Available online at www.elixirpublishers.com (Elixir International Journal)

Geography

Elixir Geography 116 (2018) 50000-50005

ISSN: 2229-712X

Evaluating the Water Balance of Sokoto Basement Complex to Address Water Security Challenges

Murtala Abubakar Gada and Aliyu T. Umar
Department of Geography,Usmanu Danfodiyo University, Sokoto.

ARTICLE INFO

Article history:
Received: 21 January 2018;
Received in revised form:
24 February 2018;
Accepted: 5 March 2018;

Keywords
Hydrological processes,
Sustainable water resource Management,
Basement complex.

ABSTRACT

A substantial part of Nigeria is part of semi-arid areas of the world, underlain by basement complex (hard) rocks which are very poor in both transmission and storage of appreciable quantity of water. Recently, a growing attention is being paid on the need to develop water resources in these areas largely due to concerns about increasing droughts and the need to maintain water security challenges. While there is ample body of knowledge that captures the hydrological behaviours of the sedimentary part, reported research which unambiguously illustrates water distribution in the basement complex of the Sokoto basin remains sparse. Considering the growing need to meet the water requirements of those living in this region necessitated the call for accurate water balance estimations that can inform a sustainable planning and development to address water security challenges for the area. To meet this task, a one-dimensional soil water balance model was developed and utilised to assess the state of water distribution within the Sokoto basin basement complex using measured meteorological variables and information about different landscapes within the complex. The model simulated the soil water storage and rates of input and output of water in response to climate and irrigation where applicable using data from 2001 to 2010 inclusive. The results revealed areas within the Sokoto basin basement complex that are rich and deficient in groundwater resource. The high potential areas identified includes the fadama, the fractured rocks and the cultivated lands, while the low potential areas are the sealed surfaces and non-fractured rocks. This study concludes that the modelling approach is a useful tool for assessing the hydrological behaviour and for better understanding the water resource availability within a basement complex.

1.0. Introduction

Appropriate decision making is vital to ensure a secured water resource management. This is even so when water resource is limited or if there is high spatio-temporal variability of the resource in an area. More than one third of the global population are still living in areas with water scarcity despite the target set by the United Nation Millennium Development Goals (UNMDG's) to reduce the proportion by halve before the year 2015 especially in Sub-Saharan Africa which accounts for about ¾ of the number. The problem became more pronounced in Africa because of the slowest and poorest technological advancement, low income and institutional capacity to mitigate the problem (MacDonald, 2005, Kevin and Nicholas, 2010).

Northern Nigeria falls within the prescribed region in the sub-Sahara Africa, an area prone to extreme aridity and drought condition. The area is characterized by short rainy season and small seasonal rivers and streams (Austine, 2001, Ayoade and Bamwo, 2007). Despite the additional vast groundwater reserve and some natural water bodies like lakes, ponds and lagoons in the coastal areas, the incidence and amplitude of water security challenges continue to rise in the region. The growing population and the recent droughts occurrence attributed to climate change (Paul *et al.*, 2008, Friedrich *et al.*, 2008) leads to further variable changes and uncertainty putting the available water resources under pressure and calling for new approaches for water security, development, planning and management (Parry *et al.*, 2007, WaterAid, 2007). Understanding the hydrological processes in Sokoto basin as it relates water movement over time will no doubt improve the understanding of the presence and availability of water over time which in turn would help the decision makers in planning and execution of water development projects to ensure security especially to rural areas where the scarcity is more severe.

The major sources through which people obtain water in Sokoto basin are surface sources such as rainfall, rivers and lakes and the ground sources. These sources of water are not always available at both the right place and time, nor are they always well managed. Surface sources such as rivers, streams and lakes have always been easier to harness, extract and utilized, but are also vulnerable to contamination and are most often subjected to dwindling as a result of evaporation, careless extraction and misuse (Kevin and Nicholas, 2010). Groundwater is relatively safe source of water supply but requires a lot of efforts and investment to harness and extract.

Tele: +2348036027104
E-mail address: murtala.abubakar@udusok.edu.ng

With a huge reserve of about 97 % of liquid fresh water, groundwater appears to be more promising in terms of sustainability in the basin.

This paper is aimed at improving the understanding of the hydrological processes in the basement complex areas of Sokoto Basin to address water security challenges.

2.0. The Study area

The study area is part of the basement complex area of the Sokoto basin located in the north-western part of Nigeria (Figure 1) between the latitudes 11° 30" and 12° 00" N and longitudes 4° and 7° E. The region forms the major river basin of the riverine lowlands of the Rima valley. The area forms the catchment of the river Ka (also known as *Gulbin Ka*) at the southern end of the basement complex (Figure 1). The river originates from the basement highlands around Dansadau in Zamfara State, it runs some 250 kilometers west into Kebbi State before joining the Sokoto River and shortly afterwards, join the Niger River. The general elevation ranges between 190 m above sea level in the lowland *fadama* floodplains which range between 0.3 – 2 km in width along the river and its tributaries to 450 m above sea level at the upper lands around Gusau and Dansadau. The catchment area above Fokku gauge was given as 15000 km^2 (Anderson and Ogilbee, 1973, JICA, 1990).

The climate of the area is tropical continental dominated by two opposing air masses; the tropical maritime and tropical continental air masses. The position of their convergence is called the inter-tropical discontinuity (ITD) and largely determines the onset and cessation of rainfall at a particular time of the year (Bello, 1997). The tropical maritime air mass is moist and blows from the Atlantic, while the tropical continental air mass is dry and blows from the Sahara Desert. The onset of rainfall in the region is usually from April, but properly commences by June to September, while the dry season takes over from October to March. The average annual rainfall ranges from 500 mm around the northern boundary with Niger Republic to 1200 mm towards the southern edge of the basin (NIMET, 2012).

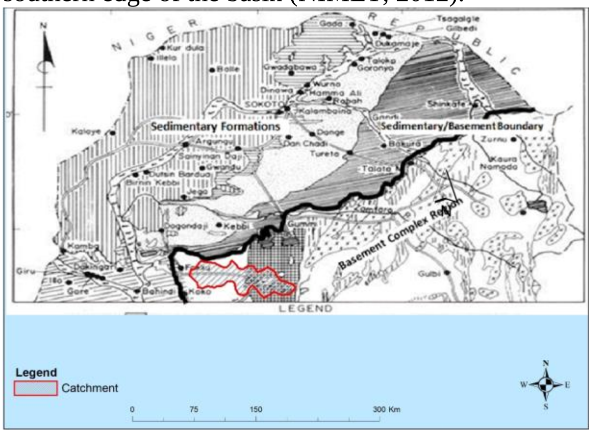

Figure 1. The study area showing the river Ka catchment boundary (Modified from Kogbe, 1989).

The highest temperatures occur towards the end of the dry season from March to April. The daily maximum and minimum temperatures similar to the precipitation vary from the northern part to the southern part of the basin (Ekpoh and Nsa, 2011). Temperatures range between a daily minimum temperature of 9 ^{o}C in the cold season (from early December to early February) to a daily maximum temperature of 45 ^{o}C from March to end of May. The low temperatures are associated with the Harmattan, a northeasterly dry and dusty West African trade wind which blows from the Sahara into the Gulf of Guinea from November to February.

The geology of the study area has been described by Obaje *et al*. (2013), Kogbe (1989), Anderson and Ogilbee (1973), and Offodile (2002). Basement rocks dominate about 50 % of Nigeria's surface area while Cretaceous and Cenozoic sediments cover the other 50% (Adelana, 2003). According to Eduvie (2006) Hazell *et al* (1988), and Anderson and Ogilbee (1973), the basement complex of Nigeria lies within the Pan-African terrain with four broad lithological units as follow:

- A polycyclic basement of migmatites and gneisses together with relics of ancient metasediments of schist, phyllite, and quartzite.
- Younger low to medium grade metasediments and metavolcanics, which form distinct NNE-SSW trend within the migmatite-gneiss complex.
- Syntectonic to late tectonic Older Granite suite which intruded both the migmatitegneiss and the metasediments.
- Unmetamorphosed alkaline, calc-alkaline volcanic and hypabbysal rocks, which overlie or intrude the basement and sedimentary rocks.

The depth of the weathered zone sometimes extends down to 50 m and the surfaces are often covered by laterites and Aeolian sands.

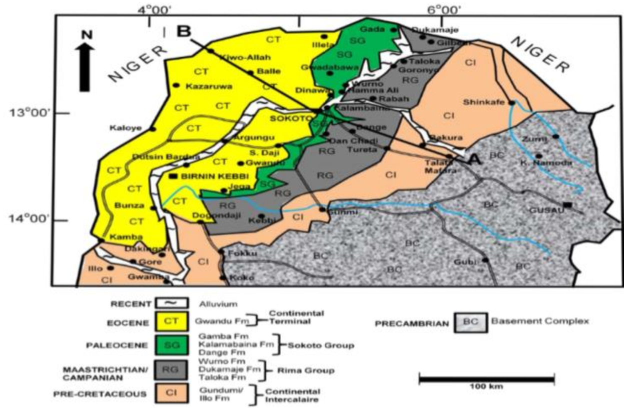

Figure 2. Geological map of the Sokoto Basin (source: Obaje et al., 2013).

The important hydrogeological studies within the study area was done by Anderson and Ogilbee (1973), Oteze (1979), Offodile (2002), Adelana et al. (2006) Ndubuisi (2007), SARDA / WADROP (1988), JICA (1990) and Graham et al. (2006). Groundwater in the crystalline rocks is generally available in small quantities and occurs within fractures and weathered rocks. The fractures are sometimes open up to a depth of 91 m, but even so, yields to boreholes are relatively low and cause high drawdowns. The availability of groundwater in the crystalline basement rocks depends on the development of thick soil overburden or the presence of fractures that are capable of holding water. The storage of groundwater is confined to fractures and fissures (JICA, 1990) in the weathered zone of igneous, metamorphic and volcanic rocks, the thickness of which range from <10-60 m in arid and humid rain forest (MacDonald et al., 1995, Chimphamba et al., 2009).

The soils within the catchment area fall within four major groups in the Harmonised World Soil Database (HWSD, 2012), Soil Atlas of Africa classifications (2013). The major soil classes identified are: Lithosols, Lixisols, Plinthosols and Gleysols.

The catchment falls within the Sudan Savannah zone with vegetation consisting of short grasses characterised by thorny species (Kaltho et al., 1997) and a scatter of acacia species which are interspersed with herbaceous cover of annual grasses. A comparative analysis of vegetation density towards the northern part of Zamfara state (which includes the drier part of the study area) between 1962 and 1991 (ARCA, 1995) shows that increasing human pressures on land such as expansion of cropland, livestock overgrazing and cutting of trees for firewood has resulted in the loss of about 71 - 85 % of the natural vegetation (Hassan, 2000; Kuppers, 1998; Schafer, 1998). Eyre (2013), states that the woody plant species are now more common on the steep and rocky slopes where cultivation doesn't take place than the surrounding level areas which are dominated by grass.

3.0. Materials and Methods

A summary of the data types used in this research and its sources are described below with a summary given in Table 1 .

Table 1. Description of data types for the paper.

Type of Data	Available Records		Nature of Data/ Source	Location
	From	To		
Rainfall & Temperature	1991	2010	Daily records / (NIMET)	Sokoto, Gusau and Yelwa
Borehole records	1983	1989	Well log, depth, water level and yield / (SARDA)	Old Sokoto state
DEM, GIS Map layers	2000 2010	2000 2010	Nigeria Digital Elevation Model (SRTM), GIS Layers (NGSA)	Nigeria
Soil Map	2012	2012	Soil map (HWSD)	Sokoto Basin (River Ka catchment)

The methodology employed for this research starts with the desk study (i.e. literature review, study area identification and mapping and initial conceptualization); fieldwork (reconnaissance survey and actual field work); conceptualisation (catchment classification and characterization) and model set up.

The fieldwork processes

Fieldwork was conducted in the three selected areas from 17th June – 30th August 2012. Visitation to the three sites was dependent on the timing of likely occurrence of rainfall within the fieldwork period. The fieldwork conducted involved measurement of water table depth in dug wells and boreholes; soil type and depth identification; observation of surface runoff processes (such as the origin, flow paths and destination) during and after rainfall; vegetation / crop types, cover and growth behaviour. Other aspects recorded included water sources and location in towns and surrounding environment, available streams, lakes or ponds and identification of hard rock types (broken or non-broken) and their runoff behaviour after rainfall.

Modelling

The data and information gathered from the fieldwork in addition to that from literature were used to model the individual conceptual models developed; to validate their behaviour against information given in literature and reports; and to aggregate all the information to the catchment scale. To achieve this, water balance modelling was carried out for the different conceptual landscapes developed after the fieldwork.

WaSim model was chosen because of its flexibility, data availability and demonstrated value as a research tool in hydrological studies (e.g. Fasinmirin et al. 2008; Holman et al. 2009; Hess et al. 2010). WaSim is a one-dimensional daily soil water balance model that simulates inputs (precipitation), outputs (actual evapotranspiration, surface runoff, potential recharge and drainage) and changes in soil water storage in response to weather (Hess & Counsell 2000). The soil is divided into up to five compartments (Fig. 3). Water moves from upper compartments to lower compartments when the soil layer exceeds field capacity and any water draining out of the lowest layer of a freely drained soil is taken as potential recharge. Surface runoff comprises the infiltration-excess runoff (estimated using the widely recognised SCS curve number method of Conservation Engineering Division 1986) and runoff because of saturated soil. Any precipitation that does not run off is assumed to infiltrate.

Actual evapotranspiration is taken as the area-weighted average of soil evaporation (estimated using the method of Ritchie 1972) and plant transpiration. Plant transpiration is assumed to occur at a rate proportional to the reference evapotranspiration (Allen et al.1998) depending on the plant type and soil water content. It occurs at the potential rate when the root zone soil water content is between field capacity and the limit of easily available water, and decreases linearly to zero at permanent wilting point under restricted water supply (Brisson 1998). For soil water contents above field capacity, it decreases linearly to zero when the root zone soil water content reaches saturation.

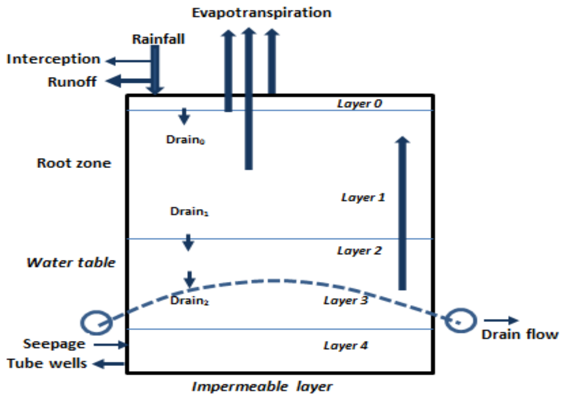

Figure 3. Water flow processes and distribution in WaSim (After Hess *et al.*, 2000).

Conceptualisation of HRUs as Landscape Units (LUs)

The river Ka catchment require a landscape to be subdivided into smaller areas or sub-units based on the heterogeneity which determines their hydrological responses (Arnold *et al.*, 1998). Many researchers (Eagleson, 1978; Farmer *et al.*, 2003; Triphathi *et al.*, 2006) believe that this is the best approach in assessing the hydrological behaviour of a catchment. There is no standard procedure for deciding the number of LUs subdivision to adopt. The approach therefore depends on the number of heterogeneous features identified and the hydrological response components you are trying to assess. In this research, six major LUs, some of which are further sub-divided, are identified within the catchment. The six major LUs are as follows:

- Towns landscape units
- Cultivated landscape units
- Sealed surface landscapes units
- Hard rock landscape units
- Forest landscape units
- Fadama landscape units

After identifying the different landscape units that are considered to behave in hydrologically distinctive ways, water balance modelling was carried out for each of the landscapes to better understand and quantify the importance of the different hydrological processes influencing the water balance.

4.0. Results and Discussion

The soil water balance simulations have been run for 10 years (2001-2010) to see the variations of landscapes hydrological behaviour under wet and dry conditions.

The runoff processes: In the overall water balance, the non-fractured rocks has largest runoff contribution equalling about 40 % of the runoff generated. The fadama has the second highest individual landscape contribution of runoff generated in the 10 year water balance having about 16 % of the total. Then followed by fractured rock landscapes with about 15 % of the total. This is not unexpected in view of the fact that the broken hard rocks occupy about 15 % of the total land area and a significant proportion of runoff from this landscape goes directly to the river.

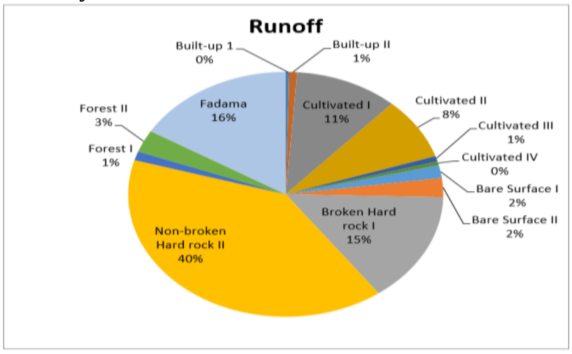

Figure 4. Percentage 10 year area weighted runoff contribution to the river from individual landscape unit.

Despite the large total runoff from the two sealed surface landscapes, their relatively small size (5 % of total land area) compared to other landscapes shows that their weighted runoff contributions to the overall catchment water balance is small (14 %) compared to for example, the four cultivated lands with total land area of 30 %, which together, contributes about 20 % runoff to the river.

The actual evapotranspiration (AET): The cultivated landscapes I - IV contribute the highest area-weighted AET in the catchment water balance as shown in Figure 6.0. The four landscapes together occupy about 30 % total land area of the catchment and contribute about 33 % of the total AET. The fadama has the second highest contribution equalling about 18 % of the total AET. Despite the large AET contribution from the fadama of about 18 % in the water balance, its relatively small land area (10 %) compared to cultivated lands I-IV makes its contribution smaller than the former.

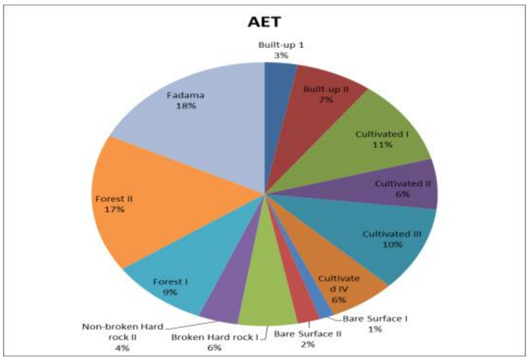

Figure 5. Percentage 37 year area weighted AET contribution from unit landscapes.

The built-up areas and hard rocks contributes similar amount of AET (10 % each) in the basin water balance despite the fact that hard rocks (broken and non-broken) occupy three times the land area (30 %) of the town landscapes (10 %). In hard rocks, the process is actual evaporation and not AET, and the dominant processes that take a larger proportion of the rainfall are surface runoff and fissure outflow. The sealed surfaces have the least AET in the total basin water balance, contributing only about 3 %. This is not unexpected because of the small land area and absence of vegetation on the surface.

Groundwater outflow: Figure 7.0 shows that the highest contribution is the fissure outflow from fractured hard rocks alone accounting for about 55 % of the 10 year groundwater outflow. The non-fractured rocks do not have any outflow contribution to the water balance because the rainfall is annexed to runoff and evaporation.

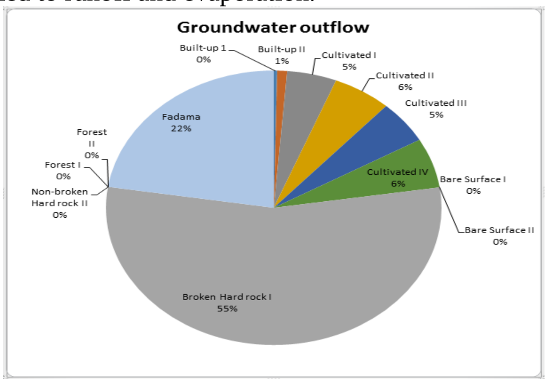

Figure 6. Percentage 37 year groundwater outflow contributions from individual unit landscapes.

The cultivated lands (I-IV) and fadama contribute similar groundwater outflow (22 % each). The fadama has a small land area (10 %) compared to 30 % for the cultivated lands, but because of the run-on received from other landscapes as described earlier, this results in a high amount of groundwater outflow. The town landscapes contributes small groundwater outflow (1 %) to the basin water balance because runoff and AET takes a larger proportion of the rainfall. The forest landscapes however, did not produce any groundwater outflow because the high AET utilizes much of the water on these landscapes. Groundwater outflow is not allowed in the model for the sealed bare surfaces due to the surface nature of the landscape.

5.0. Conclusion / Recommendation

This paper developed a conceptual understanding of the processes governing the hydrological and hydrogeological responses in the basement complex region. The processes are demonstrated to be more complex than what is perceived and represented in most literature. Six major landscape units were identified which have significantly different hydrological behaviour which controls the water balance of the basement complex catchment. They represent the towns, cultivated lands, sealed surfaces, hard rocks, forests and fadama landscapes. The paper also identify that the hydrological processes within the basement complex area are influenced by the spatial variability of key landscape features including the vegetation characteristics, soil properties and the depth of the weathered material or regolith.

The paper therefore has improved the understanding of the hydrological behaviour of the basement complex region, recommending that a unified rational approach to water resources planning and development that takes cognizance of actual hydrological behaviours of different landscape units is needed to ensure water security. To address water security challenges during the dry season, the paper recommends the targeting of efforts to capture runoff from high generating landscapes during rainy season for storage in small earth dams or the augmentation of groundwater resources through artificial or enhanced recharge of aquifers in downstream areas with deep weathered zones. The areas with deep weathered material within the catchment identified in this research are crucial in any successful water resource development in the region. This will improve the livelihood of the people in the area through improved access to water during difficult times of the year.

References

Adams S (2009) Basement aquifers of southern Africa: Overview and research needs. In Rian T, Hans B, Shafick A and Leslie S (eds), *The Basement Aquifers of Southern Africa Report to the Water Research Commission*, WRC Report No. TT 428-09 August 2009

Adelana SMA, Olasehinde PI, Vrbka P (2003) Isotope and Geochemical Characterization of Surface and Subsurface Waters in the Semi-Arid Sokoto Basin, Nigeria, *AJST*, Vol. 4, No. 2

Adelana, SMA, Olasehinde PI, Vrbka P (2006) A quantitative estimation of groundwater recharge in part of the Sokoto Basin, *Journal of Environmental Hydrology* 14, p5

Anderson HR, Ogilbee W (1973) Aquifers in the Sokoto Basin, Northwestern Nigeria, with a description of the general hydrogeology of the region, *U.S Geological Survey, Water Supply Paper 1757-L*

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large Area Hydrologic Modeling and Assessment, Part I: Model Development. Journal of the American Water Resources Association (JAWRA) 34(1):73-89

Austine ON (2001) Forecasting Seasonal Rainfall for Agricultural Decision Making in Northern Nigeria, *Agricultural and Forest Meteorology 107, 193-205*

Ayoade JO, Bamwo Y (2007) Changes in Annual Rainfall Characteristics in Nigeria between 1931-1960 and 1961-1990. *The International Journal of Meteorology, Vol. 32, No. 318*

Bello NJ (1997), Investigating the spatial pattern of the characteristics of the onset and cessation of the rains in Nigeria, *GeoJournal* 43: 113–123

Chandra S, Nagaiah E, Reddy DV, Ananda Rao V, Ahmed S (2012) Exploring deep potential aquifer in water scarce crystalline rocks, *J. Earth Syst. Sci.* 121, No. 6, pp. 1455–1468

Chimphamba J, Ngongondo C, Mleta P (2009) Groundwater chemistry of basement aquifers: A case study of Malawi, In: Titus R, Beekman H, Adams S, Strachan L, (Eds.). *Basement Aquifers of Southern Africa.* WRC Report No. TT 428-09. ISBN 978-1-77005-898-9

Eagleson PS (1978b) Climate, soil, and vegetation, 2, The distribution of annual precipitation derived from observed storm sequences, *Water resources Research 14*, (5), 713– 721

Eduvie MO (2006) Borehole failures and groundwater development in Nigeria[1], Paper presented at a *National Seminar held on the Occasion of Water Africa Exhibition (Nigeria 2006) at Ikoyi Hotels & Suites, Victoria Island, Lagos*, on 15th November, 2006

Ekpoh IJ, Nsa E (2011) The effects of Recent Climatic Variations on Water Yield in the Sokoto Region of Northern Nigeria, *International Journal of Business and Social Science, Vol. 2 No 7*

Eyre SR (2013) Vegetation and Soils: A World Picture, 2nd edition, Edward Arnold *books.google.co.uk/books?isbn=1412851009*

Farmer D, Sivapalan M, Jothityangkoon C (2003) Climate, soil, and vegetation controls upon the variability of water balance in temperate and semiarid landscapes: Downward approach to water balance analysis, *Water Resour. Res., 39*(2), 1035, doi: 10.1029/2001WR000328

Fasinmirin, J.T., Olufayo, A.A. and Oguntunde, P.G. (2008) Calibration and Validation of a Soil Water Simulation Model (WaSim) for Field Grown Amaranthus. Int. J. Plant Prod., 2 (3), 269–277.

Graham W, Pishiria I, Ojo O (2006) Monitoring Groundwater Quality for Small-Scale Irrigation: Case Studies in the Southwest Sokoto-Rima Basin, Nigeria, *Agricultural Engineering International: the CIGR Ejournal, Vol.8*

Hassan WA (2000) Biological productivity of sheep and goats under agro-silvo-pastoral systems in Zamfara Reserve in north-western Nigeria, *Cuvillier Verlag*, Goettingen, Germany

Hazel JRT, Cratchley CR, Preston AM (1988) The location of aquifers in Crystalline and alluvium in Northern Nigeria using combined electromagnetic and resistivity techniques, *Quarterly Journal of Engineering Geology*, Vol. 21, 159-175

Hess, T.M. and Counsell, C. (2000) A Water Balance Simulation Model for Teaching and Learning: WaSim. HR Wallingford, Wallingford

Hess, T.M., Holman, I.P., Rose, S.C., Rosolova, Z. and Parrott, A. (2010) Estimating the Impact of Rural Land Management Changes on Catchment Runoff Generation in England and Wales. Hydrol. Proc., 24 (10), 1357–1368.

Holland M (2012) Evaluation of factors influencing transmissivity in fractured hard-rock aquifers of the Limpopo Province, *Water SA* Vol. 38 No. 3 *International Conference on Groundwater Special Edition*, Available on website http://www.wrc.org.za

Holman, I.P., Tascone, D. and Hess, T.M. (2009) A Comparison of Stochastic and Deterministic Downscaling Methods for Modelling Potential Groundwater Recharge under Climate Change in East Anglia, UK: Implications for Groundwater Resource Management. Hydrogeology J., 17 (7), 1629–1641.

Japan International Cooperation Agency (JICA), (1990) The Study for Groundwater Development in Sokoto State, *Unpublished Report Vol. II*, Federal Ministry of Water Resources and Rural Development, Nigeria

Kevin CN, Nicholas O (2010) Impacts of climate change on water resources in Africa: The role of adaptation. *African technology policy studies network (ATPS)*

Kogbe CA (1979) Cretaceous and Tertiary of the Iullemmeden Basin in Nigeria. In: C.A. Kogbe (eds), Geology of Nigeria, 2nd edition. Rock View, Jos

Kuppers K (1998) Evaluation of the ligneous strata of the vegetation of Zamfara Reserve, North-West Nigeria. In Hoffmann, I. (ed.) *Prospects of pastoralism in West Africa*, pp. 41-47

MacDonald AM (2005) Developing groundwater: a guide for rural water supply,ITDG Publishing, http://www.developmentbookshop.com

MacDonald AM, Calow RC (2009) Developing Groundwater for Secure Rural Water Supplies in Africa, *Desalination* 248, 546-556

Macdonald OMJ, Thompson DM, Herbert R (1995) Sustainability of yield from wells and boreholes in crystalline basement aquifers, BGS Technical Report WC/95/SO

Ndubuisi OL (2007) Assessment of Groundwater Recharge in Semi-Arid Region of Northern Nigeria: Using Soil Moisture Deficit Method. *Journal of Engineering and Applied Sciences* 2 (9), 1377-1382

Neil WA, Huq S, Brown K, Conway D, Hulme M (2003) Adaptation to Climate Change in the Developing World. *Progress in Development Studies 3, 3 pp. 179-195*

Offodile ME (2002) *Groundwater Study and Development in Nigeria*, Mecon Geology and Engineering Services Ltd, Jos, Nigeria

Oteze GE (1979) *The Hydrogeology of North-Western Nigeria Basin*, In: C.A. Kogbe (eds), Geology of Nigeria, 2nd edition. Rock View, Jos

Parry ML, Canziani OF, Palutikof JP, Van der Linden PJ, Hanson CE (eds), (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Reports of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 982pp.

Robins N, Jeffrey D, John F (2013) Groundwater supply and demand from southern Africa's crystalline basement aquifer: evidence from Malawi, *Hydrogeology Journal* 21, 905–917, DOI 10.1007/s10040-013-0956-5

Sambroek WG, Zonneveld IS (1971) Ancient Dune Fields and Fluviatile Deposits in the Rima-Sokoto Basin, North-West Nigeria. *Soil Survey Papers* No. 5. Soil Survey Institute, Wageningen, The Netherlands

Schäfer C (1998) Pastorale Wiederkäuerhaltung in der Sudansavanne: Eine Untersuchung im Zamfara Forstschutzgebiet im Nordwesten Nigerias, *Cuvillier Verlag*, Gottingen, Germany

Sokoto Agricultural and Rural Development Authority (SARDA), (1988) Sokoto Fadama Shallow Groundwater Study, *Unpublished Field Report Vol. II*, Ministry of Agriculture, Sokoto

Tripathi MP, Raghuwanshi NS and Rao GP (2006) Effect of watershed subdivision on simulation of water balance components, *Hydrol. Process.* 20, 1137–1156

UNDP/FAO (1969): *Soil and Water Resources Survey of the Sokoto Valley, Nigeria,* Final Report, Vol. V, Soil Survey and Land Classification

WaterAid (2007) *Climate Change and Water Resources*, produced by ERM for WaterAid, 47-49 Durham Street, London, SE11 7JD

Wyns R, Baltassat M, Lachassagne P, Legchenko A, Vairon J, Mathieu F (2004) Application of SNMR soundings for groundwater reservoir mapping in weathered basement rocks (Brittany, France), *Bull. Soc. Geol. Fr.* 175(1) 21–34