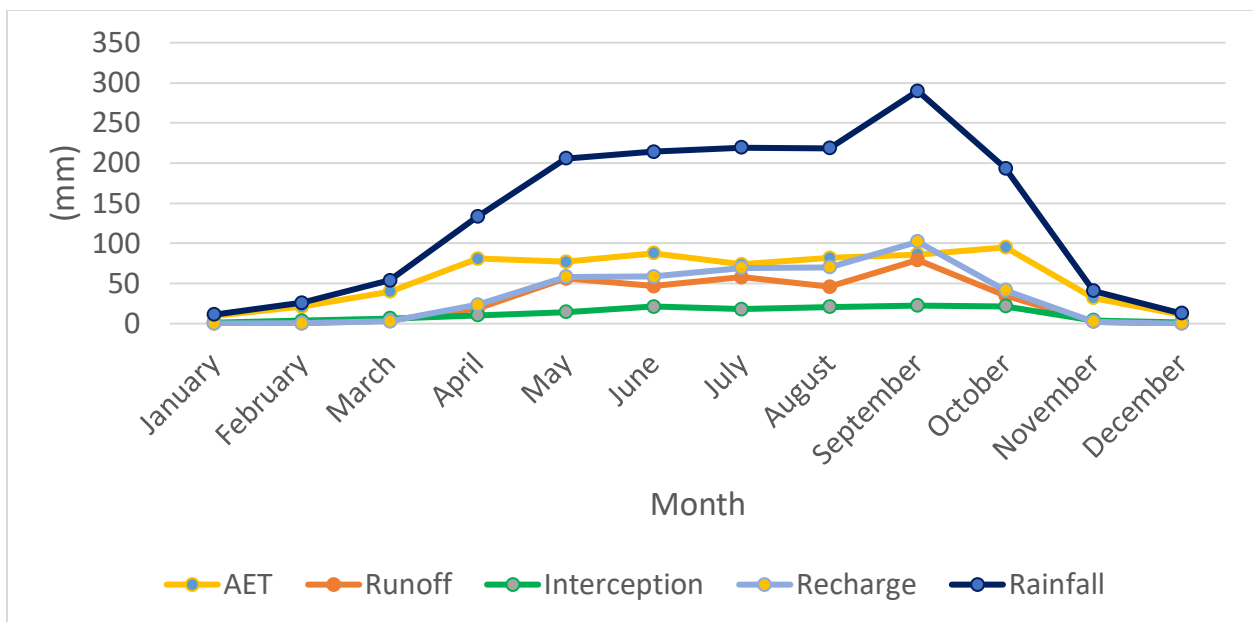


Figure 6.1: Mean Monthly Water Balance for Osun Drainage Basin 1976-2015

Source: Author's Computation, 2017

This indicates that most of the mean monthly and annual budget components follows the change in rainfall amount in the basin. Most of the mean annual water budget components in Lake Chad basin had earlier been observed to follow the change in annual rainfall amount (Babama’aji, 2013, p. 69). The observed mean monthly hydrological feedbacks in Osun drainage basin suggests that most of the rainfall is lost to evapotranspiration, especially in the dry months of November to March (Figure 6.2).

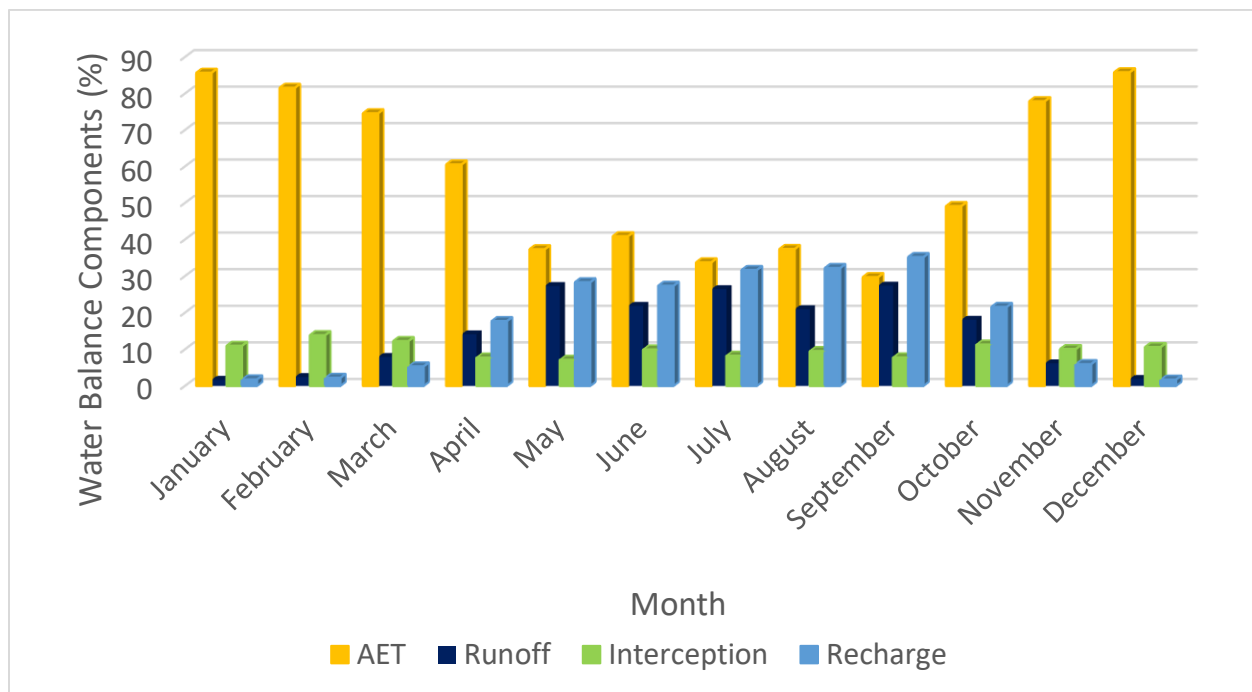


Figure 6.2: Mean Monthly Hydrological Feedbacks in Osun Drainage Basin, 1976-2015
Source: Author’s Computation, 2017

However, more water is able to infiltrate into the soil and percolate to recharge the groundwater system in the wet months of September, which coincides with the month of highest rainfall amount. In general, 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 and perhaps rainfall intensity and the antecedent soil moisture. Interception is the least important component of the hydrological budget in Osun drainage basin. Section 6.2 shows

the results of the four estimated water budget components and are subsequently discussed in detail.

6.2 Water Budget Components

6.2.1 Interception

The monthly mean interception in Osun drainage basin for the period 1976 to 2015 ranges from 1.22mm in January to 22.50mm in September (Table 6.1), while the mean annual interception is 146.22mm. This accounted for 9.4% of the mean annual rainfall amount (1,619.58mm) from 1976 - 2015 (Table 6.1). 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 at 2015 which was used for this estimation was 21.70% of the original 52.62% of forest area in 1984. Interception is often high in vegetated areas compared to other land cover types and it is the first hydrologic response of rainfall in an environment (Muzylo et al., 2009), and it depends to some level on the Leaf Area Index (LAI) (Babama'aji, 2013, p. 26).

Table 6.1: Mean Monthly Interception and Rainfall Amount, 1976-2015

	<i>Months</i>	<i>Interception (mm)</i>	<i>Rainfall (mm)</i>	<i>Interception/Rainfall (%)</i>
1	January	1.22	11.14	10.93
2	February	3.59	25.89	13.84
3	March	6.58	53.81	12.22
4	April	10.33	133.68	7.72
5	May	14.63	205.94	7.11
6	June	21.29	214.29	9.93
7	July	18.05	219.41	8.23
8	August	20.77	218.41	9.51
9	September	22.50	289.95	7.76
10	October	21.79	193.35	11.27
11	November	4.11	40.91	10.04
12	December	1.35	12.78	10.59
<i>Total (Mean Annual)</i>		146.22	1619.58	9.04

Source: Author's Computation, 2017

Interception rate is high in the wet months compared to the dry months with records of fewer rainfall amount and number of rainy days. Other factors such as rainfall intensity, wind speed and LAI contribution to interception were duly catered for in the WetSpass-M model adopted for this estimation. Thus, the rainfall-interception ratio indicated that the interception percentage depends largely on the amount of rainfall received in any particular month. Figure 6.3 shows the relationship between mean monthly interception and rainfall amount in the basin.

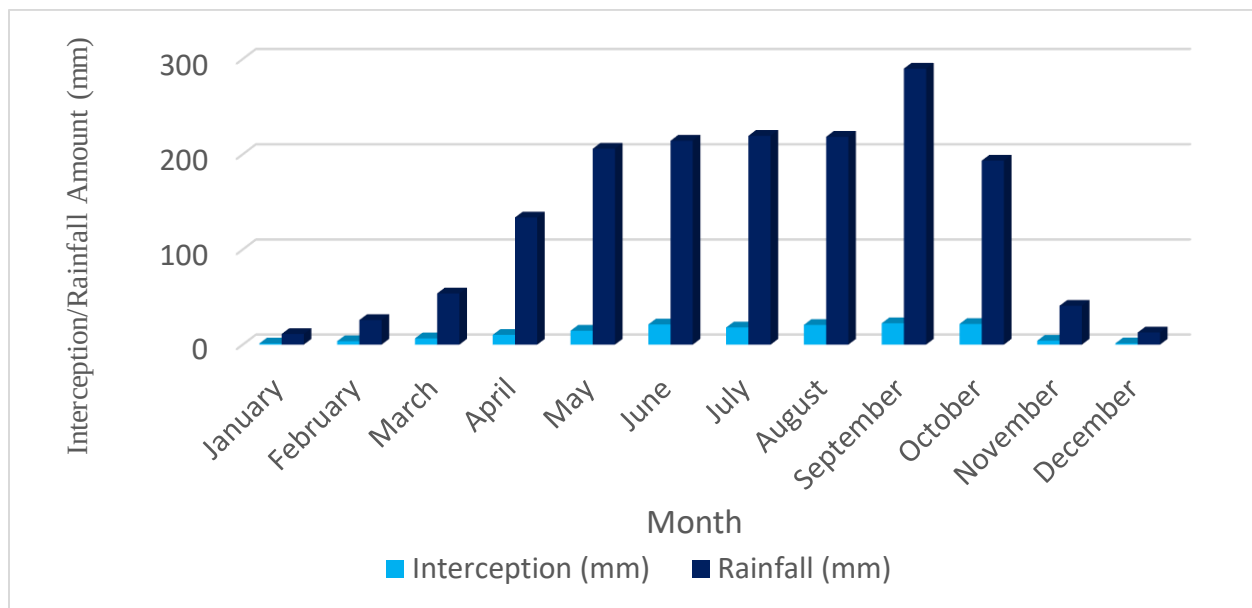


Figure 6.3: Mean Monthly Interception and Rainfall Amount in Osun Drainage Basin
Source: Author's Computation, 2017

The distribution pattern of mean monthly interception in Osun basin show that high interception rate is found in the forest area in Awaiye, Apomu, Alagutan, Apoje, Ijebu Ife, Akata and Epe, etc. in the middle of the basin down to the southern part (Figures 6.4 and 6.5). This result is similar to the earlier observation by Babama'aji, (2013, p. 77) that the Lake Chad basin exhibited highest 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, Pen'a-Arancibia, and Bruijnzeel (2011), also revealed that interception was higher in areas of tall forests compared to those of lower vegetation such as grassland or agricultural crops.

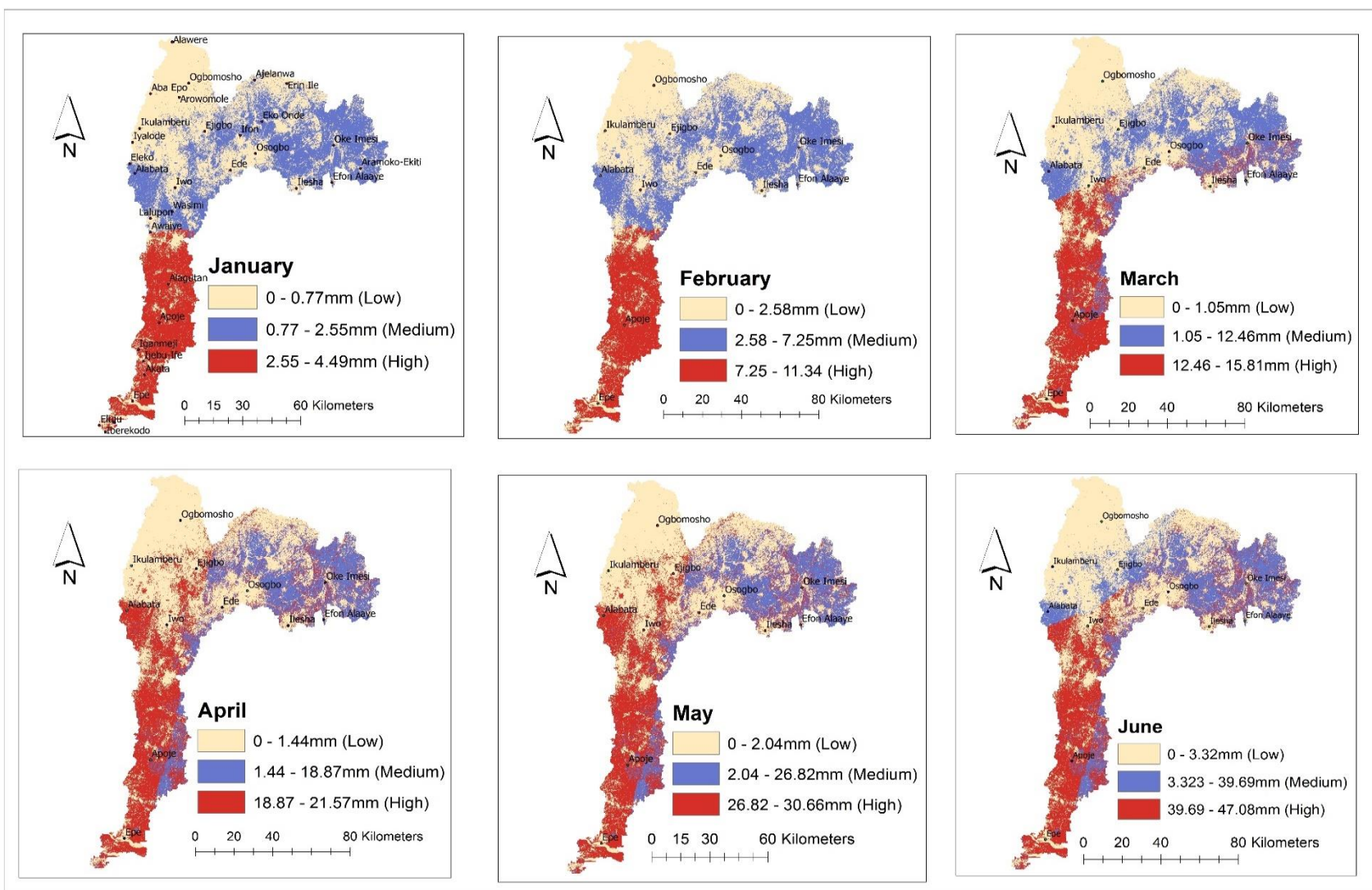


Figure 6.4: Pattern of Mean Monthly Interception Amount (January-June) in Osun Drainage Basin (1976-2015)

Source:

Author's

Computation,

2017

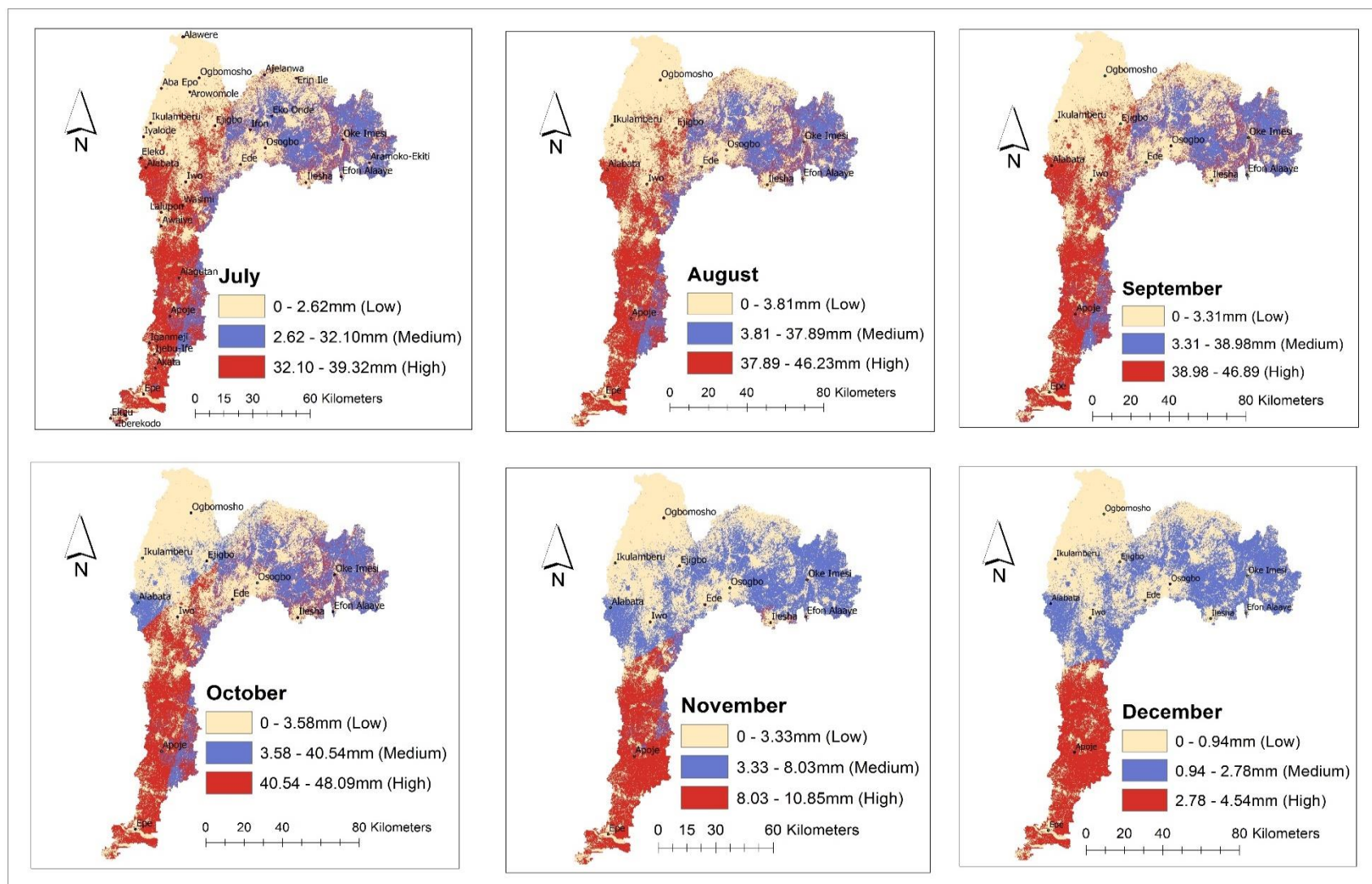


Figure 6.5: Pattern of Mean Monthly Interception Amount (July-December) in Osun Drainage Basin (1976-2015)

Source:

Author's

Computation,

2017

Low interception rate is found in Alawere, Ikoyi, Ogbomosho, Aba Epo, Arowomole Tafun, Iyalode and other places in the northwest zone of the basin. (Figures 6.4 and 6.5). Of course, this are areas where lower vegetation such as grassland or agricultural crops are dominant. The zone also received lower rainfall amount compared to other parts of the basin.

6.2.2 Surface Runoff

The estimated mean monthly surface runoff ranges from 0.19mm to 79.36mm, with a mean annual value of 347.63mm/year (Table 6.2). The highest mean rainfall amount occurred in September. As much as 27.37% of the rainfall becomes surface runoff. The highest surface runoff in September can be attributed to the antecedent soil moisture of preceding months. This is because the soil has become completely saturated from rainfall of the previous months, thus making infiltration low or non-existent.

Table 6.2: Mean Monthly Runoff and Rainfall Amount, 1976-2015

	<i>Months</i>	<i>Runoff (mm)</i>	<i>Rainfall (mm)</i>	<i>Runoff/Rainfall (%)</i>
1	January	0.19	11.14	1.66
2	February	0.63	25.89	2.42
3	March	4.26	53.81	7.92
4	April	18.81	133.68	14.07
5	May	56.19	205.94	27.29
6	June	46.85	214.29	21.86
7	July	57.95	219.41	26.41
8	August	45.75	218.41	20.94
9	September	79.36	289.95	27.37
10	October	34.88	193.35	18.04
11	November	2.516	40.91	6.15
12	December	0.24	12.78	1.91
	<i>Total (Mean Annual)</i>	347.63	1619.58	21.46

Source: Author's Computation, 2017

The lowest surface runoff (0.19mm) which is 1.66% of the rainfall amount occurred in January. This month coincides with the lowest mean monthly rainfall amount (11.41). The soil matrix is expectedly dry during this period, hence, the little rainfall received is quickly absorbed by the

soil, thereby resulting in little surface runoff. It was discovered that about 22% of total annual rainfall amount becomes surface runoff in the basin during the period under investigation. This result is slightly higher than what was found in the semi-arid, arid and temperate environment by earlier studies (Tesfamichael et al., 2013, p. 115; Teklebirhan et al., 2012, p. 106; Al Kuisi & El-Naqa, 2013, p. 105; Dams et al., 2007). For example, in the arid desert of Jafr basin, Jordan, Al Kuisi and El-Naqa (2013, p. 105) observed that as low as 4.9% of the total annual rainfall became surface runoff. This is as a result of the dry nature of the area. The relationship between mean monthly surface runoff and rainfall amount is presented in Figure 6.6 and it revealed that the months with high rainfall experienced higher surface runoff compared to months with low rainfall. The implication is that flood occurrence should be expected in the months with high rainfall amount, especially in the month of September.

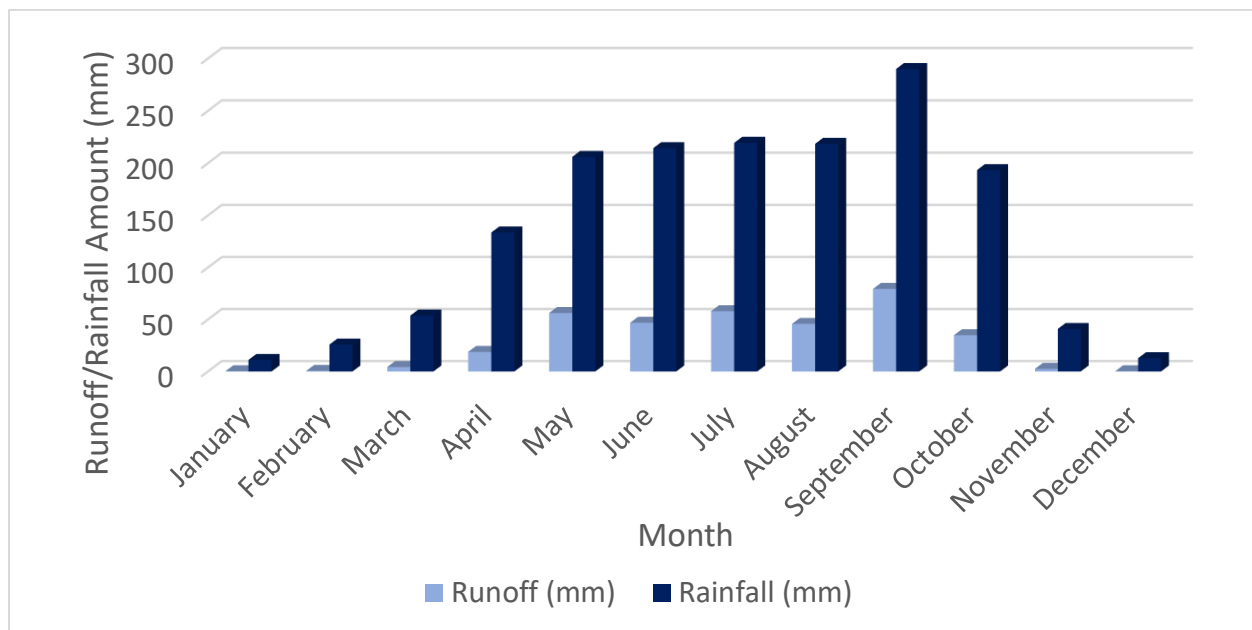


Figure 6.6: Mean Monthly Runoff and Rainfall Amount in Osun Drainage Basin
Source: Author's Computation, 2017

The mean monthly surface runoff maps of the basin show that the highest surface runoff is observed in Apomu, Alaguntan, Apoje, Iganmeji and Akata, etc. located in the central part

towards the southern part of the basin in most of the months. This result is expected as surface runoff is usually high in areas towards and close to the mouth of a drainage basin. 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 (Figures 6.7 and 6.8). This is an indication 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. In fact, the low permeability of clay soil enhanced surface runoff in this part of the basin. Similar results, observed by Babama'aji (2013, p. 88) in the Lake Chad basin, was also attributed to the low permeability nature of clay soil. Al Kuisi and El-Naqa (2013, p. 105) 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. 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, tend to generate high amount of surface runoff, while places with sandy clay loam and sandy loam soils generate lower surface runoff. The 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 and slope. High surface runoff has been attributed to soil texture, rather than land use/land cover types in some earlier studies (Teskamecheal et al., 2013, p. 115; Babama'aji, 2013, p.88; Al Kuisi & El-Naqa, 2013, p. 105; Teklebirhan et al., 2012, p. 106).

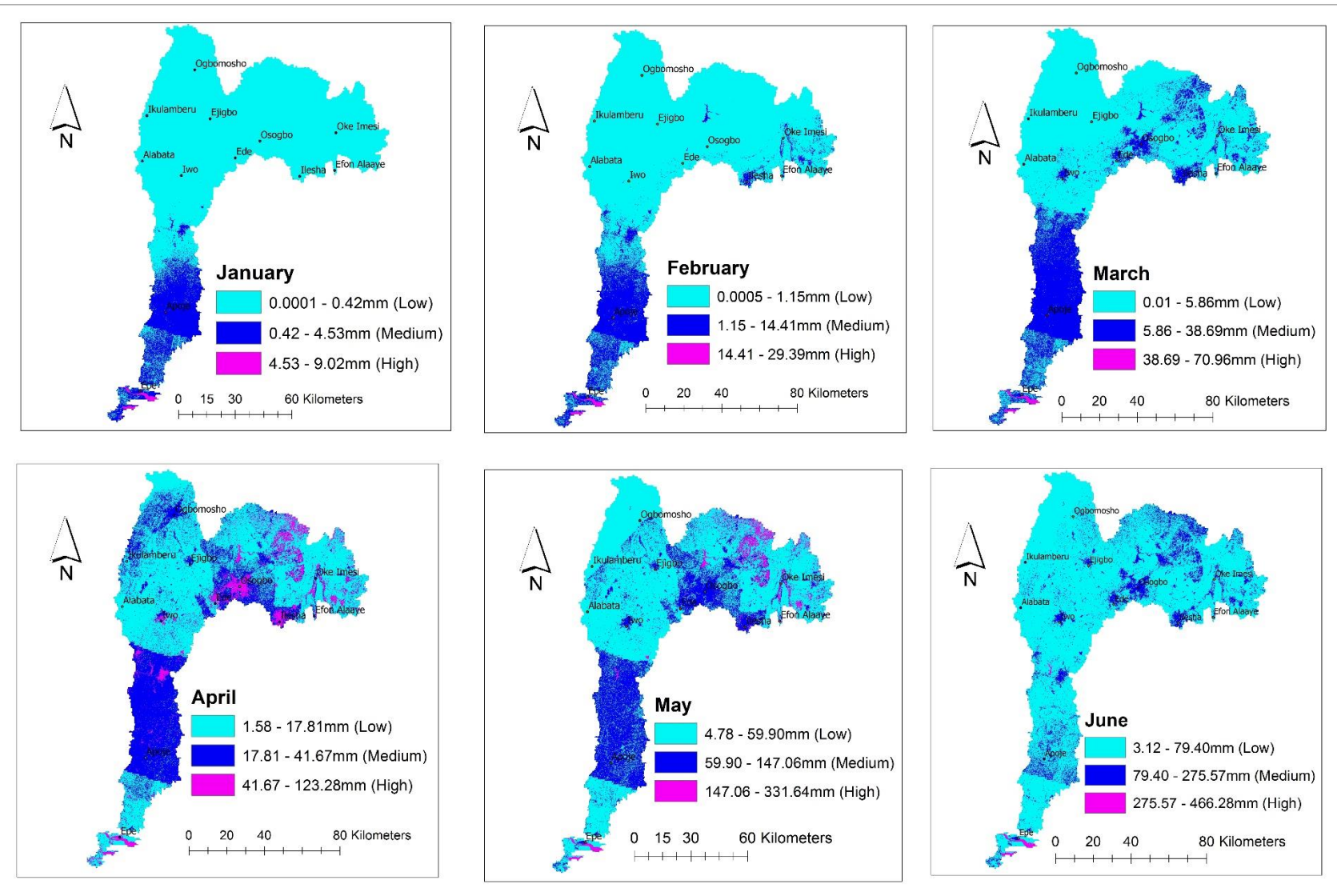


Figure 6.7: Pattern of Mean Monthly Runoff (January-June) in Osun Drainage Basin (1976-2015)

Source:

Author's

Computation,

2017

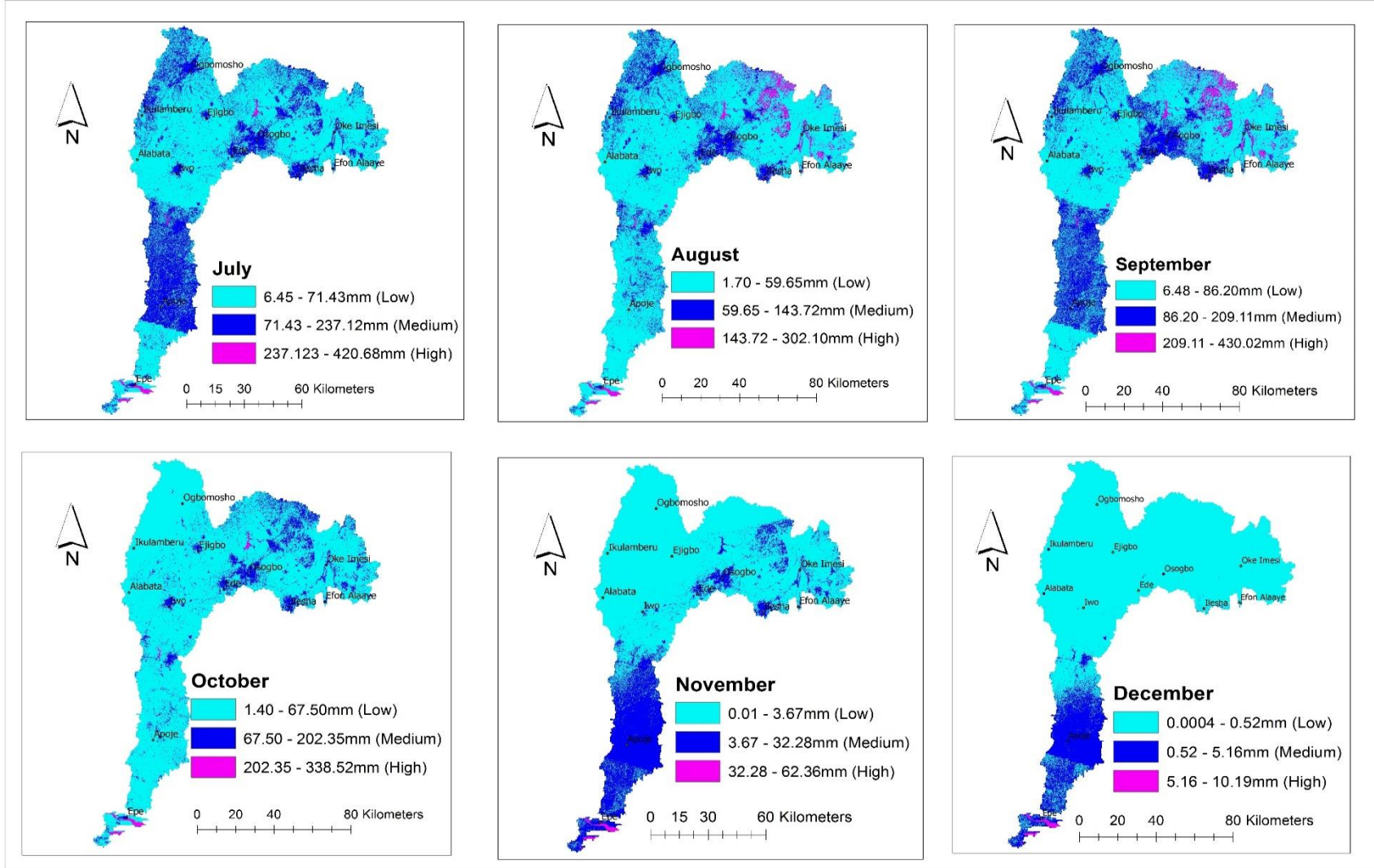


Figure 6.8: Pattern of Mean Monthly Runoff (July-December) in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

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 (Figure 6.9). The comparison suggests that WetSpa-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. 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 0.71 exists between the observed and simulated surface runoff, while the Nash-Sutcliffe coefficient is 0.89. The results of these two coefficients indicates that the WetSpa-M model is an efficient tool that can be used to predict surface runoff in the Osun basin. The efficiency of the model in predicting surface runoff in Osun drainage basin, therefore imply that the other three water balance components in this study are also well fitted.

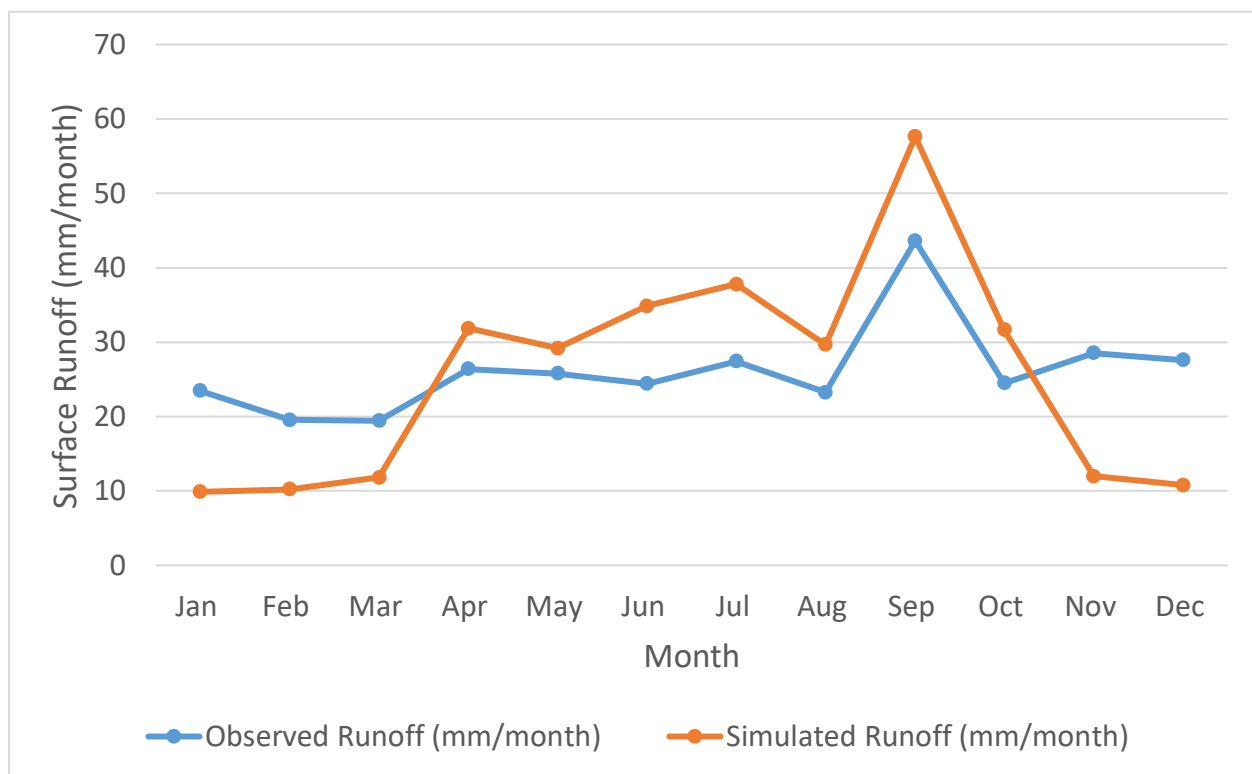


Figure 6.9: Observed Runoff versus Simulated Runoff in Osun Drainage Basin (1999)
Source: Author's Computation, 2017

6.2.3 Actual Evapotranspiration

The actual evapotranspiration is presented in this section, having estimated and discussed the potential evapotranspiration in chapter 4. The mean monthly AET in the basin ranges from 9.54mm in January to 84.98mm in October (Table 6.3). The annual mean AET in the basin is 695.67mm/year. AET is the largest component of the water budget in Osun basin, constituting 42.95% of the annual rainfall amount. AET is the summation of evaporation and transpiration, which is the water loss to the atmosphere from the ground surface, surface-water bodies, shallow groundwater table, and the transpiration of groundwater by plants whose roots tap the capillary of the groundwater table (Babama'aji, 2013, p. 27; Batelaan and De Smedt, 2001, p.12).

Table 6.3: Mean Monthly Actual Evapotranspiration (AET) and Rainfall Amount, 1976-2015

	<i>Months</i>	<i>AET (mm)</i>	<i>Rainfall (mm)</i>	<i>AET/Rainfall (%)</i>
1	January	9.54	11.14	85.67
2	February	21.12	25.89	81.54
3	March	40.11	53.81	74.56
4	April	80.90	133.68	60.52
5	May	76.83	205.94	37.31
6	June	87.60	214.29	40.88
7	July	74.01	219.41	33.73
8	August	81.62	218.41	37.37
9	September	86.11	289.95	29.70
10	October	94.98	193.35	49.12
11	November	31.86	40.91	77.87
12	December	10.97	12.78	85.80
<i>Total (Mean Annual)</i>		695.67	1619.58	42.95

Source: Author's Computation, 2017

The results of AET in Osun basin agrees with studies 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 and temperature;

and vegetation of such a 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, Tesfamichael et al., (2013, p. 115) 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, p. 104). A very large percentage of 94.6% and 95% of the annual rainfall were lost to evapotranspiration in Jaffr basin, Jordan (Al Kuisi & El-Naqa, 2013, p. 103) and Lake Chad basin (Babama'aji, 2013, p. 72), respectively.

The percentage of AET to rainfall amount in the basin are highest in 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 may be responsible for this observation. The few rainfall amounts received in these months evaporates and transpires quickly because of the dry nature of the atmosphere. However, in terms of volume in millimeters, the highest AET (94.98mm) occur in October, while lowest (9.54mm) is in January. Figure 6.10 shows the relationship between mean monthly AET and rainfall amount in the basin. Though, the month of September recorded the highest rainfall amount, the highest AET occurred in the month of October. In other words, there is about 8mm difference in AET occurrence between the two months, which is attributable to the evaporative power of the atmosphere during this period.

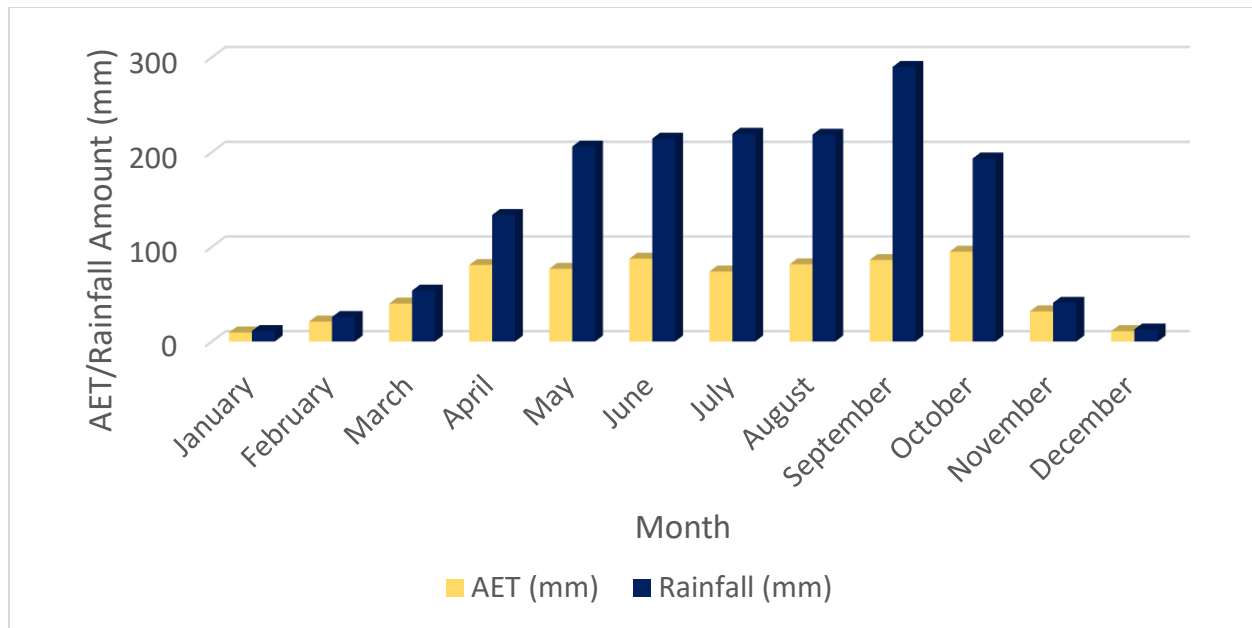


Figure 6.10: Mean Monthly AET and Rainfall Amount in Osun Drainage Basin
Source: Author's Computation, 2017

The distribution pattern of mean monthly AET in Osun basin show that open water body have high evapotranspiration rate and this was more noticeable in the five dry months of November to March (Figures 6.11 and 6.12). The observed pattern 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, p. 77) 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 area with tall trees.

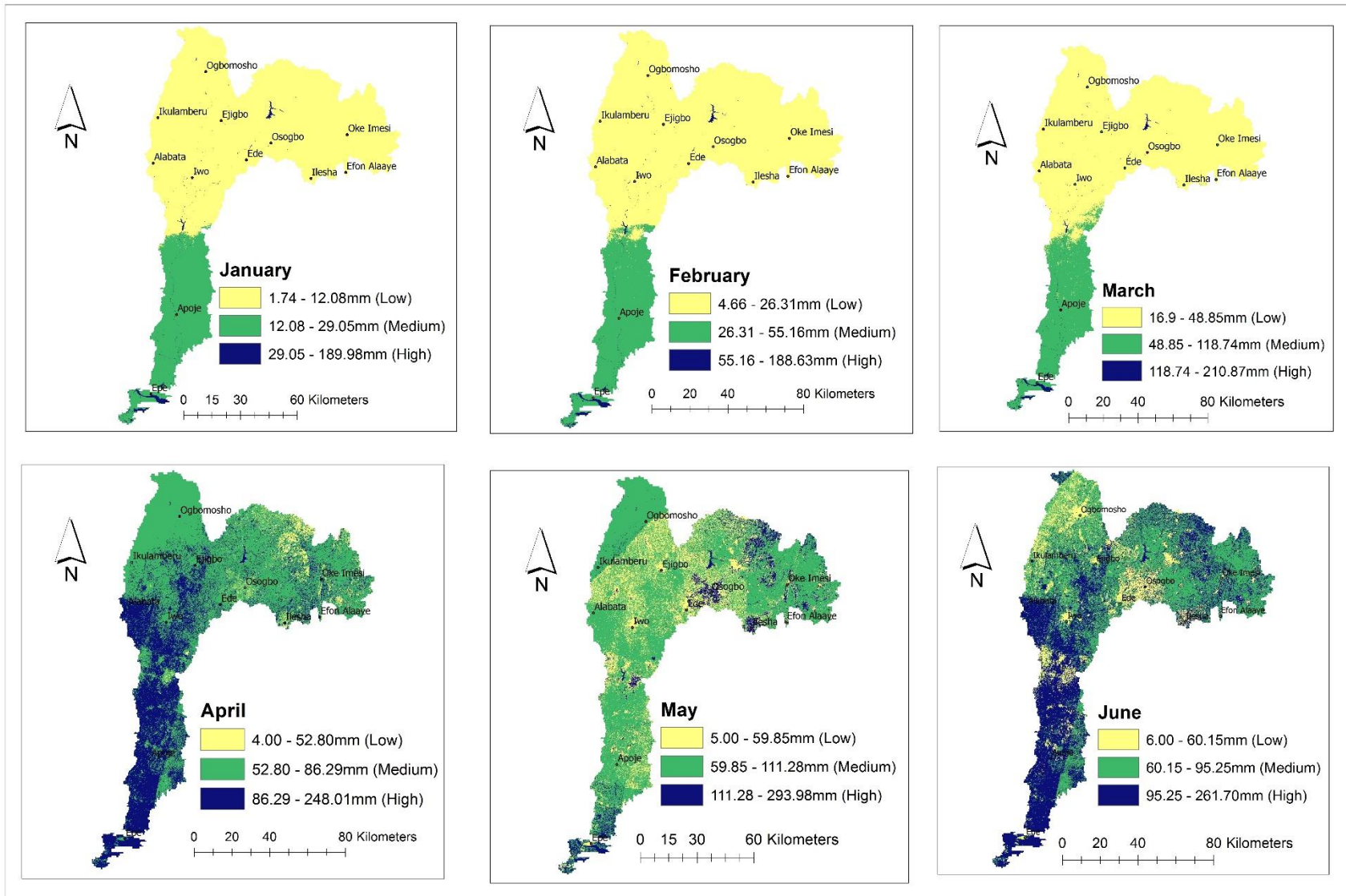


Figure 6.11: Pattern of Mean Monthly Actual Evapotranspiration (January-June) in Osun Drainage Basin (1976-2015)

Source:

Author's

Computation,

2017

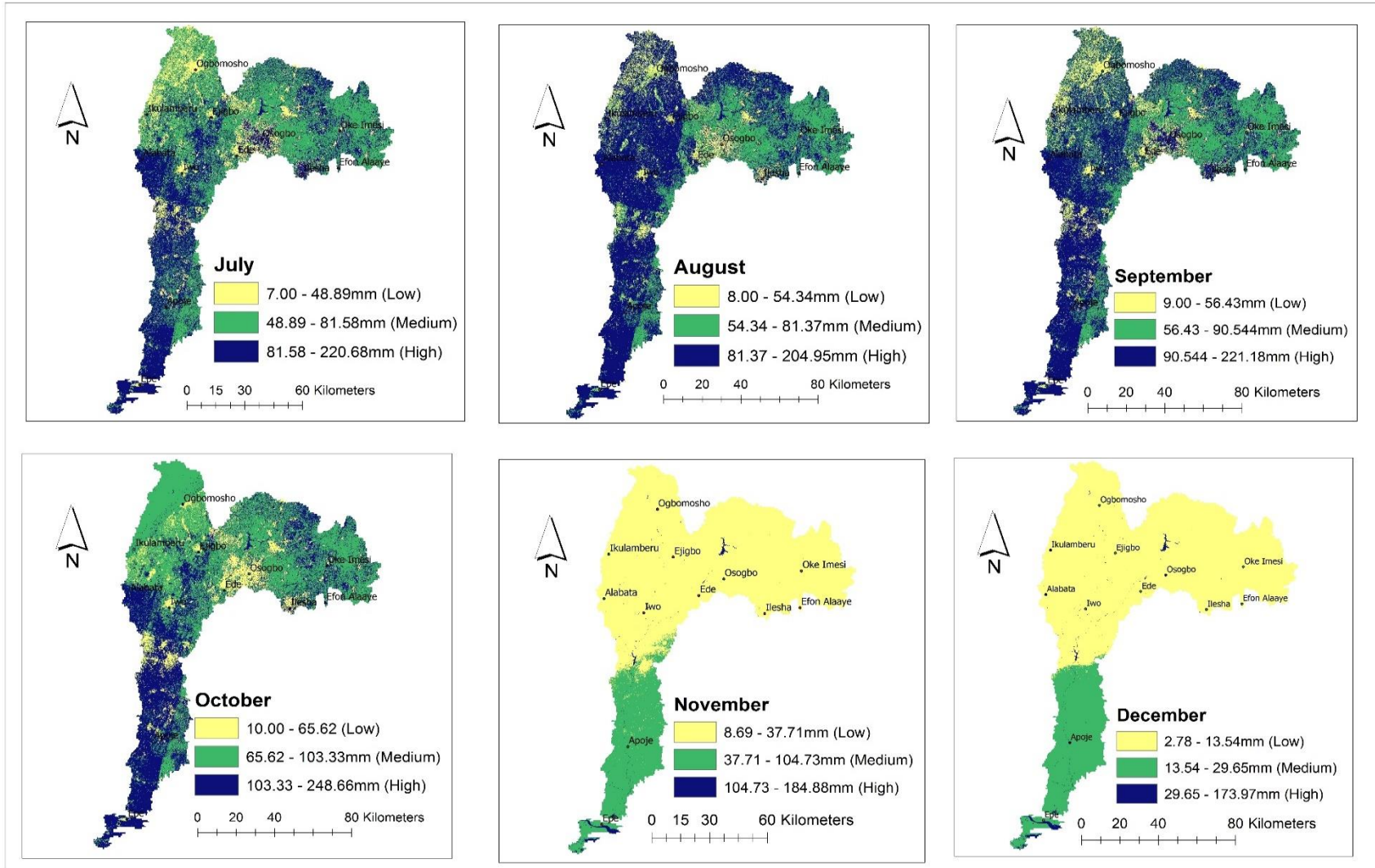


Figure 6.12: Pattern of Mean Monthly Actual Evapotranspiration (July-December) in Osun Drainage Basin (1976-2015)

Source:

Author's

Computation,

2017

6.2.4 Groundwater Recharge

The estimated monthly distribution of groundwater recharge in Osun drainage basin is presented in Table 6.4. The mean monthly groundwater recharge varies from 0.19mm in January to 101.97mm in September. The highest mean rainfall amount occurred in September, of which 35.17% recharge the groundwater system, while 1.74% of rainfall amount in January becomes groundwater recharge (Table 6.4). The estimated mean annual recharge in the basin was 430.06mm. This is 26.55% of the mean annual rainfall recorded in the basin for the period of study. The result is almost double the values given by Oke et al. (2015, p. 59) that adopted three empirical methods, and FMWR (2014a) that employed rainfall-runoff model in Ogun-Osun River basin. The mean annual groundwater recharge of the three methods by Oke et al., (2015, p. 59) range from 232.1mm to 204.6mm, or about 16 to 18% of mean annual rainfall amount, while FMWR (2014a) recharge estimates was 236mm/year.

Table 6.4: Mean Monthly Groundwater Recharge and Rainfall Amount, 1976-2015

	<i>Months</i>	<i>Recharge (mm)</i>	<i>Rainfall (mm)</i>	<i>Recharge/Rainfall (%)</i>
1	January	0.19	11.14	1.74
2	February	0.57	25.89	2.19
3	March	2.85	53.81	5.30
4	April	23.64	133.68	17.68
5	May	58.28	205.94	28.30
6	June	58.55	214.29	27.32
7	July	69.40	219.41	31.63
8	August	70.28	218.41	32.18
9	September	101.97	289.95	35.17
10	October	41.69	193.35	21.56
11	November	2.43	40.91	5.93
12	December	0.22	12.78	1.70
	<i>Total (Mean Annual)</i>	430.06	1619.58	26.55

Source: Author's Computation, 2017

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. While Oke et al., (2015,

p. 55) adopted an empirical method that does not consider other factors influencing recharge in the basins, FMWR (2014a, p. 20) adopted a rainfall-runoff model that contain only rainfall, temperature and runoff as input parameters. The percentage of rainfall that recharge aquifer in Osun drainage basin is significantly higher than what was reported in studies in dry environment (Adelana et al., 2006; Tesfamichael et al., 2013, p. 117; Teklebirhan et al., 2012; Al Kuisi and El-Naqa; 2013, p. 105; Babama'aji, 2013, p. 93) and relatively lower to what was reported in temperate environment (Dams et al., 2008, p. 1376). The results of the estimated groundwater recharge revealed that rainfall amount (precipitation) plays a significant influence on the amount of rainfall that recharge the groundwater system. This explains why the arid and semi-arid regions with less rainfall amount have low recharge rate compared to what obtains in the temperate and the tropical environments where the current study area is located. Further, most recharge occurred between April and October, which coincides with the rainy season in the study area. The relationship between mean monthly rainfall amount and groundwater recharge is presented in Figure 6.13.

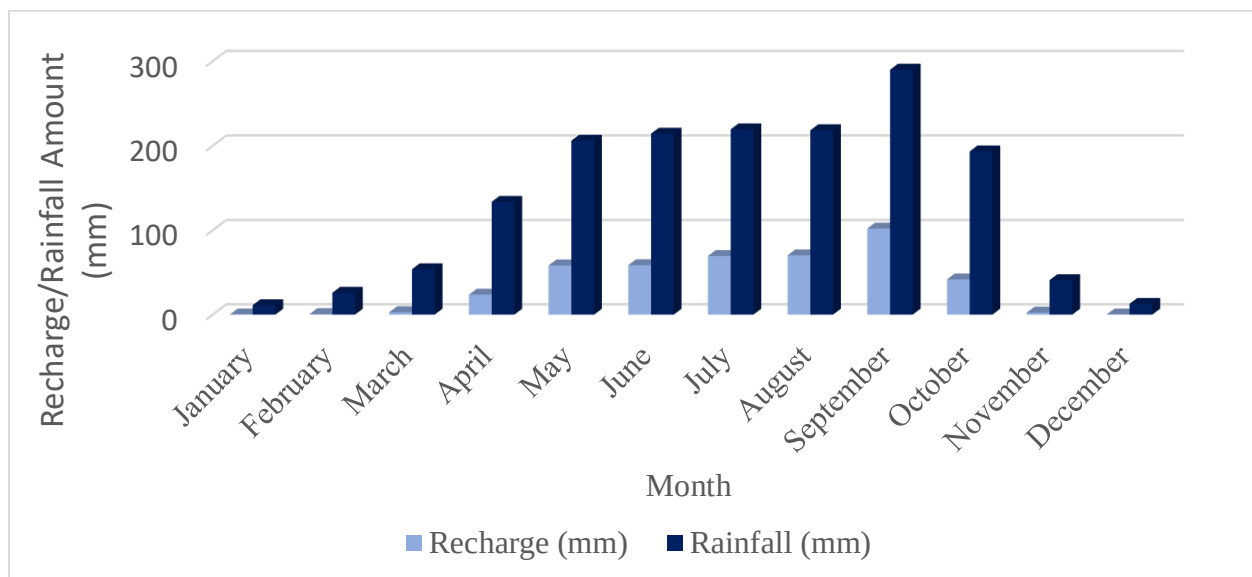


Figure 6.13: Mean Monthly Recharge and Rainfall Amount in Osun Drainage Basin
Source: Author's Computation, 2017

The months with the highest rainfall amount are those with higher recharge to the groundwater system (Figure 6.13). The mean monthly distribution pattern of groundwater recharge in Osun basin are presented in Figures 6.14 and 6.15. Akata, Epe, Eluju, Iberekodo located in the southern part of the basin have high recharge in the five dry months of November to March, because 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, because of late rainfall onset and 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 fails, 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 Leki 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. Most of the built-up area have a reasonable monthly mean recharge rate of between 68 to 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, 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 pattern, local variation in recharge rate among settlements occur from one month to another. For example, in April, while recharge ranges between 0-21.19mm in Ogbomosho and Ikulamberu in the northwestern part, it is while 21.19 to 35.61mm 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, Ibokun Imesi 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, p. 203) in those settlements that fall within Osun and Ekiti States. 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.

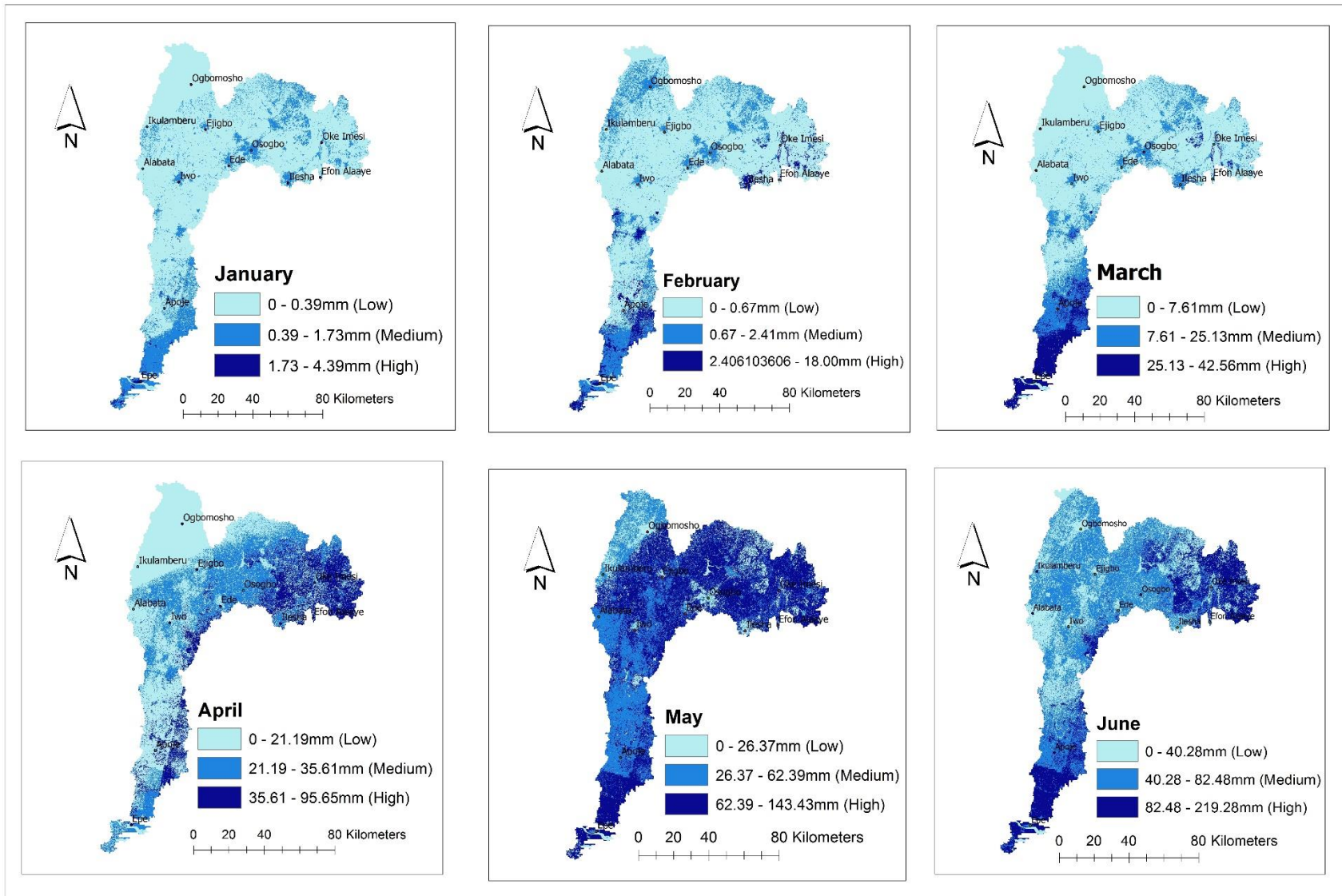


Figure 6.14: Pattern of Mean Monthly Recharge (January-June) in Osun Drainage Basin (1976-2015)

Source:

Author's

Computation,

2017

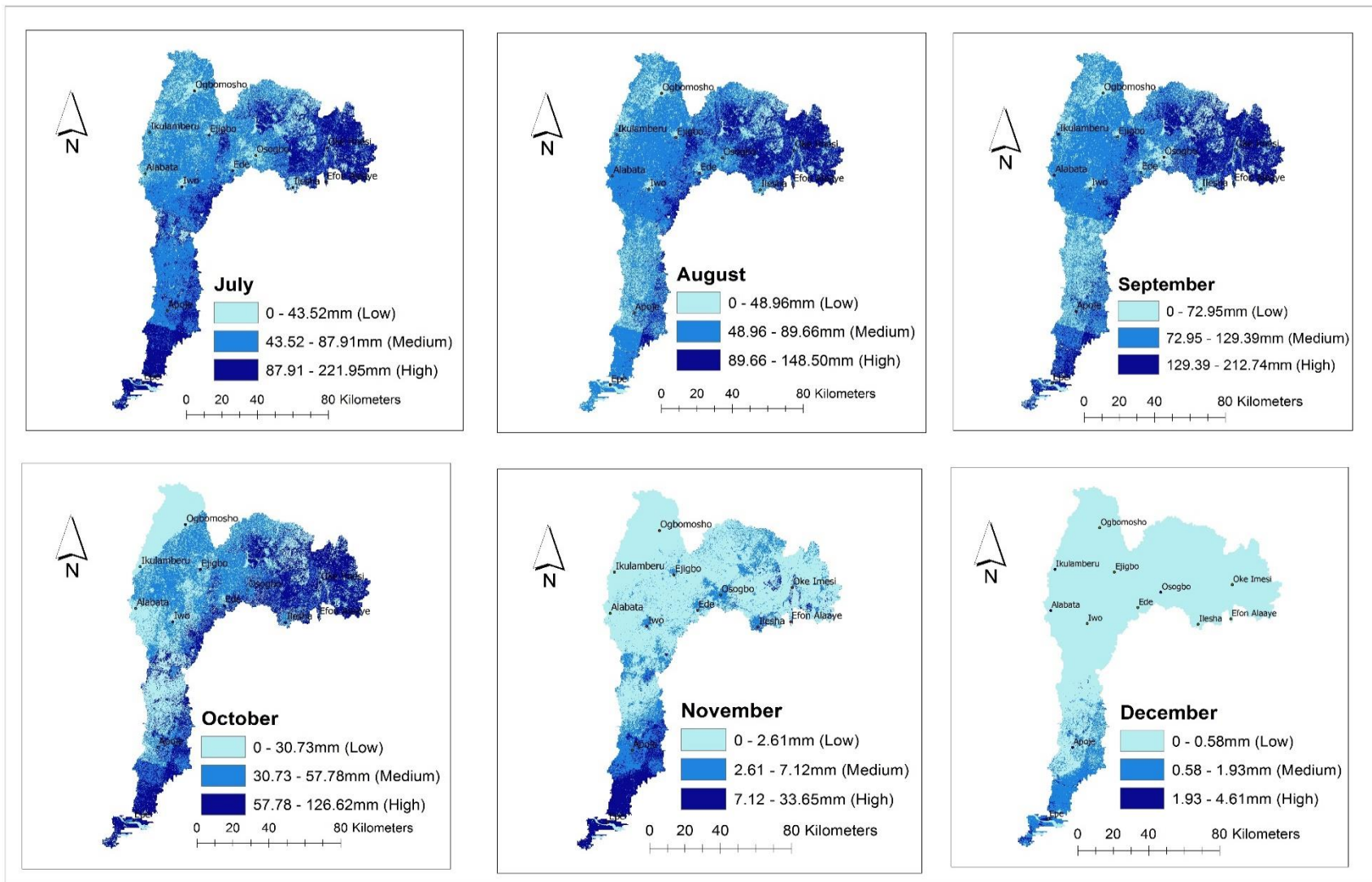


Figure 6.15: Pattern of Mean Monthly Recharge (July-December) in Osun Drainage Basin (1976-2015)
Source: Author's Computation, 2017

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, Ijebujsa and Ijeda. The recharge rates in the month of September in these locations ranged between 129.39-212.74mm. High recharge rate in this part are attributed 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, p. 203) 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.

6.3 Conclusion

Actual evapotranspiration (AET) is the largest water balance component of the water budget in the basin. In other words, the larger percentage of water received from rainfall is lost to AET. The percentage of annual rainfall amount that become runoff and groundwater recharge in the basin are relatively close, while interception would appear to be the least important component of the hydrological budget in Osun basin. This result is considered reasonable because of the fact that the tropical rainforest typical of the basin has apparently been replaced with secondary forest, crops and shrubs.

CHAPTER SEVEN

EFFECT OF CLIMATE AND LAND USE/LAND COVER CHANGE ON GROUNDWATER RECHARGE

7.0 Introduction

The focus of this chapter is on the effect of climate and land use/land cover on groundwater recharge in Osun drainage basin. The mean monthly groundwater recharge and climatic variables were first highlighted and discussed. Then the relationship that exists between climatic variables and groundwater recharge examined and discussed. Thereafter, the effects of each classified land use/land cover on groundwater recharge in the basin was discussed.

7.1 Effect of Climate on Groundwater Recharge

Table 7.1 shows the mean monthly groundwater recharge and the climate variables adopted for the analysis. The highest mean monthly groundwater recharge, rainfall amount and relative humidity in the basin are in the wet months of April to October, while the lowest are in the dry months of November to March of each year during the period of study. This is an indication that groundwater recharge is controlled by rainfall, but it is also affected by other processes such as interception, evapotranspiration, and surface runoff as observed in chapter six of this study.

The lowest mean monthly temperature is in the wet months of April to October, while the highest are in the dry months of November to March. It is pertinent to note that the lowest wind speed was recorded in the dry months, except March, while lowest mean monthly sunshine hours in the basin occur in the months of June to October. From Table 7.1, rainfall amount, relative humidity and wind speed have similar monthly pattern with groundwater recharge. Consequently, these climate variables and groundwater recharge were subjected to further statistical analysis so as to understand their relationships.

Table 7.1: Mean Monthly Groundwater Recharge and Climate Variables

Months	Groundwater recharge (mm)	Rainfall amount (mm)	Mean temperature (°C)	Wind speed (m/s)	Relative humidity (%)	Sunshine hour (ml)
January	0.19	11.14	27.57	2.07	56.05	5.87
February	0.57	25.89	28.85	2.39	61.35	6.19
March	2.85	53.81	29.39	2.74	67.27	5.98
April	23.64	133.68	28.91	2.88	72.73	6.11
May	58.28	205.94	27.53	2.58	78.86	6.01
June	58.55	214.29	25.92	2.51	84.04	5.00
July	69.40	219.41	24.43	2.50	87.02	3.55
August	70.28	218.41	24.14	2.49	87.70	2.91
September	101.97	289.95	24.95	2.15	88.24	3.71
October	41.69	193.35	26.23	2.00	84.76	5.27
November	2.43	40.91	27.53	1.86	73.86	6.72
December	0.22	12.78	27.18	1.89	61.08	6.44

Source: Author's Computation, 2017

In order to identify the amount of variability in groundwater amount that can be explained by climate, five climate variables and the mean monthly recharge data were subjected to multiple regression analysis. The results obtained are in Table 7.2. The multiple linear regression model, has an R^2 value of 0.981. Thus, about 98% of the variation in monthly groundwater recharge in the basin can be explained using this model. Based on the results obtained, the relationship between groundwater recharge and climatic variables in the basin can be represented as shown in equation 7.1:

$$\text{Recharge} = 142.452 + .389_{\text{RainfallAmount}} - 1.873_{\text{MeanTemperature}} - 6.658_{\text{Windspeed}} - .944_{\text{RelativeHumidity}} - 4.186_{\text{SunshineHour}} \dots \quad \text{eq. 7.1}$$

7.1

Coefficient of determination (R^2) = 98.1%, (Standard Error of estimate) SE = 6.58

In other words, rainfall amount, temperature, wind speed, relative humidity and sunshine hour combined to explain 98.10% of the monthly variability of groundwater recharge in the basin. The

results of the multiple regression indicated that for every one percent increase in monthly rainfall amount, there is 0.389 % increase in monthly groundwater recharge in the basin. On the other hand, for every one percent decrease in monthly temperature, monthly wind speed, monthly relative humidity, and monthly sunshine hour, there is 1.873 %, 6.658%, 0.944% and 4.186% decrease, respectively in monthly groundwater recharge (Table 7.2).

Table 7.2: Relationship between Groundwater Recharge and Climate Variables

<i>Independent Variables and Intercept</i>	<i>Regression Coefficient</i>	<i>Standard Error</i>	<i>T-test</i>	<i>Significance Level</i>	<i>R² % Explanation</i>
<i>Intercepts</i>	142.452	93.911	1.517	-	98.1%
<i>Rainfall amount</i>	.389	.062	6.247	.001	
<i>Temperature</i>	-1.873	4.307	-.435	.679	
<i>Wind speed</i>	-6.658	10.768	-.618	.559	
<i>Relative humidity</i>	-.944	.530	-1.780	.125	
<i>Sunshine hour</i>	-4.186	5.048	-.829	.439	

Source: Author's Computation, 2017

The data were further subjected to stepwise multiple regression, to identify the percentage contribution of each of the climatic variables. The stepwise multiple regression analysis knocked out temperature, windspeed, relative humidity and sunshine hour. From the perspective of climate, rainfall amount explains about 95% of the variability in groundwater recharge in the basin (Table 7.3). From this result of stepwise regression analysis, the relationship between monthly groundwater recharge and monthly climatic variables in the basin can be given as in equation 7.2:

$$\text{Groundwater Recharge} = -10.769 + .345_{\text{Rainfall Amount}} \dots\dots\dots (7.2)$$

Coefficient of determination (R^2) = 94.90%, (Standard Error of estimate) SE = 8.39

Thus, the higher the variation in rainfall amount received, the higher the variation in recharge of the groundwater system in the basin. A similar situation in Odeda, Ogun State Nigeria where

98.3% of the variability in groundwater recharge was determined by rainfall amount had earlier been observed (Adeleke et al., 2015, p. 279). The result also conforms to that of Nolan et al. (2007) that used nonlinear regression analysis to discover that rainfall was the most significance factor influencing groundwater recharge in the eastern part of United States. The result differs however from that of Saghravani, Ismail, Sa'ari and Saghravani (2013) in Selangor, Malaysia where rainfall amount and wind speed were the most significant climatic variables influencing groundwater recharge. The physically based method adopted in this study considered the temporal variations in the climatic variables and their implications on water cycle, but also took into account the spatial variation in surface and subsurface characteristic of the basin. Therefore, the little variant in the results might be attributed to the approaches used in estimating groundwater recharge.

Table 7.3: Relationship between Groundwater Recharge and Most Significant Climate Variables

<i>Variable</i>	<i>Parameter Estimates</i>	<i>Standard Error</i>	<i>R</i>	<i>R²</i>	<i>Coefficient of determination</i>	<i>% of Contribution</i>
<i>Intercept</i>	-10.769	4.181				
<i>Rainfall amount</i>	0.345	0.025	0.974	0.949	94.90	94.90

Source: Author's Computation, 2017

The result of the stepwise multiple regression analysis indicated that for every one percent increase in monthly rainfall amount, there is 0.345 % increase in monthly groundwater recharge in the basin (Table 7.3). However, the percentage increase in groundwater recharge as a consequence of rainfall amount will not be uniform over space and time in the basin. Figures 7.1 and 7.2 show the spatial and temporal relationship between mean monthly rainfall amount and groundwater recharge. These figures further emphasized how rainfall variability over space and time also influences spatio-temporal pattern of recharge as observed in chapter 6. Despite the similar spatial pattern of rainfall amount and groundwater recharge observed, the characteristics

of the ground surface such as land cover and slope; texture/nature of the underlying soils also influence recharge pattern (Jyrkama and Sykes, 2007).

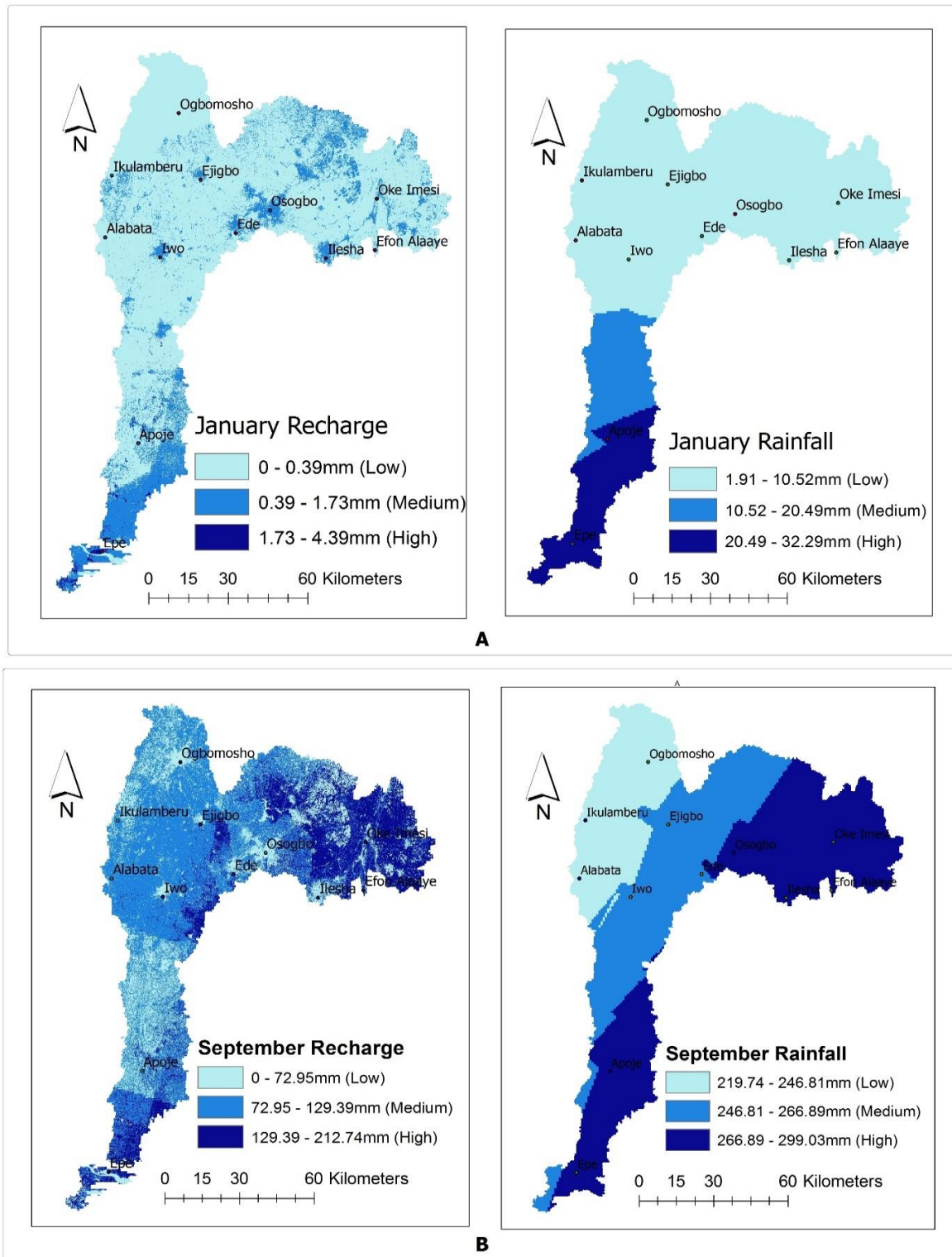


Figure 7.1: Relationship between Recharge and Rainfall Amount, (A) Month with Lowest Rainfall and Groundwater Recharge, (B) Month with Highest Rainfall and Groundwater Recharge.
Source: Author's Computation, 2017

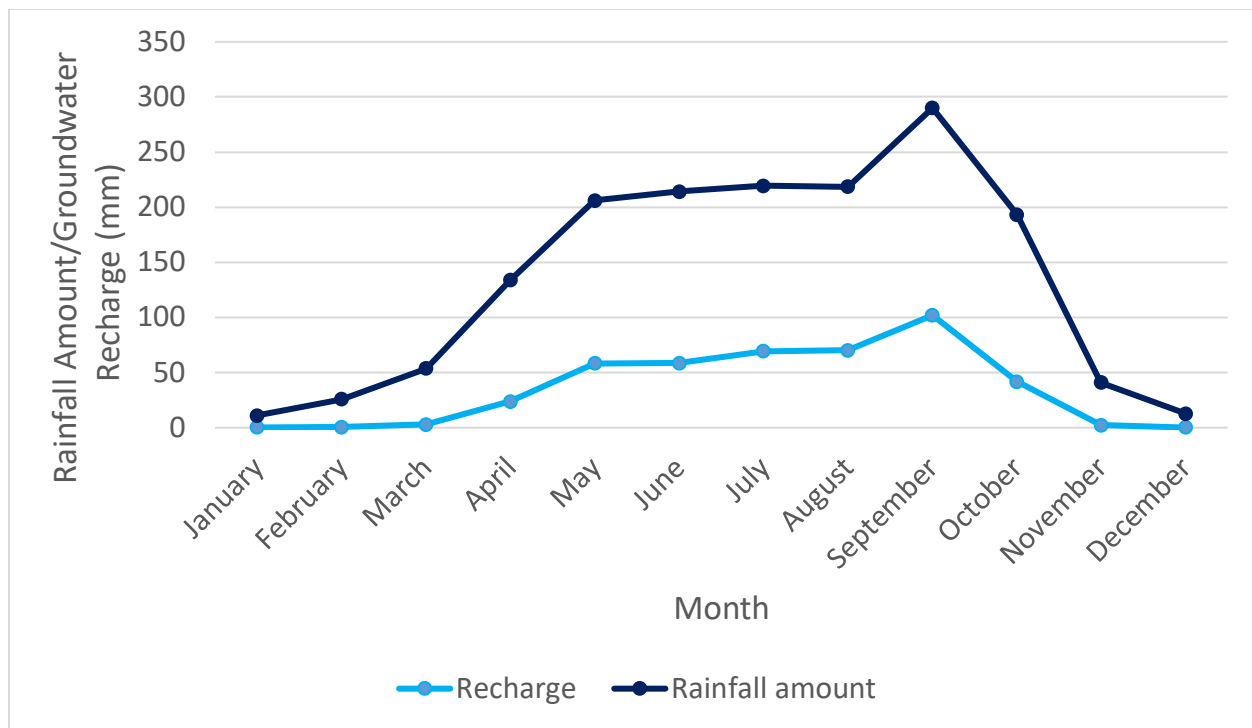


Figure 7.2: Relationship between Mean Monthly Rainfall Amount and Groundwater Recharge
Source: Author's Computation, 2017

The climatic data and groundwater recharge were further tested with Spearman Rank correlation to see the relationship between the climatic variables as well as their associations with groundwater recharge. The resulting correlation matrix from the analysis is presented in Table 7.4. The results indicated a strong positive relationship ($r = .993$) between monthly rainfall amount and groundwater recharge at 99% confidence level. This suggests that as monthly rainfall amount increases, monthly groundwater recharge increases and vice versa. This is similar to the result of Adeleke et al. (2015, p. 278) which revealed strong positive relationship between rainfall amount and estimated recharge in Odeda, Nigeria. In addition, relative humidity has a strong positive ($r = .958$) relationship with groundwater recharge at 99% confidence level. This can be associated with rainfall, because relative humidity determines the occurrence of rainfall. Although, monthly wind speed has a positive relationship ($r = .343$) with groundwater recharge, the relationship is low and not statistically significant.

Table 7.4: Association between Groundwater Recharge and Climate Variables

	<i>Rainfall Amount</i>	<i>Temperature</i>	<i>Wind speed</i>	<i>Relative Humidity</i>	<i>Sunshine Hour</i>
<i>Recharge</i>	.993**	-.715**	0.343	.958**	-.769**
<i>Rainfall Amount</i>		-.708*	0.35	.951**	-.762**
<i>Temperature</i>			0.256	-.781**	.708*
<i>Wind speed</i>				0.105	-0.245
<i>Relative Humidity</i>					-.727**

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).

Source: Author's Computation, 2017

Both temperature ($r = -.715$) and sunshine hour ($r = -.769$) show a strong negative relationship with groundwater recharge at 99% confidence level. This indicate that both temperature and sunshine hour build up enhances evapotranspiration. Hence, the higher the evapotranspiration, the lesser the available water from rainfall to recharge the groundwater system.

There is an inverse relationship between temperature and rainfall, which suggests that high temperature will result in less rainfall, and vice versa. The observed relationship between temperature and rainfall in the basin deserves more attention because of the future climate scenario and groundwater recharge of the basin. Indeed, it has been argued elsewhere that rainfall and temperature in a dry climate scenario will have an inverse relationship which will result to an adverse effect on groundwater recharge (Woldeamlak et al., 2007). Thus, if the climate of the basin become drier in the future, available groundwater resources of the area may be completely depleted. In fact, it was noted in chapter four that rainfall amount in the basin is decreasing, while temperature is increasing. Despite the non-statistical significance decrease in rainfall amount, it should be a cause for concern because the increasing trend in temperature is statistically significant. This type of scenario coupled with the nature of the aquifer might signal a future water crisis in the basin if not properly managed.

7.2 Effect of Land Use/Land Cover Change on Groundwater Recharge

The sensitivity of LULC change on groundwater recharge in the basin is presented in Table 7.5. The LULC with highest groundwater recharge in 1984, 2000 and 2015 was on forest land cover which are 48.56%, 33.64% and 37.29%, respectively. This might be due to the influence of vegetation in slowing down the speed of running water across the forest area, that allows more infiltration and deep percolation into the water table. The result agrees with the study of Zamlot et al. (2015) that discovered that forest land-use type have a positive higher effect on groundwater recharge, in Flanders, Belgium. High recharge in the forested area in the basin can be attributed to the preferential flow mechanism through the unsaturated zone. Preferential flow is often associated with tree roots that have created preferential path ways/macro pores in the unsaturated zone with a relatively high infiltration and percolation capabilities (Obuobie, 2008; Lerner et al., 1999; 1990) that allows rainfall easy passage into the saturated zone to recharge the groundwater system.

Table 7.5: Effect of each LULC Classes Change on Groundwater Recharge

<i>Land Use/Land Cover Types</i>		<i>1984 LULC</i>	<i>1984 Groundwater Recharge per LULC</i>	<i>2000 LULC</i>	<i>2000 Groundwater Recharge per LULC</i>	<i>2015 LULC</i>	<i>2015 Groundwater Recharge per LULC</i>
		%	%	%	%	%	%
1	Bare Surfaces	20.56	20.69	27.30	24.76	31.10	25.98
2	Built Up Areas	3.20	9.46	4.63	10.29	10.72	10.81
3	Crops/Shrubs	16.58	7.55	41.94	19.28	31.38	19.48
4	Forest	52.62	48.56	20.75	33.64	21.71	37.29
5	Rock Outcrops	4.97	4.49	3.45	3.09	4.23	2.44
6	Water Bodies	0.51	0.00	0.62	0.00	0.62	0.00
7	Wetland	1.55	9.25	1.32	8.93	0.24	4.00

Source: Author's Computation, 2017

The least groundwater recharge in relation to LULC for the three periods was on the rock outcrops, while no recharge takes place on the water bodies. About 4%, 3% and 2% of the total annual recharge occurred on the rock outcrops in 1984, 2000 and 2015, respectively. This is

because recharge can only occur on this type of LULC classes in the interface between the outcrops and the loose cracks found around the flat area of the rock outcrops. The least recharge found on rock outcrops is expected and may be attributed to the fact that infiltration can only occur around or on decomposed rock outcrop, which may result in minute recharge to the groundwater system.

Built-up area increases slightly from 3.20% in 1984 to 4.64% in 2000, which resulted in slight increase in total annual groundwater recharge occurrence in built up area from 9.46% to 10.29%. The significant increase in built-up areas from 4.64% in 2000 to 10.72% in 2015 resulted to the built-up area doubling its size. During this period, the relative contribution of built up area to groundwater recharge only increased meagerly from 10.29% to 10.81%. The groundwater recharge occurrence on built-up area did not increased in relation to its size as observed between 1984 and 2000. This suggests that there are more paved surfaces within the built-up expansion by the year 2015. In other words, the spatial expansion of built up area by 2015 in the basin have more impervious surfaces that prevent water to infiltrate and percolate to recharge the groundwater system in and around the built-up areas like the preceding years. The result differs from that of Dams et al. (2008, p. 1377) that used four LULC change between 2000 and 2020, where they observed a reduced recharge in urban centres. The mean monthly occurrence of groundwater recharge in built up LULC class in 1984, 2000 and 2015 is presented in Figure 7.3.

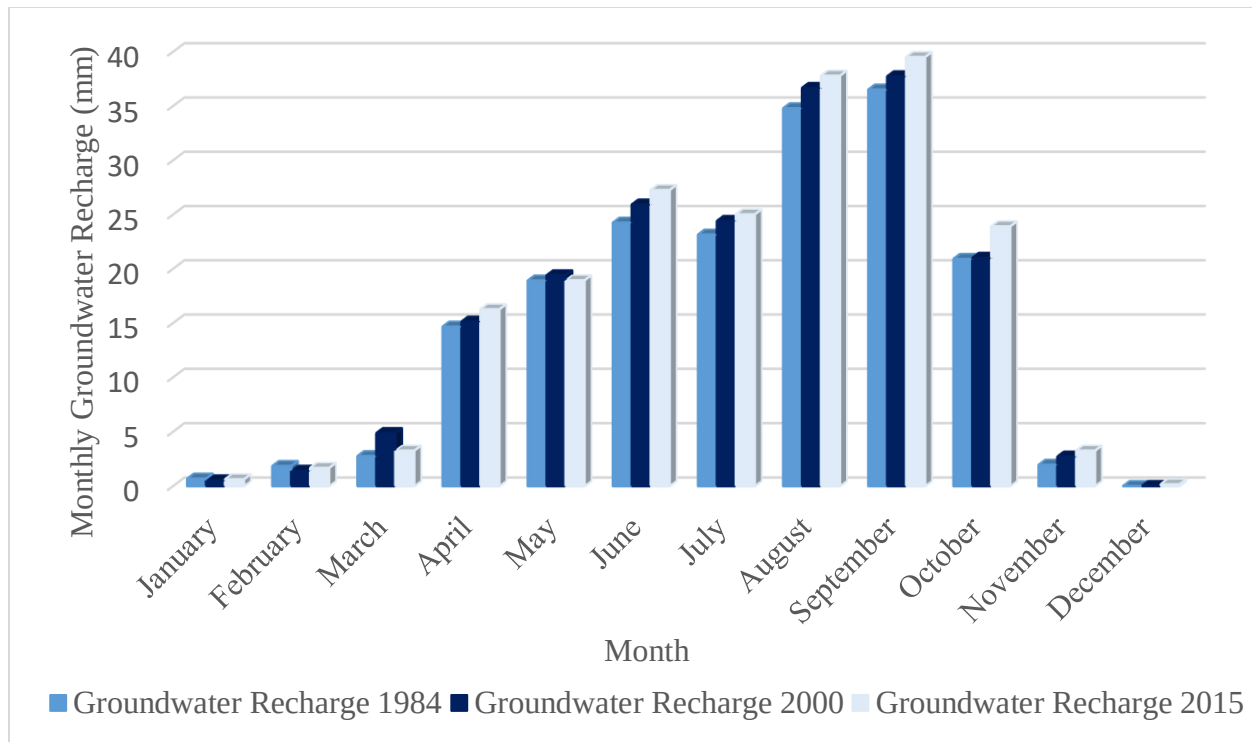


Figure 7.3: Mean Monthly Recharge on Built UP Area LULC Class
Source: Author's Computation, 2017

Groundwater recharge occurrence on crops/shrubs LULC classes increased from 7.53% to 19.28% between 1984 and 2000. The 11.25% increase in groundwater recharge occurrence on this LULC type, was a consequence of significant increase in crops/shrubs between the same period. Despite about 10% decrease in crops/shrubs between 2000 and 2015, less than 1% increase in groundwater recharge occurrence was still discovered. Groundwater recharge varies over space in all the LULC classes, with some areas of crops/shrubs LULC having little to zero recharge. Therefore, about 10% area of crops/shrubs converted to another use by 2015 might be those areas with little or no recharge. A similar low increase on crops and shrubs LULC was observed in upper Berg catchment, South Africa (Albhaisi et al., 2013). The monthly occurrence of groundwater recharge in 1984, 2000 and 2015 on crops/shrubs LULC class is presented in Figure 7.4.

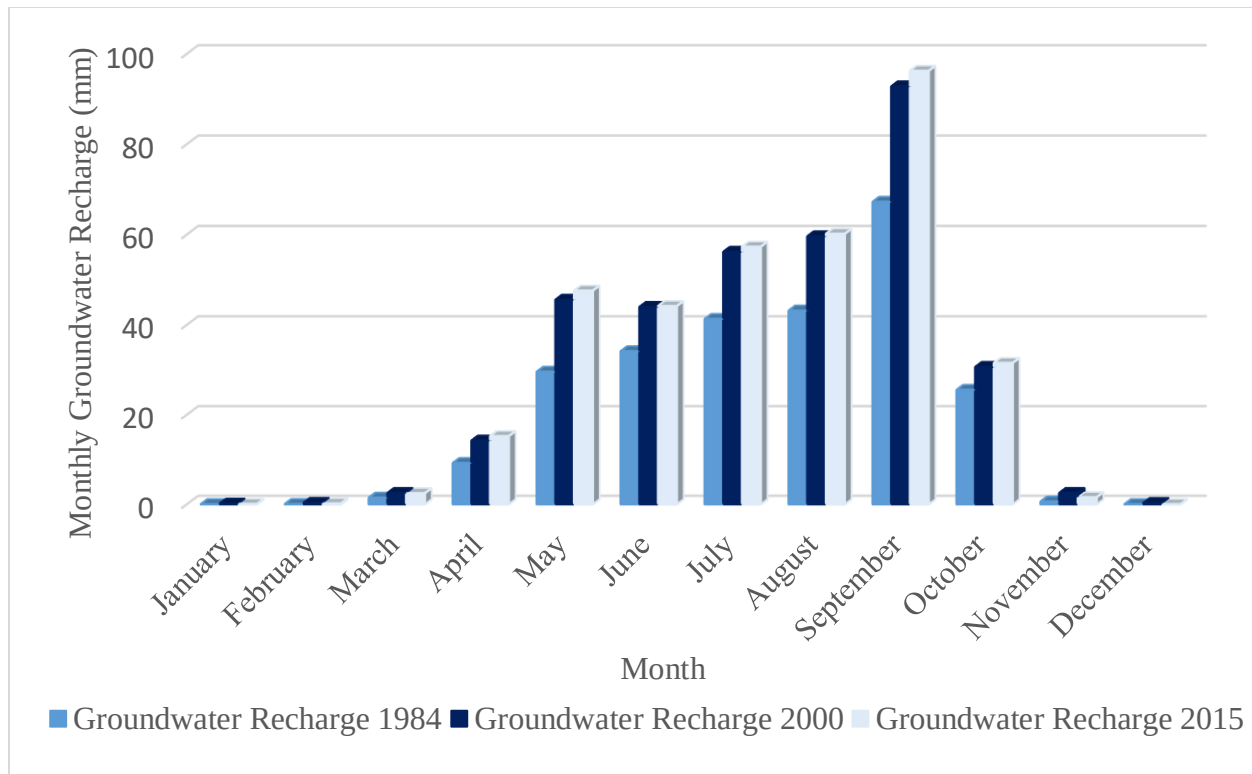


Figure 7.4: Mean Monthly Recharge on Crop/Shrubs LULC Class

Source: Author's Computation, 2017

The occurrence of groundwater recharge in forest area decreased from 48.56% in 1984 to 33.64% in 2000. During this period, the forested area declined significantly as a consequence of human anthropogenic activities in the basin. As it was noted earlier that highest recharge was found in forest area, increased deforestation signals reduced recharge in the basin. The result obtained between 1984 and 2000 is similar to the study of Albhaisi et al. (2013, p. 218) in South Africa between 1984 and 2009. Forest area later increased slightly between 2000 and 2015, which also increased groundwater recharge occurrence on forest LULC from 33.64% to 37.29%. The about 4% increase in ground water recharge can be attributed to the slight increase in forest area that lead to reduced overland flow, more infiltration and percolation to the groundwater table to recharge the aquifer. Figure 7.5 shows the monthly contribution of forest LULC class to groundwater recharge in 1984, 2000 and 2015 in the basin.

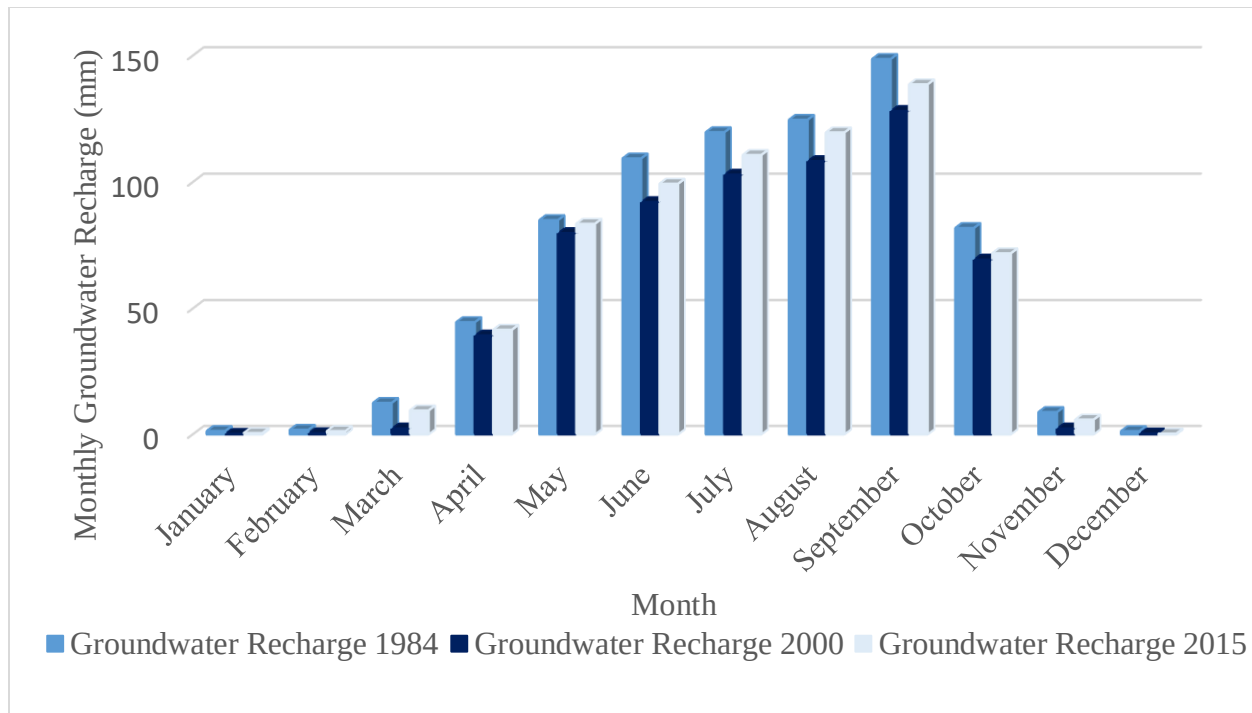


Figure 7.5: Mean Monthly Recharge on Forest LULC Class
Source: Author's Computation, 2017

Groundwater recharge occurrence on bare surface increases from 20.69% to 24.76% between 1984 and 2000, while it increased further to 25.98% in 2015. This was an increase of 4.07% in groundwater recharge between 1984 and 2000, while it was 1.22% increase between 2000 and 2015. The relatively small increase rate of recharge occurrence on this LULC is as a result of less than 6.74% and 4% increase in areal coverage of bare surface between 1984 and 2000; and from 2000 to 2015, respectively. The minute increase in recharge occurrence on bare surface in Osun drainage is at variant with the observation of Albhaisi et al. (2013, p. 218) in upper Berg catchment, South Africa, where groundwater recharge on bare LULC class increases significantly from 23% in 1984 to 64.7% in 2008. The significant increase observed in their study may be attributed to the fact that bare land use tripled its areal extent of 1984 by the year 2008. The monthly occurrence of groundwater recharge in bare LULC class in 1984, 2000 and 2015 is presented in Figure 7.6.

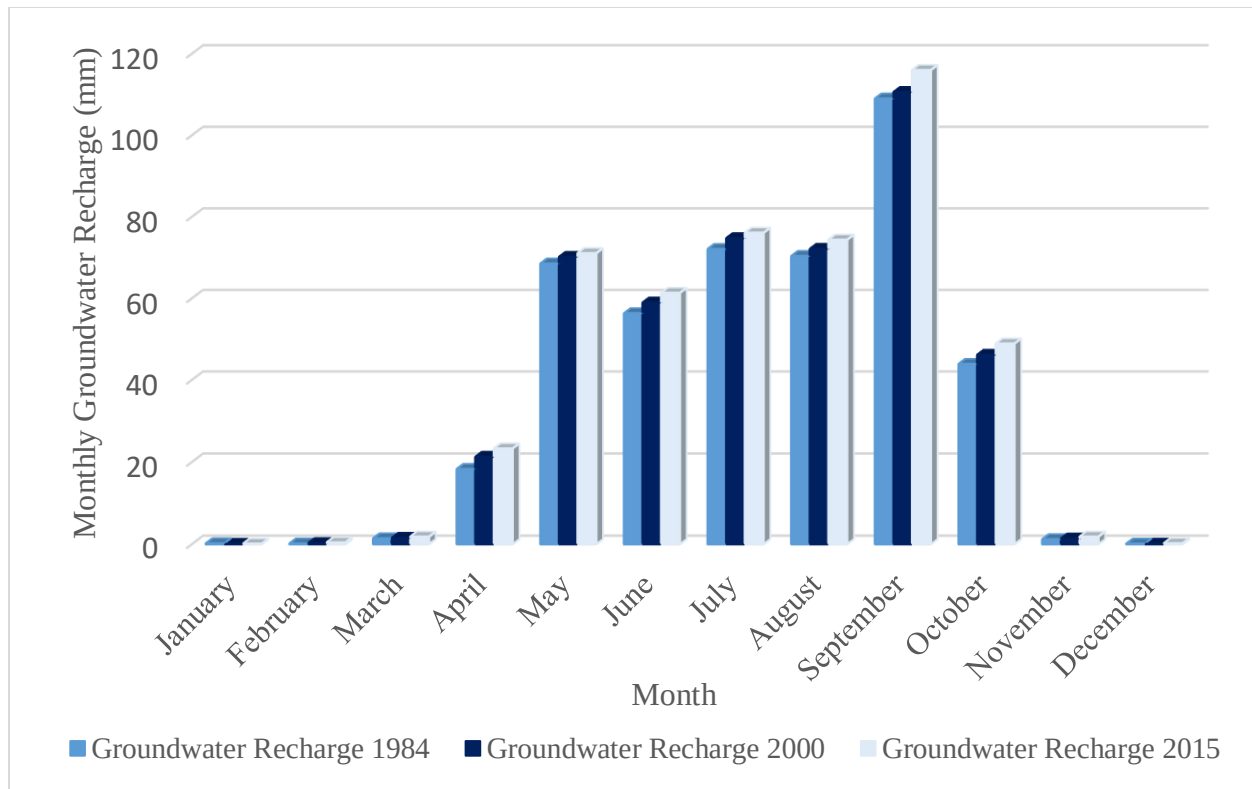


Figure 7.6: Mean Monthly Recharge on Bare Surfaces LULC Class
Source: Author's Computation, 2017

Wetland decreased from 1.55% in 1984 to 1.32% in 2000, which accounted for slight reduction in groundwater occurrence from 9.25% to 8.98%. Also, wetland decreased from 1.32% in 2000 to 0.24% in 2015, which was about 1.08% reduction in wetland between the period. The change in wetland leads to reduction in groundwater recharge on wetland from 8.93% in 2000 to 4.00% in 2015. This was slightly more than 50% reduction in groundwater recharge occurrence on wetland as a result of about 1.08% change in wetland LULC between 2000 and 2015. Monthly contribution of wetland LULC class to groundwater recharge in 1984, 2000 and 2015 is presented in Figure 7.7.

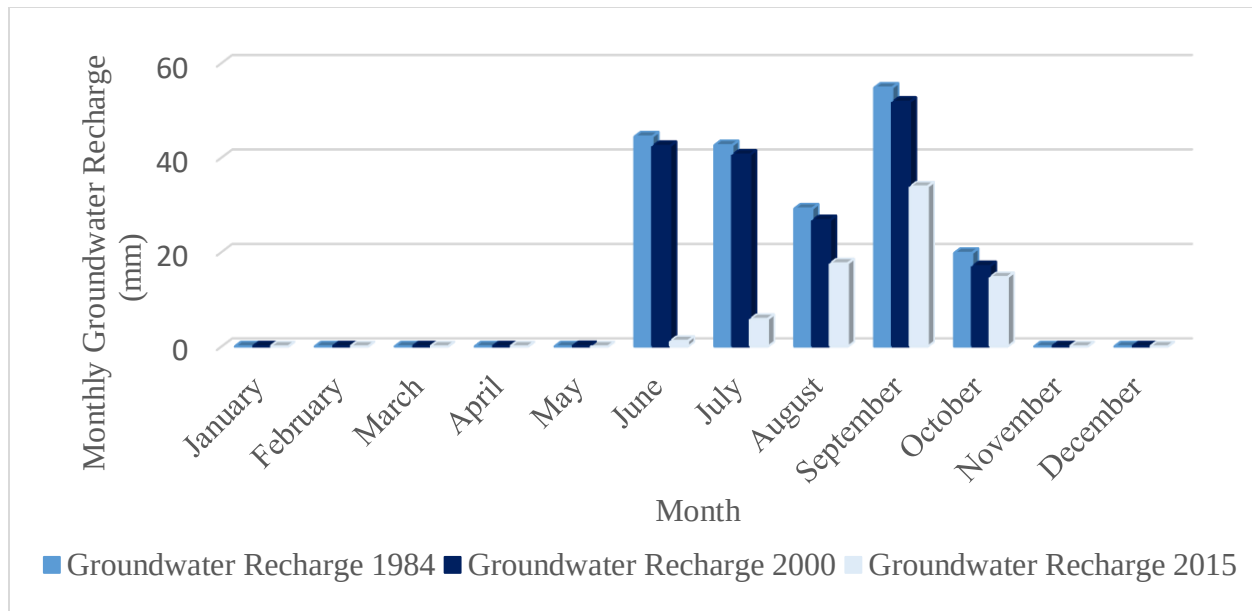


Figure 7.7: Mean Monthly Recharge on Wetland LULC Class
Source: Author's Computation, 2017

The mean annual groundwater recharge of the basin for the land use maps of 1984, 2000 and 2015 are 476.54, 411.07 and 430.06 mm/y, respectively (Table 7.6). This shows that mean annual groundwater recharge decreased by 13.72% between 1984 and 2000, while it increased by 4.61% between 2000 and 2015. There was a general decrease of 9.75% in mean annual groundwater recharge between 1984 and 2015. As stated earlier, the forest area decreased from its areal extent of 5223.61 km² in 1984 to 2154.87 km² in 2015. The observed decrease in groundwater recharge can be attributed to a larger extent to the deforestation of the tropical rainforest under which highest groundwater recharge occurred in the basin. As the main source of replenishment of the groundwater resources, groundwater recharge over time and space in a Basement complex aquifer determines the groundwater reserve. Hence, it can be deduced that the groundwater reserve of the basin declined with about 10% between 1984 and 2015 as a result of change in LULC. The result is at variant with the observation of Albhaisi et al. (2013, p. 219) in upper Berg catchment, South Africa where an increase in groundwater recharge of about 8%

was observed between 1984 and 2008. The reason for the variance in results is that highest groundwater recharge occurrence was found in the forest area in this present study which has decreased to 21.71% by 2015, while, highest groundwater recharge occurred in bare land which has increased to 65% of the Berg catchment by 2008.

Table 7.6: Overall Effect of LULC Change on Groundwater Recharge in the Entire Basin

Sn	Years	Mean Annual Recharge	Change in Groundwater Recharge		
			Period	mm	%
1.	1984	476.54	1984-2000	-65.40	-13.72
2.	2000	411.07	2000-2015	+18.99	+4.61
3.	2015	430.06	1984-2015	-46.48	-9.75

Source: Author's Computation, 2017

- signifies decrease in groundwater recharge

+ signifies increase in groundwater recharge

The effect of LULC change on groundwater recharge in Osun drainage basin indicates that there are only little changes in recharge to groundwater system that can be associated to change in LULC. However, change in LULC have resulted to changes in recharge pattern in the basin. The reasons for the observed change in recharge pattern can be attributed to the fact that most often, change in LULC is a transition from one LULC class to another. The recharge pattern is influenced based on the amount and degree of transition taking place and the characteristics of the dominant LULC at a particular area of the basin. This correspond to Finch (2001) when he observed in a rural catchment of southern England that the mean annual groundwater recharge response to land cover change led to changes in the recharge pattern. Figure 7.8 shows the percentages of the mean annual groundwater recharge occurrence on different LULC classes of 1984, 2000 and 2015 in Osun drainage basin.

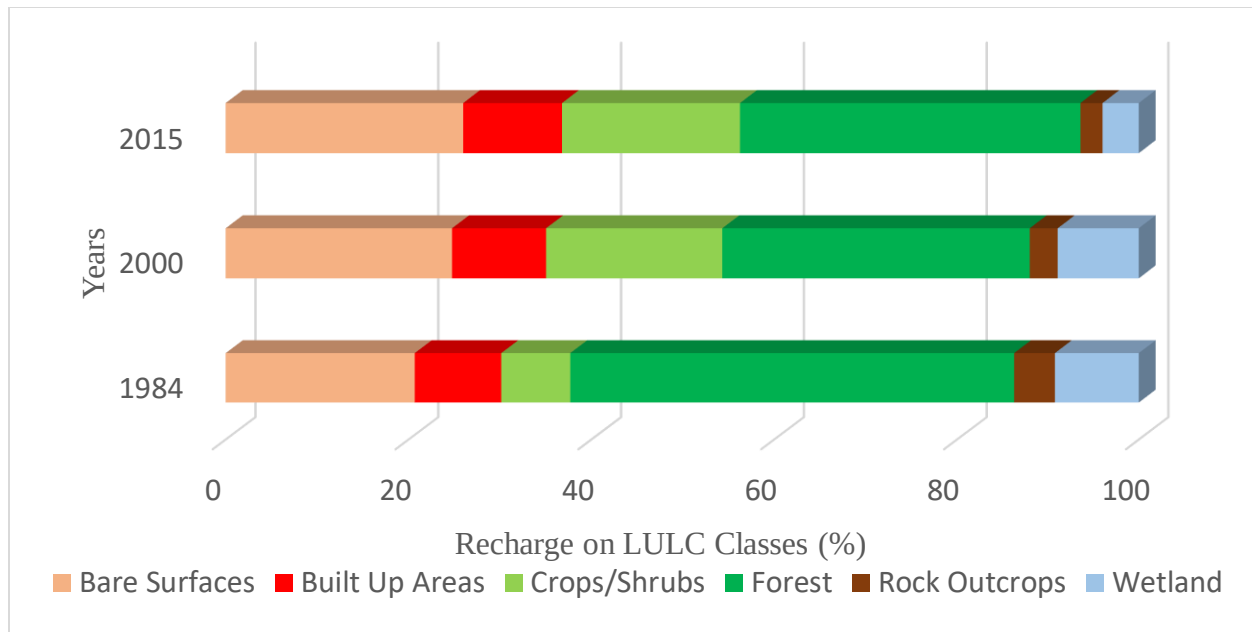


Figure 7.8: Mean Annual Groundwater Recharge Occurrence on Different LULC Classes
Source: Author's Estimation, 2017

Nevertheless, it is important to note that the percentage contribution of the seven LULC classes to groundwater recharge was based on the mean of groundwater recharge observed on each LULC class in the basin. Looking at it from the spatial perspective, a relatively higher change in recharge occurred on some LULC classes between 1984, 2000 and 2015. For example, the recharge amount occurrence on bare surface LULC in September 2000 in the northeastern and northcentral part of the basin in Oke Imesi, Efon Alaaye, Osogbo, Ede and Ilesha ranged between 118.45mm to 174.59mm. In 2015, bare surface in the same part of the basin contributed groundwater recharge that ranged between 121.54mm to 138.61mm (Figure 7.9). This revealed the change in spatial pattern of groundwater recharge as a result of change in LULC classes.

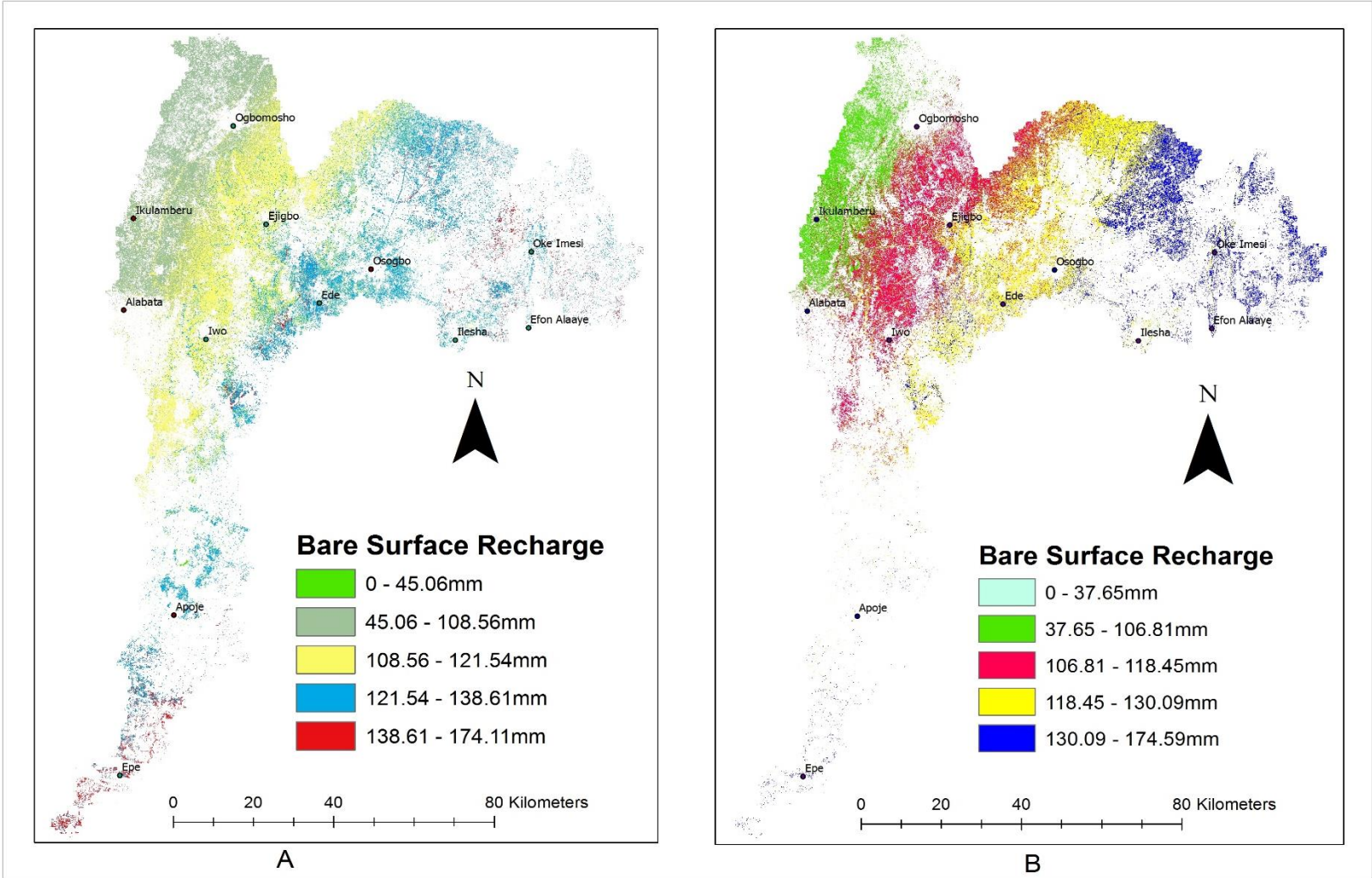


Figure 7.9: (A) Bare Surface Recharge in September 2015 (B) Bare Surface Recharge in September 2000
 Source: Author's Estimation, 2017

7.3 Conclusion

The effect of climate and LULC change on groundwater recharge was examined in this chapter. It was observed that rainfall amount is the most significant climate variable influencing groundwater recharge in the basin. A result that underscore early observations that direct recharge to the groundwater system on a Basement complex aquifer is characterized by rainfall. The contribution of each LULC class to groundwater recharge were examined for the years 1984, 2000 and 2015. The change in LULC between 1984, 2000 and 2015 influence only the recharge pattern but with little effect on the overall groundwater recharge in the basin. The groundwater recharge between 1984 and 2015 revealed a decrease of about 10%. This decrease was associated with decrease in forest area where larger percentage of groundwater recharge takes place in the basin. The average rate of change (decrease) in forest area for the 32-year period was 1.84%, which resulted to about 10% decrease in groundwater recharge for the period investigated. The 10% overall decline in groundwater recharge might become pronounced if the current rate of deforestation continues in the basin unabated.

CHAPTER EIGHT

SUMMARY, CONCLUSION AND RECOMMENDATIONS

8.0 Introduction

This study evaluated the effect of climate and LULC change on groundwater recharge in Osun drainage basin. Data on climatic variables, Landsat imageries, DEM, soil, slope, groundwater depth and river discharge were collected from various sources for analysis. WetSpass-M hydrological model, GIS and remote sensing methods; and various statistical analysis were employed to achieve the aim of the study. The spatio-temporal pattern of climate and LULC change in the basin was examined. The monthly water budget which include interception, actual evapotranspiration, runoff and groundwater recharge in Osun drainage basin computed. Finally, the effect of climate and LULC change on groundwater recharge were investigated. The study discovered some significant findings on the basis of which it concluded and offered some recommendations.

8.1 Summary of Findings

The findings of the study revealed that:

- i. rainfall amount and relative humidity in Osun drainage basin decreased at the rate of 2.65 mm/year and 0.06% /year for the 40 years period of investigation, but the decrease are not statistically significant.
- ii. potential evapotranspiration, minimum and maximum temperature increased at 3.63mm/year, 0.01 and 0.03 °C/year, respectively for the same period and are statistically significant at 95% confidence level.
- iii. eighteen (18) dry years and nineteen (19) hotter years occurred in the 40 years of rainfall amount and temperature records, respectively.

- iv. thirty-nine percent (39%) of total dry years and 32% of the hotter years for the period of study occurred between 2006 and 2015, indicating that the Osun drainage basin is becoming drier in recent years.
- v. water budget analysis indicates that rainfall amount received in Osun drainage basin were lost through evapotranspiration (43%), surface runoff (21%) and interception (9%).
- vi. about 27% of the total annual rainfall amount recharge the groundwater system in the basin.
- vii. rainfall is the dominant climatic variable influencing recharge in Osun drainage basin because rainfall contributed 94.90% variability in groundwater recharge in the basin.
- viii. the month with highest groundwater recharge rate is September and it ranges between 0-72.95mm in the north and 129.39-212.74mm in the south.
- ix. there was about 234% increase in built-up areas and 89.22% in crops/shrubs LULC in the Osun drainage basin between 1984 and 2015.
- x. the most significant decrease in LULC classes occurred in forest (58.75%) and wetland (84.69%) between 1984 and 2015.
- xi. change in LULC account for only 10% reduction in mean groundwater recharge occurrence between 1984 and 2015.
- xii. highest groundwater recharge of 48.56%, 33.64% and 37.29% occurred in forested area in 1984, 2000 and 2015, respectively.
- xiii. reasonable groundwater recharge amount of between 68.19 to 86.61mm/month were found in most of the built-up areas during the wet months, which suggests that the ratio of bare land to impervious surface is high in built up areas of the basin.

- xiv. low groundwater recharge is dominant in the northern part of the basin, except in the north-eastern part especially in the settlements of Oke Imesi, Efon Alaye, Igbajo, Iwaraja, Ijebujesa and Ijeda located on the uplands that have high recharge rate which can be attributed to the effect of orographic rainfall dominant in the area.
- xv. the predicted future LULC change shows that about 33%, 33%, 17% and 12% of the basin will be bare surface, crops/shrubs, built-up and forest area, respectively by the year 2046.

8.2 Conclusion

Rainfall and temperature that are the two major climatic driver are decreasing and increasing, respectively in Osun drainage basin. The fluctuating trends in rainfall amount and temperature are possibly related to climate change. The declining trend in rainfall amount though not statistically significant, it nevertheless signifies uncertainty in the future direction of rainfall occurrence in the basin. The increasing temperature that is statistically significant, suggests that the basin may become hotter in the future. Thirty-nine percent (39%) of total dry episode and 32% of the hotter years for the period under study occurred between 2006 and 2015, indicating that the Osun drainage basin is becoming drier. In other words, rainfall and temperature anomalies observed over the period of investigation is a pointer to the fact that Osun drainage basin is becoming drier in the last 10 years. Meanwhile, the inverse relationship between rainfall amount and temperature observed in the Osun drainage basin that is becoming drier, may have adverse consequence on groundwater resources of the basin. This might eventually lead to a significant decline in groundwater availability in the foreseeable future.

The LULC change in the basin revealed that built-up area increased by about 235% between 1984 to 2015. Forest area declined by 59% and crops/shrubs increased with about 89%, during

the same period. The rate of change of LULC was attributed to population increase and settlement expansion with their accompanying anthropogenic activities which include fuel wood extraction, wood logging, and sand mining, etc. All these anthropogenic activities resulted into the loss of the original rainforest in the basin. In fact, the predicted future LULC change suggests that only about 12% of the basin will remain under forest cover by the year 2046. The Sudano-sahelian zone is advancing south ward as a consequence of climate change, which has aggravated the effect of anthropogenic activities on LULC change in the basin.

The study revealed that actual evapotranspiration is the largest (43%) water budget component, followed by groundwater recharge (27%) in Osun drainage basin. September is the month with highest recharge occurrence in the basin, which is also the month with the highest rainfall amount. Unlike the popular view obtainable in the developed countries, that increase in built-up area significantly reduced infiltration, percolation and groundwater recharge, a reasonable amount of groundwater recharge was found in most of the built-up areas in the basin. This suggests that there are more bare surfaces within the settlements in the basin that allows infiltration and percolation of rainwater into the groundwater system, unlike in most of the developed countries where there are extensive paved surfaces. The groundwater resources of the basin might be vulnerable to contamination especially in areas with high recharge in built-up areas and crops/shrubs LULC types. 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 recharge process. Also, there might be salt water intrusion from the Atlantic Ocean into the groundwater system in the southern part of the basin on the sedimentary rock where highest recharge rate occurred in most of the months.

The effect of climate on groundwater recharge shows that rainfall amount is the most significant climatic variable influencing variability in groundwater recharge in Osun drainage basin. Thus, high recharge amount was found in areas with high rainfall amount. About 10% decline in groundwater recharge was discovered from the sensitivity analysis of LULC change between 1984 and 2015. The observed percentage decline in recharge as a consequence of LULC change, coupled with decreasing rainfall and increasing temperature is an indicator of the likely future water crisis in the basin. The continued deforestation of the forested area under which higher percentage of groundwater recharge occurred will not only pose a significant threat to groundwater reserve, but also to streamflow maintenance during dry months and the ecosystem of the basin if it remains unabated. Although the change in overall recharge as a consequent of LULC change is about 10%, the role of LULC on recharge cannot be ignored. Thus, a proper land use allocation and change strategy in sustainable management of groundwater resources becomes paramount.

Finally, the present study succeeded in estimating the spatio-temporal pattern of groundwater recharge in Osun drainage basin, on a monthly time scale, unlike previous studies that used annual recharge estimation; and lumped Ogun and Osun basins together as a unit of investigation. This is very important in a basin where the aquifer depends on present day recharge. The monthly time scale study such as this becomes a useful technique of monitoring groundwater recharge in the area and places with similar characteristics. Thus, the monthly spatio-temporal status of the groundwater recharge in Osun drainage basin should be taken into consideration in preparing sustainable groundwater resources management plan for the basin.

8.3 Recommendations

Based on the findings of this study, a number of recommendation are made. These include:

- i. The monthly groundwater withdrawal should be regulated by Ogun-Osun River Basin Development Authority and relevant agencies such that it will not be more than the mean monthly recharge over time and space. This is because groundwater sustainability can only be achieved when the amount of groundwater withdrawal is lower than the natural recharge on a small-time scale.
- ii. Efforts should be geared towards improving 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.
- iii. Issuance of groundwater right should become imperative to discourage proliferation of groundwater development especially in areas of low recharge.
- iv. afforestation in terms of planting of native trees that were lost through anthropogenic activities in the basin should be policy option for groundwater sustainability, because highest groundwater recharge occurred in forested area.
- v. the adoption of artificial recharge in form of low cost tube recharge to store rainfall that might runoff during the period of high rainfall. This will substantially improve the groundwater supply in dry months and a likely future groundwater crisis situation.
- vi. dedicated drainage basin observatories should be installed to enhance detailed monitoring of the physical processes by which groundwater recharge occurs in the basin for prompt decision making.

8.4 Areas for Further Investigation

This study examined the effect of climate and land use/land cover change on groundwater recharge in Osun drainage basin. This has enabled us to identify the most significant climatic

parameter that influences groundwater recharge and also isolate the effect LULC change on groundwater recharge. However, it has not been possible to:

- i. identify the spatio-temporal pattern of groundwater quality in the basin using remote sensing and GIS,
- ii. mapping aquifer vulnerability in Osun drainage basin for sustainable groundwater development, allocation and use, and
- iii. examine the impact of future climate change using global climate change models and future LULC change on groundwater quality and recharge in Osun drainage basin.

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