Mapping spatial and temporal distribution of Groundwater Recharge in Basement Complex region of Nigeria using remote sensing and GIS approach: A case study of south-eastern part of GSN Sheet 50 (Ilorin)

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Abstract

Evaluation of groundwater recharge is necessary to assist in meeting the groundwater increasing demands for various needs of communities located on the Basement Complex region of Nigeria. This region is characterized by thin overburden (3–25 m), making structural features such as lineament important factor in hydrogeological exploration. Potential recharge and zones of good recharge were mapped using satellite imageries (ASTER GDEM, Landsat ETM+ and TRMM) and Ancillary data (Lithology, drainage, weather data and lineament Map) to derive Evapotranspiration, Land use Classification, and Precipitation, Drainage Density, Slope and Lineament density Maps. Precipitation data (TRMM data) for February and September, which are the driest and wettest months, were used. The spatial Evapotranspiration, estimated using SEBAL, ranged from 0–2 mm/month for February and 5–26.5 mm/month for September. Recharge was estimated using water balance model in which Surface Runoff (calculated using the SCS-CN model) and Actual Evapotranspiration were subtracted from Precipitation. Spatial Groundwater Recharge from remote sensing ranged from 15 mm/month to 40 mm/month during dry season and 63 mm/month to 110 mm/month during wet Season.

Keywords: Groundwater Recharge, TRMM, SEBAL, Evapotranspiration and Runoff.

1. INTRODUCTION

In Sub-Saharan Africa, many people rely on groundwater for domestic, municipal, industrial, and agricultural uses. There is therefore the urgent need for improvement in exploration of groundwater sources for sustainable water supply for the growing urban, semi-urban and rural population needs. A large area of the developing world is underlain by Basement Complex rocks in which groundwater occurs mainly in fractured zones, with and or without saturated weathered zones (Olorunfemi and Olorunniwo, 1985; Olorunfemi, 1990; Olorunfemi and Okhue, 1992). Probably the greatest challenge posed by the hydrogeology of tropical Africa is to obtain reliable estimates of the groundwater resources in the regoliths. The recharge into the weathered aquifer is predominantly through infiltration of rainwater (Adelana *et al.,* 2005).

This paper aims to estimate the recharge of water into subsurface of Oyun and Asa River Catchment area using remote sensing and Geographic Information System approach. The model employed Precipitation data, Evapotranspiration, Slope, drainage density, Land use Classification, Lithology and Lineaments to estimate zones of potential groundwater recharge.

Study Area

The study area lies between longitude $4^0$00'E and $4^0$45'E and latitudes $8^0$00'N and $8^0$50'N covers two river catchment areas; the Asa Catchment area and the Oyun Catchment area. The drainage density of the study area is high; a dendritic drainage patter is predominant. Although the confluence area of the two rivers appears to be at right angle, several portions of the streams and rivers are rectilinear. The highest part of the area is found in the southeast of the study area while the northern parts are generally low with height of 250-550 m. The study area has been demarcated and studied for sundry purposes such as township water supply scheme, water resources assessment, geological mapping, agriculture and rural development, national water resources inventory and water resources master planning (KSWC, 1973; LNBDA, 1981; Oyegun, 1983; Oluyide *et al.*, 1998; JICA, 1993 and JICA, 2014). It is one of the 9 identified as priory for Water Resources development in Nigeria. Spatially continuous recharge maps such as those derived from Geographical Information System (GIS)-based water balance models, are gaining in accuracy and detail.

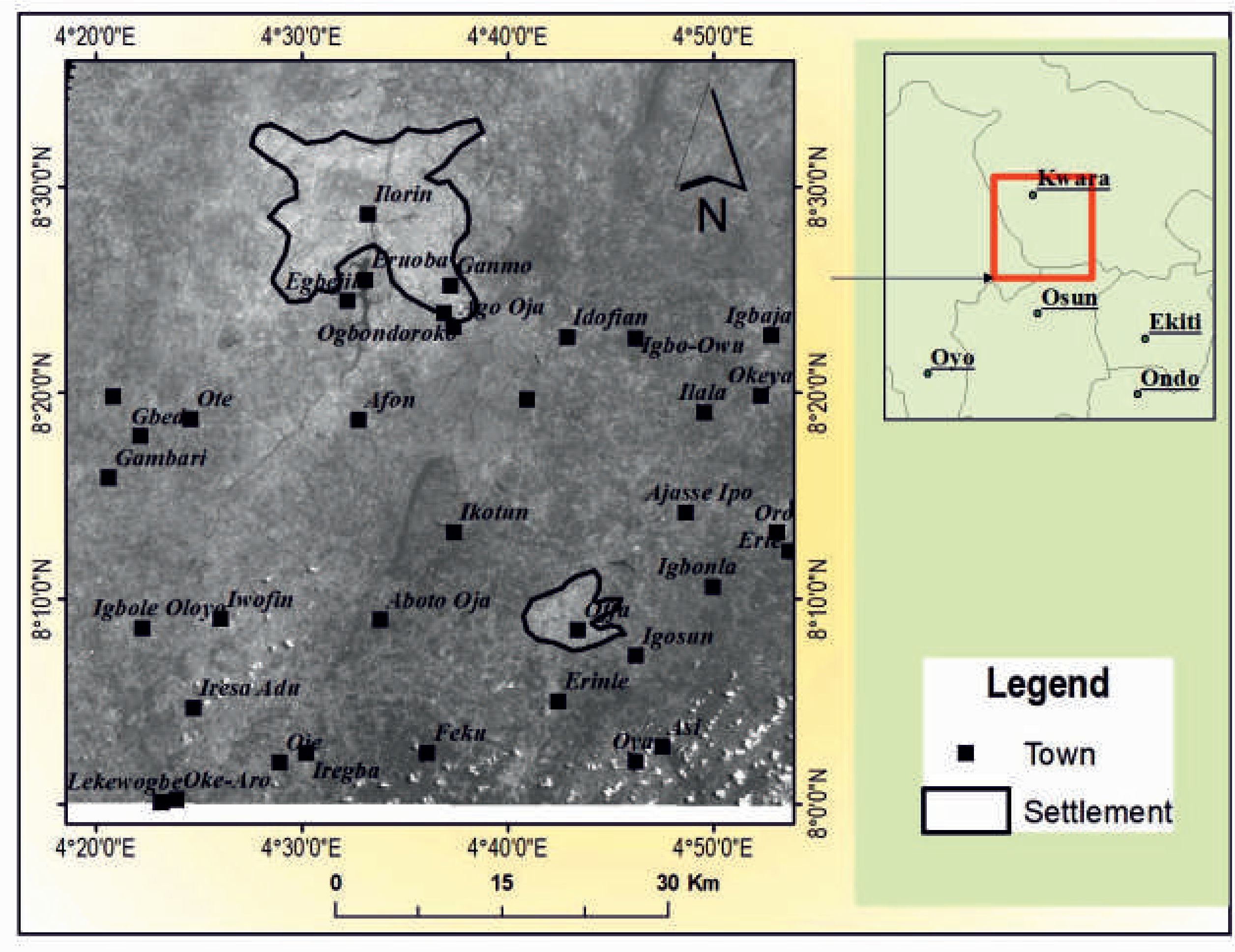


Figure 1: Landsat Imagery of the study Area

2. METHODS AND METHODS

Table 1: Data source, resolution and date acquired for the study

Data Acquired	Description	Source	Resolution	Date Acquired
Landsat	Landsat 7ETM+ (used for Evapotranspiration and Land use Classification)	Global Landcover Facility Glovis data centre		2000 2006 2009 2015
TRMM data	Tropical rainfall measuring mission Precipitation rate data (3B42RT V7)	Giovanni Earth data	0.25^0X0.25^0 Omnibus	February and September of the selected years.
ASTER GDEM		GLOVIS	1^0X1^0	2011

Lithology

The lithology of the study area was determined by digitizing south-eastern part of GSN Ilorin Sheet of 1:250,000 scale (Oluyide *et al.,* 1998) using the ArcGis 10.1 software.

The weightage assigned to the lithologies within the study is shown on table 3. Quartzite, Schists and Biotite gneisses were favoured in the weightage (Fashae *et al*., 2014; Williams *et al*., 2005; UNESCO, 1982)

Drainage Density

Drainage was digitized from three maps; Ogbomoso Sheet 222 SE (1:50,000), Ilorin Topographic Sheet (1 : 100,000) and GSN Ilorin Sheet (1:250,000); and Advanced Space borne thermal emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM). The drainage density is derived through the line density of the Spatial Analyst toolbox. The drainage density is calculated using the formula given below:

$$\mathrm{D_d(km^{-1})} = \frac{\text{length of drainage (km)}}{\text{Area Extent (km}^2\text{)}} \qquad 1$$

Lineament density

Secondary porosity and permeability imposed on hard rocks by fracturing, fissuring and jointing on weathering through which water percolates, makes it favourable for groundwater storage (Omorinbola, 1979; Oluyide *et al*., 1998; Magowe and Carr, 1999; Alao, 2000; Adelana and Olasehinde, 2004; Garba, 1999; Adagunodo *et al*., 2013).

Lineament was digitized from ancillary data (Oluyide *et al*., 1998; Garba, 1999). Also, the line density sub-tool of the spatial analyst toolbox was used to generate the lineament density using the formula,

$$L_d(km^{-1}) = \frac{length\ of\ Lineament\ (km)}{Area\ Extent\ (km^2)} \qquad 2$$

Lineament density of an area indirectly reveals the potential of that area since the presence of lineaments usually denotes a permeable zone (Hammouri *et al*., 2012; Fenta *et al*., 2015). The length of the lineaments ranges from 160 m to 4371 m.

Slope

The Slope map was created from ASTER GDEM using the Hydrology tool box of the Spatial Analyst tool box of the ArcGIS 10.1 software.

Precipitation

The precipitation map was prepared using 3-hourly Precipitation data collected by the Tropical Rainfall Measuring Mission (TRMM) with resolution of 0.25^0X0.25^0 (more about TRMM is given on table 1). The data were downloaded in grids and interpolated using the Inverse Distance Weighted tool of ArcGIS 10.1 software.

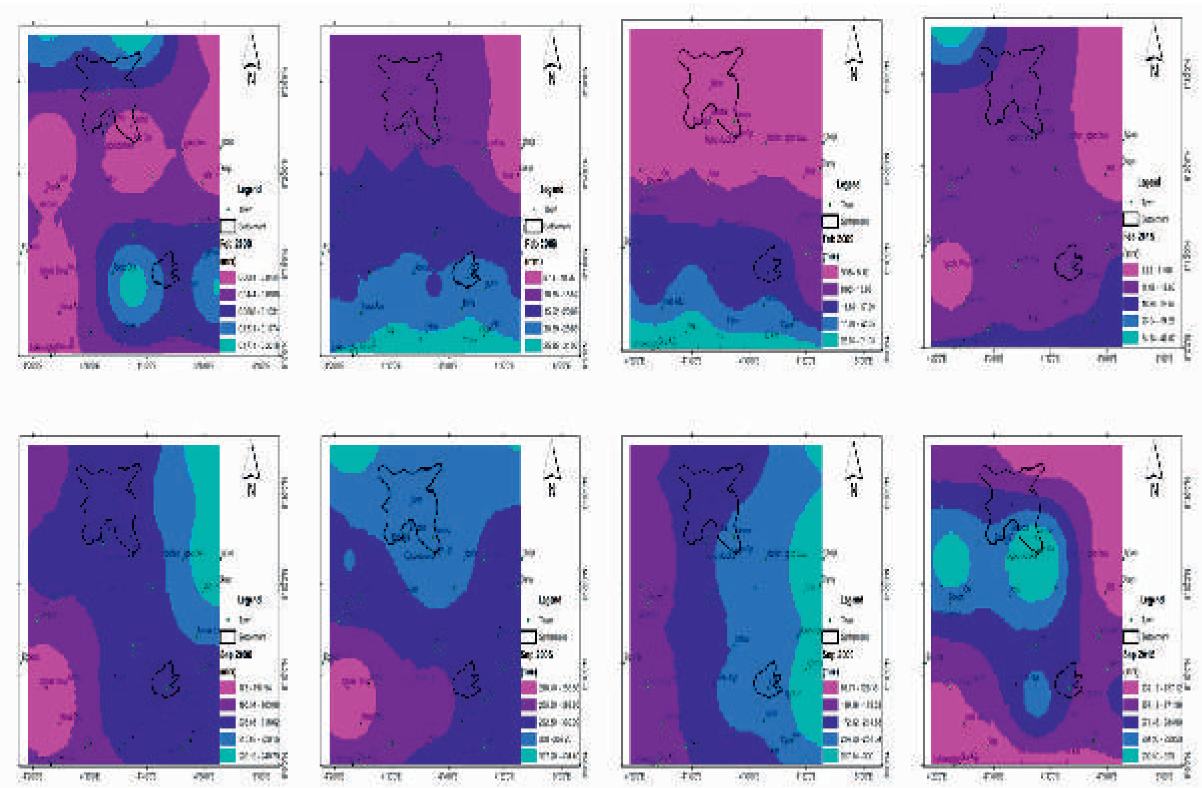


Figure 2. Precipitations of the wettest and driest Months of the selected years

The satellite derived data was compared with the ground rainfall data using t-test test to test the difference in the mean of the satellite-derived dataset and the ground rainfall dataset. To ensure this, Ilorin Township was used by comparing the ground rainfall data and the satellite-derived data. The ground rainfall dataset were collected from Lower Niger Basin Development Authority. The test failed to reject that there is significant difference between the two compared data set. It is seen from the table below that the critical value of t for two tail test (at confidence level of 95%) is ±2.228 and t stat value of -0.47791 falls within the t critical value range. This implies that there is no significant difference between the satellite-derived rainfall and the ground dataset.

Table 2: Statistical Comparison of Satellite derived rainfall and Ground rainfall

	Variable 1	*Variable 2*
Mean	91.78767	123.45
Variance	8095.982	18239.56
Pooled Variance	13167.77	
t Stat	-0.47791	
t Critical two-tail	2.228139	

Table 3: Satellite derived and ground rainfall dataset of Ilorin

Date	Satellite (mm)	Ground (mm)
Feb-00	0.006	0
Sep-00	171	281.7
Feb-06	19.35	10
Sep-06	195.9	262.1
Feb-09	13.27	1.2
Sep-09	151.2	185.7

Land Use Classification

Land is the foundation of all forms of human activity such as Agricultural activities, settlements and housing/construction (Briassoulis, 2000). Land use and land cover changes are one of the main human induced activities altering the groundwater system (Calder, 1992).

Landsat ETM+ imageries were processed using ILWIS 3.3.1 (Academics) image processing software. True Colour Composite using bands 3, 2, and 1 for Red, Green and Blue (RGB) composite was used in the supervised classification of the imageries into four land use classes which includes bare land, vegetation cover, water bodies and settlement.

Table 4: Area Extent (in km^2) covered by the Land Use Classes

	Landuse	2000	2006	2009	2015
1	Bare land	1863	1775	2329	2411
2	Settlement	144	276	213	432
3	Vegetation Cover	2425	1684	1994	1812
4	Water bodies	11	354	61	75

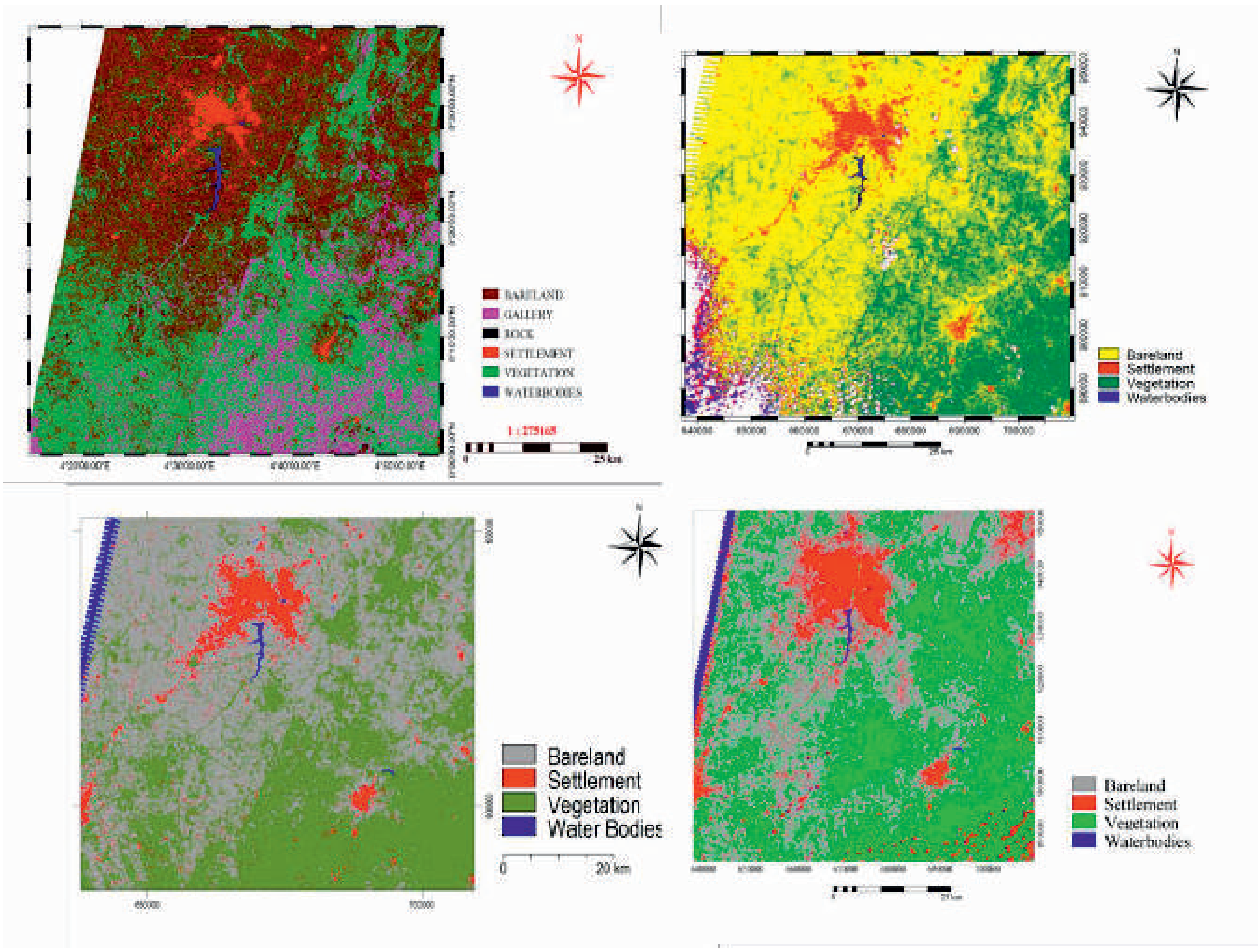


Figure 3: Land use Classification of the study area

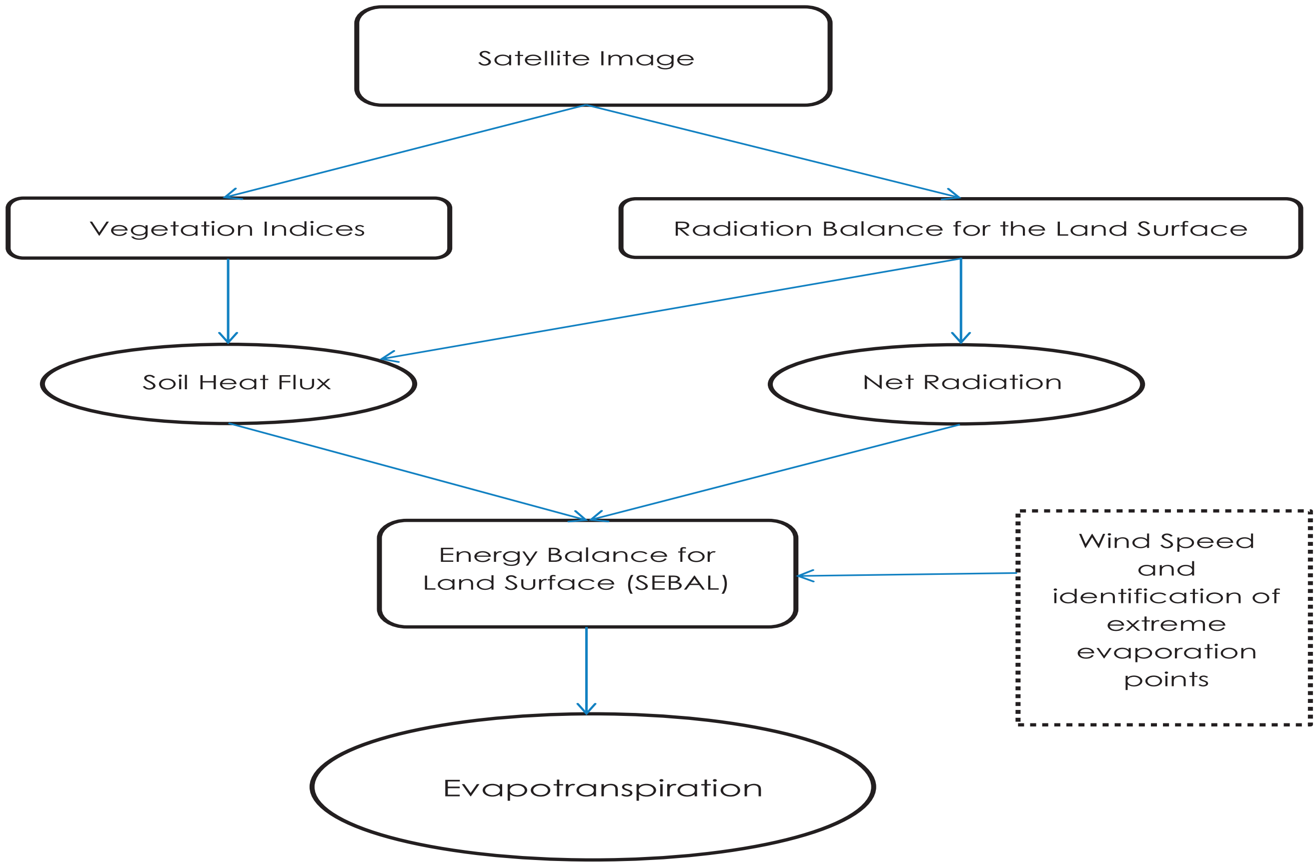
Evapotranspiration

Evapotranspiration was calculated spatially using the Surface Energy Balance Algorithm for Land (SEBAL) model was introduced by Wim Bastiaanssen (Bastiaanssen *et al.*, 1998a). SEBAL is an image processing model comprised of 25 computational steps that calculate Evapotranspiration. It computes radiation and energy balance along with the resistances for Momentum, heat and water vapour transport for every individual pixel.

The resistances are function of state conditions such as Soil water potential, wind speed and air temperature and change from day-to-day (Mekonnen, 2005).

$$\lambda ET = Rn - G - H$$

Where λET is the Latent heat flux (W/m^2); R_n is Net Radiation flux at the surface (W/m^2); G is Soil heat flux (W/m^2) and; H is the Sensible heat flux to the air (W/m^2).



A. Net radiation flux at the surface (R_n) is the actual radiant energy available at a surface. It is however, computed by subtracting all outgoing radiant fluxes from all incoming fluxes.

Net surface radiation = gains – losses

$$Rn = (1-\alpha)Rs\downarrow + Rl\downarrow - Rl\uparrow - (1-\varepsilon 0)Rl\downarrow \quad ...3$$

Where Rs↓ is the Incoming shortwave radiation (W/m^2)))) is the Surface Albedo (dimensionless) Rl↑ is the Outgoing longwave radiation (W/m^2) and ε0 is the Surface thermal emissivity (dimensionless).

B. Sensible Heat Flux (H)

Sensible heat flux is estimated from surface temperature, surface roughness and measured wind speed.

$$H = \frac{\rho_a C_p \Delta T}{r_{ah}} \quad 4$$

Where ρa is the density of air (kgm-3), Cp is air specific heat (1004JKg-1.K-1), ΔT is the difference between surface and air temperature (K) and rah is the aerodynamic resistance for heat transport (sm-1)

C. Soil Heat Flux (Go)

Soil Heat Flux can be calculated using the formula below

$$Go\ is\ the \left(\frac{Ts}{\alpha}\right).(0.0038\alpha + 0.0074\alpha^2).(1 - 0.98NDVI^4).Rn \qquad ...5$$

Where Ts is the surface temperature (K); Rn is the net Radiation; is the surface Albedo; and NDVI is the normalised Difference Vegetation Index.

Recharge Estimation

Recharge was estimated using the water balance equation:

$$GWR = P - EVP - R \qquad ...6$$

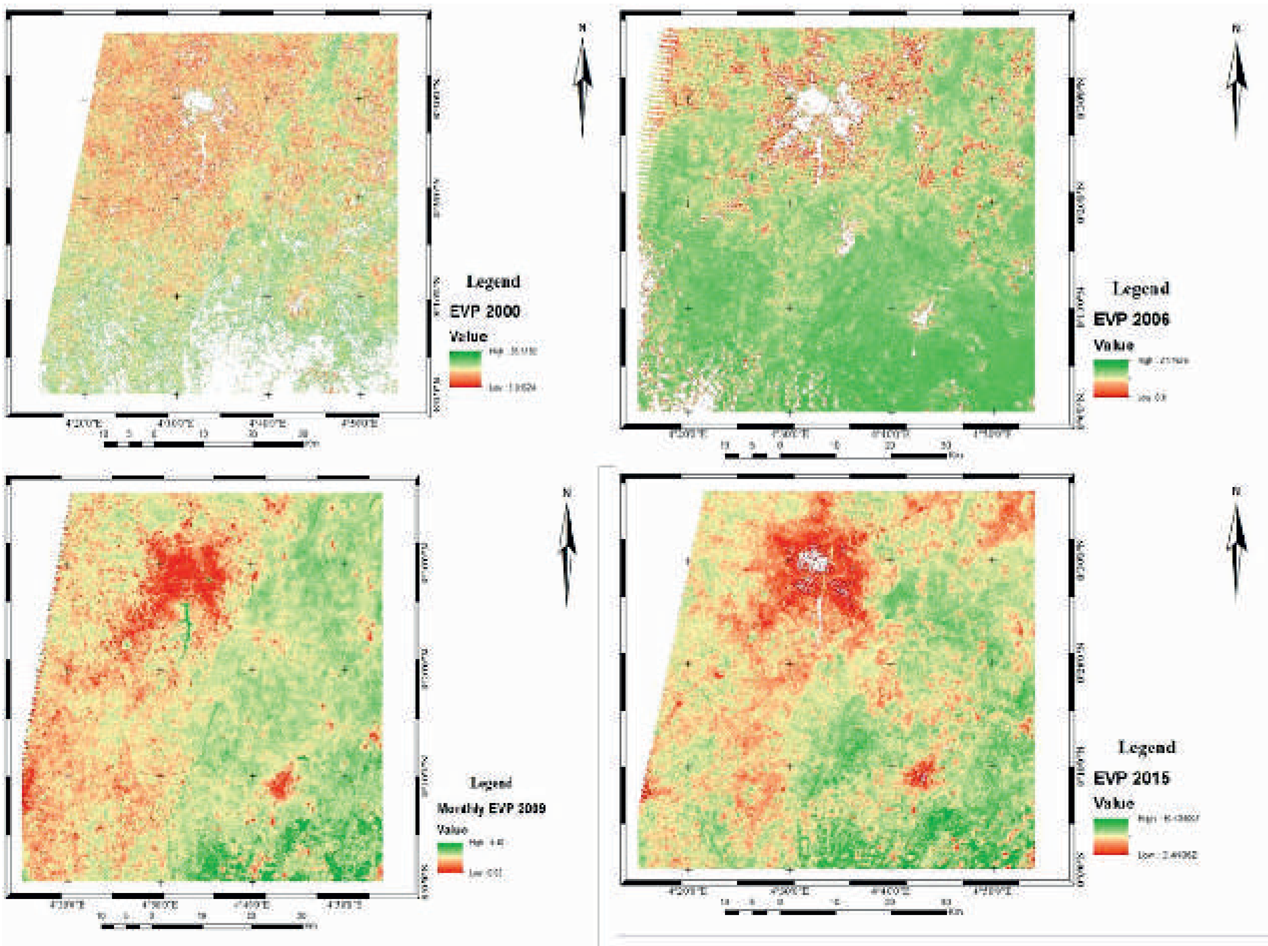


Figure 5: Spatial Evapotranspiration Maps of the selected years

Run-off

Run-off was calculated using the soil conservation services (SCS-CN) model. Based on this model, precipitation and Runoff curve number (CN), which is based on Soil type and land use type, were used. A CN value of 70 was used for the study area based on previous work by Sule *et al.*, (2011).

Table 5: Determination of infiltration index and the rate of contribution factors on potential recharge

	Factor	Class Description	R	W	Infiltration Index	%
1	Slope	$0^0 – 18^0$	9	3	27	21
		$18^0 – 36^0$	8		24	
		$36^0 – 54^0$	5		15	
		$54^0 – 72^0$	2		6	
		$72^0 – 90^0$	1		3	
2	Lineament Density (Km^{-1})	0 – 31.72	5	1	5	10
		31.72 – 63.44	6		6	
		63.44 – 95.16	7		7	
		95.16 – 126.88	8		8	
		126.88 – 158.61	9		9	
3	Drainage Density (km^{-1})	0 – 29.5	5	1	5	10
		29.5 – 59	6		6	
		59 – 88.5	7		7	
		88.5 – 118	8		8	
		118 – 147.5	9		9	
4	Rainfall		1	5	5	22
			2		10	
			3		15	
			4		20	
			5		25	
5	LULC	Bareland	7	2	14	10
		Settlement	3		6	
		Vegetation	8		16	
		Waterbodies	9		18	
6	Evapotranspiration		1	3	3	16
			2		6	
			3		9	
			6		18	
7	Geology/Lithology	Porphyroblastic Gneiss	5	1	5	11
		Pegmatite	5		5	
		Quartzite	9			
		Granite Gneiss	4		4	
		Biotite-Hornblende Gneiss	4		4	
		Amphibolite Schist	6		6	
		Migmatite	4			

General Discussions

Within the study area, recharge varies with precipitation as precipitation determines the rate of recharge. Recharge in the study area is divided into three zones; Good Recharge zone, moderate/intermediate recharge zone and poor recharge zones. Areas with good recharge, both in the dry and wet seasons, include Sapati Oko, Ira, Gaa Akanbi and Igosun. Previous studies on boreholes drilled in areas around Ira have yield between 1.9 ltr/s and 3.00 ltr/s but such boreholes are structure related which is revealed by high conductivity anomaly in such areas (Olayinka, 1990). Also, boreholes drilled in Gaa Akanbi and Sapati Oko gave yields of 2.0 ltr/s and 1.2 ltr/s respectively (KSWC, 1973).

Built up areas in the study area generally have fair to poor recharge rates as shown in the recharge maps. This accounts for the poor recharge rates in Ilorin and Offa as most people living in these cities depend on Kwara State Water Corporation for water supply and people in rural communities seek out for ponds, Streams and Rivers (Mohammed, 2016). Boreholes within Ilorin have yields ranging from 0.3 ltr/s in poor boreholes to 2.75 ltr/s in productive ones while boreholes in Offa have yields between 1.33 ltr/s and 3.00 ltr/s.

The rate of recharge is dependent on precipitation; the lower the precipitation, the lower the recharge rate while the higher the precipitation, the higher the recharge rate. The recharge rate is also dependent on the general slope of the area. The area has a steep slope as shown on the slope map of the study area (Steep angle >70^0).

$$Recharge\ zone = 0.21SLP + 0.1LIN + 0.1DD + 0.22RF + 0.1LLC + 0.16EVP + 0.11LTH \quad (7)$$

Where SLP is the Slope; LIN is the lineament density; DD is the Drainage density; RF is the Rainfall, LLC is the Landuse classification and LTH is the Lithology.

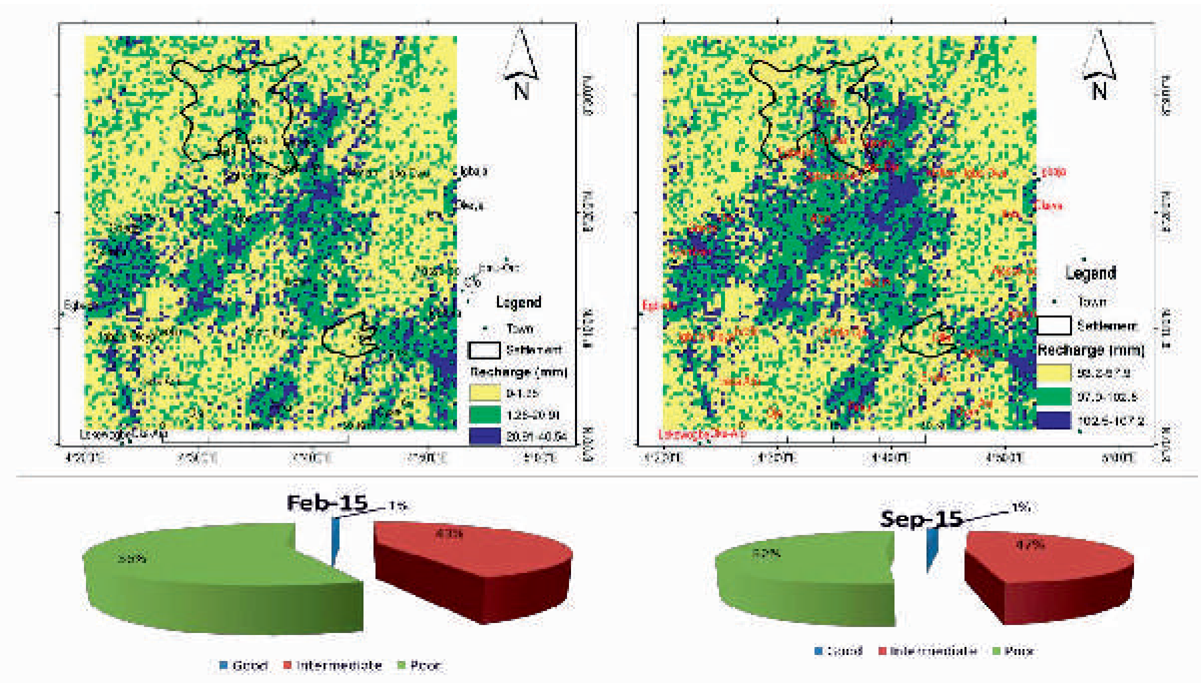


Figure 6: Recharge for February and September 2015

CONCLUSION

Recharge is affected by a number of factors like precipitation, Surface runoff, land use classification, Lineaments, Drainage and Lithology. Precipitation plays a leading role as it accounts for the water which will be recharged into the soil. Lineaments however, plays vital role as secondary porosity in Basement Complex environments. Water likes to flow in direction of weakness, drainage network within the study area are structurally controlled.

The overall result points out that those cities within the study area, like Ilorin and Offa, have low recharge rates which can be accounted for by the effects of urbanisation within the cities coupled with low precipitation. Also, the differences in recharge rates may be related in part to differences in soil drainage within the studied area.

RECOMMENDATIONS

In view of the popularity in resorting to groundwater usage, groundwater age or residence time methods should be applied to compliment spatially derived studies as techniques to evaluate groundwater sustainability and susceptibility. As irrigation agriculture such as Amodu Asumgbo scheme in Ifelodun Local Government area in Oyun River, system are being installed to complement a precipitation-dominated agricultural settings, more serious attention should be paid to recharge studies of downstream fractured crystalline aquifers. Moreso, empirical estimates or spatial and temporal recharge studies are even yet to be integrated into local-scale recharge variations associated with sediment texture, topography, vegetation, land use, and other factors. With increase in indiscriminate drilling of boreholes, it is recommended that proper groundwater management practice and government be encouraged to regulate exploitation of groundwater in the area studied.

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