HYDROLOGICAL PROCESSES AND WATER RESOURCE MANAGEMENT IN SOKOTO BASEMENT COMPLEX REGION

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ABSTRACT

The achieved success reported by WHO and UNICEF Joint Monitoring Programme (JMP) in March 2012, on the Millennium Development Goals (MDGs) target 7c was greeted with outcries regarding the skewedness of the reported global figures. This is in view of the fact that there are still about 783 million people (more than one in 10 people in the world) without access to drinking water. This paper is aimed at examining the hydrological processes and water resource management in Sokoto basement complex. To achieve this, a one dimensional model was developed and utilised to assess the state of water distribution within the study area using measured meteorological variables and information about different landscapes within the complex. The model simulated the soil water storage as well rates of input and output of water in response to climate using data from 1991 to 2000 inclusive. The study identified six major geomorphological landscape units which significantly controls the hydrological behaviour of the basement complex catchment; the paper also revealed 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. This study concludes that modelling approach can be used to assess the hydrological situation and to better understand water distribution within a basement complex for appropriate development. The paper suggest that for water resource management, the rich areas to be targeted are the fadama, fractured rocks and cultivated landscapes; while areas to be avoided are the non-fractured rocks, bare surface and forests landscapes.

Keywords: Hydrological Processes, Water Resource Development, Basement Complex, Modelling, Semi-Arid

INTRODUCTION

The achieved success reported by WHO / UNICEF Joint Monitoring Programme (JMP) in 'Progress on Drinking Water and Sanitation 2012' (UNICEF/WHO, 2012) that the Millennium Development Goals (MDGs) target 7c [*reduce by half the proportion of people without access to sustainable water supply and basic sanitation by the year 2015*] had been met 5 years ahead of schedule, was greeted with outcries regarding the skewedness of the reported global figures which masked massive disparities between /within regions and countries.

The report however, highlights that the world is still far from meeting the MDG's target for sanitation, and is unlikely to do so by 2015. The most notable opinion is that the target is yet to be achieved because there are still about 783 million people (more than one in 10 people in the world) without access to drinking water. Out of this figure, China has the largest number with about 119 million people, followed by India with 97 million, and then Nigeria with 66 million (UNICEF/WHO, 2012). The remaining 304 million people are distributed in the so-called least developed countries (LDCs), who lack the capacity and resources to confront this huge challenge (Ford, 2012; Lake, 2012; Onda *et al.*, 2012; Bradley and Bartram, 2013; Pullan *et al.*, 2014).

Sub-Saharan Africa is within the arid and semi-arid part of the continent characterized by limited water resources and increased pressure of accessibility due to expanding urban, industrial and agricultural water requirements. WHO/UNICEF (2012) reported that globally, over 40% of all people who lack access to drinking water live in Sub-Saharan Africa. The problem persists more in the region because of slow and poor technological advancement, low incomes and institutional capacity to mitigate the problem (MacDonald, 2005; Kevin and Nicholas, 2010; WHO, 2011).

Water is the major limiting constraints to development in many sub-Saharan African countries. Water is one of the critical factors that determine settlement and development of people in Nigeria. As water demand is increasing due to modern developments, changing life styles and population growth, the challenges of meeting the increasing demand became necessary for improving development and economic growth of the region. There is therefore the need for good understanding of the hydrological processes that controls the occurrence of both surface and groundwater resources in order to devise the best way of managing it. Water balances, which calculate catchment inputs and outputs, are another way of understanding the hydrologic setting and functioning of catchment systems, as well as analysing the sustainability of water resources (Dingman, 2002).

In basement complex areas within Sub-Saharan Africa such as parts of the Sokoto basin in northwest Nigeria, groundwater is heavily relied on as major source of water supply. This water is unevenly distributed spatially below the surface, and its occurrence is highly dependent on climate, geomorphology and landscape distribution in the region. High rainfall variability has over the years increased the occurrence of severe drought or floods during the wet seasons (Ati *et al.*, 2009; Ekpoh and Nsa, 2011; Ati *et al.*, 2012). The aggravation of changing characteristics of seasonal rainfall due to changing climate may have compounded the uncertainty and vulnerability of water resources in Sokoto basin.

In the Sokoto basin, groundwater is the primary water source in the basement complex areas accounting for 70% of rural water supply (CIGEM, 2006). It forms a vital source of water in areas where surface water sources are not sufficient to meet the demand for water or due to dryness of rivers and streams during dry season. The basis for sound water management starts with the reliable estimation of the quantity of water moving in and out of any hydrological system (Healy *et al.*, 2010). Understanding the hydrological balance is therefore a prerequisite for efficient and sustainable water resource management in this region. Hydrological modelling is a valuable, if not essential tool for this purpose. The advantage of hydrological modelling is that they can be used for hydrologic prediction and to improve the understanding of hydrologic processes because all the terms of the hydrological balance can be estimated over an unlimited time frame; thus, providing scientific basis for research and management of water resources.

This research which focused on basement complex areas comes from the recognition of increasing stress on available water resources, and over dependence on groundwater in the

Sokoto basin. The geology of a catchment strongly controls the occurrence and distribution of groundwater in the basement complex region (Macdonald and Edmunds, 2014). Water occurrence is dependent on rainfall but with a complex relationship with the hydro-climatology and geomorphology of the area which determine the availability and accessibility of the resource (Calow and MacDonald, 2009).

Many studies have been conducted throughout the world looking at hydrological processes for different catchments e.g. Ragab *et al.* (1997), Finch (1998), Flerchinger and Cooley (2000), Wesemael *et al.* (2000), Scanlon *et al.* (2002), De Silver (2005), Rushton *et al.* (2006), De Silver and Rushton (2007), Eilers *et al.* (2007) and Schulz *et al.* (2013). But the hydrological processes in basement complex semi-arid catchments like the Sokoto basin presents some interesting challenges due to the combined effects of climate, geology and landscape complexes. Estimating the hydrological processes in a basement complex region with a complex landscape pattern is even more challenging considering the high spatial variability in hydrologic processes occurring on different heterogeneous landscapes in the catchment.

The aim of this paper is to identify the major geomorphological landscape features that influence and control the spatio-temporal hydrological processes in the study area.

STUDY AREA

The study area is part of the basement complex area of the Sokoto basin located in the north-western part of Nigeria between Latitudes 11° 30´ to 12° 00´ N and Longitudes 4° to 7° E. The region forms the major river basin of the riverine lowlands of the Rima valley.

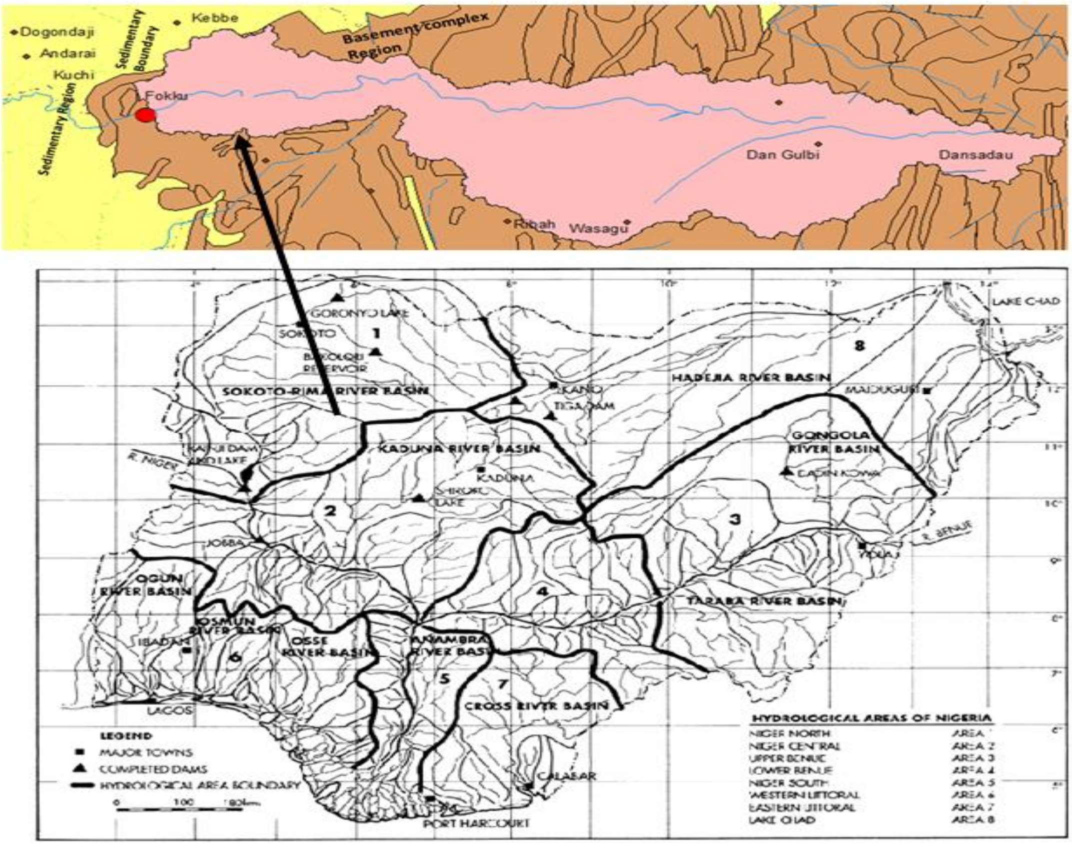

Fig. 1: The study area showing the catchment boundary
Source: www.fao.org

The area lies within the crystalline basement complex region of northern Nigeria dominated by low and highly variable precipitation and evapotranspiration, and complex geomorphological landscape units that are not addressed by most hydrologic models. Thus, this catchment presents problems to hydrologists in their hydrological processes assessment where they occur. To overcome these, there is need to understand the interaction between different geomorphological/landscape features and how their spatial variability and distribution e.g. land use, topography, soils and vegetation determines the hydrological behaviour of the area.

The occurrence of groundwater in the region is restricted to areas with thick weathered overburden or the presence of fractures that are capable of holding water. The spatial distribution of these features is also related to the variability of geomorphological landscape features from one location to another.

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 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 Inter Tropical Discontinuity (ITD) and largely determines the onset and cessation of rainfall at a particular time of the year (Bello, 1997). 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. There is high variability in the annual rainfall received at different stations within the basin, with rainfall being higher towards the south-eastern part around Gusau and Yauri than in the northern part of the basin at Sokoto. The average annual rainfall ranges from 500 mm around the northern boundary with Niger Republic to 1500 mm towards the southern edge of the basin (NIMET, 2012).

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 of 9^oC in the cold season (from early December to early February) to a daily maximum of 45^oC from March to end of May.

A brief description of the geology in the study area has been given by Anderson and Ogilbee (1973), Kogbe (1989) and Offodile (2002), as a series of crystalline massif rocks outcropping to the east and south of the basin consisting of granite gneisses, schist, phyllites, quartzites and some amphibolite, diorite, gabbro and marble of pre-Cambrian age. The rocks are fractured and deeply weathered in many places especially in the western part of the catchment JICA (1990). The lowlands and plains of the basement areas are sometimes covered on the surface by Quaternary sediments of Aeolian and fluvial origin especially along the flood plains of the major rivers and streams (Offodile, 2002). Japan International Corporation Agency (JICA, 1990) reported similar geological observation as aforementioned and added that the basement complex occupies about 42 % area of Sokoto basin.

In the crystalline basement rocks of the Sokoto basin, boreholes yield very little, if any water from the weathered rock (Anderson and Ogilbee, 1973; Oteze, 1979); therefore, the water bearing alluvium in the fadama is often the best source of water to boreholes because it is usually very permeable. Due to the high stream gradients in the crystalline-rock areas, the alluvium is commonly coarser and contains less silt than that found in the fadama of the sedimentary areas. These alluvium in the smaller stream valleys however, become dewatered during the dry season due to high abstraction and the water table declines into the underlying un-weathered crystalline rocks (JICA, 1990; Offodile, 2002). In the fadama (along rivers and stream floodplain), an average alluvium thickness of 14 m can be found in some locations, with a width of up to 2 miles, an average water-table gradient of 0.6 m per mile and the rate of ground-water flow of 3785 l/h through the cross section of the fadama (Offodile, 2002).

The soils within the catchment area falls within four major groups in the Harmonised World Soil Database (HWSD, 2012) and 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 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 (Kuppers, 1998; Schafer, 1998; Hassan, 2000). 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 (Eyre, 2013).

The major sources of water supply in the study area are the surface waters (rivers and streams), and groundwater (boreholes and hand dug wells). The rivers and streams are seasonal and therefore utilized during the rainy season. Utilization of surface water is mainly for livestock and domestic usage such as building and construction works, because the water requires some form of treatment before direct consumption by the people due to poor quality. People therefore mostly prefer to abstract groundwater from dug wells which are cheaper to construct than boreholes, of which there are few within the region due to their cost (Iliya and Gada, 2010).

Quantifying the number of hand dug wells in the study area is practically impossible because they are abundant throughout the area. They are the principal source of water supply in the rural areas where a dug well can be found with almost every single house. The major problem of dug wells in the basement areas is that they have a shallow water table with high seasonal fluctuation and mostly dry up during dry season. The sanitary condition around the dug wells is also of great concern because the water can easily get polluted due to man's activities and sometimes natural conditions.

MATERIALS AND METHODS

The method 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. A summary of the data types used in this research and its sources are given in Table 1.

The overall study area (River Ka catchment) was estimated using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of Nigeria with 90 m resolution. Using the ArcGIS software, calculation of flow direction was done to determine the extent of flow directed into each cell. Flow accumulation was later executed to estimate the amount of water accumulated into each cell. The river Ka outlet (gauging station at Fokku), otherwise known as a pour point in ArcGIS was located using geographical coordinates and arc catalog to determine the watershed outlet point. Finally, the flow direction and pour point layer were fed into the watershed tool to estimate the area of the watershed contributing water to the river Ka. The total area of the gauge catchment is calculated as 9631 km^2.

Table 1: Description of data types for the paper

Type of Data	Available Records		Nature of Data/ Source	Location
	From	To		
Rainfall & Temperature	1991	2000	Daily records / (NIMET)	Gusau station
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 Fieldwork Processes

Fieldwork was conducted in the three selected areas as follows: Dansadau, Ribah and Fokku from 17th June – 30th August 2012. Visit 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 (fractured or non-fractured) and their runoff behaviour after rainfall.

Potential evapotranspiration was estimated using the Hargreaves method and other processes were computed using a water simulation model 'WaSim' (Hess *et al*, 2000)

Modelling

The data and information gathered from the fieldwork in addition to that from literature were used to model the hydrological process; to validate their behaviour against information given in literature and reports; and to aggregate all the information to the catchment scale. A description of hydrological processes in response to precipitation input as simulated in WaSim model is presented in Figure 2.

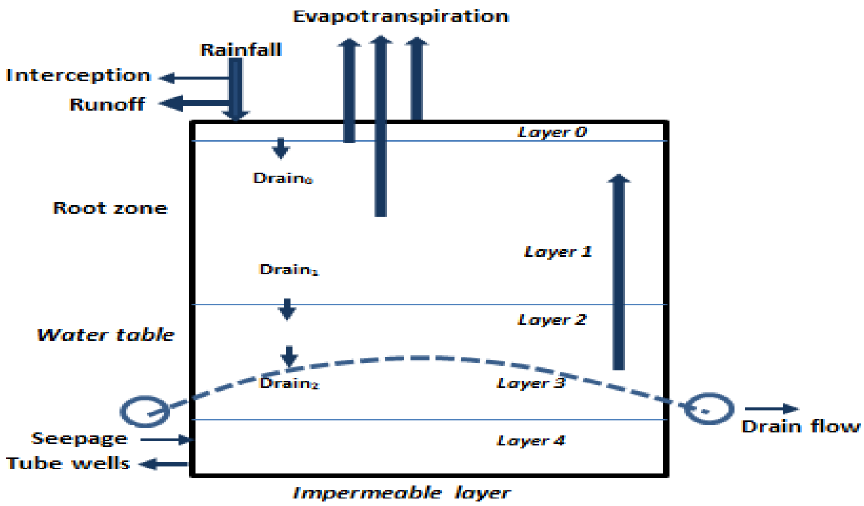

Fig. 2: Water flow processes and distribution in WaSim (After Hess *et al.*, 2000)

Conceptualisation of HRUs as Landscape Units

The study area requires that the geomorphological landscape 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 one is trying to assess. In this research, six major Landscape Units (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, 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.

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 results of the ten years simulation is given in Table 2 with a total rainfall for the ten year period as 10602 mm.

Table 2: Ten years hydrological balance for different geomorphological landscapes

No	Conceptual Landscapes	Total for 10 Years (1991 – 2000)				
		Rain (mm)	Runoff (mm)	AET (mm)	Groundwater discharge / Outflow (mm)	Surplus / Deficit Balance (mm)
1	**Residential 1**	10602	2930	6347	1314	11
2	**Residential II**	10602	2958	6352	1281	11
3	**Bare Surface I**	10602	6000	4545	0	57
4	**Bare Surface II**	10602	6002	4698	0	-98
5	**Forest I**	10602	378	10183	0	41
6	**Forest II**	10602	475	10049	0	78
7	**Fractured Rocks**	10602	2745	2560	5283	14
8	**Non-Fractured Rock**	10602	8042	2560	0	0
9	**Cultivated I**	10602	2185	6927	1493	-3
10	**Cultivated II**	14221	3314	8155	2743	9
11	**Cultivated III**	10602	2162	6974	1451	15
12	**Cultivated IV**	14221	3242	8143	2822	14
13	**Fadama**	22983	6921	11230	4667	165

Source: Fieldwork, 2015

The Runoff Processes

In the overall hydrological balance, the non-fractured rocks has largest runoff processes equalling to about 800 mm of the runoff generated (Figure 3). The fadama has the second highest individual landscape contribution of runoff generated in the 10 year water balance having about 700 mm of the total. Then followed by fractured rock landscapes with over 400 mm 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.

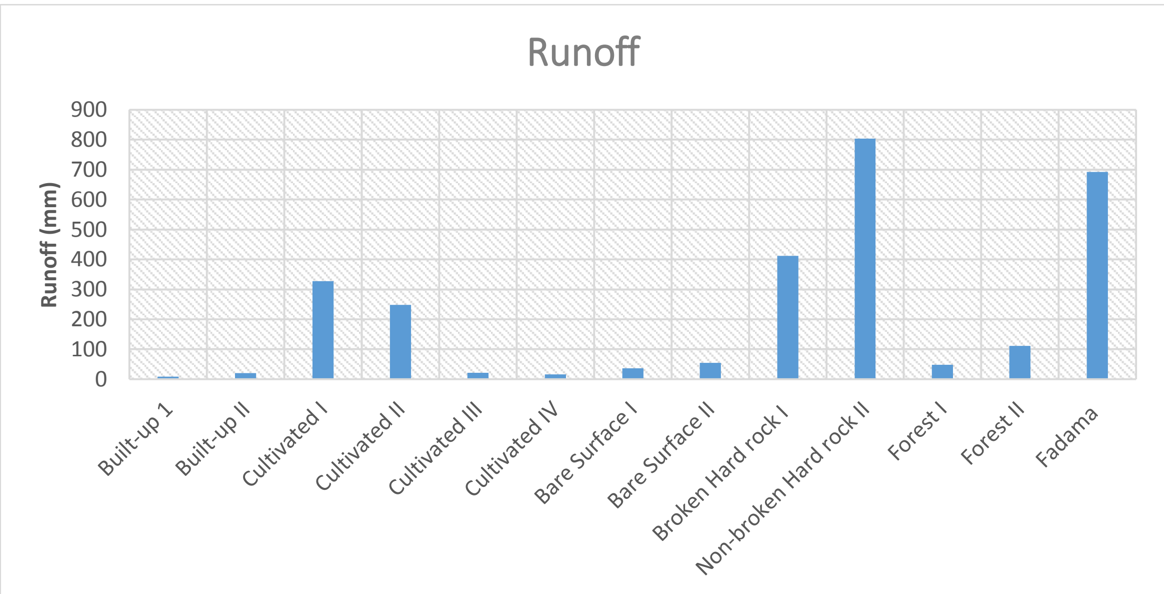

Fig. 3: Area weighted runoff contributions from individual landscapes

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 (< 100 mm combined) compared to for example, the four cultivated lands with total land area of 30%, which together, contributes about 400 mm of runoff totals.

The Actual Evapotranspiration (AET)

The cultivated landscapes I - IV contribute the highest area-weighted AET in the catchment hydrological balance as shown in Figure 4. The four landscapes together occupy about 30 % total land area of the catchment and together contributes over 2300 mm of the total AET. The forest has the second highest contribution with a little over 2000 mm of the total AET. The fadama is third, contributing over 1000 mm of the total AET. Despite the large AET contribution from the fadama of about in the hydrological balance, its relatively small land area (10%) compared to cultivated lands I-IV makes its contribution smaller than the former.

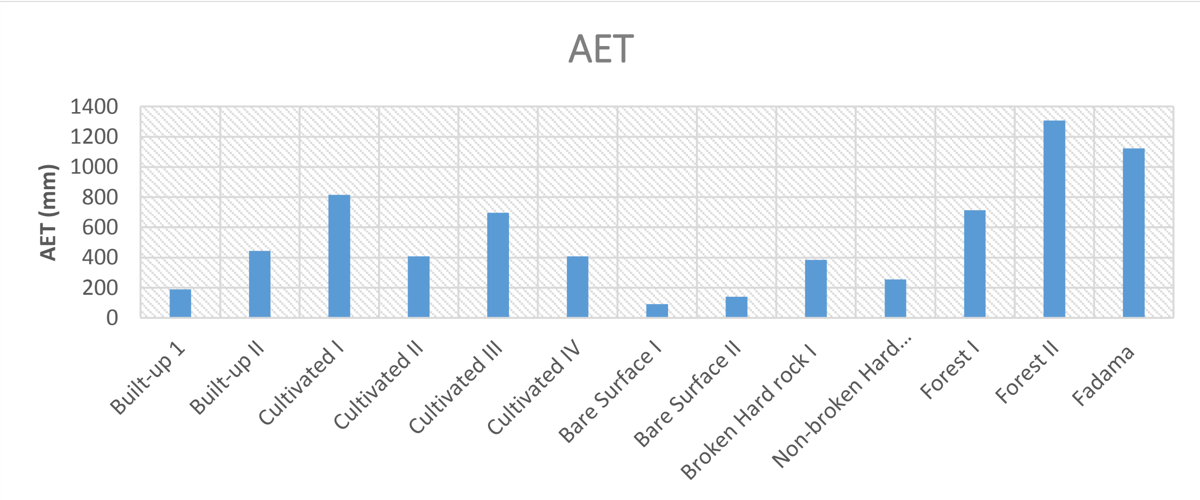

Fig. 4: Area weighted actual evapotranspiration from different landscapes

The built-up areas and hard rocks contributes near similar amount of over 600 mm each in the overall catchment hydrological balance despite the fact that hard rocks (broken and non-broken) occupy three times the land area (30%) of the built-up 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 bare surfaces have the least AET in the total catchment hydrological balance, contributing a little over 200 mm of the total. This is not unexpected because of the small land area and absence of vegetation on bare surfaces.

Groundwater Outflow

Figure 5 shows that the highest contribution is the fissure outflow from fractured rocks, which alone accounts for about 800 mm 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.

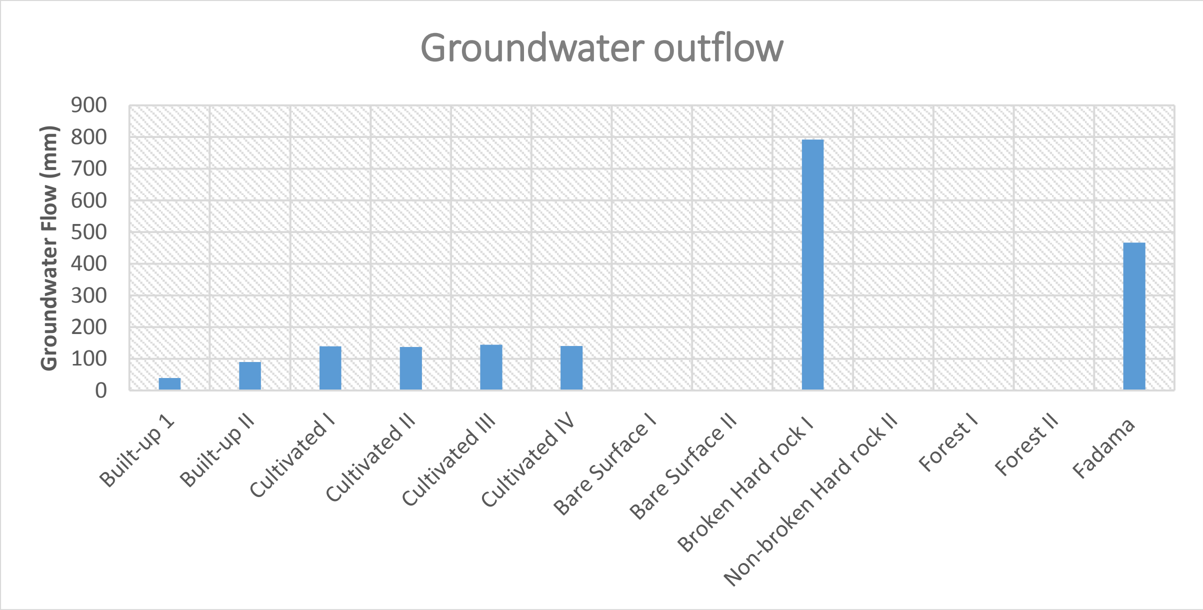

Fig. 5: Total area weighted groundwater outflow from different landscapes

The cultivated lands (I-IV) and fadama contributes near similar groundwater outflow (> 450 mm). 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, this results in a high amount of groundwater outflow. The built-up landscapes contributes small groundwater outflow (>100 mm) to the catchment hydrological 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 bare surfaces due to the surface nature of the landscape.

CONCLUSION

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 geomorphological landscape units were identified which have significantly different hydrological behaviour which controls the water balance of the basement complex catchment. They represent the built-up areas, cultivated lands, bare 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.

Despite a number of functional government agencies (e.g. SRRBDA, State Water Boards and other NGOs) responsible for water resource management, people in the study area are in most cases left with the responsibility for their own water supply Most of the water supply programmes established by the responsible agencies failed within few months or a year after their commissioning. This is largely due to lack of monitoring and supervision or improper maintenance. The local people therefore have to devise other ways to source water for their needs; the cheapest and most viable option being the hand dug wells constructed in many households.

The weathered basement rocks are known to provide avenues through which water can be developed for community water supply. What is needed is a unified rational approach to water resources planning and development that takes cognizance of actual hydrological behaviours of different landscape units. The areas with deep weathered material within the catchment identified in this research are crucial in any successful water resource development in the region. Attention should always be focussed on areas with deep weathering which normally render the impermeable crystalline rocks suitable for admission and storage of water.

For water management, 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. Most important locations are the deep weathered zones of cultivated lands and fadama landscapes, the natural springs of the fractured rocks and fadama valleys with lots of springs during the rainy season and groundwater outflow. This will improve the livelihood of the people in the area through improved access to water during difficult times of the year.

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